Towards a Continuum of Computational Building Simulation Tools to Support the Design and Evaluation of Complex Built Environments

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ABSTRACT

This paper describes the development of a Computational Building Simulation (CBS) tool, termed KRONOS that is being used to work on advanced architectural research questions such as user behaviour in buildings. The intention is to provide better support for dynamic space-time related research as well investigations into static building modelling and simulations such as energy performance. The authors (CSIR researchers) view CBS as a technical specialization of Building Product Models (BPM). The research findings, supported by two empirical case studies, indicated that building performance can not be predicted through the development of building and environmental models alone. It must be understood as a product of both an environment and its users. To study or predict building performance requires both advanced static and dynamic capabilities. The research team created a modelling and simulation environment based on a BPM. Within this environment agents and props were placed to dynamically simulate and predict user behaviour. The data from the case studies used in KRONOS indicated that the approach is feasible.

Keywords: **Computational Building Simulation, User Behaviour, Building Product Model, Architectural Design**

1.1 INTRODUCTION

Building Product Models (BPM) were originally intended to facilitate collaboration between different architectural and engineering design systems such as Computer Aided Design (CAD).

According to Eastman (Eastman, 1999) a building Product Model (BPM) is a digital information structure of the objects making up a building, capturing the form, behaviour and relations of the parts and assemblies within the building. A BPM is potentially a richer representation than any set of drawings and can be implemented in multiple ways, including as an ASCII file or as a database.

The current commercially available BPM's place much emphasis on the form and relationship of the parts, but very little on user behaviour. The International Alliance for Interoperability Industry Foundation Classes standard (IFC) is at this stage the most advanced and simultaneously complex general-purpose BPM available. The conceptual current IFC architecture (IFC 2x2) consists of four basic layers, i.e. Resource Layer, Core Layer, Interoperability Layer and Domain Layer. BPM's have also not previously been used for dynamic simulation in the built environment.

Due to resource constraints the team decided to use a much simpler model that contains the essence without making too many compromises. The closest existing model to fulfil this requirement was a XML based model offered by the Cambridge based Informatix company.

1.1.1 Reasons for Project

The research had useful precedents where attempts were made to improve architectural design in projects such as AEDES (Conradie, 1999), ARGOS (Conradie, 2000) and ESPACE. The latter software tool was produced in 2005 to efficiently study the proportions of different office space types in case study office buildings. This formed the basis for a new South African Department of Public Works space planning norm that was promulgated in September 2005 (Department of Public Works, 2005).

Analysing buildings can be complex because they need to be understood both as human creations as well as a physical entity. As human creations designs are developed that reflect social concerns, scientific theories and architectural trends. These are manifest in the completed building. A building not only structures how we use and experience the space it also influences internal environmental conditions. Building performance analysis must therefore reflect the performance of a building both in terms of human activities and experience as well as in terms of physical and environmental performance. (Assefa, 2007)

The built environment is very complex, requiring both static and dynamic simulations. At the moment many static type of simulations are widely used in academia and industry such as energy evaluation, shading simulation, daylight calculation, structural design, acoustical simulation and fenestration simulation. The Massachusetts Institute of Technology (MIT)

designed a multi-function design advisor that addresses comfort, energy, natural ventilation, day lighting, building codes and the life cycle aspects of design (MIT, 2005). MIT also created an innovative particle spring system that can be used to design thin shell type of structures using a similar approach to the catenary approach of the architect Antonio Gaudi (Kilian, 2005).

It was realized that the technical improvement of a BPM could offer the possibility to create a generic technical modeling and simulation platform. The researchers attempted to create a technical support platform, which is not only almost photorealistic, but also scientifically correct. The intention was that many different types experiments and building related evaluations could in future be undertaken on this generic technical platform.

In architectural simulations of the abovementioned nature one of the most important resources, time, has not been explored or utilized fully.

Recently an increased emphasis has being placed on the simulation of multiple physics. This is necessary so that complex building designs can be better explored and validated.

