INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Complex

Evolution Artificielle et Fractales

Rocquencourt

THEME COG

Activity Report

2004

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1. Team

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2. Overall Objectives

Keywords: *2-microlocal analysis*, *Hölder functions*, *IFS*, *TCP traffic*, *evolutionary algorithm*, *fractal*, *fractal compression*, *fractional Brownian motion*, *genetic algorithm*, *image analysis*, *image compression*, *inverse problem*, *iterated functions system*, *large deviations*, *multifractal analysis*, *optimisation*, *signal analysis*, *stable laws*, *texture analysis*, *time-frequency analysis*, *watermarking*, *wavelets*.

The tools developed in the *COMPLEX* team deal with the mathematical, algorithmic and computational aspects of the modelling and analysis of complex signals. Examples include radar images, internet or road traffic data, financial series, speech or musical signals, biomedical signals or robotic data.

Research is centered around two synergetic topics:

- Fractal Analysis and Modelling: multifractal analysis, 2-microlocal analysis, fractal stochastic processes.
- Evolutionary Algorithms.

Evolutionary stochastic optimisation methods have proved efficient in the framework of fractal signals and allowed to address formerly unresolved applications. Conversely, analyzing the fractal irregularity of signals brings up new elements for the theoretical understanding of evolutionary techniques. Interaction between Evolutionary Algorithms and Fractals is central to the team's research topics.

Applications developed in the team concern:

- Image and Signals: denoising, segmentation, stereovision, audio2midi,
- Telecom: analysis and modelling of TCP traffic,
- Interactive systems: art and design, data-retrieval, e-learning and resource allocation.

The COMPLEX team also develops several freewares, most notably FRACLAB (a matlab/scilab toolbox for 1D and 2D signal processing) and EASEA (a specification language for evolutionary algorithms).

The COMPLEX team has strong collaborations with IrCcyn in Nantes, and regularly collaborates with ENSTA, with French universities: Orsay (LRI), Calais (LIL), Toulouse, and with several foreign universities: St-Andrews (Scottland), Montréal (Quebec), Yale (USA). The team is involved in the European organisation (former Network of Excellence) EVONET.

The COMPLEX team has industrial contracts with Dassault Aviation, Novartis Pharma (Switzerland), and Paraschool.

3. Scientific Foundations

3.1. Pointwise regularity

Keywords: *2-microlocal analysis*, *Hölder exponent*, *pointwise regularity*.

Participants: Julien Barral, Jacques Lévy Véhel, Stéphane Seuret.

In collaboration with Stéphane Jaffard (Université Paris XII).

In many applications, the local regularity of a function contains essential information for further processing. Studying the local regularity may be done in several ways. We focus on Hölder exponents and 2-microlocal analysis, which is an extension of the Hölder regularity.

There are many ways to perform the fractal analysis of a signal. Our team deals with two of these: Local regularity and multifractal analysis

In the first case, one associates to a signal $f(t)$ a function $\alpha(t)$, the *Hölder function* of f, which measures the regularity of f at each point t. This quantity may be evaluated in several manners. For instance, the pointwise Hölder exponent α of f at x_0 is defined as:

$$\alpha(x_0) = \lim_{\rho \to 0} \sup \{\alpha \quad : \exists c > 0, |f(x) - f(x_0)| \leq c|x - x_0|^{\alpha}, |\, x - x_0| < \rho\}$$

(this definition requires that α is not an integer and that f is non differentiable).

One may also define a local exponent $\alpha_l(x_0)$ as:

$$\alpha_l(x_0) = \lim_{\rho \to 0} \sup \{\alpha \quad : \exists c > 0, |f(x) - f(y)| \leq c|x - y|^{\alpha}, |x - x_0| < \rho, |y - x_0| < \rho\}$$

α and α_l are different in general (for $f(x) = |x|^{\alpha} \sin \frac{1}{|x|^{\beta}}$, $\alpha(0) = \alpha$, while $\alpha_l(0) = \frac{\alpha}{1+\beta}$). They have very different properties. For instance, α_l is stable through differentiation ($\alpha_l(f', x_0) = \alpha_l(f, x_0) - 1$), as α is not.

As a rule, the smaller $\alpha(t)$ is, the more irregular the function f is at t. A discontinuous bounded function has exponent 0, while $\alpha(t) > 1$ entail that f is at least once differentiable at t. Characterizing signals through their Hölderian regularity has been considered by many authors, both from a theoretical point of view (for instance in relation with wavelets decompositions) and in applications (e.g. turbulence analysis, image segmentation). Such an approach is fruitful as soon as some relevant information is contained in the irregularities of the signal, rather than, for instance, in its amplitude or Fourier content. This occurs in particular when ones tries to detect edges in images, or to analyze non-voiced parts of speech signals. Natural questions in this frame, that we have partially solved, include the characterization of the Hölder functions, the comparison of the different ways to measure the local regularity, and the problem of their estimation on real signals.

A generalization of Hölder regularity is provided by 2-microlocal analysis. This analysis allows to describe in great details the local regularity behaviour. Our work deals with various extensions of 2-microlocal analysis, providing time domain characterization of 2-microlocal spaces, and the estimation of 2-microlocal quantities from sampled data.

3.2. Multifractal analysis

Keywords: *Hausdorff spectrum*, *large deviations spectrum*, *multifractal analysis*.

Participants: Julien Barral, Jacques Lévy Véhel, Stéphane Seuret.

In collaboration with Claude Tricot (Université de Clermont-Ferrand).

Multifractal analysis provides both a local and a global description of the singularities of a signal: The local description is obtained via the Hölder exponent; The global one is contained in the various multifractal spectra. These multifractal spectra describe geometrically or statistically the distribution of singularities on the support of the signal.

