



INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Project-Team metalau*

*Methods, algorithms and software in  
automatic control*

*Paris - Rocquencourt*

Theme : Modeling, Optimization, and Control of Dynamic Systems

*Activity*  
*R* *eport*

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# 1. Team

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# 2. Overall Objectives

## 2.1. Overall Objectives

### 2.1.1. Research fields

The project-team is particularly active in the following areas:

- classical theory of dynamical systems
- optimal deterministic, stochastic and robust control
- failure detection in dynamical systems (both passive and active)
- network control and monitoring for transportation systems
- hybrid systems, in particular the development of Scicos
- maxplus linear systems: applications to transportation systems
- numerical matrix algebra and its implementation in ScicosLab
- numerical algorithms.

### 2.1.2. Objectives

The objectives of the project-team are the design, analysis and development of new methods and algorithms for detection, identification, simulation and control of dynamical systems and their software implementations.

These methods and algorithms are implemented in Scilab and ScicosLab which are scientific software packages originally developed in the project-team.

The project-team is actively involved in the development of control, signal processing, optimization and simulation tools, in particular Scicos, a modeler and simulator for dynamical systems developed based on research on hybrid systems. Encouraged by the interest in Scicos, expressed both by the academia and industry, developing a robust user-friendly Scicos has become an important objective of the project-team. A lot of effort is put into the development of Scicos within the project-team.

As theory and applications enrich mutually, many of the objectives of the project-team can be seen through the applications:

- modeling and simulation of physical systems (mechanical, electrical, fluids, thermodynamics,...) based on the theory of implicit systems
- modeling, simulation and code generation of control systems based on the theory of hybrid systems
- modeling, analysis and control of transportation systems using the maxplus algebra
- using robust control theory, and finite element models for identification purposes in the framework of failure detection and default localization for space systems, civil structures and other dynamical systems.

## 3. Scientific Foundations

### 3.1. Classical system theory

#### 3.1.1. *Systems, Control and Signal Processing*

Systems, control and signal processing constitute the main foundations of the research work of the project-team. We have been particularly interested in numerical and algorithmic aspects. This research which has been the driving force behind the creation of Scilab has nourished this software over the years thanks to which, today, Scilab and now ScicosLab contain most of the modern tools in control and signal processing. ScicosLab is a vehicle by which theoretical results of the project-team concerning areas such as classical, modern and robust control, signal processing and optimization, is made available to industry and academia.

Ties between this fundamental research and ScicosLab are very strong. Indeed, even the design of the software itself, elementary functions and data structures are heavily influenced by the results of this research. For example, even elementary operations such as basic manipulation of polynomial fractions have been implemented using a generalization of the the state-space theory developed as part of our research on implicit systems. These ties are of course normal since Scilab has been primarily developed for applications in automatics.

Scilab has created for our research team new contacts with engineers in industry and other research groups. Being used in real applications, it has provided a guide for choosing new research directions. For example, we have developed the robust control tools in collaboration with industrial users. Similarly for the LMI toolbox, which we have developed with the help of other research groups. It should also be noted that most of the basic systems and control functions are based on algorithms developed in the European research project Slicot in which METALAU has taken part.

#### 3.1.2. *Implicit Systems*

Implicit systems are a natural framework for modeling physical phenomena. We work on theoretical and practical problems associated with such systems in particular in applications such as failure detection and dynamical system modeling and simulation.

Constructing complex models of dynamical systems by interconnecting elementary components leads very often to implicit systems. An implicit dynamical system is one where the equations representing the behavior of the system are of the algebraic-differential type. If  $\xi$  represent the “state” of the system, an implicit system is often described as follows:

$$F(\dot{\xi}, \xi, z, t) = 0, \tag{1}$$

where  $\dot{\xi}$  is the time derivative of  $\xi$ ,  $t$  is the time and the vector  $z$  contains the external variables (inputs and outputs) of the system. Indeed it is an important property of implicit systems that outside variables interacting with the system need not be characterized a priori as inputs or outputs, as it is the case with explicit dynamical systems. For example if we model a capacitor in an electrical circuit as a dynamical system, it would not be possible to label a-priori the external variables, in this case the currents and voltages associated with the capacitor, as inputs and outputs. The physical laws governing the capacitor simply impose dynamical constraints on these variables. Depending on the configuration of the circuit, it is sometimes possible to specify some external variables as inputs and the rest as outputs (and thus make the system explicit) however in doing so system structure and modularity is often lost. That is why, usually, even if an implicit system can be converted into an explicit system, it is more advantageous to keep the implicit model.

