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The Virtual Scylla: an exploration of "serious games", artificial life and simulation complexity

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Abstract This paper addresses the integration of artificial life simulations with interactive games-based technologies and describes how the results are being exploited not only for scientific visualisation and education, but also for fundamental research into simulation complexity, focusing on the behavioural representation of species in fragile or long-vanished landscapes and ecosystems. Earlier research is described that supported the development of a virtual recreation of a submerged Mesolithic river valley, discovered during petrochemical surveys of the Southern Basin of the North Sea. Using pollen sample records and vegetation predictions from previous studies, a new alife "engine" was developed that simulated the interaction between "artificialised" vegetation and environmental factors, thus helping researchers to postulate pre-glacial melting migratory and settlement patterns of ancient civilisations from continental Europe to the British Isles. More recently, and to take advantage of the existence of a more accessible and living ecosystem, work has been conducted in collaboration with the UK's National Marine Aquarium, this time focusing on the *Scylla* Artificial Reef—a Royal Navy frigate scuttled off the coast of Cornwall in South West England. The resulting "serious games"-based test beds are now providing the foundation for scientific investigations into how models and simulations of marine ecologies behave under different measures of complexity. The exploitation of the artificial life and underwater rendering efforts in others areas, including education and naval training, are also described.

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1 Introduction

Virtual Heritage has become one of the few active application domains to survive from the technology-driven Virtual Reality "era" of the 1990s. Projects throughout the final decade of the 20th century produced a range of interactive 3D archaeological "exhibits", including 3D models of Stonehenge, Pompeii, the Caves of Lascaux, the Basilica of San Francesco d'Assisi and the Tomb of Nefertiti (Stone 1999). These projects have attracted considerable interest from organisations such as English Heritage and UNESCO and even prompted the launch of an international Virtual Heritage Network. Unfortunately, many of the Virtual Heritage demonstrations to date have been very sterile—lacking the dynamic natural features evident in the real-world, such as environmental effects and the life cycles of flora and fauna. From an underwater perspective, again very few examples of virtual archaeology exist and, of those that have been developed, most exist in a form that is not accessible to a wide population of beneficiaries—scientists, schoolchildren, students, even members of the general public.

This paper describes the first two phases of a research programme under way at the University of Birmingham that seeks to develop a fundamental understanding of how *artificial life* concepts can be used to drive "serious games"-based simulations of the evolution of British coastal marine flora and fauna communities on and around Europe's first (and currently only) artificial reef, the ex-Royal Navy Frigate HMS *Scylla* scuttled in 2004. In very broad terms, artificial life is the scientific study of the behaviour of biological organisms and systems in order to simulate how they interact with, and exploit, their natural environments in order to survive, reproduce, colonise and evolve (or "emerge"). Environmental and species data from the *Scylla* Reef have been used to undertake early research into the relationship that different measures of complexity have on simulations of Marine Biology. Experiments on behavioural, model and data complexity have examined how these measures affect the results of simulations, especially with regard to accuracy in comparison to real-life data.

The main aspiration of the *Virtual Scylla* project is the development of long-term evaluation and prediction tools, charting the condition of the *Scylla* Reef and its ecosystems as they may be influenced by colonisation dynamics, environmental changes, pollution, physical decay and other factors. Appropriate-fidelity, real-time visual and behavioural simulation techniques (based on contemporary *games engine* technologies, e.g. Stone 2005) are being exploited to deliver the results of the research in a form suitable for supporting further scientific research and educational awareness. The research is also relevant to maritime archaeology activities, from the digital archiving of historical wreck sites and associated artefacts, pre-dive planning and safety training to larger coastal and marine management programmes.

1.1 Artificial reefs

Artificial reefs, constructed using scuttled vessels, aircraft, surplus military equipment or modular subsea "building blocks", are becoming increasingly popular as a means of creating, restoring or regenerating marine ecosystems, particularly in areas where natural reefs are absent, or have been destroyed through pollution, erosion or catastrophic environmental events such as Tsunamis. The artificial reef "movement" is particularly active in the US (home of the Reef Environmental Education Foundation, or REEF), from locations off the coast of California, South Carolina, Florida, to the Gulf of Mexico, where the toppling of redundant oil rigs to provide marine "safe havens" forms part of the US Minerals Management Service's *Rigs to Reefs* Initiative. New Zealand and Canada are also active, with high profile sinkings by the organisation Canadian Artificial Reef Consulting of numerous vessels, including the HMNZS *Wellington* (another ex-Royal Navy *Leander* Frigate, HMS *Bacchante*), featured in the *National Geographic* 2006 video "The Ship Sinkers".

As well as playing a key role in the regeneration process, artificial reefs are becoming an important source of educational material, raising the awareness of schoolchildren and public audiences to the importance of protecting global oceanic resources. The results of marine biological research performed using artificial reefs could also benefit the offshore engineering community in the future development and maintenance of wind farms, oil and gas platforms and subsea habitats. Such research is also relevant to maritime archaeology management, including English Heritage's Historic Environment Local Management, or HELM coastal and marine initiatives (Roberts and Trow 2002) and *the Ministry of Defence's* Salvage and Marine Operations Unit's activities, such as the survey of HMS *Royal Oak* in Scapa Flow for oil removal planning (e.g. Flack and Rowland 2006).

In due course, it is hoped that the research will also provide scientific support for future (and responsible) at-sea disposal of large merchant and military marine vessels and other forms of artificial reefs. Despite earlier European Union initiatives such as European Artificial Reef Research Network (EARRN), this represents an activity that has yet to be embraced by UK and continental European organisations to the same extent as those in the USA and Canada (witness regular online articles from the US Maritime Executive and the Artificial Reef Society of British Columbia). However, it is felt that the *Virtual Scylla* project described herein is an early positive step in the right direction.

