Siconos

An opensource software platform for the modeling, the simulation and the control of nonsmooth mechanical and electrical systems

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Tripop team. INRIA Rhône–Alpes, Grenoble. & LJK

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Generalities
NonSmooth Dynamical Systems (NSDS)
Complementarity Systems (LCS)
Electrical Circuits
Lagrangian dynamical systems with unilateral constraints and friction
Examples in Mechanical Engineering and Computational Mechanics
Control. Optimal Control and Sliding Mode Control
Simulation of Hybrid Systems

The Siconos Platform
Introduction
Siconos/Numerics
Siconos/Kernel Modeling
Siconos/Kernel Simulation

Illustrative Examples

Siconos/mechanics. a multibody toolbox
Multibody Systems and Newton-Euler formalism

Documentation and Distribution
Non-smooth dynamical systems

- Non-smooth solutions in time (jumps, kinks, distributions, measures)
- Non-smooth modeling and constitutive laws (set-valued mapping, inequality constraints, complementarity, impact laws)
Application fields.

- Mechanical systems with unilateral contact, Coulomb friction and impacts: multi-body systems, robotic systems, frictional contact oscillators, granular materials.
- Switched electrical circuits (diodes, transistors, switches).
- Hybrid and Cyber–physical systems
- Gene regulatory networks
- Fluid transportation networks with queues.

Nonsmooth approach is crucial for a correct modeling and an efficient simulation.
Non-smooth dynamical systems

**Difficulty:** Standard tools of numerical analysis and simulation (in finite dimension) are no longer suitable due to the lack of regularity.

\[
0 \leq y \perp \lambda \geq 0
\]

\[
- y \in N_{\mathbb{R}^+} (\lambda)
\]

\[
y^\top (\lambda' - \lambda) \geq 0, \forall \lambda' \in \mathbb{R}^+
\]

Specific tools

- Differential measure theory. Convex, non-smooth and variational Analysis (Clarke, Wets, & Rockafellar).
- Complementarity theory. Maximal monotone operators.

Examples of non-smooth dynamical systems

- Piecewise smooth systems
- Complementarity systems and differential variational inequality.
- Specific differential inclusions (Filippov, Moreau sweeping process, Normal cone inclusion).
What is a Non Smooth Dynamical System (NSDS) ?

A NSDS is a dynamical system characterized by two correlated features:

- a non smooth evolution with the respect to time:
  - Jumps in the state and/or in its derivatives w.r.t. time
  - Generalized solutions (distributions)

- a set of non smooth laws (Generalized equations, inclusions) constraining the state $x$

NSDS are a special class of Hybrid Systems coupling:

- A set of continuous dynamical systems (modes)
- A set of discrete rules governing the mode selection.
Non Smooth modeling vs. General Hybrid Modeling

NSDS: a special class of Hybrid Systems, but . . .

A NSDS is a special class of Hybrid Systems with

- a strong mathematical structure
- well-posedness results (existence, uniqueness, continuity with the respect to data)
- Efficient simulation tools

Two examples

- Use of mathematical programming (Optimization) formulations and techniques (LCP, QP)
  - Better than enumerative algorithm for conditional statement
  - polynomial complexity for well-posed physical systems.
- Use of specific time-stepping schemes without explicit event handling.
  - Better than Event-driven strategies for a huge number of discrete events.
  - Ability to handle functions of bounded variations (finite accumulations of discontinuities.)
  - Definition of global solutions in the space of distributions.
Typical examples

- Differential inclusions & variational inequalities
- Mechanical systems with unilateral contact, Coulomb's Friction and impacts
- Complementarity systems
- Optimal control with state constraints
- Sliding Mode Control
- ...
Typical examples

Linear Complementarity Systems (LCS)

\[
\begin{aligned}
\dot{x} &= Ax + B\lambda, \quad x \in \mathbb{R}^n, \lambda \in \mathbb{R}^m \\
y &= Cx + D\lambda \\
0 &\leq y \perp \lambda \geq 0
\end{aligned}
\] (1)

with \( A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, C \in \mathbb{R}^{m \times n}, D \in \mathbb{R}^{m \times m} \), for \( m \) constraints.
Piecewise linear systems

Mixed complementarity systems

\[ \begin{align*}
M\dot{x} &= f(x, t) + g(x, \lambda, t), \quad x \in \mathbb{R}^n, \lambda \in \mathbb{R}^m \\
y &= h(x, \lambda, t) \\
-y &\in N_K(\lambda)
\end{align*} \]

with \( K = \prod_i [l_i, u_i] \) and \( M \) may singular. (The relative degree is assumed to be less than 1)
Example (The RLC circuit with a diode. A half wave rectifier)
A LC oscillator supplying a load resistor through a half-wave rectifier.

