INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Complex

Evolution Artificielle et Fractales

Rocquencourt

THEME COG

Activity Report

2005

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2. Overall Objectives

2.1. 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 and robotic data.

Research is centred on 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, analysing 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 deal with:

- 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, with ENSTA, with French universities: Orsay (LRI), Calais (LIL), Toulouse, and with several foreign universities: St-Andrews (Scottland), Montréal (Quebec). 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: Jacques Lévy Véhel, Pierrick Legrand.

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

Fractal properties of a signal may be analyzed a number of ways. Our team deals with two of these: Local regularity and multifractal analysis.

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

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

(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:

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

α and α_l are different in general (e.g. for $f(x) = |x|^\alpha \sin \frac{1}{|x|^\beta}$, $\alpha(0) = \alpha$, while $\alpha_l(0) = \frac{\alpha}{1+\beta}$) and 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 $\alpha(t)$, the more irregular the function f at t. A discontinuous bounded function has exponent 0, while $\alpha(t) > 1$ entail that f is differentiable at least once 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 wavelet decompositions) and in applications: e.g. turbulence analysis, image segmentation. Such an approach is fruitful when relevant information is contained in the irregularities of the signal, rather than, for instance, in its amplitude or Fourier contents. This occurs in particular when ones tries to detect edges in images, or to analyse non-voiced parts of speech signals. We have partially solved natural questions in this frame, including the characterisation 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 generalisation of Hölder regularity is provided by 2-microlocal analysis. This analysis allows to describe in great detail the local regularity behaviour. Our work deals with various extensions of 2-microlocal analysis, providing time domain characterisation 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: Jacques Lévy Véhel, Evelyne Lutton.

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

Abstract. 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 are also irregular signals for which the Hölder function is even more irregular. For instance, f might be continuous but α_f discontinuous everywhere. A typical example of this situation is the graph of a Fractal Interpolation Function. In such a situation, it is more rewarding 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 into a subset E_α. The irregularity is then characterised globally by computing, for each α, the Hausdorff dimension $f_h(\alpha)$ of the set E_α. Thus one evaluates geometrically the "size" of the subsets of the domain of f where a given singularity occurs. 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 decay speed of the probability to encounter a singularity equal to α at resolution n, when n tends to infinity.

This kind of analysis, which was first introduced in the study of turbulence, has undergone wide development both in theory (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 theoretical computation of spectra, their comparison (multifractal formalism), and the design of robust estimators in deterministic and stochastic frames.

3.3. Fractal Processes

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

Participants: Antoine Ayache, Michel Guglielmi, Erick Herbin, Jacques Lévy Véhel.

In collaboration with Olivier Barrière (IrCcyn).

Abstract. 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 certain

of these processes such as (multi-)fractional Brownian motion and Lévy processes. These processes exhibit fractal properties such as self-affinity.

We study processes such as the fractional Brownian motion (fBm) or α-stables processes, which exhibit fractal properties such as self-affinity ($x(at) \stackrel{d}{=} a^H x(t)$, where $\stackrel{d}{=}$ 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 $\alpha < 2$, an infinite variance. This induces 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 certain applications. For instance, the local regularity of fBm is almost surely the same at each point. This prevents from using fBm as a model in certain situations (e.g. TCP traffic modelling). We have defined a generalisation of fBm, called multifractional Brownian motion (mBm), which allows to control independently 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: Pierrick Legrand, Jacques Lévy Véhel, Yann Landrin-Schweitzer, Evelyne Lutton.

Abstract. 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 built, with increasingly better fitness (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 the help of genetic operators. This assumption can be proven to be connected to some notions of "GA-difficulty" of the function to be optimised: one usually talks about "deception".

Theoretical investigations on GAs and EAs generally deal with 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 a simple GA, analysis is based on several approaches: proof of convergence based on Markov chain modelling [48], [46], deceptive functions analysis, based on Schema analysis and Holland's original theory [50], and finally modelling as dynamical systems, where fractal-like behaviour has been exhibited [51].

From a theoretical viewpoint, some tools, developed in the framework of fractal theory, can be used in order to perform a more accurate analysis of Genetic Algorithms behaviour (mainly based on the schema theory). Actually, an analysis of how GA optimises some "fractal" functions (Hölder functions) makes it possible to model the influence of some parameters of the GA. Such an analysis can then be generalised 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 coding in a GA to be analyzed [10].

3.5. New evolutionary models

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

Participants: Pierre Collet, Yann Landrin-Schweitzer, Evelyne Lutton.

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

Abstract. 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 tends 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 build the searched solution. Such a formulation is not always possible for optimisation problems (the problem has to be split 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,” human fatigue. Solutions have to be found in order to avoid systematic and boring interactions. Our work deals with the analysis and development of various user-interaction modes, including 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*.

Participant: Jacques Lévy Véhel.

Abstract. Compared to conventional traffic, internet traffic possesses radically different characteristics, 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 exhibits on 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. Signal and Image analysis

Keywords: *2-microlocal analysis*, *Hölder exponents*, *Internet traffic*, *biomedical signals*, *change detection*, *denoising*, *financial records*, *interpolation*, *medical images*, *multifractal analysis*, *radar images*, *segmentation*.

Participants: Jacques Lévy Véhel, Pierrick Legrand, Evelyne Lutton.