1.2 HMS *Scylla*

On 27 March 2004, Europe's first artificial reef was "launched" by the National Marine Aquarium (NMA), as a result of the scuttling, in Whitsand Bay (off the southeast Cornish coast), of the ex-Royal Navy Batch 3 *Leander* Class Frigate, HMS *Scylla* (Leece 2006). HMS *Scylla* (Fig. 1) was the last frigate to be built at Devonport Dockyard in 1968. During her service in the Royal Navy between 1970 and 2003, she saw action in the Icelandic Cod Wars of the 1970s, engaging in a tit-for-tat ramming session with the Icelandic gunboat *Aegir*. She missed active duty during the Falklands crisis in 1982, due to an extensive modernisation programme, as a result of which she was equipped with *Exocet* and *Seawolf* missile systems. Much later, in 1991, *Scylla* took part in *Operation Desert Storm* in the Middle East.

After decommissioning in 1993, *Scylla* was moored in Fareham Creek near Portsmouth, from where she would normally have been removed in due course for dismantling at a commercial scrap yard or sold on to another one of the world's navies. However, some 7 years later, and supported by the South West Regional Development Agency, she was purchased by the NMA for £200,000 and towed back to her "birthplace" in Devonport Dockyard for pre-scuttling stripping, cleaning and hull modifications to support safe penetration by divers.

Fig. 1 HMS *Scylla*, in her operational heyday (image courtesy of the National Marine Aquarium)

Today resting on the sea floor at a keel depth of 24–26 m (depending on tidal conditions, Fig. 2) and close to another famous West Country wreck—the torpedoed US Liberty Vessel *James Egan Lane*—the *Scylla* provides an excellent opportunity for conducting regular validation and verification studies throughout the course of the *Virtual Scylla* project. Indeed, at the time of writing, the authors of the present paper have undertaken four expeditions to the wreck, accompanied by marine and technical specialists from the NMA. The expeditions have yielded a considerable amount of information about the declining condition of the vessel and colonisation cycles of various forms of marine life, and the use of the Aquarium's *VideoRay* remotely operated vehicle (ROV, Fig. 1) has been invaluable in this respect. As well as the NMA, stakeholder and technical support for the project has been forthcoming from the Marine Biological Association (MBA), the Society for Underwater Technology (SUT), Plymouth Marine Laboratory (PML) and the University of Plymouth's Marine Institute.

2 Artificial life

Artificial life or *alife* is "the study of man-made systems that exhibit behaviours characteristic of natural living systems" and such systems attempt to "synthesise life-like behaviours within computers and other artificial media" (Langton 1986, 1989, 1995). In what way can a man-made system exhibit such characteristics? Concepts central to the study of alife have been exploited in the study of biological entities and, in the discipline's formative years as a new science, the field has seen a tremendous increase in the applications of its principles to the solution of real-world

Fig. 2 Images from the stern of the *Scylla* Reef, from a *VideoRay* ROV survey (August 2008)

problems. These include controlling multiple robot systems using natural group or "collective" behaviours (Kube and Zhang 1993), *Swarm Smarts*, where software agents mimic models of ants and social insects to solve complex problems such as the rerouting of traffic in a busy telecom network, cooperative robots and paint booth scheduling in a truck factory (Bonabeau and Theraulaz 2000). A host of other applications, including data mining, economics and music have been reviewed by Kim and Cho (2006). One of the fundamental concepts in alife is *emergence* (Holland 1998), more appropriately understood via theories of complexity (Lewin 1993; Waldrop 1993; Holland 1995), coupled with experiments on cellular automata (von Neumann and Burks 1996; Langton 1986; Kauffman 1996).

According to Holland (1998), the hallmark of emergence is a sense of "much coming from little", where, in true Gestalt fashion, the behaviour of the whole is much more complex than the behaviour of the parts. The interaction of the local rules of these decentralised agents (Resnick 1994) necessarily generates spontaneous self-organisation and self-assembly, a phenomenon in nature fundamental to studies related to alife. Extracting the principles behind nature's fundamental mechanisms into a set of simple rules for synthesising nature and for ecosystem-specific problem solving is gaining more and more research attention (Kim and Cho 2006). This serves to demonstrate the power of contemporary alife techniques, which model a minimum set of rules sufficient for synthesising the effects of nature.

Building on these principles, the ultimate goal of the *Virtual Scylla* project is to develop a comprehensive interactive simulation of marine ecosystems on and around artificial reefs and marine engineering structures (offshore oil/gas platforms, wind farms, turbines, etc.). The integration of alife and Virtual Environments to develop visually rich, interactive scientific tools for assessing and predicting the status of ecosystems based on biological lifecycles and environmental change offers a new, challenging and highly topical research opportunity. Very few researchers have tackled the complexities of merging the two fields of endeavour and only one example has been found that specifically addresses the marine environment. That project (Refsland et al. 1998) was based on a multi-participant virtual aquarium simulating a region of the Great Barrier Reef. However, the project was highly conceptual in nature and did not result in any real-world implementation.

2.1 From the Mesolithic North Sea to the present-day English channel

The initial impetus for the *Virtual Scylla* project evolved from a research study that resulted in the development of a Virtual Environment representation of a world that existed in Mesolithic time, over 10,000 years ago, before the Ice Age glaciers melted and flooded what is, today, the Southern Basin of the North Sea.

In the mid-to-late 1990s, Southern North Sea seismic datasets gathered by Petroleum Geo-Services (PGS) revealed a significant topological feature in the form of part of a large river valley, some 600 m wide with an observed length of 27.5 km (Ch'ng et al. 2004). The river landscape, which, during the period from 8,000 to 18,000 years before the present day, seemed to form part of a large plain on which, according to geographical and archaeological specialists Reid (1913) and Clark (1936), offered habitable conditions for hunter-gatherers moving between what is now the British Isles and Continental Europe. The long-submerged river has been named the *Shotton*, after the famous Birmingham Pleistocene geologist Prof. Fred Shotton (1906–1990). Amongst his many achievements, Shotton specialised in military geology, initially helping to locate water supplies for troops in North Africa and the Middle East during the Second World War. One of his most famous contributions to the War involved the generation of geological maps of the D-Day landing sites, pinpointing those littoral regions that might be problematic for the deployment of military vehicles.