It turns out that many of the methods developed for the analysis and synthesis of control systems modeled as explicit systems can be extended to implicit systems. In fact, in many cases, these methods are more naturally derived in this more general setting and allows for a deeper understanding of the existing theory. In the past few years, we have studied a number of systems and control problems in the implicit framework.

For example in the linear discrete time case, we have revisited classical problems such as observer design, Kalman filtering, residual generation to extend them to the implicit case or have used techniques from implicit system theory to derive more direct and efficient design methods. Another area where implicit system theory has been used is failure detection. In particular in the multi-model approach where implicit systems arise naturally from combining multiple explicit models.

We have also done work on nonlinear implicit systems. For example nonlinear implicit system theory has been used to develop a predictive control system and a novel nonlinear observer design methodology. Research on nonlinear implicit systems continues in particular because of the development of the “implicit” version of Scicos.

## 3.2. Failure detection in dynamical systems

### 3.2.1. Active failure detection

Failure detection has been the subject of many studies in the past. Most of these works are concerned with the problem of *passive failure detection*. In the passive approach, for material or security reasons, the detector has no way of acting upon the system; the detector can only monitor the inputs and the outputs of the system and then decides whether, and if possible what kind of, a failure has occurred. This is done by comparing the measured input-output behavior of the system with the “normal” behavior of the system. The passive approach is often used to continuously monitor the system although it can also be used to make periodic checks.

In some situations however failures can be masked by the operation of the system. This often happens in controlled systems. The reason for this is that the purpose of controllers, in general, is to keep the system at some equilibrium point even if the behavior of the system changes. This robustness property, desired in control systems, tends to mask abnormal behaviors of the systems. This makes the task of failure detection difficult. An example of this effect is the well known fact that it is harder for a driver to detect an under-inflated or flat front tire in a car which is equipped with power steering. This tradeoff between detection performance and controller robustness has been noted in the literature and has led to the study of the integrated design of controller and detector.

But the problem of failures being masked by system operation is not limited to controlled systems. Some failures may simply remain hidden under certain operating conditions and show up only under special circumstances. For example, a failure in the brake system of a truck is very difficult to detect as long as the truck is cruising down the road on level ground. It is for this reason that on many roads, just before steep downhill stretches, there are signs asking truck drivers to test their brakes. A driver who ignores these signs would find out about a brake failure only when he needs to brake going down hill, i.e., too late.

An alternative to passive detection which could avoid the problem of failures being masked by system operation is *active detection*. The active approach to failure detection consists in acting upon the system on a periodic basis or at critical times using a test signal in order to detect abnormal behaviors which would otherwise remain undetected during normal operation. The detector in an active approach can act either by taking over the usual inputs of the system or through a special input channel. An example of using the existing input channels is testing the brakes by stepping on the brake pedal.

The active detection problem has been less studied than the passive detection problem. The idea of injecting a signal into the system for identification purposes has been widely used. But the use of extra input signals in the context of failure detection has only been recently introduced.

The specificity of our approach for solving the problem of auxiliary signal design is that we have adopted a deterministic point of view in which we model uncertainty using newly developed techniques from  $H_\infty$  control theory. In doing so, we can deal efficiently with the robustness issue which is in general not properly dealt with in stochastic approaches to this problem. This has allowed us in particular to introduce the notion of *guaranteed failure detection*.

In the active failure detection method considered an auxiliary signal  $v$  is injected into the system to facilitate detection; it can be part or all of the system inputs. The signal  $u$  denotes the remaining inputs measured online just as the outputs  $y$  are measured online. In some applications the time trajectory of  $u$  may be known in advance but in general the information regarding  $u$  is obtained through sensor data in the same way that it is done for the output  $y$ .