In collaboration with Antoine Echelard (IrCcyn).

Abstract. Multifractal processing of signals and images is based on a fine analysis of the local regularity of various measures definied from the data. The corresponding Multifractal spectra are then computed. Contrarily to more classical approaches, there is no filtering. Segmentation, denoising, interpolation or change detection are performed on signal/image points using local as well as global information provided by the spectra.

Signal processing is a required task in many applications, such ECG/EEG and other biological and medical signal analysis, Internet traffic monitoring, financial records analysis, ...

Image analysis is a fundamental component of computer vision problems, with applications in robotics, medical or satellite imaging, ...

Signals and images have often to be "denoised" prior to processing: This is in particular the case for radar images and most medical signals/images. Segmentation is also an important step that provides a description of an image in terms of regions and contours, and that splits signals (in particular biomedical and financial ones) into homogeneous zones. In many applications, one is interested in detecting change points, or variations in sequences of images. Finally, it is sometimes useful to resample the data, e.g. in order to improve resolution

Classical approaches in these domains are based on the general assumption that the available data represent the sampling of an underlying process which is *globally* piecewise regular (e.g. belongs to some Hölder space C^α or some Besov space $B^s_{p,q}$). One may then apply for instance certain filters that will yield "gradients" where extrema roughly correspond to contours. Multi-resolution techniques may be used to refine the results. One drawback of this approach is due to preliminary smoothing, resulting in loss of precision. In addition, the hypothesis of a piecewise regular underlying process is not always realistic: Textures for example will in general puzzle these processors.

An alternative approach is to consider that the signal/image represents a function or 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 or signal amplitudes. The corresponding Hölder exponents and multifractal spectra are then computed, providing both local (via α) and global (via $f(\alpha)$) information. No hypothesis is made on signal regularity, and there is no prior filtering. We have in particular developped methods that allow to perform segmentation, denoising, interpolation or change detection by using both the local and global regularity information encompassed in multifractal analysis. Contours, for instance, correspond to points where the multifractal spectrum assume a specific value. Denoising may be achieved by increasing, in a controlled way, the Hölder exponent at each point.

4.3. Complex interactions

Keywords: *fractal inverse problems*, *interactive evolutionary algorithms*, *interactive genetic programming*.

Participants: Pierre Collet, Pierrick Legrand, Jacques Lévy Véhel, Evelyne Lutton.

Abstract. We study the use of evolutionary optimisation tools for modelling, controlling or optimising complex interactive systems. In particular, some of them involve fractal inverse problems and multifractal analysis: For interactive design (Artie-Fract software), interactive multifractal denoising (in Fraclab), cochlear implants optimisation (HEVEA project), and termites nest modelling (TERMCAO project).

A standard inverse problem can be formulated 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, due to highly non-linear (complex) interactions between input components. In such cases, a “black-box” approach is the only solution: Optimise the input data so that their computed output resembles the given output.

In the domain of fractal analysis, several inverse problems have been successfully addressed using evolutionary optimisation, including the famous inverse problem for IFS, [55], [53], [52]. Our contribution to this domain deals with the use of complex IFS models (mixed, polar) with genetic programming and Parisian approach. The efficient resolution of such fractal inverse problems is crucial to several applications like image compression [54], [49], and fractal antennas optimisation [47].

Additionnally, human interactions in such computer systems tends to add irregularity and unpredictability, but are often necessary to provide useful and efficient algorithms. The example of multifractal image denoising is characteristic : the notion of a “good” denoising strongly depends on the user (a medical practicionner, a photograph, an art expert, etc ...) and on the applicative framework. An additionnal judgement given by the end-user is necessary to identify a satisfying result.

Applications currently considered in the team are artistic interactive design of fractals (ArtiE-Fract, with the Cetoine company), text-retrieval (ELISE, with Novartis-Pharma), resolution of over-constrainted problems for resource allocation (CONSENSUS, in collaboration with the CONSTRAINTS team), termite nest formation (TERMCAO project, with biologists) and cochlear implants optimisation (HEVEA project, with the Avicenne Hospital).

5. Software

5.1. FRACLAB: a Fractal Matlab/Scilab toolbox

Participants: Pierrick Legrand, Jacques Lévy Véhel.

In collaboration with Olivier Barrière, Antoine Echelard (IRCCyN).

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 3000 times. A few dozens laboratories seem to use it. FracLab has been referenced in several research papers.

