IMECE2003-43729

HARDWARE-IN-THE-LOOP SIMULATION FOR CONTROL DEVELOPMENT IN EHPV APPLICATIONS

Sooyong Jung[*], Young J. Lee[†] and Wayne J. Book[‡]
Geroge W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, GA 30332
{sooyong.jung[*],wayne.book[‡] }@me.gatech.edu, gt6982a@mail.gatech.edu[†]

ABSTRACT

The creation of a PC-based Hardware-In-the-Loop Simulation facility for testing hydraulic and other drive components and their controllers is described. High performance electric motors are used to produce both drive and load characteristics as commanded by the simulated environment. To enable rapid development of new application scenarios an integrated software environment has been incorporated to rapidly model, program and simulate the environment's behavior and the controlled response. In order to validate the HIL testbed developed, the experiment is performed on hydraulic component with wide range of applications. For the next stage, a novel Electro Hydraulic Poppet Valve (EHPV) is targeted to be studied.

INTRODUCTION

Increased computing power now enables the rapid simulation of very complex system models. Models can be created and simulated with high order to represent most predictable behaviors. Some behaviors are not predictable, however. Sliding or dry friction is a notorious example. Extreme sensitivities to initial or environmental conditions can produce different outcomes. Furthermore, the repeatability of a simulation is both its greatest strength and weakness. Simulations are doomed to succeed, and a false sense of security in a carefully tuned controller developed under simulation can be rapidly destroyed by a single experiment using real hardware. For this reason, confidence in simulation results alone is justifiably low.

The modelling of complex systems is made ever easier by the introduction of object oriented modelling packages. These have become very popular and useful. Conversion from a graphical depiction of the system components and their connection can be directly converted to simulation code and even to real time code to run on a variety of real-time platforms of a dedicated or general nature. When running in real-time, certain modifications are needed in the simulation differential equation solvers to insure the completion of necessary calculations by the time their results are needed.

Another way to use Information Technology (IT) to enhance our ability to design and control fluid power and other drive systems is to combine simulation in the same loop with that part of the hardware that we find either difficult to model or so central to the questions to be answered that we want the perfect model, that is the hardware itself. This is referred to as Hardware-In-the-Loop (HIL) simulation.

HIL simulation requires the modelling and real time simulation software mentioned above and interface(s) to the hardware. That interface must convert from the digital signal domain to the analog power domain in a form that the hardware will experience in the application. Control signals might be input into the real hardware from the simulation as well. In the case of drive systems, two or more energy ports will exist: drive port(s) and load port(s). The drive port is usually supplying energy to the hardware and the load port is usually removing it. The power flow can be reversed temporarily and commonly is. Lowering a load in a gravitational field or decelerating an inertia are obvious examples.

To create a HIL simulation facility in a cost effective manner, it may be necessary to use components that are targeted for a wider market. Personal computers have a tremendous amount of

computational power, for example, and because they are mass-produced for office and home applications, provide excellent computational power for the dollar. They are not optimized for the tasks of real-time processing. Never the less, software to adapt them for that purpose is available as is interfacing hardware and software and modelling tools. Interfacing to the energy ports of a drive component means that power variables of angular velocity and torque or velocity and force or flow and pressure must be provided in a carefully controlled fashion. High performance servomotors can do this effectively and can be directly interfaced to digital electronics and can themselves be powered by electronic drives with regenerative rectifiers. Since these components are produced for industrial purposes in quantity, their cost will be less than special purpose components produced for HIL and like purposes alone.

It is the intent of this paper to describe a HIL simulation facility assembled for the purpose of testing hydraulic and other drive components. We are targeting a particular component, an Electro Hydraulic Poppet Valve (EHPV) with unique and promising characteristics as our first experimental case. We are treating the creation of the facility as an experiment itself and believe that this technology can enable research institutions, particularly academic institutions, to expand their horizons, testing components in realistic simulated environments that would never be available to them in complete hardware form. Excavators, presses, extrusion machines, machine tools, power steering, active ride control environments might all be imitated in software with only critical components present in hardware form. In addition to the EHPV a fork-lift truck imitation available in the laboratory is treated to enable comparisons to the alternative of complete hardware implementation.

While preliminary experiments are available at this time to indicate the feasibility of the project, much remains to be done to improve the performance of the system. Consequently, only fragments of the results are included at this time.

HIL Simulation System

A full software simulation is quite flexible, relatively economical and usually repeatable. Its validity, however, mostly depends on the accuracy of the modelling which may be hard to achieve in many cases. As an alternative, a full hardware test can be used to get the direct results with validity and accuracy. But it is very expensive, timing-consuming in setting-up and reconfiguration, and sometimes invokes safety problem in testings. Therefore, HIL simulation is proposed to provide the flexibility of software simulation with the accuracy of hardware test which is applied into a variety of field like Aerospace, Automotive [1] [2], Minimally Invasive Surgical (MIS) system with Haptic operation [3], Hard Disk Drive (HDD) Control system [4], Electro-Hydraulic Powertrain System [5] etc.