Figure: Electrical oscillator with half-wave rectifier
Example (The RLC circuit with a diode. A half wave rectifier)
Example (The RLC circuit with a diode. A half wave rectifier)
Example (The RLC circuit with a diode. A half wave rectifier)

- Kirchhoff laws:
  
  \[ v_L = v_C \]
  \[ v_R + v_D = v_C \]
  \[ i_C + i_L + i_R = 0 \]
  \[ i_R = i_D \]

- Branch constitutive equations for linear devices are:
  
  \[ i_C = C \dot{v}_C \]
  \[ v_L = L \dot{i}_L \]
  \[ v_R = R i_R \]

- "branch constitutive equation" of the ideal diode?
Example (The RLC circuit with a diode. A half wave rectifier)

Figure: A nonlinear model of diode

\[ i_D = i_s \left( \exp\left(-\frac{v_D}{nVT}\right) - 1 \right) \]
Example (The RLC circuit with a diode. A half wave rectifier)

**Figure:** A ideal diode

Complementarity condition:

\[ i_D \geq 0, -v_D \geq 0, i_D v_D = 0 \iff 0 \leq i_D \perp -v_D \geq 0 \]
Example (The RLC circuit with a diode. A half wave rectifier)

- Kirchhoff laws:

\[
\begin{align*}
    v_L &= v_C \\
    v_R + v_D &= v_C \\
    i_C + i_L + i_R &= 0 \\
    i_R &= i_D
\end{align*}
\]

- Branch constitutive equations for linear devices are:

\[
\begin{align*}
    i_C &= C \dot{v}_C \\
    v_L &= L \dot{i}_L \\
    v_R &= R i_R
\end{align*}
\]

- "Branch constitutive equation" of the ideal diode

\[
0 \leq i_D \perp -v_D \geq 0
\]
Example (The RLC circuit with a diode. A half wave rectifier)

The following linear complementarity system is obtained:

\[
\begin{pmatrix}
\dot{v}_L \\
\dot{i}_L
\end{pmatrix} = \begin{pmatrix}
0 & \frac{-1}{C} \\
\frac{1}{L} & 0
\end{pmatrix} \cdot \begin{pmatrix}
v_L \\
i_L
\end{pmatrix} + \begin{pmatrix}
\frac{-1}{C} \\
0
\end{pmatrix} \cdot i_D
\]

together with a state variable \( x \) and one of the complementary variables \( \lambda \):

\[
x = \begin{pmatrix}
v_L \\
i_L
\end{pmatrix}, \quad \lambda = i_D
\]

and

\[
y = \begin{pmatrix}
-1 & 0
\end{pmatrix} x + \begin{pmatrix}
R
\end{pmatrix} \lambda,
\]

Standard form for LCS

\[
\begin{cases}
\dot{x} = Ax + B\lambda \\
y = Cx + D\lambda \\
0 \leq y \perp \lambda \geq 0
\end{cases}
\]
Example (The RLC circuit with a diode. A half wave rectifier)

\[
\begin{align*}
\{ \ & y = Cx + D\lambda \\
& 0 \leq y \perp \lambda \geq 0 \Rightarrow \left\{ \begin{array}{l}
-\nu_D = -\nu_L + Ri_D \\
0 \leq -\nu_D \perp i_D \geq 0
\end{array} \right. \tag{3}
\end{align*}
\]

- \(i_D = 0, -\nu_D = -\nu_L \geq 0, \nu_L \leq 0\)
- \(i_D > 0, -\nu_D = 0, i_D = \frac{\nu_L}{R}, \nu_L > 0\) \(\Rightarrow i_D = \max(0, \frac{\nu_L}{R}) \tag{4}\)
Example (The RLC circuit with a diode. A half wave rectifier)

Note that the lead matrix of the LCP $D = (R) > 0$:

$$\begin{cases} y = Cx + D\lambda \\ 0 \leq y \perp \lambda \geq 0 \end{cases} \iff \lambda = \text{proj}_{\mathbb{R}^+}(-D^{-1}Cx) = \max(0, -D^{-1}Cx)$$

In the application, $i_D = \max(0, \frac{v_L}{R})$ and we get

$$\begin{pmatrix} \dot{v}_L \\ \dot{i}_L \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{C} \\ \frac{1}{L} & 0 \end{pmatrix} \cdot \begin{pmatrix} v_L \\ i_L \end{pmatrix} + \begin{pmatrix} -\frac{1}{C} \\ 0 \end{pmatrix} \cdot \max(0, \frac{v_L}{R})$$

Since max is a Lipschitz operator, we get a standard ODE with Lipschitz r.h.s.
A more serious example. Buck Converter
A more serious example. Buck Converter