In the light of abovementioned it was decided to first concentrate on the behaviour of the people who will occupy and use buildings. Some good commercial software products are available for this type of simulation, however the social relationships are often ignored. According to Yan (2004) at least five different methods have been used to evaluate environmental design-related human spatial behaviour:

1) Norms and regulations
2) Case studies and precedents
3) Post-occupancy evaluation
4) Direct experience behaviour simulation
5) Indirect experience behaviour simulation

Except in the case of very large buildings full-scale modeling of parts can not be justified, because the artefacts are unique. Even in large buildings only parts are normally mocked up such as a typical office layout. In many cases virtual reality has also been used to avoid building full scale realistic models. This immersive technology allows people to interact with virtual worlds in ways that approximate the real world.

1.2 COMPUTER SIMULATION OF USER BEHAVIOUR

According to Yan (2004) existing spatial behaviour simulations are mostly limited at well-defined areas of human activities where there has been considerable empirical research to support the development of cognitive models. Some of the areas of research are behaviour of pedestrians (Feurtey, 2000), evacuations from a church (Oldengarn, 2003), egress analysis from a hotel (Kuligowski, 2005) and crowd dynamics (Still, 2000).

Many emergency evacuation simulation models use cellular automata as a basis. Santos (2004) identified the following basic types of simulation models:

1) Flow based
2) Cellular automata
3) Agent-based
4) Activity-based models
5) Social scientific processes

1.3 CASE STUDIES

Because the prediction of human spatial behaviour is an area of great interest to designers and to inform the generic simulation platform it was decided to gain first hand insight into the behaviour of people in the built environment. Two different case studies were undertaken. The first study was at the Woodlands campus of the Dutch Reformed Church Moreleta Park in Pretoria, South Africa. The second one was at the Stellenbosch Traffic Department in Stellenbosch, South Africa.

1.3.1 Woodlands Case Study

This new 7100 seat mega church (Figure 162.1) was inaugurated on the 14th of May 2006. Right from the start severe traffic problems were experienced due to inadequate vehicular exits. This was due to a moratorium that was placed on the proclamation and development of new residential development on the eastern and southern sides of the complex due to alleged corruption in the administrative process of land allocation to developers. The professional design team of the complex did not know about this during the initial planning process and planned for three to four exits. Subsequently it was discovered that only one exit would be allowed by the Tshwane City Council. The team had to make an urgent appeal to create another temporary exit. This left the complex with only two exits, causing severe congestion problems from the outset.

The researchers grasped this opportunity to study the problem in detail. A series of empirical observations were made from 3 September 2006 to 15 October 2006. The prime purpose of the case study was to undertake an empirical case study of the people and vehicular traffic patterns to establish if a significant improvement of traffic flow could be established. The intention was to use the empirical information in the generic simulation and modelling research project KRONOS for calibration. On the basis of this alternative road configurations could be investigated that would hopefully lead to a significant improvement in the severe congestion problem. Three main sub-problems were identified.

Figure 162.1 The Woodlands campus of the Dutch Reformed church Moreleta Park

1.3.1.1 Sub-problem 1

Can a combination of empirical human and traffic flow information be captured realistically by means of an electronic simulation system?

The hypothesis was that cognitive, steering and artificial intelligence theory are adequately developed to capture the complexity of the interaction between human and traffic flows in a computer system.

The assumption was that due to the high level of complexity of the case study that progressive improvements might have to be made to the simulation model to ensure realistic simulations.

1.3.1.2 Sub-problem 2

Can specific combinations of human and traffic flow information be simulated and modelled by advanced simulation systems to predict the effectiveness of various church exit and road configurations?

The hypothesis was that cognitive, steering and artificial intelligence theory are adequately developed to make realistic simulation and modelling predictions with regards human behaviour and combined vehicular traffic.

The assumption in this case was that due to the high cognitive content of the case study abovementioned techniques would only partially solve the problem under investigation and that other empirical techniques would have

to be used until the virtual simulation world of KRONOS is adequately refined.

1.3.1.3 Sub-problem 3

Does a specific solution (scenario) of road configurations exist within the severe constraints of the Woodlands campus that will significantly improve the human and traffic flow?