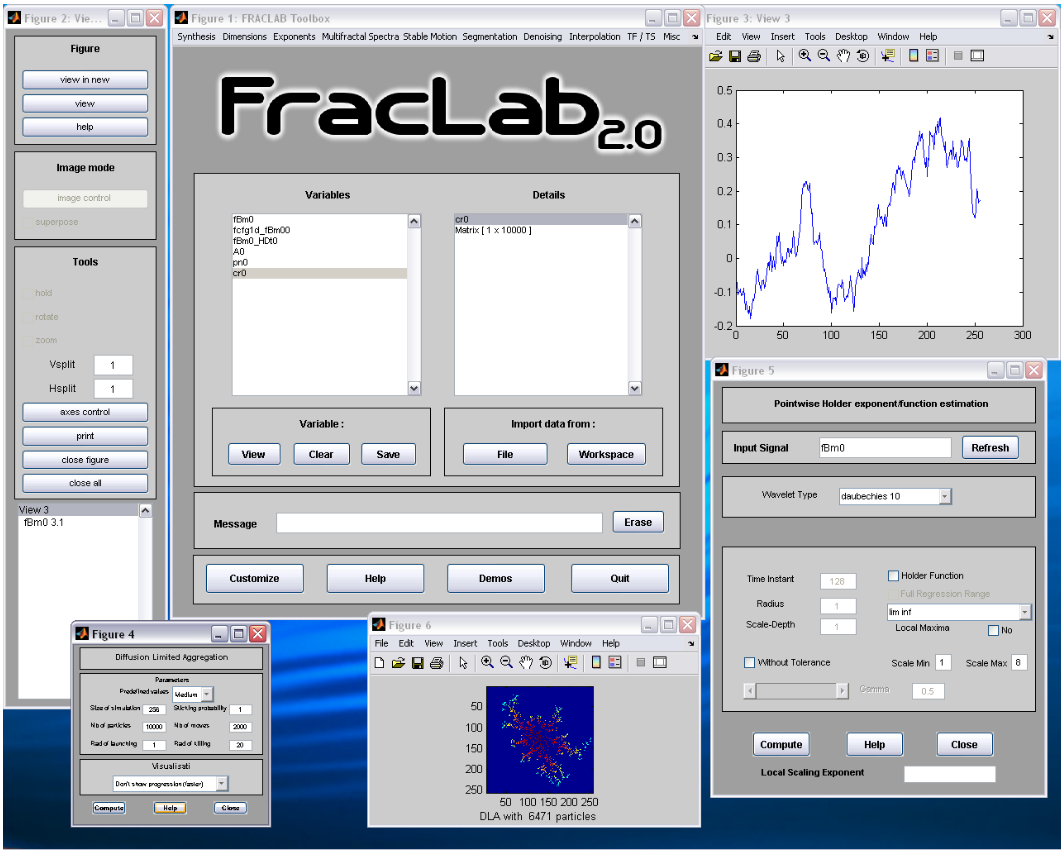

Figure 1. FracLab 2.0 graphical interface

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 broaden the access to evolutionary computing by simplify the programmation of EAs, especially for non-computer scientists. A simple specification of an evolutionary algorithm written into 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 algorithm then becomes short and simple, and thanks to the EASEA compiler this specification file can be compiled at any place. The current versions (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 a 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, Universidad de Granada).

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 http://fractales.inria.fr/evo-lab/EVO-easea-engl.html.

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 the program execution level.

XCLE provides an implementation of basic data types: integers, floats, strings, recursive lists and executable primitives, encapsulated into a generic object type. The API provides 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 constitutes a ready-made basis for a generic genetic operators library, and a tool for code portability and reusability in the GP community. A standardised primitives library and a graphical IDE complement the set of tools offered to developers.

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

6. New Results

6.1. Multifractional Brownian motion: Modelling, synthesis and estimation

Keywords: *multifractional Brownian motion*, *synthesis and estimation*.

Participants: Antoine Ayache, Erick Herbin, Jacques Lévy Véhel.

In collaboration with Olivier Barrière (IrCcyn).

The multifractional Brownian motion (mBm) is a generalization of the celebrated fractional Brownian motion (fBm) where the constant exponent H is replaced with a Hölder continuous function ranging in $(0,1)$ ([21]). Mbm was invented with the following practical application in mind: Mountains and other earth terrains modelled by fBm are not realistic because fractional Brownian fields have everywhere the same Hölder exponent, as real mountains have a space-varying regularity, due, for instance, to erosion and other phenomena. In the frame on our contract with Dassault aviation, we have put the mbm to use in the modelling of real terrains. This requires to solve two problems: Synthesis and estimation of the parameters defining an mBm.

For the synthesis problem, we have adapted the method of Peltier and Lévy Véhel with an implementation proposed by Wood and Chan in 1994. We have developed an improvement of this technique, based on a pre-quantification of the range of $H(t)$ using the K-means algorithm ([27]). We have been able to extend the method in two dimensions. This allows to generate images of size up to 2048×2048 points in a reasonable amount of time (fig. 2).

