Simulating Artificial Organisms with Qualitative Physiology

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Abstract. In this paper, we describe an approach to artificial life, which uses Qualitative Reasoning for the simulation of life within a 3D virtual environment. This system uses qualitative formalisms to describe both the physiology of a virtual creature and its environment. This approach has two main advantages: the possibility of representing integrated physiological functions at various levels of abstraction and the use of a common formalism for the simulation of internal (physiological) and external (environmental) processes. We illustrate this framework by revisiting early work in Artificial Life and providing these virtual life forms with a corresponding physiology, to obtain a complete living organism in virtual worlds.

1 Introduction

Previous work on Artificial Life has mostly considered molecular physiology, rather than higher-level physiological functions, with a few exceptions [9]. However, one of the challenges for the simulation of artificial life consists in being able to represent complex physiological functions to simulate organisms that are more complex. Our approach has been to use symbolic reasoning instead of differential equations and numerical methods to create a knowledge-based simulation of physiological functions. By this method, we are defining artificial physiology from first principles from a set of physiological processes, which opens new ways for the experimentation of artificial alternative life forms.

Using a symbolic description, a qualitative modeller could then devise a complex system that represents physiological phenomena from a library of common physical processes. The advantage of modelling such a system using Qualitative Reasoning is that using a suitably compositional approach for a model, allows the modeller to produce simple model fragments that combine to give the required complexity for the organism behaviour and produce results in real-time. The challenge in this method for model creation is choosing the best level of description and how to combine the model fragments that are produced from the analysis to create the world and phenomena for the artificial creature.

The system has been used to develop a virtual creature with internal processes and organs that react to changes in its environment. This work has evolved from research in A-Life that aimed at creating imaginary life forms [1, 2]. In addition to the creature, the environment has been simulated and integrated with the creature, which allows effects such as hot and cold currents, concentrations, and vortices to affect this creature through the qualitative simulations.

The creature we have created is an imaginary organism, which has a body comprised of organs that work together to carry on the various processes of life. Its main sustenance is extracted from the environment in which it exists and allows it to achieve homeostasis.

In the remainder of this paper, we will present the results from our ongoing research into the use of qualitative processes to simulate both creatures and "ecosystems" for artificial life within a 3D environment. We start by describing the software architecture for the virtual environment in which the virtual creature lives.

Following this are case studies into the visualisation of the processes within the virtual creature and its environment. In particular, we show how, due to the basic physical or physiological processes, we are able to instantiate multiple model fragments in the creatures' environment and have them interact with it. For example, we present an implementation of the artificial life form within a virtual "Ecosystem" as a test environment. This environment has been implemented as a fully immersive virtual reality system that the user can explore. In this virtual world, we have implemented various behaviours: for physical environment behaviour and for complex organ behaviour which are simulated in real-time. We conclude by discussion of the work completed so far and present our plans for future research into expanding the environmental effects into a self-contained ecosystem.

2 System Architecture

Our system is composed of two modules: a visualisation engine, which animates the virtual creature in its environment in real-time, and a qualitative simulation engine controlling the simulation of both the internal physiological processes of the creature, and of physical processes in its liquid environment (such as currents, heat flows, diffusion of nutrients, etc.). The integration of qualitative simulation with a 3D graphics system relies on the native event system of the visualisation engine. This event system has been extended to define high-level events that activate the QP simulations from the interaction with virtual world objects. We will refer to these events as Qualitative Physics events (abbreviated as *QP Events*). For example, when the creature enters or exits a volume, the event `enter_QPVolume` and `exit_QPVolume` are sent to the simulation. For instance the `enter_QPVolume` event can trigger processes of heat exchange between the creature and the liquid flows occurring in the volume it has just entered.