  The hypothesis was that although there are many physical constraints on the Woodlands campus such as inadequate exits (gates), it is nonetheless intuitively presumed that a more even traffic flow will significantly improve the tempo of departure after church services.

  The assumption was that due to the large volumes of traffic a solution might require a combination of road layout, electronic aids and traffic control interventions. It was also assumed that an increase in the number of exits should still be pursued in any case.

  In addition to departure measurements an actual count of the number of parked vehicles and their exact location was done on 1 and 15 October. This was also supported by detailed traffic flow counts at positions A1, A2 and B as indicated on Figure 162.2 by means of hand-held traffic loggers. The device used facilitated the accurate recording of three different categories of vehicles, as well as time, and the operator could indicate a left, right or straight driving direction. A sample of the data recorded in this way is shown in Figure 162.2. This gave an accurate indication of what the saturation flows are and whether the bottleneck was on or off site. (Bad flow on site or constraints due to traffic lights)
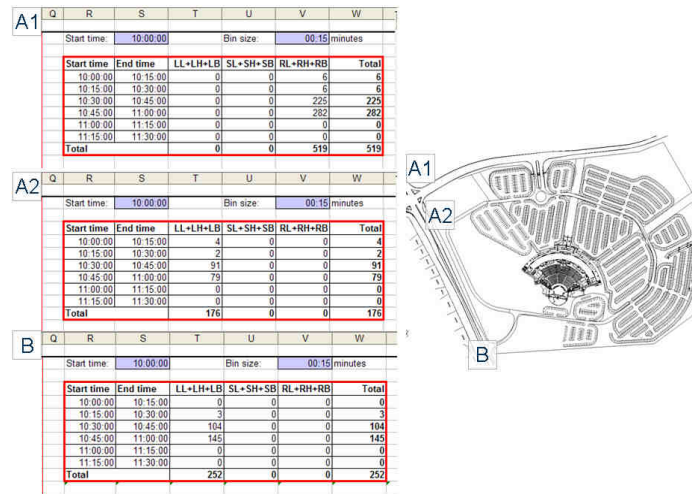
A1

Start time: 10:00:00 Bin size: 00:15 minutes

Start time	End time	LL+LH+LB	SL+SH+SB	RL+RH+RB	Total
10:00:00	10:15:00	0	0	6	6
10:15:00	10:30:00	0	0	6	6
10:30:00	10:45:00	0	0	225	225
10:45:00	11:00:00	0	0	282	282
11:00:00	11:15:00	0	0	0	0
11:15:00	11:30:00	0	0	0	0
Total		0	0	519	519

A2

Start time: 10:00:00 Bin size: 00:15 minutes

Start time	End time	LL+LH+LB	SL+SH+SB	RL+RH+RB	Total
10:00:00	10:15:00	4	0	0	4
10:15:00	10:30:00	2	0	0	2
10:30:00	10:45:00	91	0	0	91
10:45:00	11:00:00	79	0	0	79
11:00:00	11:15:00	0	0	0	0
11:15:00	11:30:00	0	0	0	0
Total		176	0	0	176

B

Start time: 10:00:00 Bin size: 00:15 minutes

Start time	End time	LL+LH+LB	SL+SH+SB	RL+RH+RB	Total
10:00:00	10:15:00	0	0	0	0
10:15:00	10:30:00	3	0	0	3
10:30:00	10:45:00	104	0	0	104
10:45:00	11:00:00	145	0	0	145
11:00:00	11:15:00	0	0	0	0
11:15:00	11:30:00	0	0	0	0
Total		252	0	0	252