In some situations, the Hölder function of a signal is simple while the signal is irregular. This occurs for instance in the case of the Weierstrass function or the fractional Brownian motion, which are nowhere smooth, but whose Hölder function is constant. There also exist irregular signals for which the Hölder function is even more irregular. For instance, f might be continuous but α_f everywhere discontinuous. The basic example of this situation is the graph of a Fractal Interpolation Function. In such situations, it is more interesting to use multifractal analysis than the raw Hölder function: Basically, instead of recording, for each t, the value of the exponent, one groups all the points with same α in a subset E_α. The irregularity is then characterized in a global way by computing, for each α, the Hausdorff dimension $f_h(\alpha)$ of the set E_α. One thus evaluates, in a geometrical way, the "size" of the subsets of the domain of f where a given singularity occur. Another possibility is to use a statistical description of the distribution of the singularities: More precisely, the *large deviation multifractal spectrum* $f_g(\alpha)$ estimates the exponential speed of decay of the probability to encounter a singularity equal to α at resolution n, when n tends to infinity.

This kind of analysis, which first appeared in the context of turbulence, has developed a lot, both theoretically (analysis of self-similar measures/functions, in a deterministic or stochastic frame, analysis of capacities, higher-order spectra) and in applications (study of DLA, geophysics, signal/image processing, TCP traffic analysis).

Our work in multifractal analysis deals with the theoretical computation of spectra, their comparison (multifractal formalism), and the design of robust estimators in the deterministic and stochastic frames.

3.3. Fractal Process

Keywords: *(multi-)fractional Brownian motion*, *Lévy processes*.

Participants: Antoine Ayache, Julien Barral, Michel Guglielmi, Erick Herbin, Jacques Lévy Véhel, Stéphane Seuret.

In collaboration with Serge Cohen (Université de Toulouse), Jacques Peyrière (Université d'Orsay).

Long-memory processes (i.e. those with slowly decaying autocorrelation) and processes with infinite marginal variance display interesting and sometimes counter-intuitive properties. We study certains of these processes such as (multi-)fractional Brownian motion and Lévy processes.

We study processes such as the fractional Brownian motion (fBm) or α-stables processes, which exhibit fractal properties such as auto-affinity ($x(at) \overset{d}{=} a^H x(t)$, where $\overset{d}{=}$ means equality in distribution), local irregularity, or long range memory (i.e. $E(x(t)x(t+\tau)) \sim |\tau|^\beta$ when $\tau \to \infty$, $-1 < \beta < 0$). These processes have two main features that make them different from << classical>> models:

- α–stables processes have, for $\alpha < 2$, infinite variance. This induce discontinuities in the sample paths.
- Long-memory processes exhibit a divergence of the spectral density at 0, which translates into << pseudo-cycles >> of all sizes on the paths.

In both cases, most classical tools (central limit theorem, usual estimators) have to be adapted. Our works deal with the description of certain fractals and multifractal properties of these processes. We also develop extensions that make them more fitted to certains applications. For instance, the local regularity of fBm is almost surely the same at each point. This prevents the use of fBm as a model in certain situations (e.g. TCP traffic modelling). We have defined a generalization of fBm, called multifractional Brownian motion (mBm), which allows an independent control of the Hölder exponent at each point.

3.4. Evolutionary Algorithms, Genetic Algorithms

Keywords: *Evolutionary algorithms*, *deceptivity analysis*, *genetic algorithms*, *inverse problems*, *schema theory*, *stochastic optimisation*.

Participants: Jacques Lévy Véhel, Evelyne Lutton.

In collaboration with Marc Shcoenauer (INRIA-Futurs, TAO team).

When using fractal tools for the analysis of complex signals, one often have to deal with large and extremely irregular optimisation problems. Evolutionary algorithms (including Genetic Algorithms) have proven to be powerful tools in this framework, and were able to provide robust solutions, impossible to obtain with other techniques. Conversely, works performed in the team proved also that "fractal" tools were efficient to refine and complement theoretical analysis of simple evolutionary algorithms.

Genetic Algorithms (GA) and more generally evolutionary algorithms (EA) are currently known as efficient stochastic optimisation tools, and are widely used in various application domains. These techniques are based on the evolution of a population of solutions to the problem, the evolution being driven by a "fitness" function that is maximized during the process. Successive populations of solutions are thus built, that fit increasingly well (the values of the fitness function increase). Their evolution is based on stochastic operators: selection (the fitness function is used as a sort of "bias" for a random selection in the population), and the "genetic" operators, mainly crossover (combination of two solutions) and mutation (perturbation of a solution). This technique is based on the assumption that well fitted solutions (also called individuals) can provide better solutions with help of the genetic operators. This assumption can be proven to be connected to some notions of "GA-difficulty" of the function to be optimized: one usually talks about "deception" or sometimes also about "fitness landscape."

Theoretical investigations on GA and EA generally concern convergence analysis (and convergence speed analysis on a locally convex optimum for Evolution Strategies), influence of the parameters, GA-easy or GA-difficulty analysis. For simple GA, these analyses are based on several approaches: Proof of convergence based on Markov chain modelling [38][36], deceptive functions analysis, based on Schema analysis and Holland's original theory [40], and finally modelling as dynamical systems, where fractal-like behaviour have been exhibited [41].

From the theoretical viewpoint some tools, developed in the framework of fractal theory, can be used in order to perform a finer analysis of Genetic Algorithms behaviour (mainly based on the schema theory). Actually, an analysis of how GA optimize some “fractal” functions (Hölder functions) makes it possible to model the influence of some parameters of the GA. Such an analysis can then be generalized and gives clues about how to tune some of the GA parameters in order to improve its efficiency. Finally, a further analysis on the same theoretical basis allows the influence of the coding in a GA to be analyzed [6].