Figure: SICONOS buck simulation using standard parameters.
A more serious example. Buck Converter

Figure: SICONOS buck simulation using sliding mode parameters and multivalued comparator.
A more serious example. Buck Converter

Figure: Eldo buck simulation using sliding mode parameters and 
\[ V_{\text{out}} = 1.5(\tanh(10000V_{\text{in}}) + 1) \] for the comparator.
A more serious example. Buck Converter

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Table: Numerical comparison on the Buck converter Example
Other applications in electrical circuits

Chain of MOS inverters
Other applications in electrical circuits

Delta-Sigma converters
Other applications in electrical circuits

Delta-Sigma converters

![Graph showing voltage over time for different points in a circuit.](image-url)
A famous nonsmooth dynamical system: the bouncing ball

Compliant model

\[ m\ddot{q}(t) = f(t) + \lambda = f(t) + \begin{cases} -kq(t) & \text{if } q(t) < 0 \\ 0 & \text{if } q(t) \geq 0 \end{cases} \]

(3)

Complementarity formulation

\[ \lambda = \begin{cases} -kq(t) & \text{if } q < 0 \\ 0 & \text{if } q \geq 0 \end{cases} \iff 0 \leq \lambda \perp \lambda + kq \geq 0 \]

(4)
A famous nonsmooth dynamical system: the bouncing ball

$$m\ddot{q}(t) = f(t) + \lambda$$ \quad \min(0, c\dot{q} + kq) = \lambda$$

if $q \leq 0$ then $\lambda > 0$
if $q > 0$ then $\lambda = 0$ \quad (5)

Complementarity formulation
Possible, but more complicated in order to maintain positive forces.
A famous nonsmooth dynamical system: the bouncing ball

Rigid limit

If we let $k \to +\infty$ (rigid contact with restitution) we get

$$
\begin{align*}
\ddot{m}q(t) & = f(t) + \lambda(t) \\
0 & \leq q(t) \perp \lambda(t) \geq 0
\end{align*}
$$

Mandatory impact law (for discrete systems)

If $\dot{q}(t^-) < 0$ and $q(t) = 0$

$$
\dot{q}(t^+) = -e\dot{q}(t^-)
$$

Therefore we pass from a piecewise linear system to a complementarity system

What do we gain doing so (compliance replaced by rigidity)?
Complementarity condition

Signorini’s condition in contact mechanics

\[ 0 \leq y \perp \lambda \geq 0 \quad (8) \]
\[ -y \in N_{\mathbb{R}^+} (\lambda) \quad (9) \]
\[ -\lambda \in N_{\mathbb{R}^+} (y) \quad (10) \]
\[ \lambda^T (y' - y) \geq 0, \text{ for all } y' \in \mathbb{R}^+(11) \]
\[ y^T (\lambda' - \lambda) \geq 0, \text{ for all } \lambda' \in \mathbb{R}^+(12) \]

A well-know concept in Optimization

- Numerous theoretical tools (variational inequalities, complementarity problems, proximal point techniques)
- Numerous numerical tools (pivoting techniques, projected over–relaxation (Gauss–Seidel), semi-smooth Newton methods, interior point methods, ... )
Compliant vs. rigid model

Compliant model

- Possibly more realistic models.
  - are we able to accurately know the behavior at contact (relation force/indentation) ?
  - Hertz’s contact model for spheres (limited validity !) dissipation ?
- Complex contact phenomena.
  - space and time scales are difficult to handle
  - numerous inner variables
- Numerical implementation ostensibly more simpler, but numerous issues
  - stiff model, high frequency dynamics (most of the time non physical), stability of integrators, small time–steps, . . .
  - high sensitivity to contact parameters
  - limited smoothness : issues in order and adaptive time–step strategy

Rigid model

- Limited description of the contact behavior
- Modeling of threshold effects
- Simple set of parameters with limited sensitivity
- Stable and robust numerical implementation
  - no spurious high frequency dynamics.
Numerical simulation: Stiff problems versus complementarity

Euler discretization of the compliant system (finite $k$)

$$\begin{cases} \frac{\dot{q}_{i+1} - \dot{q}_i}{h} = kq_{i+1} \\ \frac{q_{i+1} - q_i}{h} = \dot{q}_i \end{cases} \iff \begin{pmatrix} \dot{q}_{i+1} \\ q_{i+1} \end{pmatrix} = \begin{pmatrix} kh^2 + 1 \\ h \end{pmatrix} \begin{pmatrix} \dot{q}_i \\ q_i \end{pmatrix}$$ (13)

This problem is stiff because the eigenvalues $\gamma_1$ and $\gamma_2$ of $\begin{pmatrix} kh^2 + 1 & kh \\ h & 1 \end{pmatrix}$ satisfy $\frac{\gamma_1}{\gamma_2} \to +\infty$ when $k \to +\infty$.