Figure 162.2 Woodlands campus traffic on 1 October 2006
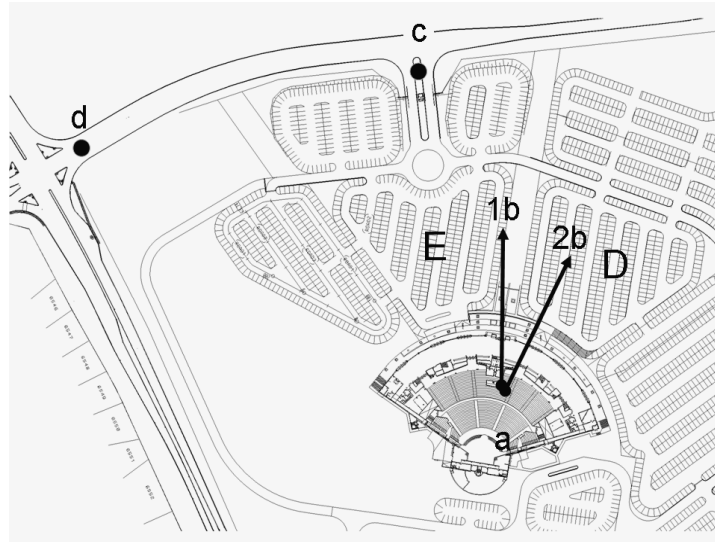
1.3.1.4 Specific Observations

Figure 162.3 Woodlands campus empirical departure measurements

Table 162.1 Time taken to depart from Moreletapark Woodlands Centre (09h00 service)

Date	Seat to foyer (s)	Foyer to vehicle (s)	Vehicle to gate (s)	Gate to traffic lights (s)
3 Sep 2006	60	120	382	68
10 Sep 2006	120	60	1560	240
24 Sep 2006	105	75	405	53
8 Oct 2006	90	120	105	30
15 Oct 2006	60	120	360	60

The departure times from various different seat positions and parking block combinations were recorded on five occasions. See Figure 162.3 and Table 161.1 for detail. On 3, 24 September and 8 October the measurements were for route was a, 1b, c and d. On 10 September and 15 October the measurements were for route a, 2b, c and d. The walking time from seat to the foyer, from foyer to vehicle, of vehicle to main exit and main exit to traffic light was carefully recorded in all cases. It was observed that the walking part was really no problem and remained reasonably constant due to the large number of doors provided in the auditorium. However significant driving time differences occurred depending on the parking location and also the particular church service characteristics. The worst case was observed in parking block D where the vehicle travel time was 1560 s to the main entrance and the best case was 360 s from the same

parking block. The situation in block E was significantly better where the longest vehicle travel time to the main entrance was only 405 s and the best case was a mere 105 s from the same parking block.

The peak flows are short but intense. On 1 October 695 vehicles left at the main entrance and 252 at the secondary entrance. (73% and 26.6% respectively). On 15 October 808 vehicles left at the main entrance and 342 at the secondary entrance. (70% and 30% respectively) Of the vehicles leaving the main entrance 64% turned right and 36% turned left on 15 October. 75% turned right and 25% turned left on 1 October.

It was interesting to note that the current traffic patterns roughly followed the "law of thirds". It became evident that the traffic flows as measured at the various exits are a direct result of the church goers parking in the best position according to their subjectively perceived proportion of the capacity of the two exits.

1.3.1.5 Recommendations from the empirical observations

The case study provided useful insights into the behaviour of people in relationship groups in combination with vehicular traffic and the resulting particular traffic patterns. This gave a clear indication of the capabilities that would be desirable in our simulation platform. One of the important observations was that people move in relationship groups. This fact makes the use of cellular automata unsuitable for this type of simulation and clearly indicated that the use of autonomous agents would be desirable. According to Wooldridge (2002) an agent is a computer system that is situated in some environment and that is capable of autonomous action in this environment in order to meet its design objectives.

One possible solution with regards this particular traffic problem is to block the site in 2/3 – 1/3 proportions and then to create a temporary one way lane in the high density areas to move the bottleneck off site to the traffic lights. There is also the possibility to optimise the traffic light cycles further to cater for higher expected traffic flows.

1.3.2 Stellenbosch Traffic Department Case Study

The nature of this case study was very different from the previous, because there was no real perceived problem. The opportunity was rather used to observe first hand the behaviour of members of the public in a public service centre with many service counters. The research team was of the opinion that the traffic department provided a manageable size of counter services for a case study within our resource constraints.

The purpose of this case study was firstly to empirically study the flow of large numbers of members of the public by means of time and volume at specific key points such as entrances and counters.