3.5. New evolutionary models

Keywords: *Parisian approach*, *co-evolution and social insects colonies*, *interactive evolution*.

Participants: Pierre Collet, Evelyne Lutton.

In collaboration with Marc Shcoenauer (INRIA-Futurs, TAO team).

The versatility of evolutionary algorithms permits to address optimisation problems that involve non-standard search spaces (lists, graphs, ...). These are very difficult, irregular, impossible to address with other techniques. It is however possible to do “more than optimisation” thanks to artificial Darwinism and population-based methods. This is a major point of our research. We are in particular interested in various evolutionary techniques based on a modified formulation of the problem to be solved: Interactive evolutionary algorithms, co-evolution and “Parisian” evolution, multi-objective optimisation.

Simulated Darwinist evolution can be exploited in various ways, and recent research tend to prove the interest of new evolutionary models. Our works cover several aspects:

- *Parisian approach*: This technique proposed by the team is related to co-evolution techniques. It consists in formulating a problem no longer as the search for an optimum with a population of points in a search space, but as the search for an equilibrium state for a population of “parts” of solutions, that collectively built the searched solution. Such a formulation is not always possible for optimisation problems (the problem has to be shared into interdependent subproblems). However, when applicable, this approach is beneficial in terms of efficiency and computation time. It has been applied to inverse problem for IFS, stereovision (the quasi-real-time “flies” algorithm) for obstacle detection, fractal compression and text-retrieval.
- *Interactive evolutionary algorithms*: When an evolutionary process involves an interaction with a human user (usually fitness evaluation is partly set by the user), one has to reconsider several important points of the evolutionary loop. This research topic is very active. For example, interaction with humans raises several problems, mainly linked to the “user bottleneck,” i.e. the human fatigue. Solutions have to be found in order to avoid systematic and boring interactions. Our work deal with the analysis and development of various user-interaction modes, including learning and Parisian approaches. Current applications include text-retrieval (ELISE), e-learning, over-constrained problems resolution (CONSENSUS), and artistic design (ArtiE-Fract).

4. Application Domains

4.1. TCP Traffic

Keywords: *TCP*, *multifractal analysis*, *multifractional Brownian motion*.

Participants: Julien Barral, Jacques Lévy Véhel.

Internet traffic possesses radically different characteristics, as compared to conventional traffic, whose study requires new tools. In particular, the strong sporadicity has important consequences on the queuing behaviour.

Conventional traffic models generally assume that the arrival processes have short-term memory. It appears that Internet traffic usually does not satisfy such an assumption. In particular, many types of traffic on the Internet are strongly sporadic on several times scales. Recent models based on fBm take into account such features. The success of fBm as a traffic model relies partly on the fact that the long term memory is controlled by a single parameter. As long range dependence is an order 2 statistics, it is natural to enquire whether fBm is also a good model for higher-order statistics of real traffic.

Multifractal analysis allows to answer this question. The multifractal spectrum of fBm is trivial, since fBm is monofractal. We have shown through intensive numerical studies that LAN traffic recorded at Berkeley and CNET exhibit to the contrary a strong multifractal behaviour over 3 to 4 time scales.

The observed spectra evidence differences between incoming and outgoing traffics. Furthermore, the shape of the spectrum of the Berkeley traffic provides information on the stationarity of the process. More generally, the multifractal characteristics of traffic traces have consequences on the queuing behaviour.

Our recent work has dealt with the possible sources of multifractality. We have in particular shown that the very mechanism of TCP is a cause of multifractality.

4.2. Inverse problems

Keywords: *evolutionary algorithms*, *genetic algorithms*, *genetic programming*, *inverse problem*, *stochastic optimisation*.

Participants: Pierre Collet, Evelyne Lutton.

Several inverse problems connected to fractal analysis of signals can be successfully solved using evolutionary algorithms: inverse problems for IFS with applications to speech signal modelling, inverse problems for finite automata. It is however crucial to efficiently exploit the evolutionary loop: Experiments have proved that a carefully parameter setting and an efficient encoding noticeably increase the algorithms efficiency.

A standard inverse problem can be formulated in the following way: For a given system it is possible to compute an output from input data but reversely it is extremely difficult to estimate the input data that have produced a given output.

A classical strategy, the “black-box” approach, considers the previous problem as an optimisation one: Optimise the input data so that their computed output resembles the given output. In general evolutionary techniques are well adapted to difficult inverse problems. Especially in the domain of fractal analysis, several inverse problems have been successfully addressed, including:

- the inverse problem for IFS, [45][43][42]. Our work deals with the use of complex IFS models (mixed, polar) with genetic programming and Parisian approach. An application to speech signal modelling has also been proposed,
- inverse problems for finite automata.

The efficient resolution of these “academic” fractal inverse problems is crucial to several applications: image compression [44][39], and fractal antennas optimisation [37].

4.3. Image analysis

Keywords: *change detection*, *denoising*, *multifractal analysis*, *segmentation*.

Participants: Jacques Lévy Véhel, Evelyne Lutton.

The multifractal analysis of images is based on the definition of measures from image grey-levels. Multifractal spectra are then computed. Contrarily to more classical approaches, there is no filtering. Segmentation, denoising or change detection are performed on image points using local as well as global informations provided by the spectra.

Image analysis is a fundamental component of computer vision problems, with applications in robotics, medical or satellite imaging ...Segmentation is an important step that provides a description of the image in terms of regions and contours.

Classical approaches in this domain are based on the general assumption that an image is the sampling of a underlying piecewise C^1 process. Filtering yields then signal gradients where extrema roughly correspond to contours. Multi-resolution techniques may then be used to refine these results.

The main drawback of this approach is due to the preliminary smoothing, that produces a loss of precision. The hypothesis of a piecewise C^1 underlying process is not always realistic: Textures for example will in general puzzle these detectors.

