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Engineering Simulation – Frontier to a New Capability

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Abstract

The aim of this paper is to examine some of the issues relating to the fast developing technology of engineering simulation. While simulation has long played a part in human exploration of the physical and even philosophical ideas it is only with the relatively recent innovation of cheap computing power and software development that it has become a significant engineering tool. A brief introduction into the origin of physics based simulation is provided and then two specific areas of research are explored. The distinction between mathematical modelling and simulation is also addressed as both are often used inappropriately. The first specific area of research explored details of how deterministic chaos problems can be handled, particularly relating to harm minimisation in helicopter crashes, this shows how data with very little if any statistically based relationships can still provide useful design information. The second study relates to Self-Organised Swarms and how the individual agents can be modified to generate useful emergent behaviour. The modification is based on processes drawn from nature in particular evolution and learning from experience. The last part of the paper deals with philosophical issues which are becoming more challenging as the technology matures and Virtual Reality technology becomes widely available.

Introduction

The construction of imaginary worlds seems to have been a practice that dates back to pre-history. There have been three distinct uses in the broadest sense in which this human construct was deployed to further human evolution. These three have, however, always overlapped in a rather confusing manner. The first of these and the main subject of this paper was to use this imaginary or virtual world as a space to practice skills and tactics which could then be used in the real world. For this to succeed it is essential the generated world exhibits the same features and physics as the real world.

The difficulty in the early simulations, often war or hunting games for strategy development and training, as today, was to ensure that the participants took it seriously. This need and difficulty is demonstrated by the challenge set by Ho Lo to Sun Tzu, and related by him in *The Art of War* about 500 BCE, to train his concubines in military drill (Butler-Bowdon 2010). He made the King of Wu's favourite concubines company commanders, over the other women of the court, and when they failed to take their role in the enactment seriously be-headed them. This, we are told, led to the replacements taking their roles very seriously.

The second use of imaginary worlds in early history was in the form of games. Games have not only been used as a form of entertainment but also as generating a space where behavioural experiments can be carried out with limited risk. The board game Chaturranga which was a predecessor of Chess is not really an early simulation, despite some claims to the contrary, as it makes no attempt to mimic the real world. It may still, however, be seen as having value in developing strategic thinking. This trend continues into modern computer games where participates can have superhuman capabilities and many lives.

The third use of imaginary worlds that can be traced from pre-history until today is in a sense the hardest to categorise. This where the virtual world becomes a cultural construct in for example drama, dance, religions etc.

All three of these categories of activities require the participants, and often an audience, to suspend belief and enter a world they know to be not real. This is as true for the Captain of an Airbus 380 simulator as it is for the teenager playing shooter games in the bedroom or the actor playing Hamlet and his audience. In this sense the human behaviour is common but the intended outcomes are very different.

Engineering Simulation

It is quite difficult to define when simulation became a practical tool in the technologies. Many observers regard the Link Trainer as the first manifestation of a technical simulator.

Figure 1: The Link Trainer

The link trainer was a pilot trainer developed in the 1930s. It was credited with increasing the speed with which allied pilots could be trained in WW11 and certainly reduced the risks involved. While it is undoubtedly the precursor of modern flight simulators it was really more a procedural trainer than a true simulator. Training simulators, particularly flight simulators but also maintenance, and management simulators drove the technology up to a decade ago and still training in its many applications dominates the market.

Computer based simulation

The first computer based engineering simulators used analogue computers. The simple reason for this is that dynamic simulation involves the ability to integrate between acceleration and velocity and again between velocity and displacement. While analogue computers are well suited to integration digital computers are not and have to depend on numerical approximation. In order to provide sufficient accuracy a considerable amount of calculation is required, a limitation on computers of the day, and to provide a realistic flight experience this has to be accomplished in real time. Despite this disadvantage it was obvious that the development of analogue based flight simulators was restricted both by their inherent unreliability and difficulty in programming.