Our system is designed to operate both on standard desktop and within immersive Virtual Reality systems. The immersive system we use is a CAVE™-like system called an SAS-Cube™ the configuration of which consists of a four-sided PC-based hardware architecture that is powered by an ORAD™ PC cluster. It supports stereoscopic visualisation at 60 fps and real-time interaction. The QR Engine utilises the technique for qualitative simulation of physiological systems [4], derived from Qualitative Process Theory (QPT) [7] which we refer to as Qualitative Physiology. Qualitative Physiology represents the physiological processes governed by physiological laws using the process-based formalism of QPT, and supports the real-time simulation of physiological sub-systems.

As the *QP Events* involve objects which are part of the simulation, they trigger the updating of relevant qualitative variables in the QP engine, hence prompting a new cycle of simulation.

In a similar fashion, to present the effects of the simulation to the visualisation engine we have devised *QP Effects*. These effects utilise the discretisation of the qualitative variables namely the "landmarks" and "limit points". When a qualitative variable passes either a landmark or limit point, a *QP Effect* is generated and sent to the graphical environment, to trigger changes in visual appearance corresponding to the landmarks reached. In addition, when the processes become active or inactive or when an object changes its *QPStates, QP Effects* are also generated. This can be used to produce a variety of visualisations, such as particle systems for fluid motion or colour changes for concentration. The software architecture for the communication of these *QP Events* and *QP Effects* utilises the UDP protocol for transmission between the qualitative simulation engine and the visualisation engine, [4,5,6]. Figure 1 shows an overview of the system architecture.

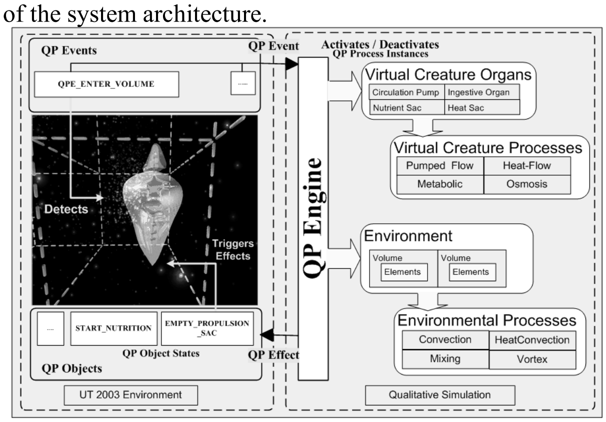

Figure 1: System Architecture.

The creation of the artificial creature includes the description of its anatomy and its physiology. The anatomical structure of the artificial creature is briefly outlined in Figure 2: Creature Physiology Overview. The visual contents have been produced using 3D modelling and animation packages such as 3D Studio Max™ and XSI™. These models as well as animations have been imported into the UT 2003 engine. These graphical representations can describe, using key-framed animation, the behaviours, and actions for the virtual creature. In our scenario, these animations represent movements of internal organs, changes in shape of the creature, as well as locomotion and since the simulation is controlled using *QP Events* we retain the interactive nature of the simulation.

We have described several physiological processes for the artificial virtual creature, dealing with elementary physiological functions such as nutrition, locomotion, and certain homeostatic processes such as thermal regulation. An essential aspect is that these are defined altogether as an integrated system, which can further be refined through experimentation, as the process description is highly modular and processes only connect through characteristic physiological variables (e.g., concentration in nutrients, temperature in certain organs, etc.). Defining the creature using this level of description is largely a functionalist approach [3], although a top-down, non-emergent one.

3 Implementation

As we previously introduced the Qualitative Simulation Engine utilises an artificial intelligence technique called qualitative process theory (QPT). Originally, this theory was developed for modelling complex mechanical and physical systems by abstracting physical descriptions of the phenomena [8].

The complete qualitative description requires us to use a method called envisionment by which we encapsulate the properties of the system and the relations between them. The qualitative description of the dynamics of the variables is described by a qualitative equation called influence equations. An example of this would be the influence equation for an osmotic system.