Bringing together geological, geographical and archaeological researchers at the University of Birmingham, a research project was established with two major aims. Firstly, to develop theories relating to the migratory and settlement patterns of ancient civilisations from continental Europe to the British Isles. Secondly, to suggest how these patterns may have been influenced by the existence of natural food and dwelling construction resources around the Shotton River. To do this, a new alife visualisation system was developed called the *SeederEngine* (Ch'ng et al. 2005). The basic premises behind the functioning of this engine were quite simple, namely that each artificial life entity has the ability to sense and react to environmental changes and each entity has a preferred condition with upper and lower tolerances for sunlight, moisture, temperature, elevation, soil type, nutrients, CO_2 and space. As the condition exceeds the preferred level, the health of the alife entity will decrease until it expires.

The *SeederEngine* consisted of three main modules: a Real-Time Rendering Engine, an ALife Engine and a "Seeder Manager" which managed the environment and plants. The environment component managed the initial settings of the virtual environment, such as the 3D terrain, simulated temperatures, moisture, sunlight and season, stored as an Ecosystem XML file. The plant component of the Seeder Manager managed the different species of plants, including 3D representations of growth stages from seed to maturity and characteristics of reproduction, competition and adaptation to environmental factors. Predictions of

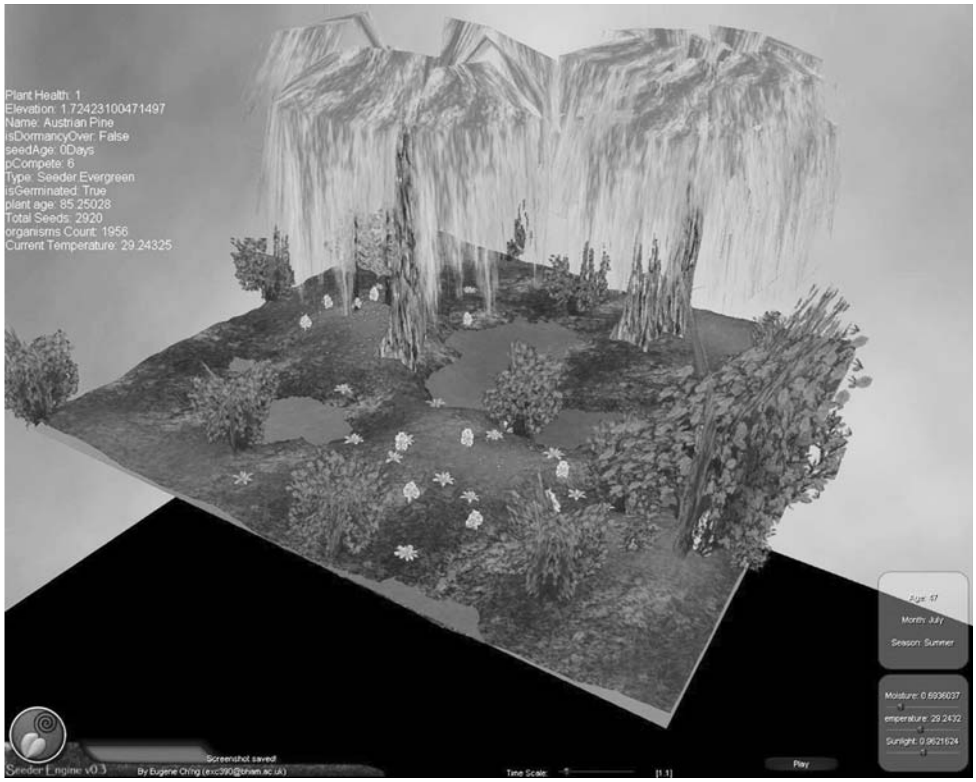

Fig. 3 Simulated growth of Mesolithic era vegetation using the *SeederEngine*

large-scale past vegetation for specific regions of Mesolithic Northern England, at a latitude that approximates that of the Shotton River Valley, were based on research by Spikins (1999) and others. The Rendering Engine was integrated with the ALife engine, displaying the state of growth of individual virtual plants as they grew and competed for simulated resources (e.g. Fig. 3).

Experiments with the *SeederEngine*, addressing the collective interaction between synthetic vegetation and simulated environmental factors produced a range of impressive results, many comparable to their natural counterparts. Indeed, the results of these experiments established the *SeederEngine* concept as a strong scientific framework for supporting geo-archaeological and landscape visualisation and for understanding the collective behaviours of these artificial vegetation (Ch'ng et al. 2005; Ch'ng and Stone 2006).

As well as delivering scientific visualisations of the alife simulations, there was also a need to develop a more user-friendly system, capable of supporting real-time exploration as may be required in educational settings by students or non-marine biology experts. Additional consultation was sought with archaeological subject matter experts in order to populate the results emerging from the *SeederEngine* with credible 3D representations of dwellings and campsites that may have been in evidence at that time (e.g. Waddington 2003). The resulting scenarios were used to construct visually rich virtual environments using a proprietary games engine (Ch'ng and Stone 2006). Due to a number of factors, such as the wide expanse of the Shotton River Valley and the need for high visual fidelity in the representation of plants and other environmental features, the engine of choice in this case was Crytek GmbH's *CryEngine*, the "power" behind the first-person action game *FarCry* (Fig. 4, upper image). In addition to the games-based simulation, a simplified, more distributable and Web-friendly version of the Shotton scenario was implemented, using the Cortona VRML Client (Fig. 4, lower image).