The first reliable easily programmed digital flight simulators were 'mimics' (Page et al. 2006). The flight performance from a real flight case is recorded and then accessed as appropriate from look-up tables. This is a very efficient method for generating a flight simulator but does not involve any physics and is only applicable when operating within previously recorded events. This is still an approach that is often used particularly when a high fidelity is required that would involve a requirement for an unacceptably high computing capacity.

One common mistake in the application of these type simulators is to expect them to generate useful information in areas outside those built into the response. For example they have been wrongly used to investigate aircraft accidents but as the stored data cannot contain non-repeatable flight cases the results are often meaningless.

These 'mimic' type simulators still have many applications particularly within the training area. Their main advantage is that they present a closed ended teaching situation. That is to say a given action always leads to the same reaction. Thus the trainee can be rehearsed in a particular set of behaviours which lead to a successful outcome. This works well, from the trainer's point of view, in situations where the aim is to attempt to get the trainee to respond in a proscribed way to a particular stimulus and has thus found many applications in Military and Health and Safety training (Mitra et al. 2013).

Figure 2: An immersive mining engineering simulation at the University of New South Wales.

Figure 2 shows a highly advanced training simulator of this type that is used both to provide simulated underground experience to mining engineering students and demonstrate OH&S issues.

In recent times simulators have started to be introduced that use physics engines to generate the environment and behaviour. This has opened up whole new fields in this area of technology. It is now possible, and commonplace, to fly an aircraft or drive a car in a virtual space at an early stage of its design (Ahmed et al. 2007). This means that the handling and performance can be provided to the design team as they develop their design. Nor is this limited to artefacts, a factory can be simulated at an early stage of conception complete with the human interactions. They behave, however, very differently from the older 'mimic' type simulators as they attempt to capture the real variability associated with a real artefact or process. Their fidelity is however limited as they need to operate in real time making processing speed a critical limitation. In training they provide an open-ended solution meaning that the result of a given action is to some extent unpredictable. This presents challenges to trainers they are not always prepared to accept.

Simulation as against modelling

The difference between modelling and simulation is not easy to define though many attempts have been made. These have tended to revolve around the assumption of a basic temporal nature of simulation but this is not satisfactory. In most cases when referring to modelling there is the assumption that mathematical modelling is under consideration. In a mathematical model an attempt is made to relate physical phenomena via mathematical logic. This means that there is no physical relationship involved. In an experimental model an attempt is made to use, a usually, simplified physical model to predict the behaviour of the more complex phenomena under consideration. Simulation lies somewhere between these two methods where the individual processes within the simulation attempt to copy the real physical relationships. What this means in practice is that a mathematical model, as long as properly constructed can produce a precise solution but not a necessarily accurate one. On the other hand simulation lends itself to predictions that are accurate but not precise. In practice it is impossible in any reasonably complex simulation to obtain the precise solution, which means true optimisation is impossible, and thus the methods selected should reflect the desired outcome (Page et al. 2013).

Examples of simulation research

There is a great deal of research being undertaken using this relatively new simulation technology but in this section we will address only two that my research group is involved in.

Complexity

Complex problems present particular difficulties from the point of view of prediction which is the major requirement of engineering analysis. There are two distinct types of these problems but both lead to a chaotic solution. The simpler of the two leads to a chaotic solution but one in which the results have a statistical relationship to each other. Such problems are often referred to as statistically chaotic problems and there are a range of methods for solving them. In the second class of these problems there is no or at best a very weak statistical relationships between the one result and another. That is to say the past history of results does not allow future results to be predicted. A simple case of this, with only two possible sensible outcomes, is the tossing of a coin. No matter how many times it has been tossed and the history recorded the likely next result remains just as unpredictable. These problems, particularly when more variables are involved, are called deterministically chaotic problems because although the process between input and output is deterministic a solution cannot be predicted with any degree of certainty. Such problems lend themselves to a simulation solution due to its ability to predict accurately. That is to say any generated solution will be a possible solution but not necessarily the one seen in the real world.

