SICONOS: Workpackage 6 - Applications

D6.1: Report on

Experimental Facilities Available Within the Consortium

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1. Introduction

The aim of this report is twofold. Firstly, it presents an overview of the experimental rigs currently available within the consortium, describing the experiments which are currently being carried out on them. Secondly, it collects other information useful for the achievement of the objectives of Workpackage 6: Applications. In particular, following discussions held at the First SICONOS General Meeting in Grenoble, January 2003, the report also contains a set of preliminary results highlighting possible testbed problems to be used for the validation of the software code and the design of feedback controllers. Where possible, an effort was made to recast the equations of the systems of interest as complementarity problems.

The results presented collectively in the report were contributed by each contractor. A questionnaire, enclosed in Appendix A, was sent to all participating teams. The answers to it were collected and elaborated as outlined in the rest of the report. Partners also contributed the documents describing different testbed problems which form an integral part of the report and are included in the Appendix.

The rest of the document is outlined as follows. In Sec. 2, a brief overview is given of the results of the questionnaire sent to all teams in November 2002. Then in Sec. 3 the detailed answers given by contractors are enclosed. A description of the testbed problems presented by different teams is included in Sec. 4 while the detailed description of each problem is presented in the appendix.
Conclusions are draws in Sec. 5 where an outline of the main achievements sofar within the scope of Workpackage 6 are given.

The following abbreviations are used in the document to refer to project contractors:

INRIA (CR1): INRIA-Rhone Alpes (Coordinator)
- **UM2 (AC2):** University of Montpellier 2
- **UJM (AC3):** University of St Etienne

DIS (CR4): University of Naples
- **CRB (AC5):** University of Benevento

UNIVBRIS (CR6): University of Bristol
KTH (CR7): Royal Institute of Technology
TU/e (CR8): Technological University of Eindhoven
- **TUD (AC11):** Delft Institute of Technology
- **TUB (AC12):** Tilburg University
- **UT (AC13):** University of Twente

UPC (CR9): Technical University of Catalonia
ETHZ (CR10): Swiss Federal Institute of Technology

2. Overview of experimental facilities available within the consortium

As shown from the detailed questionnaire results, reported in Sec. 4, there are already several experimental facilities available to the consortium. These can be grouped according to the three application areas of interest within the scope of the project: (i) power electronic converters; (ii) walking robots and other mechanical devices; (iii) automotive systems with freeplay. Rather than an exhaustive description of all set-ups, which can be found in Sec. 4 and Appendix B, an overview of the main ones is given here.

2.1 Power Converters

Experimental set-ups to investigate the dynamics of power electronic converters are available to three contractors, namely **UPC** and **CRB**. The facilities at **UPC** and **CRB** also allow the derivation of experimental bifurcation diagram from different converter configurations including AC/DC and DC/DC converters. The set-ups are complete with sensors, actuators and all necessary equipment and can be already used to test controllers of different types such as PWM and time-delay control laws. Currently, a limitation seems to be the max. commutation frequencies of the converters which is around 40 KHz at **UPC**.

2.2 Walking Robots and other mechanical devices

A walking robot is currently available at **INRIA** and can be used for both model validation, investigation of system dynamics and control design (for more details see Appendix B).

A number of mechanical devices are available at **TU/e** and **ETH**. Also, the BLADE labs at **UNIVBRIS** will host a set of large-scale experimental devices including a fully operating shaking table. Another smaller table (0.6 m x 0.8 m) is available at **UJM (ENPTE/LGM)**. The rigs available at **TU/e** include a set of systems where nonsmoothness is due to friction such as a drill-string set-up, a CD-ROM player with autobalancing unit, an inverted pendulum and an indistrial H-drive. An impact process of a fast component mounter is also available at **TU/e** courtesy of Philips/Assembleon.