I+ (Amount–of Solute (Destination), A(OsmoticRate))

I- (Amount–of Solute (Source), A(OsmoticRate))

Here I+ represents the positive influence, and I- the negative influence, of the first value upon the second. We would in this case say the amount of solute in the *destination* is directly affected by the amount OsmoticRate. These equations constitute a declarative formalisation of the causal relations between qualitative variables. During the activation of the QP they determine the evolution of qualitative variables. The propagation of the effects of these equations creates an overall pattern of parameter changes. For instance, homeostasis within the creature is maintained by parameters, which regulate the rate at which the influences (*Processes*) act. An example of this is the increase in the metabolic rate to combat heat loss into the environment when the temperature of the creature is too low.

3.1 Physiology Implementation

The definition of the creature's physiology is based on a mapping between its organs and their physiological functions. In other words, the first step consists in designing the creature's anatomy with high-level physiological functions for each organ (e.g. heat conduit, or propulsion sac). In a second step, the detailed mechanisms behind these functions are described through the physical processes that constitute them. These functions are described though the *processes* and through qualitative states that are contained within Individual Views. Individual Views are a series of qualitative equations that are mutually exclusive and are used to calculate the qualitative state, the indirect influences and generate the effects that control the organ representation.

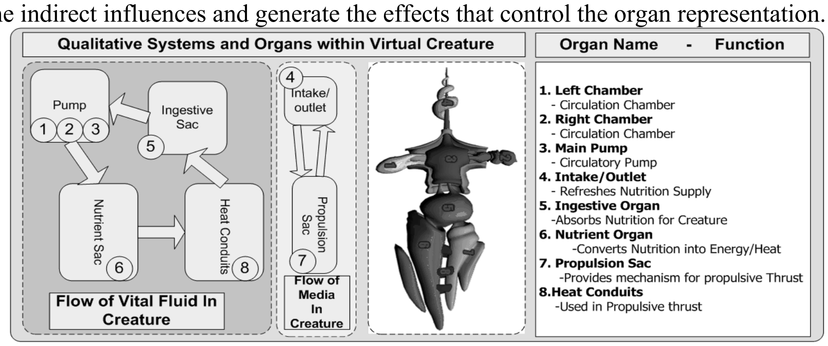

Figure 2: Creature Overview

Using this method, we have composed the creature from a number of qualitatively modelled organs each of which has a number of Processes and Individual Views. The organ processes operate primarily upon the vital fluid that they contain and the physiology operates to create homeostasis within the properties of this fluid. A brief overview of the organs functions is shown in Figure 2: Creature Overview.

Of particular impact upon the creature's homeostasis are the Nutrient organ and the Ingestive organ. These organs have, respectively an osmosis and metabolic process, which replenish and deplete the vital fluid of nutrients. Therefore, the contention between the operations of these *processes* is regulated by the creature to try to meet homeostasis. This is achieved by affecting the rate of vital fluid transfer between the organs, which is influenced by the Pump-Rate of the creature. The processes for the chemical (nutrient) homeostasis are combined with a thermal regulation system which completes the physiological systems for the creature. This thermal regulation allows the creature to combat the effects of heat-loss to the environment. The main detriment to the creatures' temperature is the aforementioned heat loss. This is combated in part by the Metabolic process. The Metabolic process occurs within the nutrient sac and its effects (directs influences) are to remove Nutrient from the vital fluid in the organ and convert it into stored energy and heat. To achieve thermal equilibrium the creature may consume its store of energy to produce heat should its average temperature fall.

The description of an organs 'individual views' is used to encompass all the behaviour states for the organ. Each organ contains a number of individual views representing states for behaviours such as saturated, compressed or failure states such as depleted energy.

Our approach supports the data-driven propagation of behaviours throughout the various compartments of the creature's organ system. In Figure 3: Example Qualitative Description of a Propulsion Sac *QPState* and associated process, we see the qualitative definition of an organ state and an example of a process, which occurs within it.