An important problem in aerospace engineering is the protection of the occupants of a vehicle in the event of a crash. Helicopters, in particular, present the designer with major problems. It is possible to mitigate possible injuries but that depends on an accurate predictions of the loads applied to the occupants which in turn depends on the impact loads on the aircraft (Pearce et al. 2011, Pei et al. 2014).

While it is not possible to predict the load in any particular case it is possible to fly a flight simulator a large number of times and record the results.

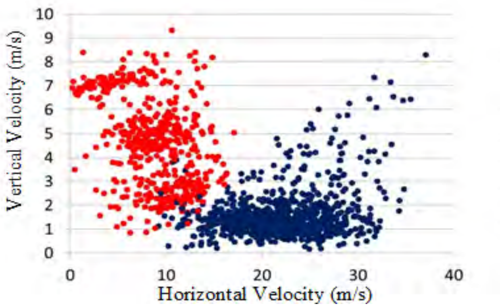

Figure 3. The results of a number of simulations of the impact of a helicopter after engine failure (Pei et al. 2014).

The red points are impacts resulting from engine failures within the area of the flight envelope that are believed to lead to serious harm while the conditions leading to the blue points are deemed less hazardous. It is not possible to find a relationship between the initial conditions and the resulting impact velocities but the data does indicate that there are different zones of results. This gives some basis for confidence in the aircraft's safety envelope.

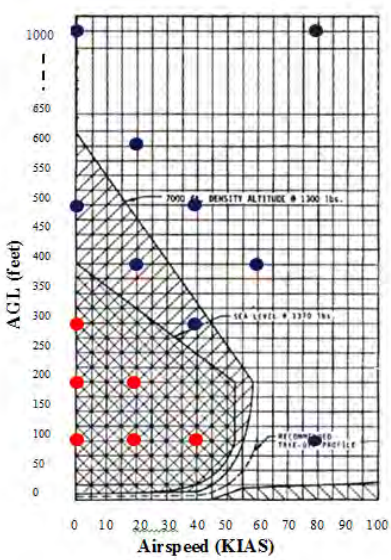

Figure 4. A typical flight safety envelope for a light helicopter (Pei et al. 2014).

The double hatched area is regarded as the values for airspeed and altitude above ground level (AGR) where serious injury is most likely to occur after an engine failure. It should be noted the worst condition is when flying low and slow that part of the plot being known colloquially as 'coffin corner'.

The six initial conditions marked as red spots are within the area of the flight envelope regarded as unsafe and lead to the generation of the cloud of red points in Figure 3. While the blue spots are taken from the less critical region giving rise to the cloud of blue points.

Though the points cannot be directly used for structural load predictions for the helicopter due to any one result being as likely as any other the information can still be used. It should also be noted that any additional tests will result in more points located somewhere within the cloud though their actual location is not predictable. The space which they occupy is, however, significant as any real crash should generate points within this space.

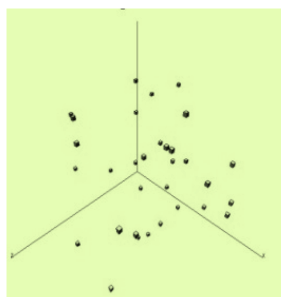

Figure 5. An arbitrary set of points.

Figure 5 shows an arbitrary set of points plotted on three axes. The result is they occupy a three dimensional area of space which can be bounded.

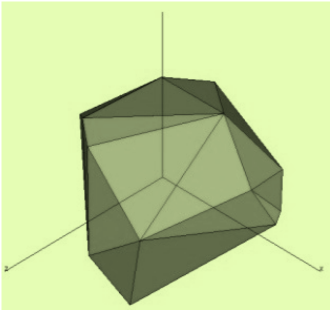

Figure 6. A complex hull.