In this study the vehicular traffic logger was used in a totally different fashion. The type and time of people arriving were recorded. Nine different types of people were recorded i.e. young, adult and old males, females and

disabled people. In addition to this the actual turn around time at selected counters were also accurately recorded by means of the logger to get an idea of the throughput and efficiency of the service. One of the characteristics of the traffic department is the range of services offered and the difference in transaction times sometimes leading to high frustration levels of the people in queues.

This case study highlighted many deficiencies in the simulation software such as inadequate support for complex queues. We also had no support to configure different task lengths depending on the transaction type for the counter clerks. Even in current commercial software this aspect appears to be neglected. The software was also improved to handle a person entering, making an enquiry and then going to a particular counter. The social grouping of people for various reasons was evident in this study. Interesting variations were observed such as an illiterate person being accompanied by a literate, a mother with two children, an elderly German speaking women selling her car assisted by an English speaking relative accompanied by the car buyer so that all parties are present in case of possible perceived bureaucratic problems. There were also sad cases of people battling for two weeks to get a particularly involved problem resolved.

The general layout of the area studied is illustrated in Figure 162.4 This drawing has already been prepared for use in KRONOS. Note that the pathways where agents will move have been cleared of all lines and all doors are in the fully open position. All text has also been removed. This is necessary to avoid collisions, during simulation, with superfluous graphic information. The entrance is marked A. One logger was positioned here to record arrivals. Another logger was positioned on the inside to log departures. The enquiry counter is marked with a B. The areas marked with C are service counters where approximately nine different transaction types are typically handed. The various forms are obtained and filled in at the desks marked D.

Various different queue types were observed in the case study such as unstructured queues, structured queue single line, structured queue multiple line and structured queue with barrier (Figure 162.5). The unstructured queuing happened quite often at the enquiry counter B.
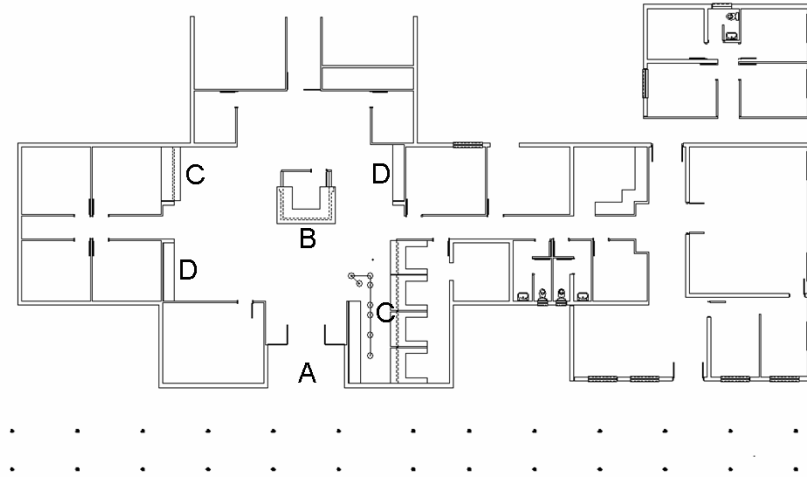
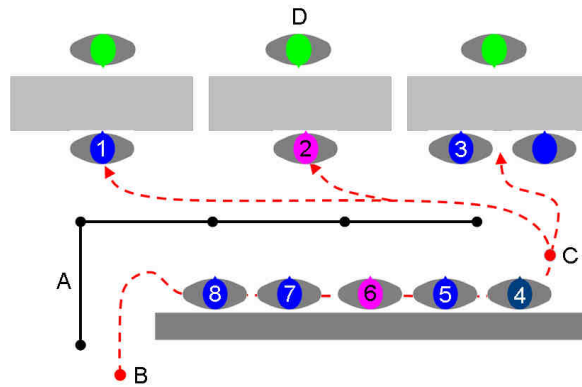**Figure 162.4** Stellenbosch Traffic Department area of study

Figure 162.5 Structured queue with barrier

The structured queue with barrier was the most complex one from a simulation point of view (See Figure 162.5). The barrier is marked with A. The queue line starts at B. As counter positions become available the agents move from the queue line to the junction C where the software decides which counter the agent must proceed to. Although the agents can roam freely it was decided to create explicit queue lines to simplify

implementation somewhat. A walking speed of 0.8 m/s and a plan area of 0.16 m² were used for the agents. Figure 162.7 below illustrates an actual simulation in progress using the 2D layout of Figure 162.4.