3 The *Virtual Scylla*—first steps

The early *SeederEngine* and *CryEngine* explorations were reasonably successful in helping a multidisciplinary academic team to begin to understand the geographical dispersal and possible life cycles of a variety of plant forms that may have existed around the Shotton River in Mesolithic times. However, a fundamental challenge still faced the development team in their attempts to establish credibility for this promising alife tool. Without the ability to be able to validate, or (at the very least) compare and contrast the results of the alife simulations with real-world counterparts, the research might well become just an interesting academic software exercise. Obviously travelling back in time to the Mesolithic era was not an option in this

Fig. 4 *CryEngine* (*upper image*) and VRML (*lower image*) renderings of a Mesolithic settlement

instance! Consequently, attention was focussed on attempting to identify a more contemporary ecosystem for study—one that was at an early stage of development, was accessible for comparative research exercises and was reasonably straightforward to incorporate into a real-time visualisation package. It was at this point that the *Scylla* Reef became the focus of interest and early discussions began with the NMA and the MBA, both based in Plymouth.

As well as visually simulating the life cycles of static life forms such as vegetation, and having discussed various options with the NMA and MBA, it was believed that the rules developed in support of the *SeederEngine* research could be extended to account for dynamic (mobile) sealife forms (including Crustaceans, Cetaceans, Cephalopods, Echinoderms, etc.). However, there was high degree of early scepticism shown by the marine biologists, particularly relating to how well the wreck of the *Scylla* could be represented, with particular concerns that the exploitation of gaming software might actually trivialise the science behind the study of ecosystems. To allay the fears of these subject matter experts, a pilot study was conducted with the aim of demonstrating the power of interactive 3D techniques.

One of the problems facing serious games developers today is that there are many game engines and 3D development toolkits available (e.g. see DevMaster.net), moreso than was ever the case for the Virtual Reality era. However, despite this, if one is searching for an engine with real-time surface and sub-surface marine rendering capabilities, many (at the outset of the *Virtual Scylla* project and even today) only focus on basic surface water effects such as reflection, refraction and Fresnel distortions. While these effects produce impressive results, they are not visible when one descends just a metre or so below the water surface. Very few mainstream computer games have ever exhibited a large proportion of deep underwater rendering and, of those that do, they are unable to represent the complex visual conditions.

As a result of earlier developments in visualising the Mesolithic River Shotton Valley, the first games engine to be investigated as a potential candidate to create the *Virtual Scylla* environment was the *CryEngine*. As well as the engine's ability to support large areas of open water (as is evident during the opening sequences of the game *FarCry*), the engine was particularly noted for its ability to accept imported 3D geometries relatively seamlessly. To confirm the choice of engine, a Royal Navy Type 21 Frigate model, downloaded from the Internet 3D Resource site TurboSquid, was imported into the *CryEngine* environment (Fig. 5). While most of *CryEngine*'s stock underwater plant objects were based on a more tropical climate, it was still possible to use these to obtain an early glimpse of how the *Virtual Scylla* subsea environment might look.

The Birmingham Team then set out to obtain as much data as possible about the *Scylla*, up to the point when she was scuttled in 2004, in order to construct as accurate a 3D (3ds Max) model as possible. In the event, and with the exception of images and schematics forthcoming from the NMA, plus access to a scale model built using plans held by Her Majesty's Naval Base at Devonport, very little information was available. Consequently the early 3D model of the vessel and her new underwater environment had to be

Fig. 5 Early *CryEngine* underwater test rendering of a "wrecked" naval vessel

Fig. 6 *CryEngine* rendering of the *Virtual Scylla* with controllable ROV and static diver

constructed from scratch, although (as mentioned earlier) the first *VideoRay* ROV expedition to the wreck, accompanied by divers from the MBA, helped significantly.

Once the 3ds Max model of the *Scylla* was completed it was imported into the *CryEngine* test environment to be scaled and textured (Fig. 6). Whilst the *Scylla* model itself looked reasonably convincing, the complete virtual environment was still devoid of an underwater "ambience". At that point, it was discovered that the *CryEngine*'s underwater fogging capabilities were less accurate than its above-water counter. Therefore, to create an acceptable underwater environment, all virtual water elements were removed from the demonstration and replaced with above-water fogging throughout. In addition, particle effects (simple, semi-transparent, sprites) were used to add an illusion of turbidity, as is evident in the real Scylla Reef's setting in Whitsand Bay. Finally, to complete the environment, a basic 3D model of an ROV was added. However, this provided one of the biggest challenges at the time, as the original *CryEngine* did not support any form of flying vehicle (which, of course, the ROV had now become, given the earlier removal of the limited underwater environment). It further transpired that, to achieve realistic ROV motion effects, any software modifications would have to be made deep within the engine's source code. As a result, the first *CryEngine*-based ROV was endowed with a very limited control system, with the vehicle's forward thrust set to be permanently on.

This problem was overcome when Crytek made their *CryEngine 2* product available, supporting not only flying vehicles, but gamepad controllers as well (thereby providing multi-axis control of such vehicles—albeit not to the level of realism as was required to simulate the dynamics of a real ROV). Unfortunately, the fidelity of the underwater scenes made possible with *CryEngine 2* was also unrealistic as, by trying to achieve a dramatic effect for first-person gamers, the result delivered a constantly modulating, refracted and distorted view of the world.

To overcome these limitations (and, in doing so, avoid having to invest considerable sums of money to secure full access to Crytek's software technologies), the decision was taken to investigate the capabilities of a little-known real-time 3D environment development tool, Act-3D's *Quest3D*. The Quest3D tool has many advantages over using commercial games engines, not least the fact that the product supports royalty-free licensing for developed applications. Real-time virtual environments developed using Quest3D can be distributed in the form of stand-alone executables, via a setup program that installs the application, or via the Web. Versions of the product also provide support for a variety of interactive devices, from joysticks to full CAVE implementations. Form the perspective of the *Virtual Scylla* project, the product provided support for the creation of an accurate and realistic control system for the virtual ROV, implemented using an Xbox gamepad controller. In addition, it was possible to create more realistic lighting and underwater distortion effects.