2.3 Automotive Systems

Rigs for the experimental investigation of automotive systems are will be available from 2004 at **CRB.** In particular, a clutch-testing rig is under construction at **CRB** (see Sec. 4 for further details). The construction of a rig to test the dynamics of systems with backlash is being considered at **UNIVBRIS.**

3. Aim and Scope of Experiments carried out sofar

The experiments carried out sofar include the investigation of the system dynamics and bifurcation diagrams together with the design of appropriate controllers. At **UPC, UNIVBRIS** and **DIS-CRB** experiments have focussed on model validation and experimental bifurcation diagrams for power converters. The investigation of limit cycles due to friction has been carried out at **TU/e** together with the design of motion control and feedforward actions (to compensate effects due to friction).

Most contractors are currently using MATLAB and its toolboxes for the numerical analysis of systems of interest. AUTO97 is the most widely used software for bifurcation analysis while self-developed code in C or FORTRAN is used for specific simulation tasks such as Lyapunov exponents computation and high-accuracy time simulations.
The mathematical frameworks used to derive models of the systems under investigations are mainly complementarity systems and piecewise smooth ODEs. Hybrid systems are also used at **TU/e** and **CRB-DIS**.

4. Questionnaire Report

In what follows we collect the answers given by contractors to each of the questions of the questionnaire enclosed in Appendix A (Questions E1-E5 and S1-S3). Negative replies are not included for the sake of brevity. Note that, following discussions held at the General Meeting in Grenoble, January 2003, further information were requested to all teams. Each team was asked to produce a document detailing testbed problems of interest. The responses are collected in Appendix B.

Q1: Do you have experimental facilities related to one of the applications indicated in the project proposal ?

- **INRIA (CR1):** Walking robot. The paper "Control algorithms and architectures of the anthropomorphic biped robot Bip2000" is available on-line as a pdf file at http://www.inrialpes.fr/bip/people/azevedo/CV/cv.htm

- **UPC (CR9):** At the Technology Centre at Vilanova i la Geltru (CTVG) our group has an available power converters plant. It can be configured with a AC/DC/AC or AC/DC arquitecture. It allows 2 kW power, with condensers of 800V of storage. The plant is controlled with a data acquisition system. The plant is not mounted yet, but it is expected to be in full operation by June 2003. The data acquisition system for controlling the plant is a question that is still open. Several possibilities are a RTLinux controller, an FPGA controller or a DSP. The control law design will be of a PWM (Pulse Width Modulation) type, which will drive the IGBTs of the plant. There is a severe limitation of the frequency commutation near 40kHz. Actually no website is available for the experimental set-up described above. Also at the CTVG other smaller DC/DC plants can be available, which can be ad-hoc mounted, regarding the control system or with convenient parameters. These plants would allow higher commutation frequencies. Obviously, no website is available yet. An experimental set-up for DC/DC converter plant is also available for the group, at the Department of Applied Physics. The plant (for small power) can be configured to act as a buck, boost or buck-boost converter. It allows PWM control with several ramp signals (including triangular wave), and several additional control laws. Parameters of the circuit can be varied at disposal, and data processing is also available through data acquisition system and a special-purpose C code, with a graphic interface. Since this is not a plant of our group, personnel costs should be provided for operation and simulation. Actually, there is not an available website.

- **TU/e (CR8):** Experimental facilities related to nonsmooth robotic devices and automotive systems, namely:
    1. Inverted pendulum
    2. Industrial H-drive

3. We are cooperating with neighboring research groups in the area of drivelines/cvt's etc.

4. Impact process of a fast component mounter at the courtesy of Philips/Assembleon. (Details follows. Sensor: linear incremental encoder; Actuator: electrical motor; DSpace for data acquisition and control).

In both 1. and 2. the nonsmooth character is due to friction.

- **UM2 (AC2):** NLR has many research facilities that would be applicable to SICONOS, however, use of them is not free in general, nor are these facilities always available. See http://www.nlr.nl/public/facilities/index.html for more information.

- **UNIVBRIS (CR6):** No experimental facilities on any of these, BUT we do have theoretical expertise on all three.