**stiff integrators**
Numerical simulation: Stiff problems versus complementarity

Euler discretization (Moreau’s scheme) of the complementarity system (infinite $k$)

\[
\begin{align*}
\dot{q}_{i+1} - \dot{q}_i &= h f_{i+1} + \lambda_{i+1} \\
0 &\leq \dot{q}_{i+1} + e \dot{q}_i \perp \lambda_{i+1} \geq 0 \\
q_{i+1} &= q_i + h \dot{q}_i
\end{align*}
\] (14)

which is nothing else but solving a simple Linear complementarity systems (LCP) (or a quadratic program QP) at each step!!!
Lagrangian systems with unilateral contact and Coulomb’s friction

Lagrangian dynamical systems

\[ M(q)\ddot{q} + Q(\dot{q}, q) + F(\dot{q}, q, t) = F_{\text{ext}}(t) + R \]

- \( q \in \mathbb{R}^n \): generalized coordinates vector.
- \( M \in \mathbb{R}^{n \times n} \): the inertia matrix
- \( Q(\dot{q}, q) \): The non linear inertial term (Coriolis)
- \( F(\dot{q}, q, t) \): the internal forces
- \( F_{\text{ext}}(t) : \mathbb{R} \mapsto \mathbb{R}^n \): given external load,
- \( R \in \mathbb{R}^n \) is the force due the non smooth law.
Lagrangian systems with unilateral contact and Coulomb’s friction

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\[ M(q)\ddot{q} + Q(\dot{q}, q) + F(\dot{q}, q, t) = F_{\text{ext}}(t) + R \]

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Kinematic linear relations

- Kinematic laws from the generalized coordinates to the local coordinates at contact.
  \[ y = H^T q + b, \dot{y} = H^T \dot{q} \]

  Mapping \( H \): Restriction mapping composed with a change of frame
- By duality, \( R = H\lambda \)
Lagrangian systems with unilateral contact and Coulomb’s friction

- Local frame at contact: \((n, t)\)

\[ y = y_n n + y_t, \quad \dot{y} = \dot{y}_n n + \dot{y}_t \]

\[ \lambda = \lambda_n n + \lambda_t, \]
Lagrangian systems with unilateral contact and Coulomb’s friction

▶ Local frame at contact: \((n, t)\)

\[
y = y_n n + y_t, \quad \dot{y} = \dot{y}_n n + \dot{y}_t
\]
\[
\lambda = \lambda_n n + \lambda_t,
\]

▶ Unilateral contact:

\[
0 \leq y_n \perp \lambda_n \geq 0 \quad \iff \quad -\lambda_n \in \partial \mathcal{P}_{IR^+}(y_n)
\]
Lagrangian systems with unilateral contact and Coulomb’s friction

- Local frame at contact: \((n, t)\)

\[ y = y_n n + y_t, \quad \dot{y} = \dot{y}_n n + \dot{y}_t \]

\[ \lambda = \lambda_n n + \lambda_t, \]

- Unilateral contact:

\[ 0 \leq y_n \perp \lambda_n \geq 0 \iff -\lambda_n \in \partial \psi_{IR^+}(y_n) \]

- Coulomb’s Friction, \(\mu\) Coefficient of friction, \(C(\mu \lambda_n) = \{\lambda_t, \|\lambda_t\| \leq \mu \lambda_n\}\)

\[ \begin{cases} 
\dot{y}_t = 0, \|\lambda_t\| \leq \mu \lambda_n \\
\dot{y}_t \neq 0, \lambda_t = -\mu \lambda_n \text{sign}(\dot{y}_t) 
\end{cases} \iff \dot{y}_t \in \partial \psi_{C(\mu \lambda_n)}(-\lambda_t) \iff -\lambda_t \in \partial \psi_{C(\mu \lambda_n)}^*(\dot{y}_t) \]
Lagrangian systems with unilateral contact and Coulomb’s friction

- Local frame at contact: \((n, t)\)

\[ y = y_n n + y_t, \quad \dot{y} = \dot{y}_n n + \dot{y}_t \]

\[ \lambda = \lambda_n n + \lambda_t, \]

- Unilateral contact:

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- Coulomb’s Friction, \(\mu\) Coefficient of friction, \(C(\mu \lambda_n) = \{\lambda_t, \|\lambda_t\| \leq \mu \lambda_n\}\)

\[ \begin{cases} \dot{y}_t = 0, \|\lambda_t\| \leq \mu \lambda_n \\ \dot{y}_t \neq 0, \lambda_t = -\mu \lambda_n \text{sign}(\dot{y}_t) \end{cases} \iff \dot{y}_t \in \partial \psi_{\mu \lambda_n}(\lambda_t) \iff -\lambda_t \in \partial \psi^*_{\mu \lambda_n}(\dot{y}_t) \]

- (Newton) Impact law, if necessary, \(e\) coefficient of restitution

\[ \dot{y}_n(t^+) = -e \dot{y}_n(t^-) \]
Mechanical systems with contact, impact and friction

Multi-body systems: Simulation of electrical circuit breakers

INRIA/Schneider Electric
Mechanical systems with contact, impact and friction

Robotic and Haptic systems

Biped Robot INRIA BIPOP

Aldebaran Robotics NAO
Mechanical systems with contact, impact and friction

Robotic and Haptic systems

Simulation of the ExoMars Rover (INRIA/Trasys Space/ESA)
Mechanical systems with contact, impact and friction

FEM cohesive zone modeling of composite. Contact, friction cohesion, etc...
Joint work with Y. Monerie, IRSN.
Mechanical systems with contact, impact and friction

Mechanics of Solids and Structures

Divided Materials and Masonry
Mechanical systems with contact, impact and friction

Dam made of blocks (Saladyn project)

Simulation: Code_Aster + Siconos + LMGC90
Mechanical systems with contact, impact and friction


La tour Saint Laurent du palais des Papes à Avignon
Mechanical systems with contact, impact and friction
Mechanical systems with contact, impact and friction

Mechanics of Solids and Structures. Masonry

Mechanical stress computation
Mechanical systems with contact, impact and friction

Granular matter

Stack of beads with perturbation
Figure: Illustrations of the FClib test problems
A first application at INRIA Chile. Mining industries

Simulation of granular flows
A first application at INRIA Chile. Mining industries

- Simulation and analysis of granular rock flows.
- Optimization of block caving techniques
  - Role of the preconditioning
  - Fracture processes.
Sliding Mode Control

Academic example

\[ \dot{x} = -\text{sgn}(x) \]  \hspace{1cm} (15)

Chattering-free stabilization

\[ \dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & -c_1 \end{bmatrix} x - \begin{bmatrix} 0 \\ \alpha \end{bmatrix} \text{sgn}(\begin{bmatrix} c_1 & 1 \end{bmatrix} x). \]  \hspace{1cm} (16)
Difference between explicit and implicit time integration

(a) $h = 0.3$. Explicit Euler  (b) $h = 0.1$. Explicit Euler  (c) $h = 0.1$. Implicit Euler  (d) $h = 0.05$. Implicit Euler

Figure: Equivalent control based SMC, $c_1 = 1, \alpha = 1$ and $x_0 = [0, 2.21]^T$. State $x_1(t)$ versus $x_2(t)$. 
Simulation challenges for hybrid systems

Simulation approach in Hybrid dynamical system modeler

- Loose coupling between a continuous dynamical simulator (ODE or DAE solvers) and a discrete event simulator
- Event-Driven approach with only external events
- Complex combinatorics to decide the right mode after an event.
- Huge problems of scalability.

Difficulties

- High number of events
- Sliding modes control
- Nonsmooth events due to the lack of regularity in models.
- Difficulties in finding consistent initial conditions
Siconos and some hybrid systems

Hybrid systems issued form a physical modeling
A lot of hybrid systems are issued form a physical modeling: Main part of the system are only “fake” logical dynamics.

- Such systems can be formulated as nonsmooth dynamical systems (Friction, Relay, diode, . . .)
- We take benefits from the nonsmooth approach to better simulate these systems.
Generalities

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Siconos/mechanics. a multibody toolbox
Multibody Systems and Newton-Euler formalism

Documentation and Distribution
Original Motivations

Context
The Siconos Platform is one of the main outcome of the Siconos EU project.

Goal: Modeling, simulation, analysis and control of NSDS
There is no other general, common and open software suitable for the modeling and the simulation all of these NSDS

Constraints

- various modeling habits and formulations
- various application fields
- various mathematical and numerical tools

Links and interfaces with existing software

- Matlab or Scilab dedicated user toolbox
- Low-level numerical libraries (BLAS, LAPACK, ODEPACK, ...)
- Simulation tools for a given application field:
  - Scicos, Simulink
  - FEM and DEM Software (LMGC90, Aster, ...)
  - Hybrid modeling Language (Modelica, ...)