The final *Virtual Scylla* environment was constructed in the following stages. Firstly, the vessel and seabed models were rendered using a high level of exponentially increasing fog density. Secondly, a particle effect was linked to the camera position (i.e. the end user's viewpoint) such that particles were emitted at relative velocities to the camera's movement only (unlike the case for both *CryEngine* products, where particle effects were generated to encompass the entire virtual scene). Finally, a Gaussian blur filter was added to approximate focusing imperfections with the ROV's camera. Another effect supported by Quest3D was remote image refraction caused by the Perspex dome surrounding the ROV camera. The effect was simulated by rendering the first three stages to a texture and applying it to a virtual 3D dome within the environment. This approximated a common effect seen with underwater photography, when there is a tendency for cameras to adjust brightness levels rapidly to compensate for current lighting conditions (high dynamic range, or HDR processing). Implementing the effect within Quest3D endowed the *Virtual Scylla* scenario with an almost photorealistic appearance (Fig. 7) especially given the real-world lighting and turbidity conditions often witnessed on and around the Reef itself.

4 *Virtual Scylla* phase 2—artificial life and simulation complexity

As well as the *Virtual Scylla*'s potential in delivering real-time visualisation of colonisation processes for education and marine biology (to mention but two applications), a key benefit for academic endeavours is the ability to exploit the *Scylla* Reef as a test bed for fundamental simulation

Fig. 7 Quest3D rendering of the *Virtual Scylla*, showing the aft helicopter hangar (with damaged roof—*upper image*) and the foredeck area (showing side railings, bridge and remains of the *Exocet* launcher rails—*lower image*, cf. Fig. 1)

research. The Reef provides researchers access to a significant amount of complex data on the marine population, due to its location and status as a destination for the diving community, its promotion by the NMA and exposure by the media. First-hand accounts from dive teams of the annual rise and decline of communities of species provide rich datasets that can be reproduced for simulation. In addition, maintenance by the MBA of *MarLIN*, the online Marine Life Information Network (Hiscock and Tyler-Walters 2006), which encourages volunteer recording through the MBA's *Sealife Survey*, provides comprehensive records on the majority of species present on and around the *Scylla* Reef, as well as references to key marine biology research papers. Furthermore, ongoing debates relating to climate change have led to an increased need to predict how marine species might react to changes in their environment. If the ultimate aim of the *Virtual Scylla* project is to develop accurate models and simulations of marine ecosystems, one must first understand how the complexity of the modelled behaviour of species may affect the results of those simulations.

With so much data available, the alife simulation developer faces the problem of how much should actually be included. The general consensus is that models should be as simple as possible, but there is also an acknowledged need to understand the effect that complexity might have on the results or outcome of the simulation. Robinson (2006) suggested that a model "should be the simplest possible to meet the objectives of the study" and went on to state that simple models are easier to build, are quicker to run computationally and require less of a data overhead. Brooks and Tobias (1999) noted the surprising lack of research into simplification of models as did Chwif et al. (2000), who commented on the potential for more research into the effect of complexity. More recently, Robinson (2006) identified the future research directions of simulation to include model simplification methods and model representation methods. Of relevance to the *Virtual Scylla*, Fulton et al. (2003) examined the effect of complexity on marine ecosystem models and partly concluded that, whilst complexity leads to uncertainty in simulation outcomes, simplistic models tend not to produce realistic behaviour.

4.1 *Virtual Scylla*—early experiments in simulation complexity

Exploiting the *Scylla* as source of marine biological data has enabled an early examination of how models and simulations of marine ecologies behave under different measures of complexity. Complexity in this case has been defined as three factors: behaviour—the level of detail of behaviour assigned to artificial life agents; data—the resolution and form of input data; and scale—the spatial and population scales of simulations. A series of early experiments were conducted to address the following research question: what relationships do different measures of complexity have on the results of simulations of marine biology?

The simulations were based on a simple ecosystem comprising starfish, sea urchins and algae. From the *MarLIN* database mentioned earlier, basic lifecycle characteristics of these three agents were identified. For example, starfish (predators of sea urchins) feeding rates are inhibited by rising temperatures; sea urchins predate on algae; higher water temperature negatively affects the growth rate of algae. Each experiment evaluated simulations for the following properties, based on criteria defined by Brooks and Tobias (1999):

1. Accuracy—how does each model compare against the results of a benchmark model? The benchmark model may be based on real-life data, or it could be modelled

at a specific level of complexity, of which other models are derivatives.
2. Flexibility—how robust is each model under changing conditions? If the model for the simulation is changed, do the results maintain their integrity?
3. Validation—what is the probability that error contributed to the results? Are the results robust or could they be misleading?
4. Model Design—how has the method used contributed to the understanding of the model? What is the likelihood that the model could be re-used for further experiments, and how did the design contribute to this?

It was first hypothesised that models of lesser complexity would appear to be more accurate than models of greater complexity. However this accuracy may be misleading and under changing environmental conditions—models of lesser accuracy could well prove to be less robust. A second hypothesis considered that increasing the complexity of a model would lead to greater robustness; however, increasing complexity further would result in diminishing returns. Five experiments were conducted and each related to how one or more of the three identified properties of complexity: behaviour, data and scale affect the results of simulations. A summary of the experiments is given in Table 1.

The first experiment compared two sea urchin models, one having aggregated behaviour calibrated to achieve maximum accuracy, and the other being more reliant on a behavioural realism to achieve accuracy. The output from both models was compared with real-world data. Results found that, as expected, the aggregate model was more accurate, but the behavioural model tended to have greater variance in its results that corresponded to the variance in the real-world data.