Figure 6 shows a complex hull constructed so as to form the minimum space encompassing all the points. The Convex Hull Algorithm defines a space within which any real crash should occur. This space can then be searched to identify loads and accelerations that might occur in any real crash. This space can be pseudo-stochastically searched to find data that can then be used to minimise the risk of harm to the helicopter occupants, by design or operational modifications.

Cognitive Relationships

Distributed logic systems offer huge potential advantages. They are far more rugged than centralised systems and, if properly designed, can respond to environmental change much more rapidly. One of the main problems is that they can generate unexpected emergent behaviour. This can of course be a great benefit if the behaviour generated has a positive effect on the mission and thus there are currently significant efforts to predict it. Like the chaos problem, this is very hard to investigate with a mathematical model and may result in unexpected harm if a physical model is used.

One sub-set of these types of systems are swarms and particularly self-organising swarms. Craig Reynolds is often seen as the first researcher to really address this problem with his BOIDS (Reynolds, 1987). He was able to program agents with just three rules that resulted in complex behavior such as flocking and shoaling. This approach has now found applications ranging from power generation and distribution through industrial management to unmanned aerial systems.

Figure 7. A sea search using self-organising UAVs and a probabilistic algorithm (Sammons 2011).

As the initial condition and the environmental conditions, in a marine search, will change each time a search is undertaken the pattern of the response will vary as will the exact tracks taken by the agents which are thus not predictable.

Another proposed use of this technology, we have investigated, is in the managing of a swarm of spacecraft. There are some real advantages to launching and operating a system based on a number of simple spacecraft rather than one very complex vehicle. The disadvantage, is however that like all spacecraft, the system's life depends of the time before the fuel is exhausted. It is thus important that each agent within the cluster operates such that the swarm remains sound as long as possible if necessary at the expense of an individual agent.

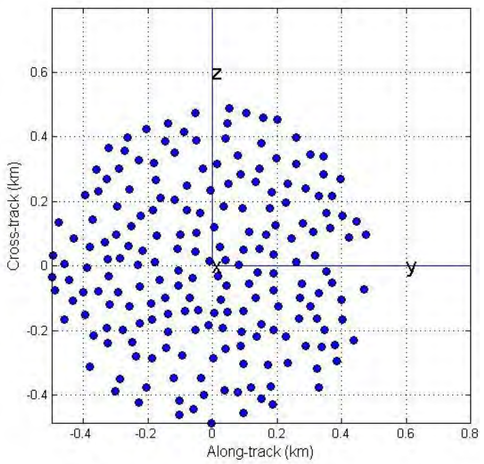

Figure 8. A swarm of spacecraft plotted on a plane (Page et al. 2014).

As each of these spacecraft is orbiting the earth at the same speed, same altitude, but on a different track the swarm will rotate each orbit. Due to disturbances each vehicle will have to use some thrust to fine tune its location. This will in general result in the outer members of the swarm using proportionally more fuel that those at the centre. The mission will be regarded as complete when sufficient vehicles have exhausted their fuel that the swarm can no longer carry out its mission. One solution to this problem is to initiate the mission with different fuel capacities in each agent so all the fuel is exhausted at the same time. This is, however, rather problematic as it depends on accurate predictions of the perturbations the individuals within swarm are likely to encounter. An alternative procedure is for each agent to construct a projected fuel cost map and adjust its behaviour to maximise the useful life of the swarm.

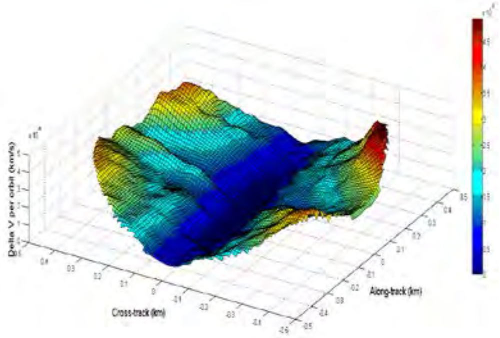

Figure 9. A projected fuel map of a satellite swarm (Page et al. 2014).