An alternate approach is to consider that the image represents a measure known at fixed resolution. The irregularities of this measure can then be studied with the help of multifractal analysis. The general principle is the following: First, various measures and capacities are defined from the image grey-levels. The corresponding multifractal spectra are then computed, providing both local (via α) and global (via $f(\alpha)$) information. No hypothesis is made on the regularity of the signal.

5. Software

5.1. FRACLAB: a Fractal Matlab/Scilab toolbox

Participant: Jacques Lévy Véhel.

FracLab is a general purpose signal and image processing toolbox based on fractal and multifractal methods. FracLab can be approached from two different perspectives:

- Fractal analysis: A large number of procedures allow to compute various fractal quantities associated with 1D or 2D signals, such as dimensions, Holder exponents or multifractal spectra.
- Signal processing: Alternatively, one can use FracLab directly to perform many basic tasks in signal processing, including estimation, detection, denoising, modelling, segmentation,classification, and synthesis.

Note that FracLab is not intended to process "fractal" signals (whatever meaning is given to this word), but rather to apply fractal tools to the study of irregular but otherwise arbitrary signals. A graphical interface makes FracLab easy to use and intuitive. In addition, various wavelet-related tools are available in FracLab.

FracLab is a free software. It mainly consists of routines developed in C-code interfaced with Matlab (Ver. 5) and Scilab (a free scientific software package for numerical computations from INRIA). It runs under Linux and Windows environments

Since version 1.0 (June 2001), FracLab has been downloaded more than 2000 times. A few dozens of laboratories seem to use it. FracLab has been referenced in several research papers.

5.2. EASEA : an evolutionary algorithms specification language

Keywords: *evolutionary algorithm*, *stochastic optimisation*.

Participants: Pierre Collet, Jean Louchet, Evelyne Lutton.

EASEA (EAsy Specification of Evolutionary Algorithms) was initiated inside the EVO-Lab collaborative action (1999-2000). Its aim was to simplify the programmation of an evolutionary algorithm, especially for non-computer scientist. A simple specification of an evolutionary algorithm written in an << .ez >> file is used by EASEA. It then produces a C++ source file using the primitives of an underlying evolutionary library. The complex programming tasks are hidden to the user.

The description of an evolutionary algorithms becomes very short, and thanks to the EASEA compiler this specification file can be compiled at any place. The current version (UNIX and Windows) can produce a C++ source file for the GALib or the EO library, or JAVA source files for the DREAM library.

EASEA is now largely used,

- as a teaching support (ENSTA, école Polytechnique, Université du Littoral, Université de Dijon, école Centrale, école des Ponts, CESTI Toulon, University of Massachusetts Dartmouth),

- as research and industrial development tool (projet SINUS, ENSTA, Laboratoire d'Informatique du Littoral, General Electric (France), Université d'Alger, University of Exeter (UK), Napier University (Ecosse), South-Bank University (Londres), Vrije University of on Amsterdam, University of Dortmund, Granada University).

A graphical interface, GUIDE is also available. It provides an unified representation of the evolutionary engines (AG, ES, EP, ...), and gives access to unexplored schemes with a versatile presentation.

EASEAv0.7 is available on EASEA .

5.3. XCLE - eXtensible Concatenative Language Engine

Keywords: *Compiler*, *Concatenative Language*, *Genetic Programming*, *Open Source Software*.

Participant: Yann Landrin-Schweitzer.

An evolution of the OKit project, XCLE has been developed to standardise code management tools for Genetic Programming developers.

XCLE addresses the need to automatically generate and manipulate program code, while retaining performance at program execution.

XCLE provides an implementation of basic data types: integers, floats, strings, recursive lists and executable primitives, encapsulated in a generic object type. The API provide the means to integrate program building capabilities into software, handling both the data and code aspects of program generation and execution. The library as a whole provides the necessary framework for manipulating concatenative code.

It constitues a ready basis for a generic genetic operators library, and a tool for code portability and reusability in the GP community. A standardized primitives library, and a graphical IDE, complete the set of tools offered to developers.

XCLE is currently available at http://varkhan.free.fr/software/xcl/XCLE/

6. New Results

6.1. 2-microlocal frontier of Gaussian processes

Keywords: *(multi-)fractional Brownian motion*, *2-microlocal analysis*, *Gaussian processes*, *Holder exponents*.

Participants: Erick Herbin, Jacques Lévy Véhel.

The frame of 2-microlocal analysis can be used to study finely the regularity of the paths of a stochastic process. For a continuous Gaussian process $X = \{X_t;\ t \in \mathbf{R}_+^N\}$, one defines the *2-microlocal frontier* of X at $t_0 \in \mathbf{R}_+^N$ as the random function:

$$s' \mapsto \boldsymbol{\sigma} = \sigma_{t_0}(s') = \sup\left\{\sigma;\ \limsup_{\rho\to 0}\ \sup_{s,t\in B(t_0,\rho)} \frac{|X_t - X_s|}{\|t-s\|^{\sigma}\rho^{-s'}} < \infty\right\}$$

defined for $-1 < s' < 0$. As in the deterministic case, this function allows to predict the evolution of the regularity of the path under the action of (pseudo-)integro-différential operators.
Define the deterministic function:

$$s' \mapsto \boldsymbol{\sigma} = \sigma_{t_0}(s') = \sup\left\{\sigma;\ \limsup_{\rho\to 0}\ \sup_{s,t\in B(t_0,\rho)} \frac{E\left[X_t - X_s\right]^2}{\|t-s\|^{2\sigma}\rho^{-2s'}} < \infty\right\}$$

We have proved that for all $t_0 \in \mathbf{R}_+^N$, the 2-microlocal frontier at t_0 of the path of the continuous Gaussian process X is almost surely equal to the graph of the function $s' \mapsto \boldsymbol{\sigma} = \sigma_{t_0}(s')$.