The rapid advances in personal computer(PC) technologies

such as faster CPU with low cost, standardizations and the advent of reliable real-time(RT) operating systems(OS) including embedded code generation techniques enlarge the applicability and reliability of HIL simulation with the accuracy and low cost. In HIL simulation, physical hardware can be tested while it is connected to RT target PCs simulating the complete environments and computing the control inputs to the hardware. The figure 1 shows the basic configuration of the HIL simulator for fluid power system. The RT models of virtual environment beyond the physical components are built by the host PC (i.e., commanding PC) and downloaded to the target PC where RTOS is being run and the RT model is executed. Furthermore, data-tracing/logging and parameter-tuning can be done between the host and target PC via an ethernet connection. The virtual components may be either drive ports or load ports interfaced with RT simulation programs (i.e., RT models). This interface converts the digital domain of RT simulations into the analog power domain (e.g. electric servomotors). The test hardware and RT models are connected by I/O boards and control-algorithms.
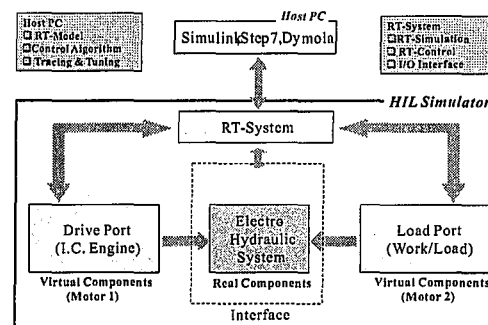

Figure 1. PC-Based HIL Simulation System

HIL Simulator for a Fluid Power System

HIL simulator for a fluid power system has been built to evaluate the performance of hydraulic components (e.g., EHPV) and corresponding control algorithms within the virtual hydraulic vehicle subsystem or complete vehicle and drivetrains. The major feature in this HIL set-up is the use of Siemens PLC & Motor drive system [6] as a RT platform which directly interfaces to the test hardware through the two servomotors (i.e., drive port and load port). The PLC system has a variety of industrial applications with a great reliability and its motor drive system also provides plenty of functionality. To enhance the capability of programming for complex model and control rules of RT models, a PC-based RT system is complemented in the target

2

PC. In this set-up, the PLC & Motor drive system is connected by a field bus system (i.e., Profibus) while PC-based RT system has ethernet connection between host PC and target PC. For the distributed control scheme, PC-based RT systems support RT bus system such as UDP/IP, CANbus, FireWire, etc. Figure 2 shows
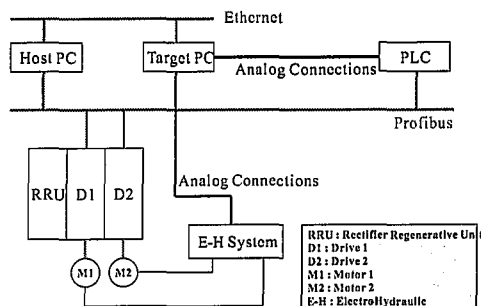

Figure 2. Configurations of the HIL Simulator for Fluid Power System

hardware configurations of the HIL simulator for fluid power system developed in Intelligent Machine Dynamics Lab (IMDL) of Georgia Institute of Technology. Detailed descriptions of components are described in the following subsections.

Hardware

The hardware of the HIL simulator developed consists of three main group which are specified by Electric Power-Generating System (Siemens PLC & Motor Drive System), Electro-Hydraulic System (Interface and Test-hardware), and Target & Host-PC System with Ethernet Connection (PC based RT System). Figure 3 shows the PLC station and drive units (left picture), and motors and hydraulic components (right picture), respectively.

A Siemens PLC & Motor Drive System comprises a PLC station (Simatic 300 S7), rectifier/regenerative unit (RRU), and two motor drives (inverter) and two 8 horse-power AC servomotors.

RT target PC interfaces directly to test-hardware by using the National Instrument I/O boards (PCI6052E) while its interface to PLC & Motor Drive System is done through the analog I/O of the PLC station and the Profibus. Therefore, in controlling the motors, the target PC computes the desired motor speeds based on the drive/load models and control algorithms, converts them into analog signals and sends them to analog ports of PLC station through the same I/O board. The PLC puts these signals on the Profibus for the motor drivers, and drivers control the corresponding motor according to the desired speeds, respectively.
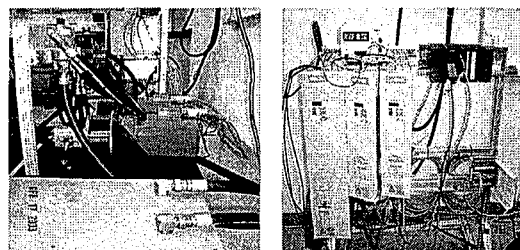

Figure 3. HIL Simulator of Fluid Power System

The E-H system provides not only the interface to the electric power system (servomotor) but also the test-hardware in the HIL simulator. The hydraulic circuit of the E-H system in the HIL set-up is shown in Figure 4. This system mainly comprises one hydraulic pump, one hydraulic motor, three relief valves, one directional control valve (DCV) and three pressure transducers. The pump driven by the electric servomotor provides the interface to drive the energy port converting the power variables of angular velocity and torque into flow and pressure variables. It is a gear-pump with 19 cc/rev. The hydraulic motor is also attached to another electric servo motor acting as the interface to the load port with regenerative mode. The DCV affects the direction of flow by turning solenoid on each end of port on/off. The on/off signal on each solenoid is provided by the target PC through digital I/Os.

