# PERPLEXUS: Pervasive Computing Framework for Modeling Complex Virtually-Unbounded Systems

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## Abstract

*This paper introduces Perplexus, a European project that aims to develop a scalable hardware platform made of custom reconfigurable devices endowed with bio-inspired capabilities. This platform will enable the simulation of large-scale complex systems and the study of emergent complex behaviors in a virtually unbounded wireless network of computing modules. The final infrastructure will be used as a simulation tool for three applications: neurobiological modeling, culture dissemination modeling, and cooperative collective robotics. The Perplexus platform will provide a novel modeling framework thanks to the pervasive nature of the hardware platform, its bio-inspired capabilities, its strong interaction with the environment, and its dynamic topology.*

## 1. Introduction

The Perplexus project aims to develop a scalable hardware platform made of custom reconfigurable devices endowed with bio-inspired capabilities that will enable the simulation of large-scale complex systems [4] and the study of emergent complex behaviors in a virtually unbounded wireless network of computing modules. At the heart of these *ubiquitous computing modules* (*ubidules*), we will use a custom reconfigurable electronic device capable of implementing bio-inspired mechanisms such as growth, learning, and evolution. This *ubidule bio-inspired chip* (*ubichip*) [11] will be associated to rich sensory elements and wireless communication capabilities. Such an infrastructure will provide several advantages compared to classical software simulations: speed-up, an inherent real-time interaction with the environment, self-organization capabilities, simulation in the presence of uncertainty, and distributed multi-scale simulations.

The strong interaction between our hardware infrastructure and the real environment circumvent the need to simulate the environment and ease the occurrence of unexpected emergent phenomena. The observation of such emergent phenomena will be now facilitated by the shorter simulation time, brought by the hardware speed-up.

One of the major difficulties of a complex system simulation is to define the structural organization of the modules composing the model [4]. The self-organization and bio-inspired capabilities of our platform will bring an innovative solution to this problem: an evolving and hierarchical structure. The function of each ubidule can be dynamically and autonomously determined by the simulation itself: it can be an independent agent or a part of a larger entity.

We have identified three domains where our modeling infrastructure will prove its usefulness as a powerful and innovative simulation tool: neurobiological modeling, culture dissemination modeling, and cooperative collective robotics. We will perform qualitative and quantitative comparisons between classical implementations of these three modeling applications and their implementation running on a network of *ubidules*. For doing so, we envision three strategic aspects to be addressed:

(1) Design and development of the hardware platform. It will consist of a set of *ubidules* that will support the simulation of our complex systems.

(2) Simulation of complex phenomena in the domains

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of realistic neural models, social sciences, and collective cooperative robotics, taking advantage of the features of our modeling hardware platform.

(3) Study of the emergent phenomena arising from the strong interaction between our ubiquitous computing modules and the real environment.

These three aspects constitute an important contribution to fields as diverse as pervasive systems, complex systems, distributed computing, culture modeling, collective robotics, and bio-inspired hardware systems, among others. For tackling these challenges we have fixed a set of objectives toward which our efforts will be focused. These objectives, which are explained in section 2, cover both technological and scientific aspects. Section 3 will further describe the targeted applications of our project.

## 2. Perplexus Objectives

The simulation of large-scale complex systems requires huge amounts of computing resources. Even if the Moore law yet guarantees increasingly more powerful chips every year, the capacity of a single device is not always able to provide the optimal solution for running this kind of application. Supercomputing, grid computing and distributed computing are possible solutions to this problem. However, a new kind of distributed computing could appear in the near future, with the advent of a new era of computing, after the mainframe era and the PC era. In this 3rd era of computing, we are likely to see a myriad of ubiquitous devices with large computing and sensory capabilities in our environment. Such devices will interact with each other using wireless communication and coordinate to seamlessly help people in their daily tasks. Anticipating this new era of computing, we can imagine a solution for simulating complex systems, inspired from the distributed computing projects, but this time using the computation, communication, and sensing resources of ubiquitous devices in our environment: the alarm clock radio on our night table, our children's electronic toys and robots, our microwave oven, our cellular phones, PDAs, etc.