- **DIS-CRB (CR4-AC5): University of Napoli and University of Sannio:** We have experimental facilities for DC/DC converters and other switching electrical systems (a DC motor PWM position control system). An experimental setup to test clutch engament control is planned to be built within the next 2 years. The automotive experimental setup for the clutch engagement which is planned to be built up by the team of Benevento will be co-sponsored by SICONOS funds. The setup consists of two electrical machines and an automotive dry clutch. The first electrical machine simulates the average internal combustion engine torque while the second electrical machine simulates the vehicle load. The aim of the test-bench is to analyse the engagement between the clutch connected to the load and the flywheel connected to the engine. The engagement is a typical nonsmooth phenomena due to friction effects and to the hybrid structure of the system which commutes between two (or more) different configurations depending on the states and external events.

Q2: List other available experimental setups related to the analysis of nonsmooth systems. Do you plan to set up new experimental facilities with the SICONOS funds ?

- **UPC (CR9):** An experimental set-up related to non-smooth systems is also available at the CTVG. Non-smooth effects have been observed when an OBS (Ocean Bottom Seismometer) is launched to the ocean from the oceanographic vessels, and also when the OBS impacts the ocean bottom. The analysis of the non-smooth dynamics is directly related to the project, but no funds from SICONOS are planned to set-up experiments in this subject.

- **TU/e (CR8):** Other experimental setups related to nonsmooth systems:

  1. Drill-string set-up: friction causing nonsmooth character

  2. CDROM-player with autobalancing unit: Nonsmooth character is due to friction and impact.

- **ETH (CR10):** A test setup for measuring impacts with wave effects will be built up within the SICONOS project. multi-contact configurations. The particular design of this device is not yet known. First drafts are expected in about 1 year.

- **UJM (AC3):** Now they (ENTPE-LGM) are developing experiments about nonlinear dynamics (2002). They have:
  1. small vibrating table (0.6m x 0.8m),
  2. metallic small size models
  3. accelerometers, force sensors, camera,
  4. source module, amplifier
  5. vibration analyser HP356xa.

- **UNIVBRIS (CR6):** None, but we will have a new BLADE lab Bristol Laboratory for Advanced Dynamic Engineering ready by Feb 2004 which will be a great place for making simple testbed experiments of mechanical systems and their control. We currently have direct plans to use this as part of SICONOS, but the possibility is there. A big part of this facility will be an earthquake shaking table and reaction wall, which will be useful for testing large structures under periodic loading.

Q3: Indicate the aim and scope of the experiments carried out so far

- **INRIA (CR1):** Experiments have focussed on development of feedback control strageies, can also serve as a test.-bed for numerical simulations

- **UPC (CR9):** Some experiments have been carried out with the experimental set-up described in E1c, with the aim of checking if the mathematical model describes accurately enough the physical situation. Waveforms in the oscilloscope show that this is the case. Also one-dimensional and two-dimensional experimental bifurcation diagrams have been obtained showing a good agreement between experimental and numerical simulations. These experimental diagrams are obtained by means of varying one or several parameters in the circuit, and through data acquisition and post-processing methods.

- **TU/e (CR8)**
    1. Investigation friction-induced limit-cycling in drilling
    2. Motion control, underactuated control, Iterative learning control, position dependent control, feedforward design (friction plays an important role)
    3. Limit cycling in observer-based controlled mechanical systems with friction.
    4. Influence of dry friction on the balancing behaviour of the system
    5. Identification (future: mode detection and control)

- **UJM (AC3):** The aim and scope of the experiments are :
    1. identification of linear and nonlinear terms so that the model with finite number of degrees of freedom of the studied structures provide numerical results in agreement with the experimental devices, identification of damping,
    2. identification of non smooth nonlinear terms (piecewise linear, impacts or quasi-impacts, friction),
    3. providing chaotic time series (from smooth and non smooth systems),
    4. application are especially devoted to Civil Engineering: so studied structures are e.g. small size models for buildings with cables (piecewise linear or quasi impact behavior) or strut elements (friction),
    5. measure and analysis of impact force according to wavelet method,
    6. Vibration analysis focused on plastic moving hinge effect.

- **DIS-CRB (CR4-AC5):** The aim and scope of the experiments are:

    1. validation of bifurcation analysis in piecewise smooth feedback systems;
    2. state feedback control of PWM systems;
    3. validation of dither theory for relay feedback systems;
    4. experimental validation of rebreather modelling.