This result may be applied in particular to multifractional Brownian motion (mBm): The almost sure 2-microlocal frontier of mBm at any point $t_0 \in \mathbf{R}_+$ equals, for all $s' \in (-1,0)$:

$$\boldsymbol{\sigma} = \sigma_{t_0}(s') = (H(t_0) + s') \wedge \beta_{t_0}(s')$$

where $s' \mapsto \beta_{t_0}(s')$ denotes the 2-microlocal frontier of H at t_0.

Moreover, in the particular case where for all $t_0 \in \mathbf{R}_+ :\ H(t_0) < \tilde{\beta}(t_0)$, one has:

$$P\left\{\forall t_0 \in \mathbf{R}_+, \forall s' \in (-1,0) : \quad \boldsymbol{\sigma} = \sigma_{t_0}(s') = H(t_0) + s'\right\} = 1$$

6.2. A set-indexed fractional Brownian motion

Keywords: *fractional Brownian motion*, *set-indexed processes*.

Participant: Erick Herbin.

In collaboration with Ely Merzbach (Bar Ilan University, Israel).

The construction of a set-indexed extension of the fractional Brownian motion seems interesting for applications, for instance in the frame of censored data. From an indexing collection $\mathcal{A}$, one defines the collection $\mathcal{C} = \left\{U \setminus \left(\bigcup_{1\leq i\leq n} U_i\right);\ U, U_1, \cdots, U_n \in \mathcal{A}\right\}$ and the increment process for a process X, $\Delta X = \{\Delta X_C;\ C \in \mathcal{C}\}$ by an inclusion-exclusion formula. The sub-familly $\mathcal{C}_0$ of $\mathcal{C}$, constituted with elements $C = U \setminus V$, where $U, V \in \mathcal{A}$, plays an important role in the construction.
The natural idea to define an set-indexed extension of fBm is to require the property

$$\forall C \in \mathcal{C}; \quad E\left[\Delta X_C\right]^2 = m(C)^{2H}$$

However, the only Gaussian process satisfying such a property is the set-indexed Brownian motion ($H = \frac{1}{2}$). The *set-indexed fractional Brownian motion (SifBm)*, with parameter of self-similarity $H \in (0,1)$, is defined as the process such that

$$\forall U, V \in \mathcal{A}; \quad E\left[B_U^H - B_V^H\right]^2 = m(U \bigtriangleup V)^{2H}$$

It verifies

$$\forall C \in \mathcal{C}_0; \quad E\left[\Delta X_C\right]^2 = m(C)^{2H}$$

The SifBm satisfies the property of $\mathcal{C}_0$-*stationnarity (ou stationnarity of its increments* $\mathcal{C}_0$*)*, in the sense of for all C and C' in $\mathcal{C}_0$ such that $m(C) = m(C')$: $\Delta B_C^H \overset{(d)}{=} \Delta B_{C'}^H$.

To study the self-similarity of a set-indexed process, it is necessary to provide the indexing collection $\mathcal{A}$ with the operation of a group G which may be extended so that

$$\forall U, V \in \mathcal{A}, \forall g \in G; \quad g.(U \cup V) = g.U \cup g.V \qquad \text{et} \qquad g.(U \setminus V) = g.U \setminus g.V$$

and to suppose that there exists a function $\mu : G \to \mathbf{R}_+$ such that

$$\forall U \in \mathcal{A}, \forall g \in G; \quad m(g.U) = \mu(g).m(U)$$

We then prove that the SifBm is self-similar with parameter H, i.e. for all $g \in G$, $\left\{B_{g.U}^H;\ U \in \mathcal{A}\right\}$ has the same law as $\left\{\mu(g)^H.B_U^H;\ U \in \mathcal{A}\right\}$

We have proved that the projection $X^f = \left\{X_{f(s)};\ s \in [a,b]\right\}$, of the SifBm X on any flow f is a time-changed fractional Brownian motion.

6.3. Multifractal processes combining additive and multiplicative chaos

Keywords: *Multifractal process*.

Participants: Julien Barral, Stéphane Seuret.

Among the measures on which multifractal analysis has been performed, two families can be distinguished by the typical shape of their multifractal spectrum.

Some measures, the construction of which is based on an additive scheme, classically exhibit linear increasing spectrum. To the contrary, atomless measures with a construction involving a multiplicative scheme usually have a strictly concave spectrum, including a decreasing part.

Let μ be a positive Borel measure on $[0,1]$, let b be an integer ≥ 2 and let $\gamma \geq 0$, $\sigma \geq 1$. We introduce and study the new class of multifractal measures, which combines additive and multiplicative chaos, defined by

$$\nu_{\gamma,\sigma} = \sum_{j\geq 1} \frac{b^{-j\gamma}}{j^2} \sum_{0\leq\, k\, \leq b^j-1} \mu([kb^{-j},(k+1)b^{-j}))^{\sigma} \delta_{kb^{-j}}.$$

Under suitable assumptions on μ, the multifractal spectrum of $\nu_{\gamma,\sigma}$ is linear on $[0,h_{\gamma,\sigma}]$ for some critical value $h_{\gamma,\sigma}$, and then it is strictly concave on the right of $h_{\gamma,\sigma}$, and deduced from the one of μ by an affine transformation. This untypical shape is the result of the combination between Dirac masses and atomless multifractal measures. These measures satisfy multifractal formalisms, and open interesting perspectives in modeling discontinuous phenomena.

The singularities analysis of the measures $\nu_{\gamma,\sigma}$ involves new results in two directions.