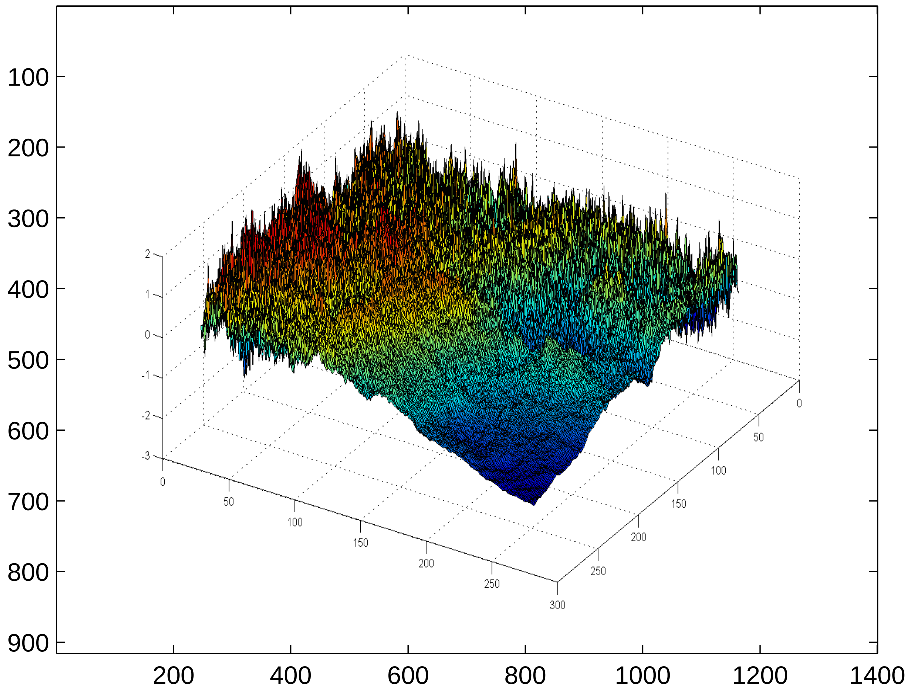

Figure 2. A 2-dimensional mBm with bilinear H function.

As for the estimation problem, we have implemented the generalized quadratic variations estimator investigated by Ayache and Lévy Véhel. In order to get rid of possible biases due to scaling factors, one usually rely on a regression. This technique however increases the variance. We have proposed a method allowing both a small bias and a small variance: It consists in aligning locally the mean of the regression-free estimator with the mean of the regression-based one (see fig. 3). This method is generic, and may be applied each time a regression is needed. We are currently investigating its performance in other situations, such as non-parametric Hölder exponent estimation and large deviation spectrum estimation. Work is also in progress concerning the theoretical properties of this method. Finally, we have developed a technique to estimate the scaling factor (which is needed for the synthesis step). While the results are satisfactory in one dimension, the 2D case still needs some improvement ([27]).

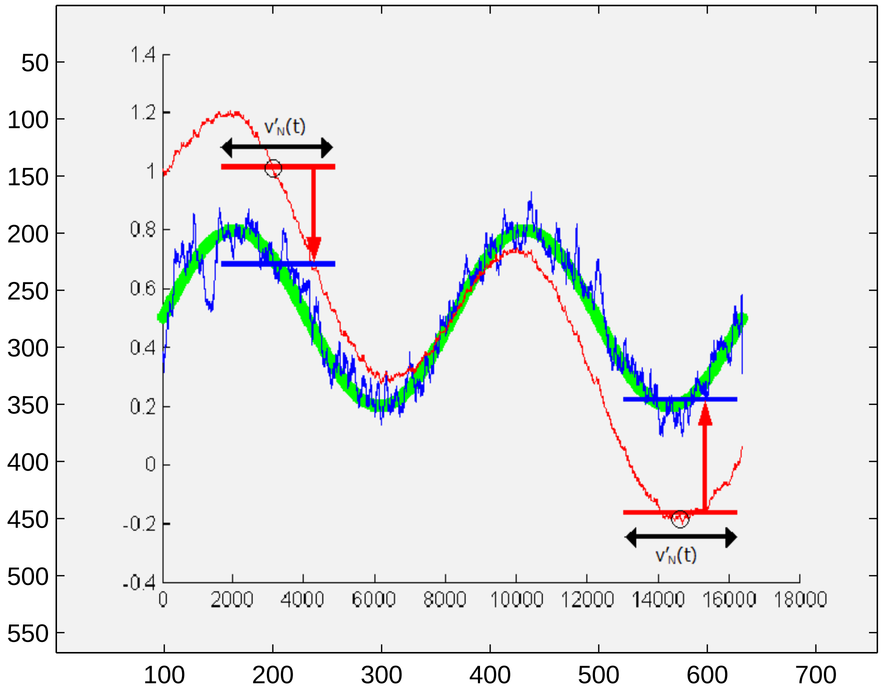

Figure 3. Estimation by aligning locally the mean of the regression-free estimator (thin, less irregular curve) with the mean of the regression-based one (thick curve).

Another path to realistic terrain synthesis with fractional processes is to use the so-called "set-indexed fractional Brownian motion" (SIFBM). This means that the index set for the process is no longer $\mathbb{R}^n$, but any sufficiently regular collection of otherwise arbitrary sets ([22]). This generalization is useful for instance in the case of censored data, or when different resolutions have to be considered simultaneously. We have made some progress on the definition and study of SIFBM which was started last year. We have also obtained some simulation results which are promising.

A related but somewhat different work has been to study an estimator for the *step fractional Brownian motion*, which is an fBm with “jumps”. We have established a central limit theorem for this estimator ([19]).

6.2. 2-microlocal and multifractal analysis

Keywords: *2-microlocal analysis*, *Hölder exponents*, *image analysis*, *multifractal analysis*.

Participants: Jacques Lévy Véhel, Claude Tricot.

In collaboration with Antoine Echelard (IrCcyn).

Our first effort has been on defining precisely a “time-domain” 2-microlocal formalism. While the 2-microlocal spectrum was initially defined using the wavelet coefficients of the signal, we have shown that it is also possible to define a time-domain 2-microlocal spectrum using the increments of the function instead of the wavelet coefficients ([30], [42]). The advantages of this approach are the following: Easier and more precise estimation procedure, simpler 2-microlocal formalism, and, possibly, application to image denoising: Indeed, wavelet thresholding is known to usually oversmooth noisy signals. It seems that the use of a time-domain procedure could allow to perform a denoising that preserves the 2-microlocal spectrum of the original signal, and thus its regularity ([45], [37]).