Each individual agent can now either change its location within the swarm to reduce or increase its projected fuel use to correspond to its colleagues or sacrifice itself by staying in a high fuel area to prolong the mission in a degraded form. This is a dynamic map based on each agent knowing the fuel state and location of the others. As each decision is enacted or perturbation occurs, the environment changes thus changing the individual agents behaviour and thus that of the swarm.

Initial Rule Selection

There is an inherent weakness in this swarm approach and that is that to initiate the behaviour a set of rules has to be selected. As the behaviour that will emerge is unpredictable at best, the rules that have such a profound effect on the swarm are really only a calculated guess.

One solution to this is to allow the individual agents to develop their own rules. There are two sources of the rules that lead to the collective behaviour of the swarm. The first is related to the physical properties of the agents and can be seen as analogous to nature while the other relates to the much more nebulous control laws that can be seen as analogous to nurture.

The first of these can be treated as a simple rule set that can be modified to improve the swarm behaviour by using evolutionary methods as in the case of a biological system. A set of plausible rules are set determining the physical behaviour of the individual agent. The simulation is then run a number of times and the emergent behaviour is recorded, the rules are then evolved by breeding the most successful agents (Price et al. 2006, Stonedahl et al. 2008).

There are two types of swarms we have investigated; homogeneous, where all the agents are identical and heterogeneous, where each individual is significantly different. The former is relatively easy to evolve as the improvement can be easily followed.

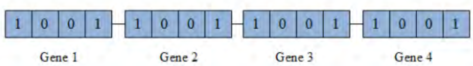

Figure 10. Homogeneous swarm chromosome coding (Tzi-Chieh Chi et al. 2014).

As can be seen the genetic makeup of a heterogeneous agent is rather more complicated.

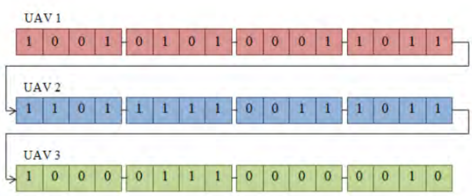

Figure 11. Heterogeneous Swarm Chromosome Coding (Tzi-Chieh Chi et al. 2014).

In practice while it is relatively easy to show the improvement in evolving rather that arbitrarily choosing as set of rules for a homogeneous swarm we have yet to achieve this for a heterogeneous one.

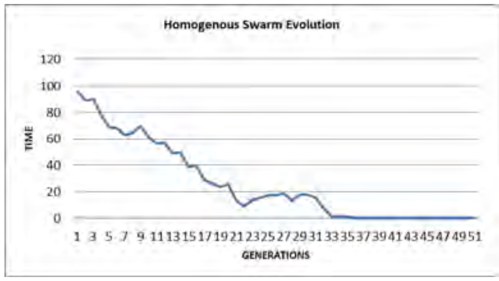

Figure 12. Simulation of homogenous swarm evolution to success (Tzi-Chieh et al. 2014).

Figure 12 clearly shows how the improvement increases up to about generation 33 after which there is no further improvement. It is expected that a heterogeneous swarm will perform better overall as it can take advantage of 'wisdom of crowds' but this is yet to be demonstrated (Galton 1907, Surowiecki 2004).

For the control, nurture, part of the problem improving fitness for purpose involves the agents learning from past events (O'Neil et al. 2014). The method adopted was to utilize neural networks. When these are combined with the physical mutations a somewhat complex picture emerges.

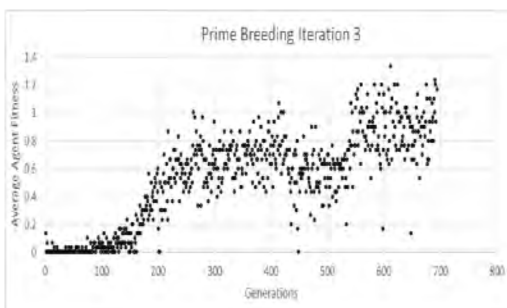

Figure 13. A typical fitness plot (O'Neil et al. 2014).