In this project we will develop a "scale model" of what a SETI-like [1] framework for ubiquitous computing would look like. We will implement a series of models that will take advantage of the modeling framework provided by the Perplexus platform, and we will study the emergent behaviors arising from such models.

### 2.1 Technological Objectives

The design and development of the Perplexus platform rises challenging technological issues. We will develop a scalable network of *ubidules* equipped with wireless communication capabilities and rich sensory elements. The platform will be modular for allowing application developers to customize their platform set-up. In this way, application developers can easily build their system by selecting what to plug to the *ubidule* from a set of peripherals. These peripherals can be a wireless communication interface (wifi or bluetooth), sensors, actuators, cameras, or flash memories. This modularity will be guaranteed by the use of standard interfaces such as USB.

The *ubidule* will also be equipped with a set of *ubichips* [11]. The *ubichip* will feature a set of reconfigurability capabilities that will support the implementation of bio-inspired hardware systems. Reconfigurability mechanisms like dynamic routing, self-replication by means of self-reconfiguration, and a simplified connectivity, will allow the implementation of bio-inspired mechanisms such as development, learning, and evolution. This reconfigurable circuit will be associated with rich sensory elements and wireless communication capabilities.

### 2.2 Scientific Objectives

We can distinguish two approaches to deal with complex systems. On the one hand, the top-down approach which functions in a divide-and-conquer manner. A problem is divided into sub-problems that are individually considered. Such an approach has the problem of missing the fact that complex behaviors need not have complex roots, and models are not scalable. On the other hand, bottom-up approaches do consider explanations of complex behavior via simple, local component interactions in a decentralized manner, generally providing a scalable model of the complex system. In this project, we consider challenging modeling problems following a bottom-up approach.

As far as the computer models of complex systems are concerned, we can also distinguish two approaches. On the one hand, there are continuous models based on differential equations. These models generally suppose a high abstraction level and do not integrate a spatial dimension. On the other hand, there are discrete models that introduce individual entities called "agents" or "particles". Agent-based modeling is very often based on discrete "grid-world" models. In this project we will explore the use of "perplex-world" models, virtually unbounded discrete models realized by interconnecting many ubiquitous computing modules (*ubidules*) and by interacting with real-world sources of information. We will determine the range of applications and the advantages of such a framework for simulating complex systems in the domains of realistic neural models, the dynamic emergence of culture, and collective robotics.

A second major scientific objective is to study the emergent phenomena arising from the strong interaction between our hardware infrastructure and the real environment. The Perplexus platform can be seen as a complex system it-

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self: it is a population of artificial organisms interacting with the real environment. We will study emergent organization mechanisms that will enable the formation of two kinds of structures: a single distributed complex organism or a population of collaborating-competing individual organisms. For instance, a growing network setup of *ubidules* could form a "small world" network.

A third scientific objective is the study of the emergence of an "artificial culture". The *ubidule* ubiquitous computing modules learn by interacting with the environment and with the user. This learning process might lead to the acquisition of "concepts" that might be communicated to neighbor *ubidules* and diffused through the Perplexus platform. The sharing of such concepts might prosper and reach a stable state throughout the platform. Such a stable state or concept consensus might be seen as an "artificial culture" shared by the *ubidule* modules of the Perplexus platform.

# 3 Perplexus Applications

Studying the emergence in complex systems such as brain processing or social interactions is a key factor in the future understanding of this kind of systems. Powerful tools are therefore needed to allow large scale simulations. The main objective of our project is the design and implementation of a pervasive, massively parallel hardware platform for real-time modeling of complex systems. The hardware acceleration provided by the *ubidules*, as well as their unbounded number will fit these requirements.