Suppose we have only one possible type of failure. Then we have two sets of input-output behaviors to consider and hence two models. The set  $\mathcal{A}_0(v)$  is the set of normal input-outputs  $\{u, y\}$  from Model 0 and the set  $\mathcal{A}_1(v)$  is the set of input-outputs when failure occurs. That is,  $\mathcal{A}_1(v)$  is from Model 1. These sets represent possible/likely input-output trajectories for each model. Note that Model 0 and Model 1 can differ greatly in size and complexity but they have in common  $u$  and  $y$ .

The problem of auxiliary signal design for guaranteed failure detection is to find a “reasonable”  $v$  such that

$$\mathcal{A}_0(v) \cap \mathcal{A}_1(v) = \emptyset.$$

That is, any observed pair  $\{u, y\}$  must come only from one of the two models. Here reasonable  $v$  means a  $v$  that does not perturb the normal operation of the system too much during the test period. This means, in general, a  $v$  of small energy applied over a short test period. However, depending on the application, “reasonable” can imply more complicated criteria.

Depending on how uncertainties are accounted for in the models, the mathematics needed to solve the problem can be very different. For example guaranteed failure detection has been first introduced in the case where unknown bounded parameters were used to model uncertainties. This led to solution techniques based on linear programming algorithms. But in most of our works, we consider the types of uncertainties used in robust control theory. This has allowed us to develop a methodology based on established tools such as Riccati equations that allow us to handle very large multivariable systems. The methodology we develop for the construction of the optimal auxiliary signal and its associated test can be implemented easily in computational environments such as Scilab. Moreover, the online detection test that we obtain is similar to some existing tests based on Kalman filters and is easy to implement in real-time. The main results of our research can be found in a book published in 2004. We have developed many extensions since, which have been published in various journals and presented at conferences.

### 3.2.2. Passive failure detection

#### 3.2.2.1. Modal analysis and diagnosis

We consider mechanical systems with the corresponding stochastic state-space models of automatic control.

The mechanical system is assumed to be a time-invariant linear dynamical system:



$$\begin{cases} M\ddot{Z}(t) + C\dot{Z}(t) + KZ(t) = \nu(t) \\ Y(t) = LZ(t) \end{cases}$$

where the variables are :  $Z$ : displacements of the degrees of freedom,  $M$ ,  $C$ ,  $K$ : mass, damping, stiffness matrices,  $t$ : continuous time;  $\nu$ : vector of external (non measured) forces modeled as a non-stationary white noise;  $L$ : observation matrix giving the observation  $Y$  (corresponding to the locations of the sensors on the structure).

The modal characteristics are:  $\mu$  the vibration modes or eigen-frequencies and  $\psi_\mu$  the modal shapes or eigenvectors. They satisfy:

$$(M\mu^2 + C\mu + K)\Psi_\mu = 0 \quad , \quad \psi_\mu = L\Psi_\mu$$

By stacking  $Z$  and  $\dot{Z}$  and sampling at rate  $1/\delta$ , i.e.,

$$X_k = \begin{bmatrix} Z(k\delta) \\ \dot{Z}(k\delta) \end{bmatrix} \quad , \quad Y_k = Y(k\delta)$$

we get the following equivalent state-space model:

$$\begin{cases} X_{k+1} = FX_k + V_k \\ Y_k = HX_k \end{cases}$$

with

$$F = \exp(A\delta) \quad , \quad H = [L \quad 0] \quad \text{and} \quad A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$$

The mechanical systems under consideration are vibrating structures and the numerical simulation is done by the finite element model.

The objectives are the analysis and the implementation of statistical model-based algorithms, for modal identification, monitoring and (modal and physical) diagnosis of such structures.

For modal analysis and monitoring, the approach is based on subspace methods using the covariances of the observations: that means that all the algorithms are designed for in-operation situation, i.e., without any measurement or control on the input (the situation where both input and output are measured is a simple special case).

The identification procedure is realized on the healthy structure.

The second part of the work is to determine, given new data after an operating period with the structure, if some changes have occurred on the modal characteristics.