We have also worked on the links between 2-microlocal analysis and multifractal analysis. Roughly speaking, the multifractal spectrum describes the distribution of set of points in the support of the function that have the same regularity (in the sense of the pointwise Hölder exponent). 2-microlocal analysis, on the other hand, describes the irregularity of a signal at a given point in a very fine way. Both analysis share some structural properties. For instance, the 2-microlocal and large deviation spectra are semi-continuous, and their Legendre transform are of direct interest: For the multifractal spectrum, it is related to the rate function in the large deviation analysis of the increments, and for the 2-microlocal spectrum, it is simply the 2-microlocal frontier. Taking advantage of these analogies, we have been able to propose a common frame to prove results in the two domains, such as the prescription of the spectra ([43]).

6.3. 2-microlocal frontier of Gaussian processes

Keywords: *(multi-)fractional Brownian motion, 2-microlocal analysis, Gaussian processes, Hölder exponents, Stochastic Differential Equation*.

Participants: Erick Herbin, Jacques Lévy Véhel.

The frame of 2-microlocal analysis can be used to finely study the regularity of the paths of a stochastic process. For a continuous Gaussian process X, we proved last year that, at any fixed location t, the 2-microlocal frontier of X is almost surely a deterministic function that may be evaluated from the incremental covariance. Since 2-microlocal analysis was introduced in the frame of (deterministic) Partial Differential Equations, it seems natural to apply our results to Stochastic Differential Equations driven by Brownian motion or other Gaussian processes. We have taken a first step in this direction by studying linear Stochastic Differential Equation. Under certain technical conditions, the 2-microlocal frontier of the solution may be deduced from the ones of the functions defining the Stochastic Differential Equation ([44]).

6.4. Fractal anaysis of agro-alimentary images

Keywords: *Besov norms, box dimension, classification, image analysis, lacunarity, regularization dimension*.

Participants: Jacques Lévy Véhel, Ina Taralova.

In collaboration with Olivier Barrière, Antoine Echelard (IRCCyN), INRA (Nantes) and ENILIA (Surgères).

This research activity deals with the fractal analysis of images from the food industry, mainly for classification purposes.

We have been working in collaboration with ENILIA (Surgères) on the characterization of milk fat microscopic images. Pictures of milk fat are taken during the maturation process, and the industry is interested in the following features: the kind of butter that was produced, the plant in which it was produced and the day of maturation of the milk fat. Several fractal parameters have been tested in view of distinguishing these characteristics. The following parameters have shown their efficiency in this task: The box dimension, the regularization dimension, the lacunarity and the Besov norms. The lacunarity has shown to be efficient in separating the different kinds of butter, the regularization dimension and the box dimension have shown to be correlated with the day of maturation and certain well-chosen Besov norms have shown to be efficient in separating some production plants. Moreover, each parameter was linked to the feature that it characterized with a physical explanation on the microstructure of the butter ([32]).

In the frame of a collaboration with INRA (Nantes) in the VANAM project, we are participating in a specific action which aims at developing biological methods for studying the degradation of scraps. It includes in particular an effort towards a better understanding of the action of the different enzymes. In this context, we have characterized the efficiency of cellulose and pectin degradation of beet pulp from the study of the regularization dimension of macroscopic images. We have shown that the variations of the regularization dimension are highly correlated with the state of degradation of the pulp ([20]).

Another research area deals with the application of Multifractal Brownian Motion to tomatoes macroscopic images. Different types of tomatoes, and different post-collection conservation conditions such as temperature or duration of conservation are to be classified and segmented. We model the tomato texture as a realization of a 2D Multifractal Brownian Motion. The local regularity is then estimated and used as a classification parameter. This research is currently in progress.

6.5. Genetic Algorithms and Multifractal Analysis for signal enhancement

Keywords: *Evolutionary Algorithm*, *Hölder Exponent*, *Image Denoising*, *Oscillation*, *Regularity*.

Participants: Pierrick Legrand, Jacques Lévy Véhel, Evelyne Lutton.

In collaboration with Gustavo Olague (EvoVision group, CICESE research center, Mexico). This work has been done under a LAFMI grant.

We use jointly some fractal analysis tools and genetic algorithms in order to denoise 1D or 2D signals. It is well known that increasing the Hölder regularity allows to partly remove the noise. It is however difficult to build signals with a prescribed regularity when one works in the time domain. Previous work on this topic [13] used a genetic algorithm with wavelet-based estimation for the Hölder regularity. The advantage of a time-domain estimation is that it yields better results for certain classes of signals.

We thus face an optimisation problem under constraint: Obtain the signal closest to the observation which achieves the prescribed regularity.

We have shown that a genetic algorithm provides a powerful tool to solve this denoising problem. The same method has been used for interpolation under constraints.

6.6. Interactive Evolutionary Multifractal Denoising

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

Participants: 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 done based on a previously proposed image denoising technique. A C/Gtk prototype has been produced and tested in 2004 (internship of Pierre Grenier). A matlab software, included in the the fraclab toolbox has then been developed by Mario Pilz during his internship.