The second experiment expanded on the first by taking the behaviourally adept sea urchin model, implementing several levels of behavioural detail and examining the relationship between behavioural complexity and diminishing returns in accuracy. It was demonstrated that increasing behavioural complexity would lead to diminishing returns in accuracy, as hypothesised. However, this tended to occur within behavioural domains. For each consecutive increase in behavioural detail for a behaviour type, such as foraging, a smaller difference is seen in the results. However, when a new behaviour type was added, such as hiding (when fleeing behaviour already occurs) there is a significant difference in the results, and this difference does not diminish with additional behaviour types.

Table 1 List of measures of complexity and marine life for each complexity experiment

Experiment	Measure of complexity	Marine life type
1	Behaviour	Sea urchins and starfish
2	Behaviour	Sea urchins and starfish
3	Data (with behaviour)	Mussels, starfish, and an abstract hierarchy of algae and other species
4	Data	Algae
5	Scale (with behaviour)	Sea urchins and starfish

The third experiment built upon the results found in the first to test the relationship between variance of water temperature and level of detail of behaviour. Input data with similar mean values over time, but different measures of variance, were considered along with a hierarchy of species that were ultimately controlled by water temperature. A series of simulations with both simple and more complex behaviour were compared against different models of waters temperature of varying realism. It was shown that, with low behavioural detail, variance in water temperature data had little difference on the results of simulations. Increasing behavioural detail led to systematic changes to the ecosystem where water temperature variance matched that of a benchmark model. This highlighted how models with increasing behavioural complexity may prove to be more robust under changing conditions.

The fourth experiment examined the effect that temporal resolution of data had on the probability of error during simulation. Lower resolutions of water temperature data were compared against a high resolution model, measuring the effect this had on the growth of algae *C. taxifolia.* The lower resolution models were optimised to better match the effect of higher resolution data. Both the end result and cumulative error of simulations using optimised models were compared with unoptimised models. It was found that unoptimised low-resolution data produced misleading results when compared to optimised low-resolution data. Using the temporal error rather than the final result to show how low-resolution data fit benchmark, the data highlighted how simple models could be less accurate than initial results suggested. This also suggested why more complex models could be more robust.

The final experiment considered the relationship between spatial scales, population scales and behaviour. Simulations of marine life agents used during the second experiment were compared over several scales. The purpose of the experiment was to first examine whether spatial and population scales would affect the overall result of simulations, and secondly whether the link between behaviour and other measures of complexity, seen in the third experiment, would apply during changing scales. The results suggested that increasing behavioural complexity over spatial and population scales did not appear to have a

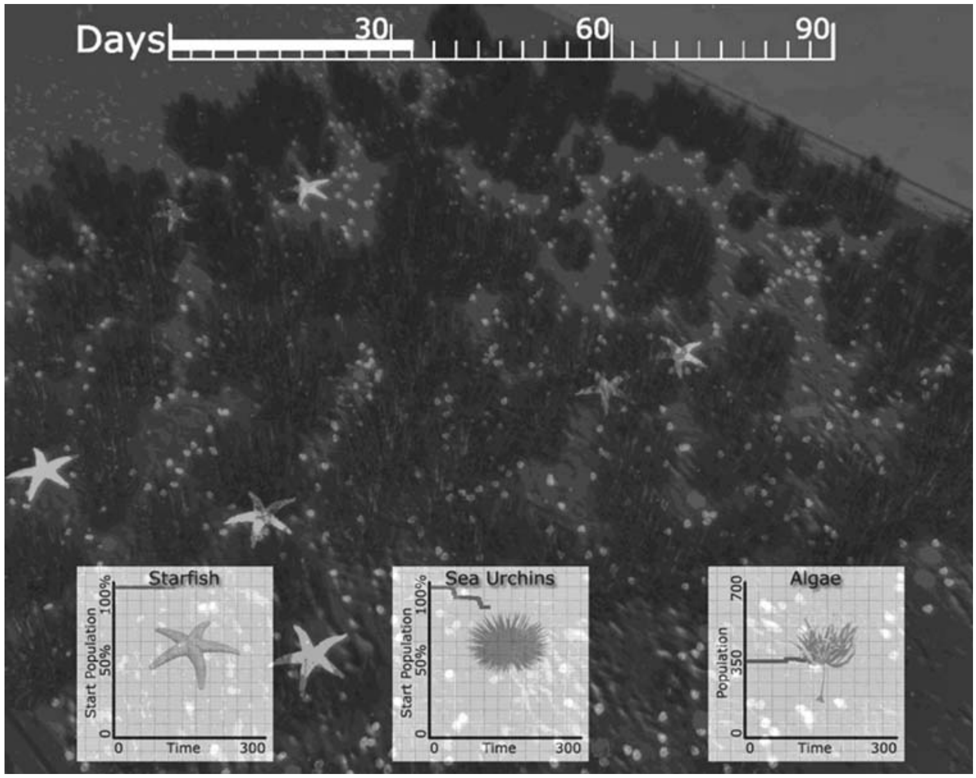

Fig. 8 *GEL* Engine "climate change game" screen shot showing 3D representation of starfish, sea urchins and algae, together with population change graphs

significant effect. It was found however that scale-adjusted variance of results decreased over uniform spatial and population increases.

The experimental results were visualised using custom built software libraries that as a package were named the *GEL* engine (Graphics and Environmental Libraries). The engine was written in C++, and the graphics were rendered using DirectX 9.0 although future incarnations of the engine would be required to be updated to DirectX 10.0 for the purposes of optimisation and the use of effects such as instancing—drawing multiple similar 3D objects in one rendering pass. As well as the academic value of conducting experiments to define appropriate levels of complexity in marine ecosystem simulation, this research has benefited the *Virtual Scylla* project in the form of an educational perspective "climate change game", shown in Fig. 8.

At the start of the "game" the user is made aware of each species' predatory behaviours and how higher temperatures may affect this and other behaviours. Two different choices are then given—firstly, the level of temperature change that will be simulated, from normal to normal + 5°C and secondly, the ratios of the predator species to each other. For example, the user can choose large numbers of starfish, large numbers of sea urchins or equal amounts of both.