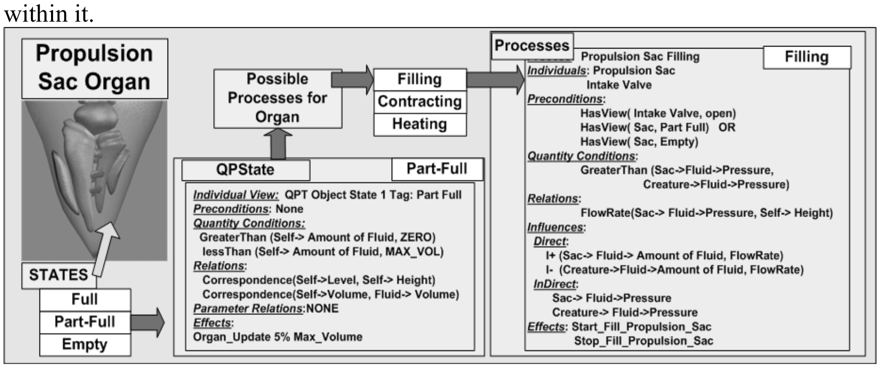

Figure 3: Example Qualitative Description of a Propulsion Sac QPState and associated process.

This description of the object itself allows it to use its form to define its function. The processes within the propulsion sac are used to control the Sac when the creature is in its locomotion *QPState*. For instance, the propulsion sac filling / contracting processes open and close the valves, which control the filling and ejection of the propulsion sac.

3.2 "Ecosystem" Implementation

In this Section, we explore the implementation of the ecosystem using qualitative formalisations for both the world physics and the creatures' physiology. Conceptually we have formed three levels of description for the ecosystem, which we label *environment*, *volume,* and *element*. These correspond to a hierarchical decomposition of the virtual space, each level being associated with different kinds of qualitative processes or variables. The highest level of the qualitative model for the environment is used to represent, in part, those behaviours that relate to the external world. For instance, one such interaction would be the heat dissipation from the environment volumes to an "external world" allowing a thermal equilibrium to be formed.

The environment is composed of "path objects" which form the interconnections for the volumes, defining a topology for the environment allowing exchanges between volumes, such as the flow of heat or particles. These "path objects" have as part of their composition, references to individual *volumes.* A "Path object" by its parameters control which of the processes act upon the referenced volume and the degree to which they act. For instance, the properties of the path objects are used by the convection process. In this case path-distance *(*a *spatial parameter* set by spatial separation for the environment*)* and conductivity are both used to determine the transfer rate parameter for the process.

The *volume* is composed of *elements*, which are particle-based representations of a fluid element within the special volume. Hence, volume parameters refer to its "microscopic" constituency in terms of elements: concentration, temperature, viscosity, etc. The *volume's* concentration is the key parameter used for the selection of its qualitative states. This parameter will be influenced, for instance, by convection currents within the environment. See Figure 4 for a description of the Convection process which occurs within a volume and the Description of the active state. The temperature of the *volume* and the viscosity of the *volume* increase as the concentration increases. The aggregation of volume properties (landmark values reached by the above *volume's* parameters) support the definition of global states for the volume. For instance, when the temperature is high and the concentration is high, the volume passes a limit point formed by the combination of these parameters and is said to enter a "perturbed" state, upon which the localised disturbance acts.