Moreover, the *ubidules* will allow to add real stimuli to the simulation of complex systems, a missing feature of software simulations. The intrinsic bio-inspired mechanisms in the *ubidules* will let them implement fault-tolerance mechanisms in case an *ubidule* works wrong.

## 3.1 Culture Dissemination Modeling

The prevailing approach to study the dissemination of culture has relied on a view of an unbounded and unbiased mind, equally open to any kind of cultural content. However, recent work integrates evolutionary and cognitive perspectives [10], and argues for an "epidemiological" approach to culture. In order to model such view we will make use of an agent-based approach coupled to artificial neural networks representing "cognitive biases" in a systematic framework. We will take advantage of our pervasive computing infrastructure by implementing complex models of culture dynamics out of dynamically interacting computing modules and by exploiting signals coming from the environment via the sensors of the pervasive units.

There is a growing interest into attempting to understand social phenomena under the umbrella of complex theory. Interacting agent models, which are typically studied using computer simulations, have been used to explore a wide range of social issues. Some studies have shown for instance that such models often show statistical behavior such as non-Gaussian fluctuations and power-law probability distributions, which are generally signatures of non-equilibrium systems governed by strong correlations between individual components. This indicates that the system's behavior is difficult to predict, but that it is not simply random. Indeed, choices in many human activities are limited and typically influenced by neighbors, which sometimes can lead to abrupt social changes when a critical mass is reached. This does not mean that we will develop models to direct social behavior but as Nature's journalist and science writer Philip Ball pointed out "models of society cannot tell us how things should be, but it can hopefully elucidate the consequences of particular choices and policies" [2]. In particular, models of dissemination of culture can be useful into understanding (and guiding policy makers) issues like opinion polarization, censure, cultural stability and diversity, the role of technology and education in the adoption of particular opinions, group formation, etc.

The study of social interactions using our platform will be greatly different from pure simulations given the use of dynamical modeling spaces resulting of the dynamical topology of the modeling infrastructure, the use of unbiased variable values coming from the environment via the sensors of the ubidules, and because of the use of unexpected new information or loss of information resulting from ubidules dynamically joining/leaving a given modeling framework. Moreover, the proposed "society of ubidules" will provide many more features like heterogeneousness and a self-organizing connectivity structure between the agents, thanks to the flexible communication means provided with such a pervasive modeling framework. Last but not least, the wireless nature of the ubidules will permit them to move within the environment, and interact with different environmental conditions by the way of sensors.

## 3.2 Neurobiological Modeling

There is experimental evidence that the cerebral cortex develops as a whole rather than regionally. Genetic programs are assumed to drive the primordial pattern of neuronal connectivity through the actions of a limited set of trophic factors and guidance cues, initially forming excessive branches and synapses, distributed somewhat diffusely [6]. The embryonic nervous system is refined over the course of development as a result of the twin processes of cell death and selective synaptic pruning. During the embryonic and postnatal development, adjacent neurons tend to be strongly interconnected in ensembles of variable size and structure. In regions of the central nervous system where specific roles can be assigned to neurons, local mosaic arrangements that provide a natural basis for a functional arrangement are identified [9].

It has been observed that the strength of a connection between a pre- and a post-synaptic neuron is increased if the presynaptic cell repeatedly or persistently contributes to the discharges of the postsynaptic cell [3]. Spike-timing-dependent synaptic plasticity (STDP) is a mechanism to explain both potentiation and depression of synaptic strength based on the timing of pre- and post-synaptic spikes. This mechanism has been proposed to explain the origin of long-term potentiation (LTP), i.e. a mechanism for reinforcement of synapses repeatedly activated shortly before the occurrence of a post-synaptic spike. STDP has also been proposed to explain long-term depression (LTD), which corresponds to the weakening of synapses strength whenever the presynaptic cell is repeatedly activated shortly after the occurrence of a post-synaptic spike. The strength of the synapses may vary between discrete mechanistic states, rather than by adjusting their efficacy along a continuum [8]. The important consequences from changes in synaptic strength may account for information transmission and for synaptic pruning, and have raised an interest to simulate the activity of neural networks with embedded synapses characterized by STDP [5].