In case there are changes, we want to find the most likely localization of the defaults on the structure. For this purpose we have to do the matching of the identified modal characteristics of the healthy structure with those of the finite element model. By use of the different Jacobian matrices and clustering algorithms we try to get clusters on the elements with the corresponding value of the "default criterion".

This work is done in collaboration with the INRIA-IRISA project-team SISTHEM (a spin-off of the project-team SIGMA2) (see the web-site of this project-team for a complete presentation and bibliography) and with the project-team MACS for the physical diagnosis (on civil structures).

### 3.2.2.2. Robust failure detection and control

Failure detection problems are formulated in such a way that mathematical techniques in robust control can be used to formulate and solve the problem of robust detection. Concepts developed for  $H_\infty$  control can be used in particular to formulate the notion of robustness and provide numerically tractable solutions.

This system approach can also be used to formulate both the detection and the control in a single framework. The Simultaneous Fault Detection and Control problem is formulated as a mixed  $\mathcal{H}_2/\mathcal{H}_\infty$  optimization problem and its solution is given in terms of Riccati equations. It is shown that controllers/detectors resulting from this approach have reasonable complexity and can be used for practical applications.

## 3.3. Exotic systems

### 3.3.1. Hybrid dynamical systems

Originally motivated by problems encountered in modeling and simulation of failure detection systems, the objective of this research is the development of a solid formalism for efficient modeling of hybrid dynamical systems.

A hybrid dynamical system is obtained by the interconnection of continuous time, discrete time and event driven models. Such systems are common in most control system design problems where a continuous time model of the plant is hooked up to a discrete time digital controller.

The formalism we develop here tries to extend methodologies from Synchronous languages to the hybrid context. Motivated by the work on the extension of Signal language to continuous time, we develop a formalism in which through a generalization of the notion of event to what we call *activation signal*, continuous time activations and event triggered activations can co-exist and interact harmoniously. This means in particular that standard operations on events such as subsampling and conditioning are also extended and operate on activation signals in general paving the way for a uniform theory.

The theoretical formalism developed here is the backbone of the modeling and simulation software Scicos. Scicos is the place where the theory is implemented, tested and validated. But Scicos has become more than just an experimental tool for testing the theory. Scicos has been successfully used in a number of industrial projects and has shown to be a valuable tool for modeling and simulation of dynamical systems.

Encouraged by the interest in Scicos, expressed both by the academia and industry, beyond the theoretical studies necessary to ensure that the bases of the tool are solid, the project-team has started to invest considerable effort on improving its usability for real world applications. Developing a robust user-friendly Scicos has become one of the objectives of the project-team.

It turns out that the Scicos formalism and the Modelica language share many common features, and are in many respects complementary. Scicos formalism provides a solid ground for modeling discrete-time and event dynamics, in a hybrid framework, based on the theory of synchronous languages, and Modelica is a powerful language for the construction of continuous-time models. We work closely with Modelica association and other actors in the Modelica community to make sure Modelica remains consistent with Scicos. We do this in particular by proposing new discrete-time extensions to Modelica inspired by Scicos formalism.

### 3.3.2. Maxplus Algebra, Discrete Event Systems and Dynamic Programming

In the modeling of human activities, in contrast to natural phenomena, quite frequently only the operations max (respectively min) and + are needed (this is the case in particular of some queuing or storage systems, synchronized processes encountered in manufacturing, traffic systems, when optimizing deterministic dynamic processes, etc.).

The set of real numbers endowed with the operation max (respectively min) denoted  $\oplus$  and the operation + denoted  $\otimes$  is a nice mathematical structure that we may call an idempotent semi-field. The operation  $\oplus$  is idempotent and has the neutral element  $\varepsilon = -\infty$  but it is not invertible. The operation  $\otimes$  has its usual properties and is distributive with respect to  $\oplus$ . Based on this set of scalars we can build the counterpart of a module and write the general  $(n, n)$  system of linear maxplus equations:

$$Ax \oplus b = Cx \oplus d,$$

using matrix notation where we have made the natural substitution of  $\oplus$  for  $+$  and of  $\otimes$  for  $\times$  in the definition of the matrix product.

A complete theory of such linear system is still not completely achieved. In recent development we try to have a better understanding of image and kernel of maxplus matrices.