- First, new investigations on self-similarity are required. Indeed, it is necessary to measure the speed at which multifractal structures reproduce themselves at small scales.
- Second, the concept of ubiquity is revisited and produce new results on the distribution of the mass of self-similar measures.

This work also has consequences on the definition and regularity analysis of functions which are natural counterparts (for functions) of the measures $\nu_{\gamma,\sigma}$.

6.4. Experiments on controlled regularity fitness landscapes

Keywords: *evolutionary algorithms*, *fitness landscapes*, *irregularity*.

Participants: Yann Landrin-Schweitzer, Jacques Lévy Véhel, Evelyne Lutton.

An experimental analysis of local irregularity influence has been done for a simple model of evolutionary algorithm. Previous theoretical as well as experimental work on this subject suggest that the perfomance of EA strongly depends on the irregularity of the fitness function.

Several irregularity measures have been derived, in order to numerically characterise this type of difficulty source for EA. These characterisations are mainly based on Hölder exponents. However the previous theoretical analyses are based on a global characterisation of fitness regularity (namely the global Hölder exponent), and the corresponding experimental validations have been conduced on uniform irregularity test functions (Mandelbrot-Weierstrass functions).

We go further in this direction by analysing now the behaviour of an EA on variable regularity functions. This opens the way to theoretical analysis based on local Hölder exponents, and poses several question with respect to on-line measurements and usage of regularity characteristics on fitness functions.

6.5. Stereovision and robot control: the Fly Algorithm

Keywords: *automatic control*, *evolutionary algorithm*, *obstacle detection*, *stereovision*, *vision systems for robotics*.

Participants: Amine Boumaza, Jean Louchet, Evelyne Lutton, Olivier Pauplin.

In collaboration with Michel Parent (projet IMARA).

Figure 1. A pedestrian, 4 metres in front of the cameras

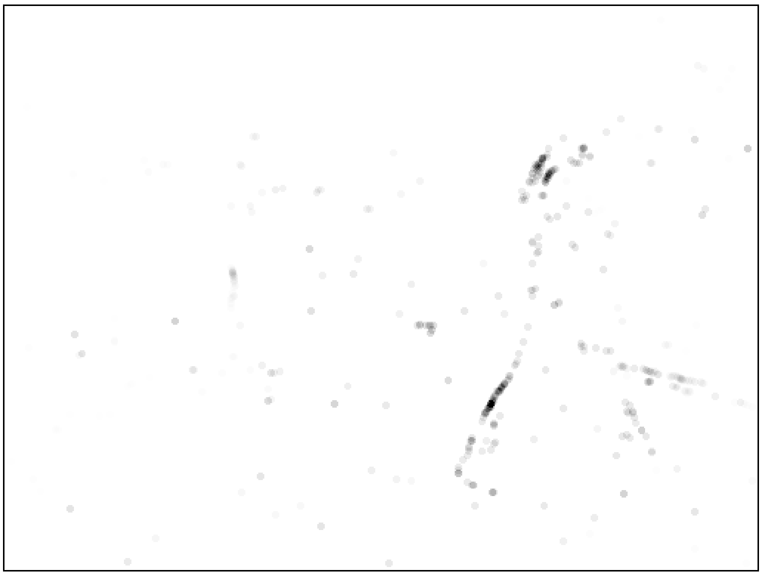

Figure 2. Probability of presence of near obstacles

Artificial vision is a key element in robots autonomy. The Fly algorithm is a fast evolutionary algorithm using pairs of stereo images. It aims to be used in particular in the field of real time obstacle detection and control for mobile robotics and automated vehicles. Based on the Parisian approach, which consists here in splitting the representation of the environment into a large number of simple primitives (the flies), the Fly algorithm produces a set of 3-D points which gather on the surfaces of obstacles. Those points are evolved following the classical steps of evolutionary algorithm.

The Fly algorithm has been demonstrated during the CyberCars final project presentation in Antibes (June 7-11, 2004). The public could see the real time detection results on a screen while cameras' images from the scene were being processed.

In order to use the Fly algorithm in the field of assisted driving, we developed a strategy to make the program quantify the probability that an obstacle is in front of the cameras. Figure 1 shows flies gathering on obstacles, and figure 2 shows the same scene as interpreted by the algorithm in terms of obstacle probability. On figure 2, the probability of a collision with an obstacle in a given direction is as high as stains are numerous and dark in that direction. These results were obtained using two commercial CCD cameras and a Pentium 2GHz computer, with a population of 5000 flies and after 30 generations. One generation takes about 20 milliseconds.

The objective, in cooperation with the IMARA project, is to integrate control strategies based on the fly algorithm into a vehicle.

6.6. Pareto Optimal Sensing Strategies for an Active Vision System

Keywords: *3D inspection system*, *Multi-objective optimisation*, *evolutionary algorithms*, *robot vision*.

Participants: Enrique Dunn, Jean Louchet, Evelyne Lutton.

In collaboration with Gustavo Olague (CICESE, Mexique).

This study takes place in a collaboration with the computer science department of the CICESE of Mexico under a LAFMI grant, and concern the study of an experimental robot vision system for 3D automated inspection. The purpose of this collaboration is to design efficient and adapted evolutionary techniques to tackle the various complex optimisation problems involved in such systems

vDuring the 3 month intern of Enrique Dunn, who is currently PhD student at CICESE under the direction of Gustavo Olague, a multi-objective formulation of the successive positions of the camera was studied.

Experiments on a simulated environment have provided convincing results. An implementation on the experimental system of the CICESE will follow.

6.7. Artificial Epidemic Approach for Dense Stereo Matching

Keywords: *evolutionary algorithms*, *robot vision*.

Participants: Cynthia Perez, Evelyne Lutton.

In collaboration with Gustavo Olague (CICESE, Mexique).