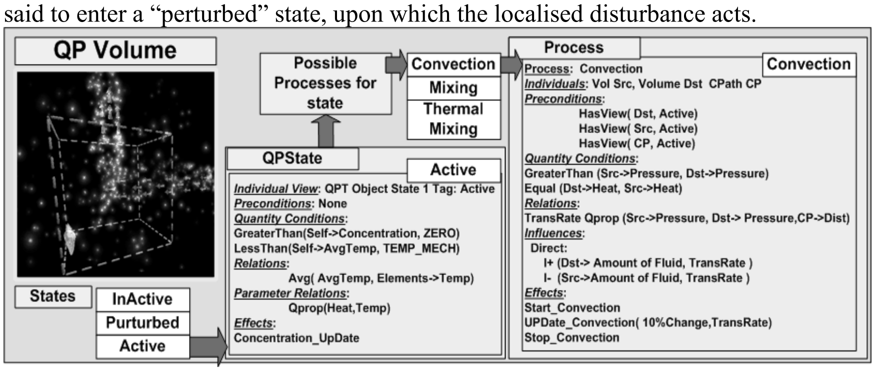

Figure 4: Qualitative Volume State Description and Process

4 Results

The integration of qualitative physiology into the simulation for the environment has given us a unique avenue of investigation that allows us to develop experiments in a virtual ecosystem. This implementation allows the simulation processes to be altered to determine the survivability of the creature as a function of its physiology. A number of processes are active between the creature and its environment when the creature is in the normal steady state producing the required homeostatic responses. We have implemented a first prototype of the system in which we have a basic set of physiological and environmental processes. In this section, we illustrate the system behaviour by describing some specific results from the simulation.

4.1 The Locomotion Scenario

The integrated approach to the simulation has allowed us to develop simulation effects for the environment as well as for the creature, which has allowed the triggering of different individual view states for the creature dependant upon the conditions that are prevalent in the environment. The major individual view states for the creature are used to control a locomotion system. When the locomotion is active the creature utilizes its own system for propulsion, in which the organ states change, and the creature expends its internal stored energy from its metabolic processes to power thrusts from the propulsion sac, which give it a hoping motion through the environment.

The normal operation for the creatures' physiology involves the transfer of vital fluid around the creatures' organs whose transfer rate is dependant upon the parameter "pump-rate", which is a property of the circulatory pump organ. The nutrients are carried within the vital fluid and are replenished by the osmosis process, within the ingestive organ, and depleted by the metabolic process, within the nutrient sac. The rate of depletion in the metabolic process is given by the organs' parameter "conversion rate". The metabolic process depletes the nutrients in the vital fluid and coverts them into heat and stored energy.

The locomotion *QPState* changes the relations between these parameters increasing the overall rate of the creatures' physiology. For instance, the "pump-rate" parameter within the circulatory pump organ becomes dependant upon the creatures' parameter "stored-energy" in away such that the parameter increases toward its maximum the further the amount of stored energy deviates from its maximum. The decrease in "stored energy" is due to consumption of the energy by the heating conduits process, which is activated by the new *QPState* and converts "stored energy" into heat.

The locomotion state changes the metabolic process, which is active in the nutrient sac, by increasing the conversion rate. Thus, the main effect of the new state is to activate the propulsion sac and the heat conduits processes and to alter the entities normal physiological system allowing the processes to occur faster. The heat conduits and the propulsion sac organs comprise the locomotive system for the creature and their processes heat fluid for expulsion/propulsion and manage the system of valves for the organ respectively.

During the Locomotion state, the flow of sea media due to the pumping operation of the intake/outlet organ (Figure 2: Creature Physiology Overview organ 4), that replenishes the nutrients within the shell of the creature from the environment, is used also as a channel for propulsive thrusts. The media within the creatures shell we label internal media. This internal media can be drawn into the Propulsion Sac organ (figure 2. organ 7) via a valve on the organ. This filling of the organ is controlled by the propulsion sac expansion process, which sends the effect `QP_Effect_Fill_Propulsion_Sac` to begin the manipulation of the propulsion organ. The Sac closes the valve when full and activates the Heat Conduits (Figure 2. organ 8) which in turn heat the sea media producing a pressure increase.