The aim is that the user learns that predation is not always a negative factor. A few starfish eating sea urchins will allow a greater abundance of barnacles and algae without decimating the population of sea urchins. If too many starfish are present, the sea urchin population will be significantly reduced, and this will in turn result in increased mortality of starfish through starvation. The end user also learns that climate change could also lead to greater diversity, but perhaps only at certain temperatures. Normal sea temperatures could lead to starfish populations consuming most, if not all, sea urchin populations. If rising temperatures lead to a reduction in this consumption, then sea urchins could potentially thrive. Higher temperatures could, however, result in the reduction of algae and barnacles, reducing the food source for urchins, and hence the food source for starfish.

5 *Virtual Scylla*—next steps

It is planned to continue the above lines of alife research by gradually increasing the number of marine species and ecosystems in the simulations and delivering the results, not only with the aim of extending the complexity research, but to ensure that the results are delivered in an educational meaningful fashion, courtesy of the games-based technologies used. This is, perhaps, one of the most rewarding aspects of the *Virtual Scylla* project in that opportunities to develop "spin-out" demonstrations, not necessarily related to the original goals of the work, occur at regular intervals.

Fig. 9 Virtual "Sub Mission" game, designed using Quest3D to test and record the remote handling motor control skills of visitors to the National Marine Aquarium's "Aquatheatre"

Fig. 10 Quest3D rendering of the *LR5* rescue submersible approaching the bow of a virtual disabled submarine

For example, an additional interactive underwater "serious game" has been designed as a research tool to capture basic remote control skills of visitors to the NMA. The game is based on a virtual reconstruction of the Aquarium's Aquatheatre—in essence an underwater "assault course" for mini-ROVs housed within a large tank. Again exploiting a real-time engine developed using Quest3D, the Virtual Sub Mission (Fig. 9) supports research into such issues as visual fidelity, simulation of underwater physics (e.g. ROV buoyancy caused by bubble "stacks"), differing control input devices, the effects of input–output time delays and so on.

The subsea rendering effects developed for the *Virtual Scylla* are also being re-used in training demonstrations for the Royal Navy. For example, at the time of writing, one project is assessing the potential for games-based technologies to support training in submarine rescue, for both the current UK Submarine Rescue System (based on the *LR5* submersible) and the future NATO Submarine Rescue System, NSRS. The demonstration features a disabled *Kilo* Class submarine with which the trainee submersible pilot has to rendezvous and dock, using a combination of direct viewing through the submersible's main viewport and simulated closed-circuit TV views, based on virtual cameras mounted on the external hull of the virtual rescue system (Fig. 10). Turbidity, underwater lighting and backscatter effects, together with viewing dome distortions are also simulated, as with the *Virtual Scylla* ROV.

Another near-term aspiration is to create an online virtual world version of the *Virtual Scylla* centrally hosted and updated on a public server and accessed over a network by multiple clients on different platforms. Online virtual worlds are designed to deliver 3D content over the Internet, commonly using a client–server architecture (Benford et al. 2001) and the ubiquitous TCP/IP protocol stack. Many proprietary systems are available, but there are currently standardisation efforts underway to create formats and protocols to increase interoperability between virtual worlds.

In July 2008 an MPEG working group published an extended call for requirements for MPEG-V, a proposed standard for "intermediate formats and protocols for Information exchange with Virtual Worlds". Separately, Linden Labs is collaborating with IBM to open up the formats and protocols used by their popular online virtual world *Second Life* (Lentczner 2008). This will aid the implementation of other interoperable worlds such as *OpenSim* (OpenSim 2008). The most established standards in this area are developed by the Web3D Consortium and allow interactive 3D content to be delivered over the Web (Web3D Consortium 2008). X3D (which has been an ISO standard since 2005) is a successor to VRML and allows the description of a hierarchical scene graph in an XML-based or binary format. X3D is a componentised and extensible standard with commercial, academic and open source implementations on multiple platforms, making it an ideal environment for multi-user online virtual worlds (Bouras et al. 2005).

WebScylla, then, is a project that will attempt to demonstrate emerging Web3D technologies through the creation of a 3D model of the *Scylla* artificial reef for delivery over the Web. The focus of the project will be on delivering interactive 3D visualisations of scientific data collated by marine biology specialists (e.g. the *MarLIN* Database, mentioned earlier) and via other sources of Whitsand Bay environmental research (e.g. CEFAS 2005; Snelling 2006).

6 Conclusions

At the time of writing, interactive demonstrations based on the Quest3D "virtual ROV" and *GEL* Engine alife systems are being installed at the NMA and the Sealife Centre in Birmingham. Following the presentation of these technologies to a large audience of Plymouth schoolchildren at the NMA's Science Week in April 2008, it became obvious that the use of familiar games-based technologies could have a significant impact on their ability to grasp the impact of climate change and other environmental "stressors" on the Scylla's fragile ecosystems.

The *Virtual Scylla* project has, to date, delivered a number of exciting developments courtesy of the involvement of a highly multidisciplinary team, comprising specialists in graphics and software, human factors, marine biology, archaeology, underwater technologies and a host of others. Evolving from an early study involving a submerged Mesolithic landscape to one based around an artificial reef constructed using a scuttled ex-Royal Navy Frigate, there is little doubt that the scope for further research is huge. New species are being discovered and reported on the *MarLIN* Website on a regular basis and there is no doubt that this trend can only continue, especially with the ongoing changes to the world's climate and the subsequent impact on coastal regions.