Q4: List up to 5 references (journal articles or Conference papers) where the results of the experiments described above have been reported.

- **UPC (CR9):**
  1. El Aroudi, L. Benadero, E. Toribio and G. Olivar. Hopf Bifurcation and Torus breakdown in a PWM Voltage-Controlled DC-DC Boost Converter, IEEE Trans. on CAS, Part I, Vol 46, pp. 1374-1382, November 1999.
  2. E. Toribio, A. El Aroudi, G. Olivar and L. Benadero. Numerical and Experimental Study of the Region of Period-One Operation of a PWM Boost Converter, IEEE trans. on Power Electronics, Vol. 15, pp. 1163-1171, November 2000.
  3. A. El Aroudi, D. Gaston, E. Toribio, L. Benadero and G. Olivar. Stabilisation of Power Electronic Converters by Time Delay Feedback Control, Proceedings of SAAEI '99, Madrid (Spain), 1999.
  4. G. Olivar, R. Quiles, A. Manuel, J. Del Río. Two-Dimensional Bifurcation Diagrams with Data Acquisition, Proceedings of IEEE IMTC 2002, Anchorage (Alaska), 2002.

- **TU/e (CR8):** Currently preparing journal and conference papers on related subjects.

- **DIS-CRB (CR4-AC5):**

  1. M. di Bernardo, F. Garofalo, L. Iannelli, F. Vasca, *“Bifurcations in Piecewise Smooth Feedback Systems”*, International Journal of Control, to appear.
  2. M. di Bernardo, F. Garofalo, L. Iannelli, F. Vasca, *“Experimental Detection of Bifurcations and Sliding in DC-DC Power Converters”*, ISCAS 2002, Phoenix (AZ), USA, May 2002.

  Some other related publications (without experimental results) are:

  3. L. Iannelli, K.H. Johansson, U. Jönsson, F. Vasca, *“Analysis of Dither in Relay Feedback Systems”*, IEEE Conference on Decision and Control 2002, Las Vegas (Nevada), USA, December 2002.
  4. F. Garofalo, L. Glielmo, L. Iannelli, F. Vasca, *“Optimal Tracking for Automotive Dry Clutch Engagement”*, 15th IFAC World Congress, Barcelona (Spain), 2002.

Q5: Will your group be able to host researchers from other SICONOS participating groups to work on your experimental facilities ? If yes, how many people per year will you be able to host ? Will you be able to provide guests with some financial support ?

- **UPC (CR9):** The group can occasionally host researchers to work on our experimental laboratories from June/July 2003. Ideally, one researcher per year, during short stays. Also, we can provide guests if some financial support is available.

- **TU/e (CR8), Mechanical Engineering, Group Dynamics and Control:** The group is able to host 1/2 researchers per year. They can not provide guests with financial support.

- **TU/e (CR8), Department of Electrical Engineering:** Siconos members are more than welcome to work on it, although we have to verify with the owners (company Philips/Assembleon) if this is OK.

- **UJM (AC3-ENTPE):** One or two (6 months to 1 year) people could join the experimental research.

- **UNIVBRIS (CR6):** Approximately 2 per year. Not much financial support available unless it also uses the EU grants held by the Civil Engineering Department who own the shaking table.

- **DIS-CRB (CR4-AC5): University of Napoli and University of Sannio:** The groups can host researchers to work on their experimental facilities: one researcher per year during short stays with possible financial support from SICONOS.

- **INRIA (CR1):** Yes, one person per year seems reasonable, but that depends a lot on the person and of what she/he comes here for.

S1: Which kind of simulation tools do you use to carry out the numerical analysis of the nonsmooth systems of interest ?

- **TUB (AC12):** *Matlab*

- **UPC (CR9):** Numerical analysis is based on some specific C codes for simulation of trajectories, orbits, bifurcation diagrams (1 and 2 dimensional), characteristics multipliers computation, and so on. Also they have used MAPLE for non-smooth continuation, MATLAB for graphical purposes, DSTOOL for simulation of trajectories and for computing invariant manifolds. They also have used AUTO97 for continuation and bifurcation detection.