Moreover, as interactive evolutionary algorithms (IEA) often suffer from what is called the “user bottle-neck,” we proposed and analyzed a method to limit user interactions, while still providing sufficient information for the EA to converge. This method is based on an approximation of the user judgment, via a "fitness map", that helps reduce the number of user-interactions.

6.7. Interactive optimisation of cochlear implants

Keywords: *Cochlear implants*, *interactive evolution*, *medical application*.

Participants: Pierre Collet, Pierrick Legrand, Evelyne Lutton.

In collaboration with Claire Bourgeois-République (univ. Bourgogne), Vincent Péan (Innotech), Bruno Frachet (hôpital Avicenne), HEVEA project (French acronym for “Handicap: Etude et Valorisation de l’Ecologie Auditive”).

Cochlear implants are surgically-implanted electronic devices that partially restore hearing of deaf people by electric stimulation of the auditive nerve. The HEVEA project aims at producing improved tuning protocols and devices by: (1) sampling the background noise, (2) characterising the background noise, (3) tune the device with respect to the background noise and (4) automatically select the appropriate parameter setting in real conditions.

This project implements an approach based on both interactive evolution and multi-scale analysis. Items (2) and (4) are classification tasks on usual environmental signals of the patient, that are addressed using a fractal/wavelet approach. Interactive evolution is used in item (3), to produce a device tuning adapted to the patient in a given environment. The interactive evolutionary tuning procedure is now functionnal and is currently tested on a set of patients, using a PDA with a graphical interface shown of figure 4. Evaluation is based on audio tests. Preliminary tests have shown an improvement of patient audition and comfort with interactive evolution.

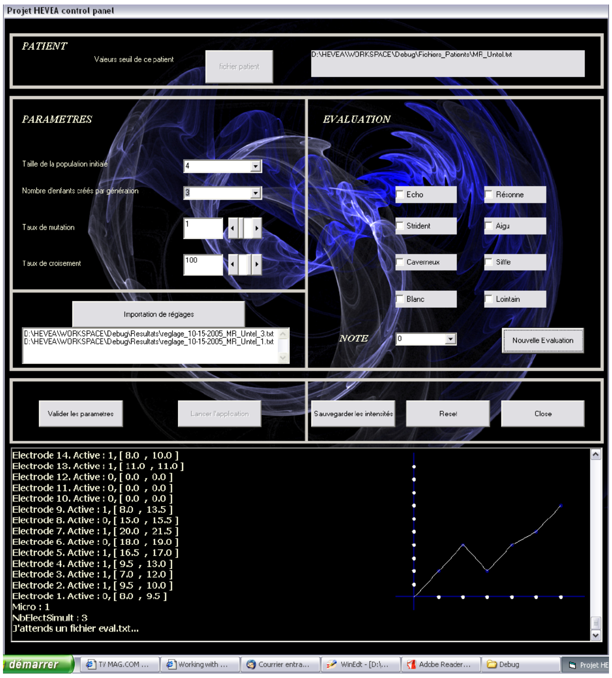

Figure 4. Graphical interface for the HEVEA project.

6.8. Multifractal Stereo Matching

Keywords: *Disparity*, *Interpolation*, *Multifractal Correlation*, *Mutual Exponent*, *Stereo Matching*.

Participants: Pierrick Legrand, Jacques Lévy Véhel, Evelyne Lutton.

In collaboration with Gustavo Olague (EvoVision group, CICESE research center, Mexico). This work has been done under a LAFMI grant.

We consider the problem of reconstructing 3D objects from stereoscopic images of a scene. This work is based on previous work of the EvoVision and COMPLEX Teams. The aim is to match the points of a stereo pair using genetic algorithms. Classical methods consider the correlation as a measure of similarity between two points. We evaluate a new quantity, the multifractal correlation, based on the estimation of the Mutual

exponent, an exponent that measure the Hölder regularity of one image in the stereo pair with respect to the other one.
The second improvement of the stereo matching technique is based on a subpixel method. Our idea is to increase the resolution of the two stereoscopic images before the matching computations. Since regularity is an important characterization of a pixel in view of matching, we use an interpolation method which maintains the Hölder regularity. The experiments on a benchmark () show an improvement of the matching precision.

6.9. Stereovision and mobile robotics: the Fly Algorithm

Keywords: *Parisian evolution, fly algorithm, obstacle detection, robot vision, stereovision, vision systems.*

Participants: Olivier Pauplin, Jean Louchet, Evelyne Lutton.

In collaboration with Arnaud De La Fortelle and Michel Parent (IMARA team).

The Fly Algorithm is basically an innovative stereovision technique, based on the principles of Parisian Evolution Strategies. A fly is defined as a 3-D point with coordinates (x,y,z). After it has been initialised randomly, the population of “flies” is evolved, using genetic operators, in order to concentrate onto the surfaces of visible objects in the cameras’ fied of view. The fitness function used is depending on image pixel grey levels and reflects the credibility of the hypothesis that the fly lies on a visible surface of an object.

Previous work, in particular Amine Boumaza’s PhD thesis in 2003, has shown the interesting real-time capabilities of the Fly Algorithm - a property which at first glance would look uncommon with an evolutionary technique - and opened the way to robotic applications through the development of a full closed-loop simulator including a simplified robot and camera model, fly-based stereovision, multisensor data fusion and robot control including obstacle avoidance.