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References

Benford S, Greenhalgh C, Rodden T, Pycock J (2001) Collaborative virtual environments. Commun ACM 44(7):79–85

Bonabeau E, Theraulaz G (2000) Swarm smarts. Sci Am 282:72–79

Bouras Ch, Panagopoulos A, Tsiatsos TH (2005) Advances in X3D multi-user virtual environments. In: Proceedings of the seventh IEEE international symposium on multimedia (ISM '05). IEEE Computer Society, Washington, DC, pp 136–142

Brooks RJ, Tobias AM (1999) Methods and benefits of simplification in simulation. In: Proceedings of the UK Simulation Society. UKSIM, Nottingham, pp 88–92

CEFAS (2005) Environmental impacts resulting from disposal of dredged material at the Rame Head disposal site, S.W. England: an analysis of existing data and implications for environmental management. Multidisciplinary contract research report for the Centre for Environment, Fisheries and Aquaculture Science (CEFAS Contract BA004). http://www.cefas.co.uk/media/29994/20050602_rame_head_report.pdf. Cited 14 Oct 2008

Ch'ng E, Stone RJ (2006) Enhancing virtual reality with artificial life: reconstructing a flooded European Mesolithic landscape. Presence 15(3):341–352

Ch'ng E, Stone RJ, Arvanitis TN (2004) The Shotton River and Mesolithic dwellings: recreating the past from geo-seismic data sources. In: Proceedings of the 5th international symposium on virtual reality, archaeology and cultural heritage, VAST04. The Eurographics Association, Brussels

Ch'ng E, Stone RJ, Arvanitis TN (2005) A virtual reality archaeological framework for the investigation and interpretation of ancient landscapes. In: Proceedings of internet and multimedia systems and applications, EuroIMSA 2005. IASTED, Grindelwald

Chwif L, Barretto MRP, Paul RJ (2000) On simulation model complexity. In: Proceedings of the 32nd conference on winter simulation. IEEE, Piscataway, pp 449–455

Clark JGD (1936) The Mesolithic settlement of Northern Europe: a study of the food-gathering peoples of Northern Europe during the early post-glacial period. Cambridge University Press, Cambridge

Flack S, Rowland C (2006) Visualising the invisible: visualising historic shipwrecks. ACM SIGGRAPH Comput Graph 40(3). http://www.siggraph.org/publications/newsletter/

Fulton EA, Smith ADM, Johnson CR (2003) Effect of complexity on marine ecosystem models. Mar Ecol Prog Ser 253:1–16

Hiscock K, Tyler-Walters H (2006) Assessing the sensitivity of seabed species and biotopes—the Marine Life Information Network (*MarLIN*). Hydrobiologia 555:309–320

Holland JH (1995) Hidden order: how adaptation builds complexity. Helix Books/Addison-Wesley, Reading

Holland JH (1998) Emergence from chaos to order. Oxford University Press, Oxford

Kauffman S (1996) At home in the universe: the search for laws of complexity. Penguin, Harmondsworth

Kim KJ, Cho SB (2006) A comprehensive overview of the applications of artificial life. Artif Life 12:153–182

Kube CR, Zhang H (1993) Collective robotics: from social insects to robots. Adapt Behav 2(2):189–219

Langton CG (1986) Studying artificial life with cellular automata. Evolution, games and learning: models of adaptation in machines and nature. In: Proceedings of the fifth annual conference of the Center for Nonlinear Studies, Los Alamos. North Holland, Amsterdam

Langton CG (ed) (1989) Artificial life. In: Proceedings of an interdisciplinary workshop on the synthesis and simulation of living systems. Addison-Wesley Publishing, Redwood City

Langton CG (ed) (1995) Artificial life: an overview. MIT Press, Cambridge

Leece (2006) Sinking a frigate. Ingenia 29:27–32

Lentczner M (2008) Second life grid open grid protocol draft 1. Linden Lab Publication, San Francisco. http://secondlifegrid.net.s3.amazonaws.com/docs/specs/SLGOGP-draft-1.html. Cited 10 Oct 2008

Lewin R (1993) Complexity: life on the edge of chaos. Phoenix, London

OpenSim (2008) OpenSim. http://opensimulator.org. Cited 10 Oct 2008

Refsland ST, Ojika T, Defanti T, Johnson A, Leigh J, Loeffler C, Tu X, Heudin JC (1998) Virtual Great Barrier Reef: a theoretical approach towards an evolving, interactive VR environment using a distributed DOME and CAVE system. In Virtual Worlds '98. Lecture notes in artificial intelligence no. 1434. Springer, Paris, pp 323–336

Reid C (1913) Submerged forests. Cambridge University Press, Cambridge

Resnick M (1994) Turtles, termites, and traffic jams: explorations in massively parallel microworlds. MIT Press, Cambridge

Roberts P, Trow S (2002) Taking to the water: English Heritage's initial policy for the management of maritime archaeology in England. English Heritage, London. [Crown Copyright. NMR (15044/14)]

Robinson S (2006) Conceptual modeling for simulation: issues and research requirements. In: Proceedings of the 38th conference on winter simulation, Monterey, California, pp 792–800

Snelling D (2006) The *Scylla* monitoring programme 2004–2006. Report compiled for the Department for Environment, Food and Rural Affairs (Defra)/National Marine Aquarium, Plymouth

Spikins P (1999) Mesolithic Northern England: environment, population and settlement. BAR British Series 283. Basingstoke Press, London

Stone RJ (1999) Virtual heritage: the willing suspension of disbelief for the moment. World Heritage Review. UNESCO, Madrid, pp 18–27

Stone RJ (2005) Serious gaming—virtual reality's saviour? In: Proceedings of Virtual Systems and MultiMedia annual conference, VSMM 2005. VSSM, Ghent, 773–786

Von Neumann J, Burks AW (1966) Theory of self-reproducing automata. University of Illinois Press, Urbana

Waddington C (2003) Howick and East Barns. Curr Archaeol XVI(9):189

Waldrop MM (1993) Complexity: the emerging science at the edge of order and chaos. Viking, London

Web3D Consortium (2008) Web3D Consortium. http://web3d.org. Cited 10 Oct 2008