System theory is concerned with the input ( $u$ )-output ( $y$ ) relation of a dynamical system ( $\mathcal{S}$ ) denoted  $y = S(u)$  and by the improvement of this input-output relation (based on some engineering criterium) by altering the system through a feedback control law  $u = F(y, v)$ . Then the new input ( $v$ )-output ( $y$ ) relation is defined implicitly by  $y = S(F(y, v))$ . Not surprisingly, system theory is well developed in the particular case of linear shift-invariant systems. Similarly, a min-plus version of this theory can also be developed.

In the case of SISO (single-input-single-output) systems,  $u$  and  $y$  are functions of time. In the particular case of a shift-invariant linear system,  $S$  becomes an inf-convolution:

$$y = h \square u \stackrel{def}{=} \inf_s [h(s) + u(\cdot - s)]$$

where  $h$  is a function of time called the impulse response of system  $\mathcal{S}$ . Therefore such a system is completely defined by its impulse response. Elementary systems are combined by arranging them in parallel, series and feedback. These three engineering operations correspond to adding systems pointwise ( $\oplus$ ), making inf-convolutions ( $\otimes$ ) and solving special linear equations ( $y = h \otimes (f_1 \otimes y \oplus f_2 \otimes v)$ ) over the set of impulse responses. Mathematically we have to study the algebra of functions endowed with the two operations  $\oplus$  and  $\otimes$  and to solve special classes of linear equations in this set, namely when  $A = E$  in the notation of the first part.

An important class of shift-invariant min-plus linear systems is the process of counting events versus time in timed event graphs (a subclass of Petri nets frequently used to represent manufacturing systems). A dual theory based on the maxplus algebra allows the timing of events identified by their numbering.

The Fourier and Laplace transforms are important tools in automatic control and signal processing because the exponentials diagonalize simultaneously all the convolution operators. The convolutions are converted into multiplications by the Fourier transform. The Fenchel transform ( $\mathcal{F}$ ) defined by:

$$[\mathcal{F}(f)](p) = \sup_x [px - f(x)],$$

plays the same role in the min-plus algebra context. The affine functions diagonalize the inf-convolution operators and we have:

$$\mathcal{F}(f \square g) = \mathcal{F}(f) + \mathcal{F}(g).$$

A general inf-convolution is an operation too complicated to be used in practice since it involves an infinite number of operations. We have to restrict ourselves to convolutions that can be computed with finite memory. We would like that there exists a finite state  $x$  representing the memory necessary to compute the convolution recursively. In the discrete-time case, given some  $h$ , we have to find  $(C, A, B)$  such that  $h_n = CA^n B$ , and  $y = h \square u$  is then ‘realized’ as

$$x_{n+1} = Ax_n \oplus Bu_n, \quad y_n = Cx_n.$$

SISO systems (with increasing  $h$ ) which are realizable in the min-plus algebra are characterized by the existence of some  $\lambda$  and  $c$  such that for  $n$  large enough:

$$h_{n+c} = c \times \lambda + h_n.$$

If  $h$  satisfies this property, it is easy to find a 3-tuple  $(A, B, C)$ .

This beautiful theory is difficult to apply because the class of linear systems is not large enough for realistic applications. Generalization to nonlinear maxplus systems able to model general Petri nets is under development.

Dynamic Programming in the discrete state and time case amounts to finding the shortest path in a graph. If we denote generically by  $n$  the number of arcs of the paths, the dynamic programming equation can be written linearly in the min-plus algebra:

$$X_n = A \otimes X_{n-1},$$

where the entries of  $A$  are the lengths of the arcs of the graph and  $X_n$  denotes the matrix of the shortest lengths of paths with  $n$  arcs joining any pair of nodes. We can consider normalized matrices defined by the fact that the infimum in each row is equal to 0. Such kind of matrices can be viewed as the min-plus counterpart of transition matrices of a Markov chain.