Olivier Pauplin’s work is dedicated essentially to transposing this technique to the real world and real mobile robots, thanks to a cooperative project with the INRIA/IMARA team.

After last year’s results on the introduction of an alert signal indicating the presence of a mobile obstacle susceptible to interfere with the robot’s trajectory, efforts have been made to improve the trade-off between processing speed, convergence and geometrical precision, through careful adjustment of the correlation window size and introduction of self-adaptivity parameters into the fly’s genome.

6.10. Parisian EA for tomographic reconstruction and scatter compensation in nuclear medicine

Keywords: *Parisian evolution, fly algorithm, nuclear medicine, tomographic recontruction.*

Participants: Aurélie Bousquet, Jean Louchet, Jean-Marie Rocchisani.

In nuclear medicine, diagnosis is based on the estimation of the distribution pattern of radioactivity in the body. In order to build an accurate pattern, we have to apply on the scintigraphies a tomographic reconstruction and a correction for the physical degrading factors (scatter and attenuation). Analytical and statistical methods already exist to solve this problem, but the process is long and costly and requires powerful computers. We use here a Parisian artificial evolution method to reduce calculation time, while maintaining good quality results. This Parisian EA is an extension of the fly algorithm principles. Here a fly is considered as a photon transmitter. The algorithm will evolve the flies in order to build a 3D pattern.

Previous works on the subject allowed to validate such an approach. However, calculation time was still high because of the physical effects compensation, and the quality of the reconstruction was not as good as for “classical” methods. A new evaluation function has been designed, and enables a quite good quality reconstruction, with an improved geometric precision and a better evaluation of the amount of radioactivity in the different regions. The algorithm has been tested on ideal data, without scatter and attenuation, and on real scintigraphic pictures.

The reconstruction times are still not competitive when a complete scatter and attenuation compensation is applied. Future work will consist in using approximate corrections to fasten the evaluation, and precise ones afterwards, when a global form of the activity regions is determined. A Parallel implementation of the algorithm is another solution that will be investigated.

6.11. Modelling Termite Nest formation

Keywords: *Social insects, fractal growing model, termites.*

Participants: Mohamed Boussaid, Evelyne Lutton.

In collaboration with Emmanuel Cayla (ESTP), Pascal Jouquet, Michel Lepage (Laboratoire Fonctionnement et Evolution des Systèmes Ecologiques, UMR 7525- Ecole Normale Supérieure) and Yves Le Goff (Ecole Nationale Supérieure des Arts et Métiers, Laboratoire Mécanique des Fluides).

The aim of this collaboration with biologists is to understand the mechanisms of nest construction for a particular species of termites (*macrotermes bellicosus*). These termites are living in Africa (in dry as well as forest areas). They build specific structures, rather irregular, but with some characteristic tower-like components. Their nest is composed of several internal and external structures, with food storage area, mushroom plantation (they actually grow and eat a particular species of mushroom), queen chamber and nursery. The nest is a structure that evolves gradually, with respect to the size and age of the colony, as well with respect to the environment and climatic conditions. The challenge is to understand the connections between nest architecture and climatic conditions (and eventually elaborate behavioural models of it).

We currently work on a simplified model of external nest structures, which are usually built by the colony within a single night. The proposed model is based on a population behaviour with elementary social interactions (an ACO model), that has been derived from biologic observations. 2D simulation proves the capability of such a model to produce fractal structures, similar to the natural ones. Efforts has been centred on the development of several models of elementar termite behaviour, including a simplified model of gravity effects.

6.12. New codings and operators for Genetic Programming

Keywords: *Genetic Programming, stack-based language.*

Participants: Asmae El Khadiri, Yann Landrin-Schweitzer.

Most implementations of genetic programming algorithms use tree-based individual representations. This implementation has the advantage of simplicity and good control of results, but also impacts evaluation speed and expressivity of the genomes.

We have explored alternative representations using a stack-based language, XCL, on the test case of symbolic regression. A first implementation of genetic operators for the stack-based coding (direct translations of the tree operators) has been implemented. As expected, the generation count was similar, while execution time was improved for the stack-based language.

Simpler initialisation schemes permitted by XCL yielded however few performance gains. The results obtained when simplifying operators where very contrasted, depending on the structure of the objective function.

We expect that studying new classes of genetic operators and languages primitives unavailable with tree-based coding will allow to obtain better results on complex regression problems.

6.13. Optimisation of an E-Learning System

Keywords: *Ant Colony Optimisation (ACO), Avatar technology, E-Learning, Elo-rating, Interactive Artificial Evolution.*

Participants: Pierre Collet, Evelyne Lutton, Gregory Valigiani.

In collaboration with Raphaël Biojout, Yannick Jamont (Paraschool Compagny).

“Man-hill” optimisation (a slightly different form of Ant Colony Optimisation) has been applied to the e-learning software of Paraschool (a French e-learning company): instead of implementing artificial ants, students visiting the site unknowingly leave stigmergic information on the Paraschool web-site graph, in order to promote the emergence of pedagogic paths. Real-size experimentations have shown that ant-hill optimisation techniques have to be adapted. The concept of an artificial “student-hill”, or more generally “man-hill” has been introduced and analysed.