- **TU/e (CR8):** Matlab as a simulation tool to support the analysis of non-smooth systems**.** Worked with Modelica once, but not on a frequent basis. They built some simple LCP solvers written in Matlab, mainly for time-integration.

- **UT (AC13):** MATLAB/SIMULINK/STATEFLOW

- **UM2 (AC2):** We use a software developed in the lab specially dedicated to contact problems. This code is called LMGC 90 it means "Logiciel de Mecanique Gerant le Contact en Fortran 90" (translation: mechanical software dealing with contact conditions implemented with Fortran 90). But we use so MATLAB to test prototype algorithm before inserting in LMGC90. We simulate essentially the quasistatic and dynamical behaviour of granular materials by time integration scheme. The formalation is based on the duality velocity-impulsion.

- **TU/e (CR8)-NLR:**
  Matlab/Simulink/Stateflow. Modelica. MOSAIC (http://www.nlr.nl/public/facilities/f190-02/index.html).EuroSim (http://www.nlr.nl/public/facilities/eurosim/index.html). Both MOSAIC and EuroSim are capable of handling complex hybrid sytems and have been used in many projects. These tools can be made available for the duration of the project.

- **KTH (CR7):** Self-developed code. Small Fortran and Matlab codes.

- **ETH (CR10):** MATLAB/SIMULINK/STATEFLOW. MODELICA. SCILAB. AUTO97/CONTENT/DSTOOLS. Self-developed code (Implementations of LCP solvers, time integration routines).

- **UJM (AC2)- ENTPE, LGM:** Self-developed codes that can provide for particular systems or classes of systems:
  1. time integration (deterministic/stochastic)
  2. bifurcation analysis
  3. frequency or time/frequency analysis
  4. piecewise linear systems, systems with friction, Saint-Venant elements, Prandtl models, impacts

- **TUD (AC11):** Matlab + own c files (for solving complementairy problems) that are called from Matlab We are also using numerical optimization libraries (NAG in the past) and currently freeware libraries such as GSL and GLPK (linear programming).

- **UNIVBRIS (CR6):** Matalab/Simulink, Auto97/DSTool, self developed code for Lyapunov exponents computations, simulations, basins of attraction, brute force bifurcation diagrams.

- **UJM (AC3):** Scilab, self-developed codes based on a penalty approximations of the unilateral constraints or based on the time stepping scheme. Type of simulations: time-integration, Poincaré maps.

- **DIS-CRB (CR4-AC5):** We essentially use Matlab/Simulink for simulation, Maple for symbolic analysis and AUTO for bifurcation analysis.

- **INRIA (CR1):** self-developed code with SCILAB routines. This is an event-driven code.

S2: What type of agreement has been achieved sofar between experiments and simulations (if applicable) ?

- **UPC (CR9):** In general, a very good agreement has been obtained between experiments and simulation of DC-DC power electronic circuits. The main problems regard the identification of exact values of the parameters of the circuits, and some parasitic elements, which are not included in the mathematical model. Also thermal noise sometimes modify the dynamics in experimental set-ups.A high number of crossings in the ramp (for PWM DC-DC circuits) also pose serious difficulties when numerically simulating the corresponding mathematical systems.

- **TU/e (CR8):** Ongoing research in the field of system identification and model validation.

- **UM2 (AC2):** Comparative studies are made with experiments given in the litterature. The main difficulty is related to the definition of a representative sample for a granular medium; in others words how many particles are necessary to represent a sand pile for instance ?

- **ETH (CR10):** From my experiences in Munich I can say that in most cases a good agreement between simulations and experiments could be achieved, in particular for systems with sufficient dissipation. It depends, of course, on the particular problem whether or not non-smooth models should be used. This question cannot be answered in a general way, because modelling is always based on experience and intuition, and is strongly related to the particular engineering problem to be solved.

- **UJM (AC3) -ENTPE, LGM:** Experiments are only starting: results will be available in 2003.