1.4 SIMULATION PLATFORM

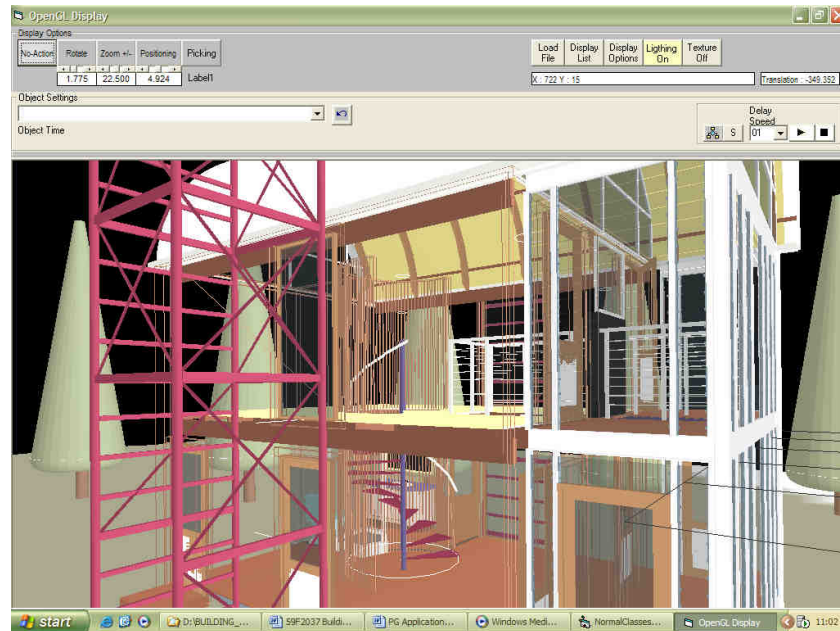### 1.4.1 Generic infrastructure to support a continuum of simulations

Figure 162.6 A typical 3D presentation of a building in the KRONOS research project

Many different types of simulations can be undertaken in the built environment over the life cycle of the building. The aim in this project was to first establish a generic platform based on XML. The two case studies discussed above informed the requirements of autonomous agent based user simulation more precisely. Figure 162.6 illustrates a fictitious 3D building that was used to test the speed and realism of the generic platform during development.

The current platform operate at three distinct levels, i.e. the model level that provides the static virtual world, the steering level that handles the movement of agents and the cognitive level where it is decided what the Belief-Desire-Intention (BDI) of the agents would be and how they are going to react to collisions. An extensive event system has been created to enable external software to interface and react on the different events.

The best known agent procedural system is the BDI system architecture, based on a model of human-like traits and mental attitudes (Bratman, 1987) In this model, each agent carries beliefs; its internal representation of what is sensed (informational attitudes). The agent also has desires or plans to achieve its goals (motivational attitudes). Finally, the agent outputs an intention, that what the agent strives to achieve in the environment (deliberative attitudes) (Pokahr, 2005). The BDI model does not cover emotional and other 'higher' human attitudes. The KRONOS reasoning engine is implemented as an advanced logical and rule-based system.

Figure 162.7 A typical 2D simulation of the Stellenbosch Traffic Department

The project is technically challenging and is informed by and depend on knowledge from the domains of military simulation, artificial intelligence, graphical world of the built environment (3D modelling, CAD and GIS), games development (realism, steering behaviours and virtual reality) and also open standards (OpenGL, XML, IAI, ISO STEP). At this stage the following aspects are addressed well:

- Support of real-time totally free roaming or predefined movement (queue lines) of agents.
- Support of social relationships. Each agent could move as part of a group or have a relationship to other agents.
- Account were taken of the amount of personal space around an agent also known as proxemics.
- A mechanism for agents to communicate with each other was established. This was used in the case of members of the public being attended to by officials in for example a traffic department.