In a refinement stage, in order to present students with exercises that match their level, it was needed to find some sort of evaluation mechanism, both for the student and for the Paraschool items. A solution was found in the Elo automatic rating process, that also provides as a side-effect a powerful audit system that can track semantic problems in exercises.

In addition to this technology, Paraschool was looking for a system that could enhance site interactivity by creating an adaptive avatar for each user. The solution currently investigated is to use an interactive evolutionary approach, and to evolve a population of avatars for each user. This work is based on *GEStyle*, a markup language which describes the behaviour and the *style* of an avatar.

6.14. CONSENSUS : Interactive optimisation of a resource allocation problem

Keywords: *adaptive search*, *constrained problems*, *evolutionary algorithms*, *resource allocation*.

Participants: Loic Fosse, Evelyne Lutton.

In collaboration with François Fages (CONSTRAINT Team).

The problem of office affectation on the INRIA Rocquencourt campus can be considered as a complex constraint 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 up within standard constraint satisfaction software. Evolutionary techniques have been used as a complement to constraint satisfaction. Actually many constraints are difficult to express and the relative importance of each constraint is an important factor to efficiently use constraint satisfaction software.

We experimented in 2003 the scheme of a multi-user interactive evolutionary approach for the management of user preferences relative weights, based on a Parisian and multi-population paradigm (on a small size problem). This work has been continued in 2004 (internship of Martin Pernollet), in order to build a prototype for real size testing, based on real data of the Rocquencourt Campus. In 2005 (internship of Sylvain Secherre in the CONTRAINTES team) the constraints expressions and their general balance has been precisely studied on the real size problem. We now develop the real-sized prototype, including ergonomic user and administrator interfaces.

6.15. ArtiE-Fract Improvement

Keywords: *Art and Design*, *Fractals*, *Interactive Evolution*, *Iterated Function Systems Attractors*.

Participants: Jonathan Chapuis, Pierre Grenier, Evelyne Lutton.

In collaboration with Emmanuel Cayla (Cetoine Compagny). This work is a technology-transfer action founded by ANVAR.

This action aims at improving several features of the ArtiE-Fract software, in order to build an industrially efficient tool, ArtiE-Fract-V2, adapted to the end-user technical contraints (textile design and HD video design). ArtiE-Fract-V2 is now running on GTK-2, providing a better interface control and increased reliabilty. The main feaures developed until now are the following.

- A “task-manager”: Generating attractors is very CPU time and disk space consuming, especially for animations. To face this, a task manager has been developed, to manage batch processing with priorities, that support interruptions.
- A style sheet, that allows the user to compose and store as many post-processing effects on the image as he wishes.
- An improved makeup window: New primitives have been added to control the movement of fixed points for animations.

- A MySQL-database, for authorship management system and artwork library. It is based on a MySQL 5.0 server and allows to optionally share data with other users, and navigate efficiently through existing data files and works.

7. Contracts and Grants with Industry

7.1. 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.
- PARASCHOOL on evolutionary optimisation of pedagogical path (e-learning, PhD of Gregory Valigiani).
- Innotech, HEVEA project on Cochlar implants optimisation.

8. Other Grants and Activities

8.1. National initiatives

Our project has collaborations with:

- IrCcyn, Institut de Recherche en Cybernétique et communications de Nantes, since 1996. Areas of collaborations include the study of mBm, 2-microlocal analysis, image analysis and denoising. In addition, the software FracLab has mainly been developed at IRCCYN in the last four years.
- Littoral university (Calais), on e-learning (P. Collet and C. Fonlupt),
- Lille University (A. Ayache) on Multifractional Brownian Motion.
- Clermont Ferrand University (C. Tricot) on multifractal analysis.
- Ecole Polytechnique-CRM, Montreal (F. Nekka, J.M. Lina) on image analysis and multifractal denoising.

8.2. European initiatives

The team belongs to EvoNet, the European Excellence Network on artificial evolution, and is involved in the european IMPAN SPADE2 project.

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 were co-chairs of the “Fractal in Engineering” conference, FE05, Tours, June 22-24. 2005.

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

Evelyne Lutton is co-chair (with Hideyuki Takagi) of the first EvoInteraction (Interactive Evolution and Humanized Computational Intelligence) Workshop, to be held in Budapest in April 2006.

9.2. Editorial Boards

Jacques Lévy Véhel is associate Editor of the journal << FRACTALS >>.

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.

J. Lévy Véhel has acted as an expert for the Canadian CRSNG. He is a member of the expert group “Signaux et Traitements Multidimensionnels et Multimodaux”.

J. Lévy Véhel has been a referee for IEEE Trans. Signal Proc., IEEE Trans. Image Proc., Fractals, ICIP conference, IEE Proc. Vision, SPA, Imavis, Eur. Phys. J. B.

Evelyne Lutton has been referee for IEEE Transactions on Evolutionary Computation, IEEE Signal Processing Letters, JESA, SMC-PartB.

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” 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. Invited talks and Scientific popularisation

Evelyne Lutton has presented the Complex team at the Welcome Seminar for new recruited INRIA staff (Nov. 2005).

The COMPLEX team has organised an Artistic Exposition "Evolutions Fractales" (PIC), in May-June 2005.

The September issue of the journal "Science et Vie" contains an article about fractals. A page is devoted to the work of J. Lévy Véhel.

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