- **UNIVBRIS (CR6):** Agreement on `rocking blocks' with tombstone data (Hogan) superb agreement between impact oscillator and impacting beam (Budd, with Popp Hannover).

- **UJM (AC3):** We have compared the numerical results with experimental results in two cases:
    1. a clamped free tube excited by a shker and guided
    2. a slender bar dropped on a rigid foundation.

- **DIS-CRB (CR4-AC5):** in general we got good agreement between simulation results and experiments for the DC-DC converters. The other experiments are still under construction.

S3: What type of mathematical formalism/framework do you typically use to describe the systems of interest (ODEs, complementarity systems, hybrid models, differential inclusions etc) ?

- **TUB (AC12)**: Complementarity systems.

- **UPC (CR9):** They usually use ODEs with discontinuous vector fields for describing the systems that correspond to DC-DC electronic circuits. Other frameworks have not been taken into account.

- **TU/e (CR8):** ODE's, differential inclusions, DAE's, complementarity systems, piecewise affine models, hybrid automata, Mixed logical dynamical systems (by Morari and Bemporad).

- **UT (AC13):** complementarity models and hybrid models

- **UM2 (AC2):** The mathematical formalism refers to complementary systems and differential inclusions.

- **KTH (CR7):** Complementarity systems

- **ETH (CR10):** Differential inclusions

- **UJM (AC3) - ENTPE, LGM:** Mainly:
  1. ODEs,
  2. Differential inclusions,
  3. Piecewise differential systems and analytical solutions,

  Sometimes:
  1. Complementarity systems,
  2. Percussion theory

- **TUD (AC11):** Complementarity systems and problems, PWA models.

- **UNIVBRIS (CR6):** ODEs.

- **DIS-CRB (CR4-AC5):** we use ODEs with discontinuous vector fields.

- **INRIA (CR1):** Complementarity Systems

5. Conclusions and Future Work

We have presented an overview of the experimental rigs currently available to the consortium which will be used to validate the numerical tools developed within the project, test the design of feedback control strategies and carry out a theoretical and experimental bifurcation analysis.

The results of a questionnaire sent to all teams in November 2002 have been discussed showing the wide range of experimental facilities available to participating teams. The problems presented, further detailed in Appendix B, are different in nature. They are characterised by different features and degrees of complexity.

The next step will be to further discuss the problems presented in this report and select a subset of the rigs described in the report as representative examples whose study will be carried out within the framework of Workpackage 6.

Appendix A

This appendix contains the original questionnaire sent to all participating teams in November 2002.

Appendix B

Following discussions held at the 1st SICONOS general meeting held in Grenoble in January 2003, contractors were invited to provide short documents detailing the main features of the problems they wished to propose as possible testbed problems to validate the numerical tools being developed during the project. It was also decided where possible to recast the problem under investigation as a complementarity problem and outline current open research problems. Preliminary results in this direction are contained in the ensemble of reports collected here. A brief description of each of the documents enclosed is given below.

- **D6.1_INRIA:** The paper provided by the team at INRIA contains a detailed description of the walking robot being studied at that institution.

- **D6.1_CRBa:** This first report by AC5, contains a description of sigma-delta converters as complementarity problems.

- **D6.1_CRBb:** This report which originated from discussions held at the General Meeting in Grenoble, contains the description of the DC-DC buck converter and its equations as a Complementarity problem (see also D6.1_UPC).

- **D6.1_UNIVBRIS:**

- **D6.1_TUE:** A description of four different experimental mechanical rigs is given in this document where open research problems are outlined. The document details the main characteristics of each rig and discusses the main problems concerning their analysis and control.

- **D6.1_UPC:** This document reports the derivation of the complementarity model of a DC/DC buck converter. Note that the model derived differs from that presented in D6.1_CRBb.

- **D6.1_ETH:** The aim of this document is to present an example of finite-dimensional dynamical system with planar unilateral Coulomb-contact constraints. An example that fitsw in with this class of problems is presented and proposed as a testbed problem for the numerical tools developed within the SICONOS project.