The problem

$$v_x^n = \min_u \left[ \sum_{i=n}^{N-1} \phi(u_i) + \psi(x_N) \mid x_n = x \right], \quad x_{i+1} = x_i - u_i$$

may be called dynamic programming with independent instantaneous costs ( $\phi$  depends only on  $u$  and not on  $x$ ). Clearly  $v$  satisfies the linear min-plus equation:

$$v^n = \phi \square v^{n+1}, \quad v^N = \psi$$

(the Hamilton-Jacobi equation is a continuous version of this problem).

The Cramer transform ( $\mathcal{C} \stackrel{\text{def}}{=} \mathcal{F} \circ \log \circ \mathcal{L}$ ), where  $\mathcal{L}$  denotes the Laplace transform, maps probability measures to convex functions and transform convolutions into inf-convolutions:

$$\mathcal{C}(f * g) = \mathcal{C}(f) \square \mathcal{C}(g).$$

Therefore it converts the problem of adding independent random variables into a dynamic programming problem with independent costs.

These remarks suggest the existence of a formalism analogous to probability calculus adapted to optimization that we have developed.

The theoretical research in this domain is currently done in the MAXPLUS project-team. In the METALAU project-team we are more concerned with applications to traffic systems of this theory.

## 4. Application Domains

### 4.1. Transport

Traffic modeling is a domain where maxplus algebra appears naturally : – at microscopic level where we follow the vehicles in a network of streets, – at macroscopic level where assignment are based on computing smallest length paths in a graph, – in the algebraic duality between stochastic and deterministic assignments.

We develop free computing tools and models of traffic implementing our experience on optimization and discrete event system modeling based on maxplus algebra.

#### 4.1.1. Microscopic Traffic Modeling

Let us consider a circular road with places occupied or not by a car symbolized by a 1. The dynamic is defined by the rule  $10 \rightarrow 01$  that we apply simultaneously to all the parts of the word  $m$  representing the system. For example, starting with  $m_1 = 1010100101$  we obtain the sequence of works ( $m_i$ ):

$$\begin{aligned} m_1 &= 1010100101, \\ m_2 &= 0101010011, \\ m_3 &= 1010101010, \\ m_4 &= 0101010101, \\ m_5 &= 1010101010, \\ &\text{etc.} \end{aligned}$$

For such a system we can call density  $d$  the number of cars divided by the number of places called  $p$  that is  $d = n/p$ . We call flow  $f(t)$  at time  $t$  the number of cars at this time period divided by the place number. The fundamental traffic law gives the relation between  $f(t)$  and  $d$ .

If the density is smaller than  $1/2$ , after a transient period of time all the cars are separated and can go without interaction with the other cars. Then  $f(t) = n/p$  that can be written as function of the density as  $f(t) = d$

On the other hand if the density is larger than  $1/2$ , all the free places are separated after a finite amount of time and go backward freely. Then we have  $p - n$  car which can go forward. Then the relation between flow and density becomes

$$f(t) = (p - n)/p = 1 - d .$$

This can be stated formally: it exists a time  $T$  such that for all  $t \geq T$ ,  $f(t)$  stays equal to a constant that we call  $f$  with

$$f = \begin{cases} d & \text{if } d \leq 1/2, \\ 1 - d & \text{if } d \geq 1/2. \end{cases} \quad (2)$$

The fundamental traffic law linking the density of vehicles and the flow of vehicles can be also derived easily from maxplus modeling : – in the deterministic case by computing the eigenvalue of a maxplus matrix, – in the stochastic case by computing a Lyapounov exponent of stochastic maxplus matrices.

The main research consists in developing extensions to systems of roads with crossings. In this case, we leave maxplus linear modeling and have to study more general dynamical systems. Nevertheless these systems can still be defined in matrix form using standard and maxplus linear algebra simultaneously.

With this point of view efficient microscopic traffic simulator can be developed in Scilab.

### 4.1.2. Traffic Assignment

Given a transportation network  $\mathcal{G} = (\mathcal{N}, \mathcal{A})$  and a set  $\mathcal{D}$  of transportation demands from an origin  $o \in \mathcal{N}$  to a destination  $d \in \mathcal{N}$ , the *traffic assignment* problem consists in determining the flows  $f_a$  on the arcs  $a \in \mathcal{A}$  of the network when the times  $t_a$  spent on the arcs  $a$  are given functions of the flows  $f_a$ .