As can clearly be seen from the plot (Fig. 13) there are instances where the swarm loses fitness while the overall trajectory is toward improvement. There is also much greater scatter in the results for later generations. In practice one would not expect to go far beyond the 250th generation. At this point the improvement tends to level off. A deeper understanding of these phenomena will be generated by further research.

Metaphysics and simulation

Any new technology offers the possibility of providing the answer to everything. These phenomena can be clearly seen as a response to Newton's Mechanics, the early understanding of thermodynamics and again replayed in the early response to computers. From the simulation point of view it can be clearly dated from the publication of Nick Bostrom's paper in the Philosophical Quarterly in 2003 (Bostrom 2003). His thesis was very simple and quite compelling. Sophisticated simulation has now been available for about thirty years and has started to be combined with Virtual Reality capability for the last decade. Full computer based immersion is still quite crude but is improving rapidly and is already providing competition for simulators that combine real and virtual environments. In the most sophisticated of these, possibly the combat flight simulators, the participants express many of the physical and mental responses they would in a real combat aircraft. In other words they have completely, or nearly completely, entered an imaginary world. While we cannot yet get that degree of fidelity in an exclusively computer generated type virtual environment most researchers active in the field believe it will be achieved, the only dispute being how long. So when we can generate a virtual world which we cannot distinguish from the real world we will be expected to generate a large number of them. Nick Bostrom contends as their will be a multitude of simulated worlds as against one real one and an individual cannot distinguish between them the probability is we are all living in a virtual world. This is of course not far removed from Plato's Cave (Plato 360 BCE).

This proposition has generated a number of interesting ideas. The first criticism is that a virtual model of everything would require the same information as sustains reality which would of course be impossible. This argument fails due to the simple fact that one does not have to simulate everything only those parts one interfaces with. A simulator for an Airbus A380 does not have to model Paris when it leaves Sydney to fly there. In fact a simulated Paris only comes into existence when it is needed to provide realism to the simulation by which time the simulated Sydney no longer exists. The basic idea that observation causes existence and the state of that existence is hard to grapple with outside quantum mechanics where physicists appear to have no difficulty.

Another challenge this philosophical view raises is the topic of both space and time. Already, though the fidelity is not yet high I can cross my office and sit by a roaring fire in Tuscany. I can just as easily stand and watch the building of the pyramids in ancient Egypt. If the fidelity was such that to the observer it was impossible to distinguish these simulations from reality how is the experience different from physical or temporal travel?

A number of physicists have tried to determine methods for establishing whether the world as we know it is simply a simulation. One approach has been to look at the high energy cut off of the cosmic ray spectrum (Beane et al. 2012). While they do not discount the possibility of the physical world being a simulation they don't confirm it either. They did raise the interesting prospect at the end of the paper that if this is a simulation then one day we may be able to make contact with The Simulator, a rather theistic suggestion.

One final interesting issue that is raised by this area of enquiry. The apparent three dimensional spaces in the virtual simulation, are generated by a single string of code. This implies that we can generate three dimensional space from a one dimensional bit string. This of course provides a physical model for those physicists promoting concept of the digital universe (Zuse 1969).

Future work

As in any rapidly developing field there are almost too many research opportunities, which makes it hard to predict which will be the most fruitful areas to explore. There are efforts to increase computing capacity but at this stage the problem is how the existing capability should be utilised. The interfaces between the virtual world and a person in the real world is an area that seems to require a great deal of further development along with finding useful niches within technology where application of this capability will make a real difference. What will delay the progress of this capability most dramatically is the lack of researchers working in the field.

Conclusion

The main thrust and aim of this paper is to provide an overview to the reader of some of the progress being achieved in this new field of technology. It is drawing on the computer games industry and the arts to produce a useful tool but due to its newness the field is still confused. By using solid examples related to real engineering problems an attempt has been made to show some of the future possibilities these capabilities will unlock.

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