The *ubidule* will provide unprecedented possibilities to study and apply the features of spatiotemporally distributed information processing in neural networks in real-time. The cutting-edge of this approach is represented by the possibility to simulate several small scale networks, each one following its faith in terms of synaptic pruning and changes of synaptic strength during a certain amount of time. These small-scale networks can interact and influence dynamically each-other information processing in order to let emerge new properties. This goal can be achieved by means of our new bio-inspired device, that allows the embedding of neural networks with spiking neurons and modifiable synapses. One ubidule will be sufficient to implement a small-scale neural network connected to local inputs (sensors and receivers) and local outputs (actuators and transmitters). The *ubichip* will allow to simulate a neural network formed by simple integrate-and-fire neuromimes connected by modifiable synapses.

Once initialized, the neural network contained in the ubidule will adapt following a faith similar to that of a newborn brain, characterized by bio-inspired mechanisms akin of massive synaptic pruning and neuronal cell death. Trigger signals by means of sensors drive an environmental information to the network and the STDP mechanisms will modify the synaptic strengths and shape a dynamic network. The ”maturity” is assumed when no more massive synaptic pruning can be observed and the dominating phenomenon is the synaptic adaptation. At this stage the neural network exhibits embedded subnetworks capable of carrying and processing complex information associated to multiple patterns of activity. The working assumption is that, once activated by a stimulus, a neural network remains activated by continuous reentry of neural excitation within its circuits with an activity pattern attuned by its reciprocal connections, thus generating stable and detectable spatiotemporal patterns of activity. This process has been proposed to explain the encoding, retention and usage of sensorimotor information [12].

### 3.3 Cooperative collective robotics

Another research field where the Perplexus platform will be tested is that of cooperative collective robotics. A group of collective robots has the ability to communicate and perform tasks jointly. This group is defined by the information and the control structures which render possible cooperation. Collective robotics is a useful way to deal with difficult tasks, first because redundancy itself provides for a robust and a flexible approach, and second, because certain tasks can only be solved by means of cooperation and division of labor. These kind of multi-robot systems have a clear analogy to biological systems [7]. Numerous examples found in Nature prove that such an approach can lead to good solutions in dynamic and hostile environments and can thus provide valuable information and inspiration for similar engineering tasks.

In the framework of the Perplexus project, we will build a population of robots that will interact in a changing environment. A *ubidule* will be integrated in the each robot, in order to equip it with the computation, communication, and sensing capabilities of the platform. Such robotic platform will allow the prototyping of distributed and mobile applications, constituting a novel platform for modeling embodied complex systems able to interact with the environment in real time.

## 4 Summary

We have introduced the Perplexus project, which goal is to develop a scalable hardware platform made of custom bio-inspired reconfigurable devices that will enable the simulation of large-scale complex systems and the study of emergent complex behaviors in a virtually unbounded wireless network of computing modules.

The platform will consist of a set of *ubidules*, which will have a *ubichip* as the core of the system. The *ubichip* will be a reconfigurable circuit capable of implementing bio-inspired mechanisms such as growth, learning, and evolution. This *ubichip* will be associated to sensory elements, actuators, and wireless communication capabilities. The main advantages offered by the Perplexus platform, compared to classical software simulations, are: an increased

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speed-up, an inherent real-time interaction with the environment, self-organization capabilities, simulation in the presence of uncertainty, and distributed multi-scale simulations.

Three applications will directly benefit from the advantages offered by the Perplexus platform: culture dissemination modeling, neurobiological modeling, and cooperative collective robotics. We will perform comparisons between classical software simulations and simulations running on a network of *ubidules*.

The Perplexus platform will thus provide unprecedented modeling capabilities thanks to the pervasive nature of the *ubidule*, its bio-inspired capabilities, its strong interaction with the environment, and its dynamical topology.

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