Siconos
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Some figures

- 2003. Beginning of the project
- Around 100000 lines of Open–source code in C++, C, Fortran, Python (GPL Licence)
- Two APP deposits.
- Around 30 users and contributors
- Human efforts for design and development

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- Human efforts for application and validation

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Architecture and Design

Numerical simulation Kernel for various modelers:
Architecture and Design

Siconos Modules

- **Siconos/Front end**
  - Command interactive user interface

- **Siconos/Kernel**
  - Modeling and Simulation tools

- **Siconos/Numerics**
  - Low level Numerical routines

- **Siconos/Analysis**

- **Siconos/Control**

- **Existing Numerical Libraries**

- **User Plug-in**
Architecture and Design

SICONOS/Numerics library

- API C
- Shared dynamic library.
- Scilab and Matlab interfaces (Obsolete).

SICONOS/Kernel library

- API C++: Shared dynamic library in other modeling environment.
- API C++: Compiled command files with high level methods (C++ Constructors and/or XML file data loading.)
- API C: Shared dynamic library in low-level environment.

SICONOS/Front-End

- API Python: Interactive environment (SWIG wrapping).
- API C: Scilab and Matlab interface (Obsolete).
Architecture and Design

Majors functionalities and modules
Software quality

Substantial effort for a high quality software

- Work in collaboration with SED from the beginning of the project
- Use of the ESA standards for the software quality method

Extensive Software Documentation

1. Project overview
2. Project proposal
3. Software Requirements Specification
   - Functional and non functional requirements
   - Feature set by functionalities and by release and priority
   - Use cases
4. Architectural and Detailed design
   - Description of components
   - Software development methodology
5. Quality assurance plan
   - Project management plan (Organization, Work Breakdown structure, Tasks, Milestones)
   - Configuration Management plan
   - Verification and Validation plan
Siconos/Numerics

Independent collection of solvers in C for standard nonsmooth problem:

- **LCP/MLCP/Relay**
  - Lemke’s method, PSOR, PGS, Enumerative (based on simplex), Semismooth newton, …

- **MCP/VI**
  - Projection/splitting methods, interface to PATH solver, semismooth Newton based on fischer-Burmeister formulation.

- **FrictionContact**
  - Nonsmooth newton (Alart-Curnier, Christensen et al.), PGS with local solvers, Extragradient, hyperplane, projection/splitting methods, optimization based on Tresca’s formulation, …

- **QP**

- **ODE/DAE integrators:**
  - Lsode suite with LSODAR (Hindmarsh, Alan C., (LLNL))
  - HEM5 DAE solver (Hairer, Ernst, Université de Genève)
Modeling Principle:

\[ \dot{x} = f(x, t) + r \]
Modeling Principle:

\[ \dot{x} = f(x, t) + r \]

\[ 0 \leq y \perp \lambda \geq 0 \]
Modeling Principle:

\[
\begin{align*}
\dot{x} &= f(x, t) + r \\
y &= h(x, t, \lambda) \\
r &= g(x, t, \lambda) \\
0 &\leq y \perp \lambda \geq 0
\end{align*}
\]
Modeling Principle:

\[ y = h(x, t, \lambda) \]

Nonsmooth Law

\[ r = g(x, t, \lambda) \]

Interaction Relation

\[ 0 \leq y \perp \lambda \geq 0 \]

Nonsmooth Dynamical System

\[ \dot{x} = f(x, t) + r \]
Kernel Modeling Part

A Nonsmooth Dynamical System:
a directed graph of Dynamical systems and Interactions

- **DynamicalSystem**: a set of ODEs
- **Interaction**: a set of input/output relations and a non-smooth law
Kernel Modeling Part

A Nonsmooth Dynamical System:

a directed graph of Dynamical systems and Interactions

- **DynamicalSystem**: a set of ODEs
- **Interaction**: a set of input/output relations and a non-smooth law
- **Topology**: A directed graph that links the dynamical systems with the Interaction and that handles relative degrees, index sets ...
Kernel Modeling Part

Simplified Modeling Tools class diagram:
Dynamical Systems in Siconos/Kernel

- Parent Class `DynamicalSystem` \[ g(\dot{x}, x, t, z) = 0 \]
Dynamical Systems in Siconos/Kernel

- **Parent Class** \textbf{DynamicalSystem} \quad g(\dot{x}, x, t, z) = 0

- **FirstOrderNonLinearDS** Linear Dynamical Systems

  \[ M\dot{x} = f(x, t, z) + r \]