We can distinguish the deterministic case — when all the travel times are known by the users — from the stochastic cases — when the users perceive travel times different from the actual ones.

1. When the travel times are deterministic and do not depend on the link flows, the assignment can be reduced to compute the routes with shortest travel times for each origin-destination pair.
2. When the travel times are deterministic and depend on the link flows, Wardrop equilibriums are defined and computed by iterative methods based on the previous case.
3. When the perceived travel times do not depend on the link flows but are stochastic with error distribution — between the perceived time and the actual time — satisfying a Gumbel distribution, the probability that a user choose a particular route can be computed explicitly. This probability has a Gibbs distribution called logit in transportation literature. From this distribution the arc flows — supposed to be deterministic — can be computed using a matrix calculus which can be seen as the counterpart of the shortest path computation (of the case 1) up to the substitution of the minplus semiring by the Gibbs-Maslov semiring, where we call Gibbs-Maslov semiring the set of real numbers endowed with the following two operations :

$$x \oplus^\mu y = -\frac{1}{\mu} \log(e^{-\mu x} + e^{-\mu y}), \quad x \otimes y = x + y.$$

4. When the perceived travel times are stochastic and depend on the link flows — supposed to be deterministic quantities — stochastic equilibriums are defined and can be computed using iterative methods based on the logit assignments discussed in the case 3.

Based on this classification, a toolbox dedicated to traffic assignment is available and maintained in Scilab.

## 4.2. Modal analysis and diagnosis

We have used the techniques developed for modal analysis and diagnosis in many different applications: rotating machines, aircrafts, parts of cars, space launcher, civil structures. The most recent examples are:

- Eureka (FLITE) project: exploitation of flight test data under natural excitation conditions.
- Ariane 5 launcher: application to a ground experiment (contract with CNES and EADS Space Transportation)
- Steelquake: a European benchmark for a civil structure.

# 5. Software

## 5.1. Scilab

Scilab has been developed by the Metalau project and ENPC (J.Ph. Chancelier) with many external contributions. Since 2003 the Scilab Consortium is in charge of the development and distribution of Scilab.

Concerning this software, the Metalau project is now involved in the knowledge transfer to the Scilab team and the maintenance and update of some toolboxes, mainly signal processing and control toolboxes.

## 5.2. ScicosLab

ScicosLab is a free environment for scientific computation similar in many respects to Matlab/Simulink, providing Matlab functionalities through Scilab 4, and, Simulink and Modelica functionalities via Scicos. ScicosLab is a GTK version of Scilab, based on the Scilab BUILD4 distribution. ScicosLab includes, in addition to the Gtk2 GUI, the maxplus built-in toolbox. Scilab and its predecessor Basile have been developed in the Metalau (formerly Meta2) project. This work has been carried out in close collaboration with J. Ph. Chancelier of ENPC who has made major contributions to Scilab such as the development of the graphics and the port to the Windows platform. The new version 4.4 of ScicosLab has been released in December 2009, in cooperation with ENPC. This release contains the latest developments made for Scicos, mostly code generation.

## 5.3. Scicos

Scicos, a tool for modeling, simulation and code generation included in ScicosLab (<http://www.scicos.org>)

## 5.4. ScicosLab toolboxes and functions

- Control and signal processing toolboxes
- CiudadSim Scilab Traffic Assignment toolboxes
- COSMAD Output modal analysis and diagnosis
- MAXPLUS Maxplus arithmetic and linear systems toolbox by the Maxplus Working Group
- LMITOOL optimization for robust control applications
- CUTER Scilab toolbox for testing linear algebra and optimization [contribution to Scilab software](#)

# 6. New Results

## 6.1. Traffic Modeling and Control

**Participants:** Maurice Goursat, Jean-Pierre Quadrat.

The thesis of N. Farhi dedicated to maxplus modeling of microscopic traffic has been defended in June 2008 where a difficult result has been obtained on the explicit computation of an approximation of the fundamental diagram given by a generalized additive eigenvalue for two roads with a junction. This result gives a good insight to what happens on general networks of roads. In this work the roads was cut in sections and the dynamic was finite dimensional. This year we have made an attempt to extend the model to the infinite dimensional case.