- Mechanisms to define a list of different tasks for agents were also introduced.
- The ability to act on and report observed conditions by means of events was improved.
- Experiments were undertaken with space-time related issues to see how closely reality would correspond to the virtual simulation world. This looks promising as good correlations have been observed for example with the real measured time of vehicles and the simulated predictions in case study 1.

At this stage multiple space-time and general physics can be supported in future projects. The research work at this stage laid the foundation for continued research and the establishment of specialized simulation applications that can use this framework. Under space-time capabilities the following can be mentioned:

- Almost photo-realistic 2D and 3D models with a large number of coordinates
- Time, distance and speed
- Agent steering behaviours (How agents move separately and in groups)
- Social relationships
- Transfer of information from agent to agent

The following general fundamental metrics can be supported as a basis for more advanced predictive simulations:

- Area
- Volume
- Colour
- Material
- Lighting level
- Acoustic attributes
- Air movement
- Any other attribute such as what will be required to implement Computational Fluid Dynamics (CFD).

One of the biggest challenges was to develop a reliable collision detection algorithm to support the movement of agents in the virtual model. Due to the dynamic nature of the project time synchronization was also crucial to ensure that the agents move at the correct speed. This is discussed in more detail below.

1.4.2 Collision detection

Efficient collision detection between moving and stationary (or other moving) objects is at the heart of the dynamics of the graphical model. To this end, an algorithm, proposed by Haines (1991) and generalised by Sunday (2006) has been adapted and implemented in the simulation environment. This algorithm determines whether a given convex polyhedron and a line segment in 3D space do intersect.

1.4.3 Time synchronisation

Time synchronization is one of the most important issues that have to be addressed in a dynamic agent-based simulation. If the time synchronization is not accurate no valid time-based simulations can be undertaken.

An Internal Windows API function is called to get the exact tick count in milliseconds from the computer system since it has been switched on. The agent current time is calibrated with the abovementioned time.

This eliminates an over dependence on CPU time, because the CPU might be occupied with other concurrent processes making this time unreliable. KRONOS will adjust the agent's movements to stay in sync with real clock time as far as possible. Unfortunately this can also reach a saturation point if there are too many agents placed in the simulation theatre. In this case the simulated and real clock time will begin to differ.

To implement time synchronization and collision detection the agents have been fitted with proximity sensors. Two sensors are placed at a 45º angle and used mainly for inter agent spacing (proxemics) and the longer centre one for looking forward. The length of the former varies with the amount of personal space configured and the latter with the speed of movement. The faster the agent moves the longer the central proximity sensor becomes. (Figure 162.8)
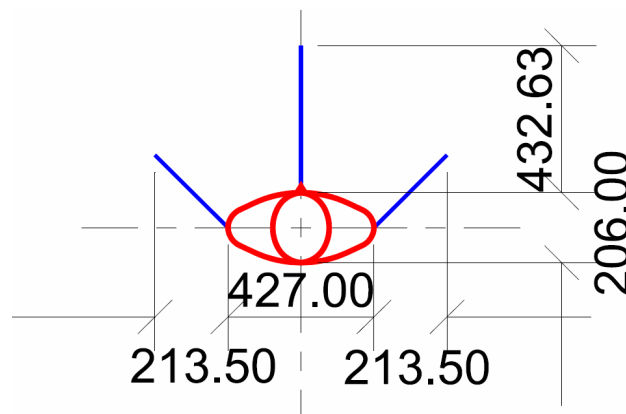

Figure 162.8 KRONOS 2D agent proximity sensors

1.5 CONCLUSIONS

In general the approach shows much promise. The toolbox has been able to tackle complex architectural research questions and provide practical solutions. In addition, by being able to visualise the problem the toolbox allows a more interactive and shared approach to problem solving. This allows non-technical role players to visualise problems and enables them to work with designers to develop ways that these can be addressed.

Although the development of autonomous agent programs is far more complex than is the case with cellular automata, the research indicates that this route has more potential to create more realistic simulations. The project also shows the increasing sophistication of current hardware and software technology which are now able to meet the challenging demands posed by autonomous agent modelling exercises.

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