- **FirstOrderLinearDS** Linear Dynamical Systems

  \[ M\dot{x} = A(t, z)x + b(t, z) + r \]
Dynamical Systems in Siconos/Kernel

- Parent Class **DynamicalSystem**  \( g(\dot{x}, x, t, z) = 0 \)
- Derived Classes
  - **LagrangianDS** Lagrangian Dynamical Systems
    \[
    M(q)\ddot{q} + NNL(q, \dot{q}) + F_{\text{int}}(\dot{q}, q, t) = F_{\text{ext}}(t) + T(q)u(q, t) + p
    \]
  - **LagrangianLinearTIDS** Lagrangian Linear Time Invariant Systems
    \[
    M\ddot{q} + C\dot{q} + Kq = F_{\text{ext}}(t) + Tu(t) + p
    \]
  - **NewtonEulerDS** Newton/Euler Systems

*Note: all operators ( \( f(x, t), M(q), \ldots \)) can be set either as matrices (when constant) or with a user-defined external function (plug-in).*
Relations

Parent Class Relation \[ y = h(x, t, \lambda, z), \quad r = g(\lambda, t, x, z) \]
**Relations**

- **Parent Class** **Relation**  \( y = h(x, t, \lambda, z), \ r = g(\lambda, t, x, z) \)
- **Derived Classes:**
  - **FirstOrderLinearTIR** First Order LTI Relation
    \[ y = Cx + Fu + D\lambda + e, \quad r = B\lambda \]
  - **LagrangianR** Lagrangian Relation
    \[ \dot{y} = H(q, t, \ldots)\dot{q}, \quad p = H^t(q, t, \ldots)\lambda \]
  - **LagrangianLinearR** Lagrangian Linear Relation
    \[ \dot{y} = H\dot{q} + b, \quad p = H^t\lambda \]
Non Smooth laws

- **Parent Class** [NonSmoothLaw](#)
- **Derived Classes**
  - [ComplementarityConditionNSL](#) Complementarity condition or unilateral contact
    \[ 0 \leq y \bot \lambda \geq 0 \]
  - [RelayNSL](#) condition.
    \[
    \begin{cases}
    \dot{y} = 0, |\lambda| \leq 1 \\
    \dot{y} \neq 0, \lambda = \text{sign}(y)
    \end{cases}
    \]
  - [NewtonImpactLawNSL](#) Newton impact Law.
    If \( y(t) = 0, 0 \leq \dot{y}(t^+) + e\dot{y}(t^-) \bot \lambda \geq 0 \)
  - [NewtonImpactFrictionNSL](#) Newton impact and Friction (Coulomb) Law.
# start time
T = 10      # end time
h = 0.005   # time step
r = 0.1     # ball radius
g = 9.81    # gravity
m = 1       # ball mass
e = 0.9     # restitution coefficient
theta = 0.5 # theta scheme

# definition of the dynamical system

x = [1,0,0] # initial position
v = [0,0,0] # initial velocity
mass = eye(3) # mass matrix
mass[2,2] = 2./5 * r * r

# dynamical system constructor
ball = LagrangianLinearTIDS(x, v, mass)

# set external forces
weight = [-m * g, 0, 0]
ball.setFExtPtr(weight)
# definition of the Interaction ball-floor

H = [[1,0,0]]

nslaw = NewtonImpactNSL(e)

relation = LagrangianLinearTIR(H)

inter = Interaction(nslaw, relation)

# definition of the NonSmoothDynamicalSystem

bouncingBall = NonSmoothDynamicalSystem(t0, T)

# add the dynamical system to the non smooth dynamical system

bouncingBall.insertDynamicalSystem(ball)

# link the interaction and the dynamical system

bouncingBall.link(inter, ball);
Kernel Simulation Part

Simplified Modeling Tools class diagram:
Kernel Simulation Part

Simplified Modeling Tools class diagram:
OneStepIntegrator:

- **Moreau**: Moreau–Jean Time-stepping integrator
- **SchatzmanPaoli**: Schatzman–Paoli Time-stepping integrator
- **D1MinusLinear**: Time–Discontinuous Galerkin method.
- **Lsodar**: Numerical integration scheme based on the Livermore Solver for Ordinary Differential Equations with root finding.
- **HEM5**: Half–explicit method of Brasey & Hairer for index-2 mechanical systems.

OnestepNSproblem: Numerical one step non smooth problem formulation and solver.

- **LCP** Linear Complementarity Problem
  \[
  \begin{cases}
  w = Mz + q \\
  0 \leq w \perp z \geq 0
  \end{cases}
  \]

- **FrictionContact** Two(three)-dimensional contact friction problem
- **QP** Quadratic programming problem
  \[
  \begin{cases}
  \min \frac{1}{2} z^T Qz + z^T p \\
  z \geq 0
  \end{cases}
  \]

- **Relay**
# (1) OneStepIntegrators
```
OSI = MoreauJeanOSI(theta)
```

# (2) Time discretisation --
```
t = TimeDiscretisation(t0, h)
```

# (3) one step non smooth problem
```
osnspb = LCP()
```

# (4) Simulation setup with (1) (2) (3)
```
s = TimeStepping(bouncingBall, t, OSI, osnspb)
```

# run the simulation

# time loop
```
while (s.nextTime() < T):
    s.computeOneStep()
    s.nextStep()
```

# or execute events
```
while s.hasNextEvent():
    s.computeOneStep()
    s.nextStep()
```
Model: Lagrangian Linear Time Invariant Dynamical Systems with Lagrangian Linear Relations, Newton Impact Law.
Simulation: Moreau’s Time Stepping or Event Driven.