When the pressure inside the Propulsion Sac passes a value it triggers the pressure valve, an expansion valve whose state depends upon the pressure, on the sac. The change in valve state activates the propulsion sac contraction process and the sea media is expelled from the Sac into the shell. The organ enters a contracting state which stops the action of the Heat Conduits and as the valve has been released starts the empting of the organ via the Propulsion Sac Contraction Process. This process directly affects the size of the Sac which indirectly affects the volume of the sac. The decrease in the size also affects the amount of media in the organ. The effects of this stage are shown in Figure 5: Propulsion Sac Organ Pressure. The propulsion sac contraction process generates the *QP Effect* *`QP_Effect_Empty_Propulsion_Sac`*, to the graphical environment, which changes the representation for the propulsion organ to deflating. The shell responds to the sudden increase by expelling fluid into the environment via an expulsion using the intake outlet organ creating a propulsive thrust. This expulsion process generates the `start_thrust` which visualises the thrust within the environment by a particle effect whose rate depends upon the rate of fluid flow. Figure 5: Propulsion Organ Pressure depicts these changes in the creature with a plot of the pressure within the organ.

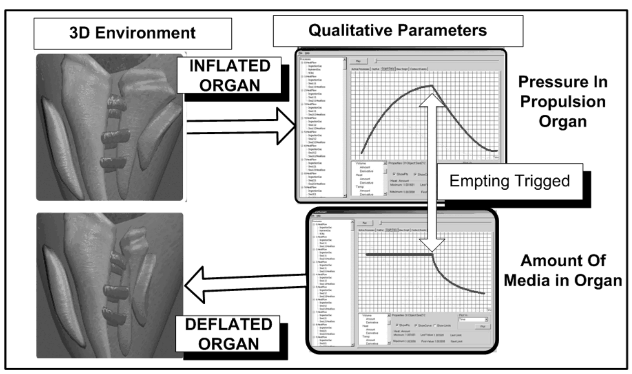

Figure 5: Propulsion Organ Pressure

4.2 Environment Localised Perturbation Scenario

The environment is composed of an imaginary media whose properties are devised to react to give thermo-mechanical effects. The vortex is a product of this effect and is created by a combination of effects upon a volume.

A volume can either have nutrients, be depleted of nutrients or have an environmental effect active. These concepts correspond to the *QPStates inactive*, *active* and *perturbed* for a *volume*. A nutrient depleted volume (*inactive*) has no *QP Effects* as it has no graphical effects present and minimal process activity between its *elements*.

A nutrient rich volume (*active*) contains a high concentration of nutrients and thus we have chosen to represent an attractive volume within the environment with a distinctive effect. This is achieved by generating the *QP Effect* `Start_Nutrition` when the *volume* enters this *QPState.* This effect relates the parameter "concentration" within the *volume* to the lifetime of the particle within the 3D environment. This creates the effect of a denser cloud of particles for higher values of concentration. Also within this *QPState* as the value evolves through the effects of convection processes an Update_Nutrition *QP Effect* is generated for appreciable changes (~10% Saturation value). Figure 6: Environmental Processes (a). The *active* state allows the convection process to occur which is visualized by the sprite emitters that represent moving media Figure 6: Environmental Processes (b). Starting the process sends the *QP Effect* `Start_Convection_Process` to the 3D environment. This effect starts the convection sprite emitter at its maximum rate, as the process starts at its maximum and works to achieve equilibrium between the two volumes and the "path object" associated with the convection process provides the direction for the flow.

The media of the environment has been designed to respond to the presence of high concentrations of nutrient and heat; this response takes the form of a localized perturbation within the volume. When these conditions are met the properties at different points within the volume are evaluated and a pressure gradient between the bottom and top of the volume and the opposing sides of the volume is created*.* When a *volume* enters into a perturbed state it generates the `Start_Vortex` QP *Effect* that stops the current animation within the volume and allows the vortex process to begin which acts to restore the balance between the elements within the volume. This process calculates the rotation direction and rate using the properties of the volumes elements and the 3D environment uses this data to generate a vortex object Figure 6: Environmental Processes (c).