Following Daganzo we have discussed the variational formulation of the Lighthill-Witham-Richards equation describing the traffic on a road. First, we have considered the case of a circular road with a very simple dynamics which is minplus linear. We have extended it to the case of two roads with a junction with the right priority. The PDE obtained is no more an Hamilton-Jacobi-Bellman equation. To study the eigenvalue problem extending the standard minplus one, we have considered a space discretization of the equation. The discrete problem can be solved analytically with the results obtained in the N. Farhi thesis, it gives the eigenvalue as a function of the car density. Then the limit when the discretization step goes to zero gives a very simple formula which is a potential solution to the eigenvalue problem of the PDE. But the existence of the PDE and the convergence to the solution of the PDE is still to be proved. We have presented this result in [23].

## 6.2. Maxplus Algebra

**Participant:** Jean-Pierre Quadrat.

We have started the writing of a book in french making a synthesis of our previous works on maxplus algebra, stochastic control and applications to production and transportation systems. A representative sample of hundred of pages has been submitted to Springer Verlag [26].

## 6.3. Computer aided control system design

### 6.3.1. *ScicosLab*

**Participants:** Jean-Philippe Chancelier, François Delebecque, Jean-Pierre Quadrat.

A new release has been diffused. It contains the latest Scicos developments and a few bug fixes.

### 6.3.2. *Validation of Scicos models*

**Participant:** Rodrigo Fraxino de Araujo.

Our contribution is to make possible the application of the mutation testing for the context of embedded systems models. We focus on dynamic systems models, specifically on Scicos and Simulink models

We investigated and analyzed all the main features of such models by applying the HAZOP study, whose purpose is to systematically examine the behavior of the underlying system, aiming to determine deviations and hazards that might arise as well as potential related problems. A testing tool was extended to put in practice the defined mutant operators.

## 6.4. Metalica working group

The objective of this working group is to define the basis of a new simulation language for dynamic systems, taking into account proper events management and implicit systems. This working group, which gathers researchers from computer science and control, has met regularly along this year.

# 7. Contracts and Grants with Industry

## 7.1. National Research Contracts

### 7.1.1. *ANR Project Parade*

**Participants:** François Delebecque, Simone Mannori.

The project has ended this year. Most of the developments realized have been in the field of the parallel simulation of the standalone code generated by Scicos using the Sundials standards. A simple complete example has been developed in the Linux/MPI environment. The joint work with Lagep has been pursued.

## 7.2. European Research Contracts

### 7.2.1. *European project EuroSysLib*

**Participants:** François Delebecque, Simone Mannori.

The work done this year, for the achievement of the project, has been the development of Scicos/Modelica blocks, directly available in a HIL loop within Scicos.

## 7.3. Contracts with Industry

### 7.3.1. *Scerne project (DGA)*

The objective is to develop a simulation tool for new generations of communication and radar systems. Metalau participates in this project to improve the efficiency of the Scicos Code Generator notably by providing all the Scicos formalism available in the generated code. We also work around the portability of the generated code to embed a standalone Scicos simulator in software applications.



### 7.3.2. Altair Engineering

Altair Engineering Inc. has purchased a non-exclusive worldwide operating license of the software Scicos developed in Metalau.

## 8. Dissemination

### 8.1. Animation of the scientific community

- Serge Steer
  - Member of evaluation committee for Scilab contest 2010.

### 8.2. Conference and workshop participations, invited conferences

- F. Delebecque : Participated to the HeDisk 2010 workshop, held at San Carlos (Costa Rica). The talk has been around a general presentation of the Scicoslab toolboxes made in the projet Metalau : MaxPlus toolbox and Scicos 4.3.

### 8.3. Ph.D. Thesis

- F. Delebecque : Alireza Esna Ashari (reviewer) et Damien Chapon (co-direction).

### 8.4. Teaching

- F. Delebecque
  - Théorie des systèmes. Master 2, University Paris 1.
- Serge Steer
  - “Modélisation et simulation numérique des systèmes dynamiques”, 15 h, master 2, Comasic, Polytechnique.

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