An artifical epidemic process, the "infection algorithm," has been proposed for stereo matching (internship of Cynthia Perez). The aim is to match the contents of a stereo pair in order to obtain dense 3D informations which allow the generation of simulated projections from a viewpoint that is different from the ones of the initial photographs (view synthesis). The proposed algorithm exploits the image contents in order to only produce the necessary 3D depth information, while saving computational time. It is based on a set of distributed rules, that propagate like an artificial epidemy over the images. Experiments on pairs of real images provide realistic reprojected images.

6.8. CONSENSUS

Keywords: *contrained problems*, *evolutionary algorithms*, *resource allocation*.

Participants: Evelyne Lutton, Martin Pernollet.

In collaboration with Francois Fages (CONTRAINTES Team).

The problem of office affectation on the INRIA Rocquencourt campus can be considered as a very complex contraint satisfaction problem: the demand of research teams exceeds the actual resource, and in the same time the constraints and preferences of each team are difficult to represent and tune within standard constraint satisfaction software. Evolutionary techniques have been used as a complement to constraint satisfaction tools with respect to the user interaction. Actually many constraints are difficult to express and the relative importance of each constraint is an important factor for effective usage of constraint satisfaction software.

We have experimented in 2003 the scheme of a multi-user interactive evolutionary approach for the management of relative weights of user preferences, based on a Parisian and multi-population paradigm. This work has been continued in 2004 (internship of Martin Pernollet), in order to produce a prototype for real size testing.

6.9. Symbolic Regression with Genetic Programming

Keywords: *Genetic Programming*, *Linear Scaling*, *Symbolic regression*, *Weighted Operands*.

Participants: Pierre Collet, Tristan Moreaux, Gregory Valigiani.

Exploitation capabilitites in genetic programing can be boosted in various ways. Two methods have been investigated here:

- Weighted Operands (WO), that consist in multiplicate the individuals by a real coefficient. A mutation on these coefficients is a convenient way to produce small variations.
- Linear Scaling (LS), adjusts some of the numerical values of an individual to the available samples via a mean square minimisation.

However, when solutions generated with WO are applied to new data, Valigiani *et al.*[35] show that, in this case, LS provides larger errors.

On the contrary, further experiments tend to prove that, when WO is not used, LS decreases error even on new data. More precisely, results with LS on new data are the same, WO being used or not. Actually, it seems that WO improvement when LS is used is not as good as when it is not.

6.10. Interactive Evolutionary Multifractal Denoising

Keywords: *Multifractal denoising*, *denoising*, *interactive evolution*.

Participants: Pierre Grenier, Jacques Lévy Véhel, Evelyne Lutton, Mario Pilz.

Multifractal denoising techniques necessitate a delicate parameter setting, which may vary for each image. Theoretical investigations do not always provide solutions to a fully satisfying parameter setting. There remains “free” parameters to be set, which actually depend on a subjective evaluation. In this work, we address the problem of parameter adaptation using an interactive evolutionary scheme. The idea is to evolve a well chosen parameter subset in order to optimise an expert evaluation, who has to compare a set of output images (the “population”) via an interface.

Experiments have been made, based on a previously proposed image denoising technique. A C/Gtk prototype has been produced and tested (internship of Pierre Grenier). It is now being currently developed in matlab, in order to include it in the fraclab toolbox (internship of Mario Pilz).

6.11. Interactive EAs for Text-Mining

Keywords: *Genetic Programming*, *data retrieval*, *interactive EA*, *text mining*.

Participant: Yann Landrin-Schweitzer.

Keyword-based document retrieval is often plagued by the difficulties of keyword relevancy assessment. Thesaurii enable sense detection by identifying related terms, and are often sought as a solution, despite their lack of adaptability and a strong specificity to document sets. We attempt to use an alternate method to provide context and sense detection, on a user-oriented basis, by using evolved personal "search profiles."

A working prototype, ELISE, has shown the feasability of the method, and validated the adaptability of our method to search context variation, using public search benchmarks from the TREC.

Despite showing properties unavailable in classical search systems (adaptability, user-specificity, semantic creativity), performance remains poor on several indicators (result precision, notably). We are examining techniques to put ELISE on pair with modern search engines on these caracteristics, while enhancing its specialisation capabilities. Two main axes are explored: improving the robustness of the evolutionary engine, and integrating state-of-the-art semantic tools.

The January-August 2004 period has been essentially devoted to strengthening the structure of the engine. Modularity has been increased, mainly to ease measurement of the relative effects of distinct improvement strategies on overall performance. The genome structure has been extended, allowing for more specific genetic operators and query-expansion tools. This has been followed by a thorought algorithmic efficiency check, to remain in line with industrial imperatives.

We are currently integrating enhanced semantic tools in the structure, to be used in three main areas: the evolutionary engine, as a base for randomizing operators, the user behaviour analysis, as a base for precise fitness computing, and to extract performance and efficiency statistics. These range from conceptual tagging tools to automatic thesauri extraction systems, and sense correlation anaysers.

We are also in the process of establishing a real-user testing platform, as a publicly available search engine for scientific publications, that will let us collect behavour data and evolutionary performance from real-world users.

6.12. Experimenting a Man-Hill to Optimize Pedagogical Paths

Keywords: *Ant Colony Optimisation (ACO)*, *E-Learning*, *Self-organisation*, *Simulation of Swarm Intelligence*.

Participants: Pierre Collet, Evelyne Lutton, Grégory Valilgiani.

In collaboration with Raphaël BIOJOUT and Yannick JAMONT (PARASCHOOL compagny).

Paraschool, the French leading e-learning company was looking for a system that could enhance site navigation by making it intelligent and adaptive to the user. This collaboration, initiated by B. Leblanc's 2002 post doctoral work and Y. Semet's 2003 M. Eng. thesis work, is now continuing with G.Valigiani's PhD thesis (2003-2006).