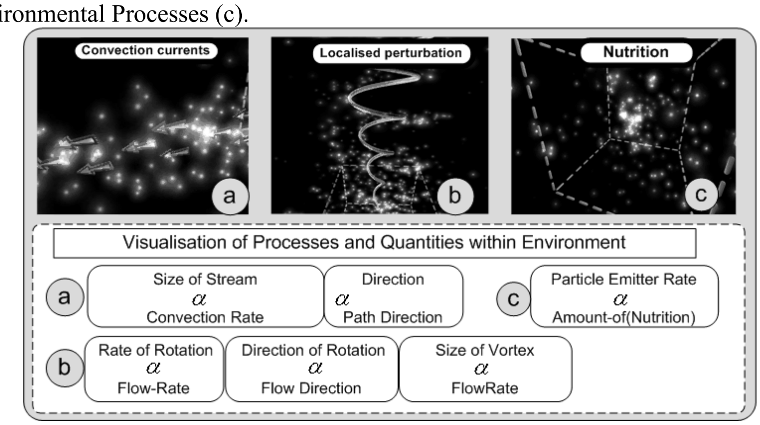

Figure 6: Environmental Processes

This leads to scenarios in which the creature can find patches of high nutrient concentration but by its presence cause instability in the volume, creating a vortex that drives the creature, either by its effect or by locomotion (if the creature has stored energy) from the volume.

5. Conclusion

This unique approach to integration of a creature's physiology and environment immerses the user within the 3D environment, modelled in real-time and provides a platform to approach new experimentations within artificial life. The system itself provides a successful attempt at real-time simulation of artificial life, which includes an imaginary physiology that interacts with the environment. The framework allows for the construction of homeostatic systems within the artificial creature that responds to influences from the environment. The environment itself provides the elements for basic creature behaviour such as a chemotactic response. Future work in this area will include the expansion of the creatures' perception of the environment, interaction between creatures and we are currently working upon linking the symbolic description of qualitative processes to evolutionary programming principles. For the environment future work will include expansion of the states of the volume to allow for different "cloud formations" for the nutrients dependent upon the parameters of the volumes elements instead of the single particle emitter which we are using.

Acknowledgements

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References

1. Bec, L., 1991. Elements d'Epistemologie Fabulatoire, in: C. Langton, C. Taylor, J.D. Farmer, & S. Rasmussen (Eds.), *Artificial Life II*, SFI Studies in the Sciences of Complexity, Proc. Vol. X. Redwood City, CA: Addison-Wesley (in French).
2. Bec, L., 1998. Artificial Life Under Tension: A Lesson in Epistemological Fabulation, In: C. Sommerer and L. Mignonneau (Eds.), Art @ Science, New York: Springer Verlag.
3. Bedau, M.A., Philosophical Aspects of Artificial Life, in: F.Varela and P. Bourgine (Eds.), Towards a Practice of Autonomous Systems, Cambridge: MIT Press, pp. 494-503. (1992)
4. Cavazza, M. and Simo, A., 2003. A Virtual Patient Based on Qualitative Simulation. In ACM Intelligent User Interfaces 2003, Miami, FL, USA, pp. 19-25
5. Cavazza, M., Hartley, S., Lugrin, J.-L. and Le Bras, M., 2002. Alternative Reality: A New Platform for Digital Arts, ACM Symposium on Virtual Reality Software and Technology (VRST2003), pp. 100-108, Osaka, Japan, October 2003.
6. Cavazza, M., Hartley, S., Lugrin, J.-L. and Le Bras, M., 2002. Alternative Reality: Qualitative Physics for Digital Arts, Proceedings of the 17th international workshop on Qualitative Reasoning 2003, Brasilia, Brasil.
7. Collins, J. and Forbus, K Building qualitative models of thermodynamic processes. *Proceedings of the Qualitative Reasoning Workshop*. (1989).
8. Forbus, K.D., Qualitative Process Theory, Artificial Intelligence, 24, 1-3, pp. 85-168.(1984).
9. Grand, S., Cliff, D. and Malhotra, A., Creatures: artificial life autonomous software agents for home entertainment, In: *Proceedings of the first international conference on Autonomous agents*, pp. 22-29. ACM Press. (1997)