Bouncing Ball

Beads column
**Model:** Linear Dynamical System with Linear Relations, Complementarity Condition
Non Smooth Law.

**Simulation:** Moreau’s Time Stepping

Comparison between the SICONOS Platform (Non Smooth LCS model) and SPICE simulator (Smooth Diode model).
Woodpecker toy (sample from Michael Moeller (CR10))

*Model:* Lagrangian Linear Dynamical System, Lagrangian Linear Relations, Newton impact-friction law.

*Simulation:* Moreau’s Time Stepping
A Robotic Arm (Pa10)

*Model:* Lagrangian Non Linear Dynamical System with Lagrangian Non Linear Relations, Newton impact.

*Simulation:* Moreau’s Time Stepping
Proximity detection

- threshold bounding box
- spatial hashing of the bounding box
Siconos internal graphs

- dynamical systems as nodes, interactions as edges
- interactions as nodes, dynamical systems as edges

Figure: adjoint graph construction
Newton Euler Formalism

Dynamical system of a rigid body

\[
q = (x_G, Q)^T, \\
M \dot{v}_G = \begin{bmatrix} F_{\text{ext}}(t, q, \Omega, v_G) \\ M_{\text{ext}}(t, q, \Omega, v_G) \end{bmatrix} + R, \\
v_G = \dot{x}_G, \\
\dot{q} = T(q)(v_G, \Omega)^T
\]

- \( q \in \mathbb{R}^7 \): absolute coordinates vector.
- \( x_G \in \mathbb{R}^3 \): coordinates of the center of mass.
- \( Q \in \mathbb{R}^4 \): unit quaternion representing the absolute orientation.
- \( \Omega \in \mathbb{R}^3 \): angular speed vector relative to the solid.
- \( M = mI_{3 \times 3} \): mass matrix.
- \( I \in \mathbb{R}^{3 \times 3} \): inertia matrix.
- \( F_{\text{ext}}(t, q, \Omega, v_G) : \mathbb{R} \times \mathbb{R}^7 \times \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R}^6 \): given external forces,
- \( M_{\text{ext}}(t, q, \Omega, v_G) : \mathbb{R} \times \mathbb{R}^7 \times \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R}^6 \): given external moments,
- \( R \in \mathbb{R}^6 \) is the force due the non smooth law.
- \( T(q) \in \mathbb{R}^{6 \times 7} \)
Newton Euler Formalism

Constraints between two rigid bodies

\[ y = h(q_1, q_2) \]
\[ \dot{y} = \nabla_q h^T(q) \begin{pmatrix} T(q_1) & 0 \\ 0 & T(q_2) \end{pmatrix} (v_{1G}, \Omega_1, v_{2G}, \Omega_2)^T \]

with the contact law
- \( y = 0 \) in the case of a joint.
- \( 0 \leq y \perp \lambda \geq 0 \) in the case of an unilateral constraint.
- \( \text{NonSmoothLaw}(y, \lambda) \) in more general case

The reaction force \( R \)

\[ R = \begin{pmatrix} T(q_1)^T & 0 \\ 0 & T(q_2)^T \end{pmatrix} \nabla_q h(q) \lambda \]
Coupling with the 3D modeling library, Open CASCADE.

Figure: Parts of a Circuit breakers (Schneider Electric).

Open CASCADE provides the following features:

- To load a mechanism from CAD files (step, iges...).
- To compute the geometrical informations needed by the Nonsmoothlaw.

It allows to simulate industrial mechanisms using the Siconos technology.
Picker example.

Figure: A simple example.
Circuit breakers example.

Figure: Modeling of a Circuit breakers using SICONOS and Open CASCADE.

- The matrices of mass and the geometrical informations are computed from the geometrical model.
Help and Documentation

- Sphinx and Doxygen for automatic documentation
- Users and developers manuals (always in progress ...)
- Examples library as templates (more than 200 examples).

Diffusion

- SICONOS is distributed under Apache 2.0 licence.
- github collaborative development framework. (git, issues, pull-request)

  http://github.com/siconos/siconos

- Visit the Web site for more info http://gforge.inria.fr/projects/siconos/

Use and Contribute !!