This work is based on the use of the Ant Colony Optimisation (ACO) heuristic. As the available online material of Paraschool is organised as a graph by means of hyperlinks between educational topics, it is searched for an optimised graph structure that facilitates the learning process for students. Actually, more than 150,000 students now go through the pedagogical graph. The very large number of students triggered the idea to apply virtual ant-hill techniques, in considering students as virtual ants.

Compared to Y. Semet's 2003 M. Eng. thesis work that has provided guidelines for this problem, real-size tests have been now perfomed, showing that a classical ant-hill optimisation technique needs to be adapted. We have rather built a so-called "man-hill" model, based on several modified behaviour of the basic entitities (namely students instead of virtual insects !). For instance, a pheromone erosion process (instead of the classical evaporation) has been developed, in order to cope with seasonnal (irregular) path preferences in the graph.

7. Contracts and Grants with Industry

The team has contracts with:

- NOVARTIS PHARMA about text-retrieval with evolutionary algorithms (PhD and Post-doctoral position of Yann Landrin-Schweitzer).

- DASSAULT AVIATION on terrain modelling based on mBm (PhD of Erick Herbin).
- PARASCHOOL on evolutionary optimisation of pedagogical path (e-learning, PhD of Gregory Valigiani).

8. Other Grants and Activities

8.1. National initiatives

Our project a has collaborations with :

- IrCcyn, Institut de Recherche en Cybernétique et communications de Nantes, since 1996. Areas of collaborations: study of $1/f$ noises, Watermarking, regularity analysis of road profiles. For the last three years, the software "FracLab" has mainly been developed at IRCCYN.
- Littoral university (Calais), on e-learning (P. Collet and C. Fonlupt),
- Clermont Ferrand University (A. A. Benassi) and Toulouse Paul Sabatier University (A. Ayache et S. Cohen) on Multifractional Brownian Motion.
- Clermont Ferrand University (C. Tricot) on multifractal analysis.
- Yale University(R. Coiffman) for data analysis in high dimension (S. Lafon Ph.D. thesis).
- Yale University (B. Mandelbrot) on multifractal analysis.
- Ecole Polytechnique-CRM, Montreal (J.M. Lina) on multifractal denoising.
- Orsay University (J. Peyrière) on multifractal analysis and warping.
- Monastir University (F. Ben Nasr, M. Mensi, H. Tlili) on multifractal analysis and diffusion on fractals.
- ROBEA: CNRS-INRIA ROBEA program (ROBotique et Entites artificielles) coordinated by Marc Schoenauer and Michèle Sebag (LRI-Orsay). Other participant: Laboratoire de Mécanique de l'INSA Rouen.

8.2. European initiatives

The team belongs to EvoNet, the European Excellence Network on artificial evolution.

8.3. International initiatives

The COMPLEX team collaborates with a Mexican research institute (CICESE, Física Aplicada, Gustavo Olague) under a LAFMI grant.

9. Dissemination

9.1. Organization committees

Evelyne Lutton and Jacques Lévy Véhel are co-chairs of the next “Fractal in Engineering” conference, FE05, Tours, June 22-24. 2005.

Pierre Collet, Evelyne Lutton and Marc Schoenauer are involved in the organisation of the << Evolution Artificielle ’2005 >> conference (Lille, Nov 2005), and are members of the streering commitee of the french association for artificial evolution.

9.2. Editorial Boards

Jacques Lévy Véhel is associate Editor of the journal << FRACTALS >>, referee for IEEE Trans. Signal Proc., IEEE Trans. Image Proc., Fractals, ICIP conference.

Evelyne Lutton is co-editor of the Special Issue on Evolutionary Computer Vision and Image Understanding of the Pattern Recognition Letters, and of a book on Genetic and Evolutionary Image Analysis and Signal Processing, with Stefano Cagnoni and Gustavo Olague.

Evelyne Lutton has been referee for IEEE Transactions on Evolutionary Computation, IEEE Signal Processing Letters, Genetic Programming and Evolvable Machine, et IEEE Computer Graphics and Applications.

Evelyne Lutton and Pierre Collet are editors of the special issue on artificial evolution of the french journal TSI.

9.3. Teaching at University

- << Wavelets and Fractals >> DEA AIA of Ecole Centrale de Nantes (Jacques Lévy Véhel, 10 h).

9.4. Other Teaching

- “Fractals and Wavelets” Ecole Centrale de Paris (Jacques Lévy Véhel, Evelyne Lutton, Julien Barral, Stéphane Seuret, 39 h).
- “Fractals and Wavelets” ENSTA (Evelyne Lutton, Jacques Lévy Véhel, 21 h)
- “Fractals and Time-frequency analysis” Centrale de Nantes (Jacques Lévy Véhel, 15 h).
- “Fractals” ESIEA (Jacques Lévy Véhel, 15 h).
- “Fractal Analysis” INT (Jacques Lévy Véhel, 6 h).
- “Artificial Evolution” ENSTA (Evelyne Lutton, Pierre Collet, Cyril Fonlupt, 21 h).

9.5. Ph.D. Theses

- Erick Herbin: ”Processus (multi-) fractionnaires à paramètres multidimensionnels et régularité Höldérienne” December 6, 2004, Université de Paris XI. Thesis advisor: J. Lévy-Véhel.
- Stéphane Lafon: ”Diffusion Maps and Geometric Harmonics”, May 18, 2004, Yale University. Thesis advisors: R. Coiffman, J. Lévy-Véhel.
- Amine Boumaza: "Introduction de méthodes d’évolution artificielle en vision tridimensionnelle et en robotique mobile", May 19, 2004, Université René Descartes. Thesis advisor: Jean Louchet.

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