RT-Platform

In this HIL set-up, two possible PC-based RTOS platforms, that is, xPC target [7] and RT-LAB real time target [8] are considered. xPC target is the PC based RT kernel by Mathworks, Inc. which is compatible to any PC with Intel 386/486 Pentium, or AMD K5/K6/Athlon processors and supports an extensive I/O device driver library. RT-LAB RT target of Opal-RT can run on any Intel x86 compatible PC running on the QNX RTOS. To evaluate the computational speed of those RT targets, two Simulink models are used to measure the execution time of the RT task in every sampling interval. The target PC is the Pentium4 with 2.0GHz of CPU speed. The first test-model is the F14 demo-version of Simulink which consists of only Simulink built-in blocks. The second test model has S-function block wrapped by the hand-written C-codes of Nonlinear Model Predictive Control algorithm with high computational loads. Whereas execution time of different RT target (xPC target:20μsec., RT-LAB target: 21 μsec) resulted from the first model shows little difference, in the second case the execution time of xPC target (4.2msec.) is faster than that of RT-LAB target (6.8msec.).
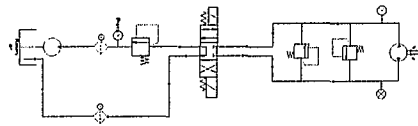
3

Figure 4. Hydraulic Circuit Diagram of E-H System

RT-Simulation Software

In the HIL simulator, the basic RT modelling tools are Simulink and Real-Time Workshop (RTW) where drive/load models are built and RT source codes are generated and complied to execute in the specified PC-based RTOS targets (i.e., xPC target and QNX). Drive/load models which are the virtual environments surrounding the test-hardware usually contain multi-domain systems with high complexity such as mechanical, electrical and hydraulic systems.

An object oriented modelling language, that is, Modelica [9] allowing in acausal and multi-domain modelling is helpful for RT modelling. Dymola by Dynasim, Inc provides graphical depiction of the system components and their connection which can be directly converted to Modelica codes. The Modelica model is converted to a S-function block of Simulink and integrated into one Simulink block format model. Also, hand-written C-code of models can be executed in real-time on the RTOS targets by using the S-function Wrapper technique of Simulink.

As for the PLC & Motor drive system, PLC programs to configure I/Os and Profibus is written by using Step7 of Siemens, and the functionality of motor drives is implemented by the parameterizations of the corresponding Siemens Function Diagrams (FD).

RT-Models

The drive port of the given HIL system represents a internal combustion engine which is represented by a hypothetical 3-D surface giving the speed-torque curve as a fuctionof the throttle opening. It has max. torque of 19.5Nm and max. speed of 3000rpm shown in figure 5 and a rotating inertia. Operating ranges of torque and speed are compatible with those of electric servomotor [6]. Figure 6 shows the drive model of Simulink blocks. When the throttle opening profile is input in this model, model-commanded speed of drive motor is calculated and output to the I/O driver block.

The load model represents the joint motion of a simple excavator rotating up from downward position about the joint. This model can be formulated as a 2nd-order system, essentially a rotating bar under gravity. The torque is computed by the measured pressure difference on the physical hydraulic motor. The joint is also affected by friction models i.e., coulomb and vis-
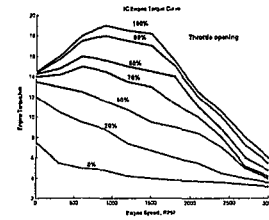

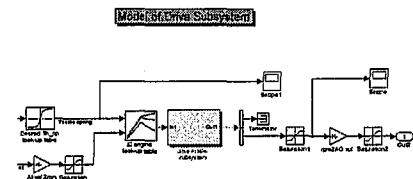Figure 5. Torque Curve of IC Engine Designed)

Figure 6. Model of Drive Port (IC Engine)

cous friction). The DCV control module is built in C-code and converted into a S-function block controlling the on/off status of each solenoid according to the experimental scenario. Figure 7 & 8 show the load model and DCV control model, respectively.
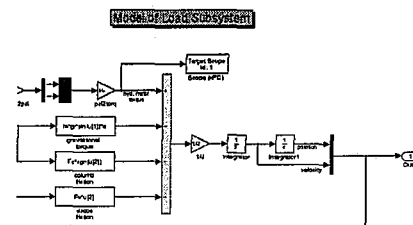

Figure 7. Model of Load Port (Excavator)

Experiment Results

The objectives of experiment using the HIL simulation is to validate the major components of the HIL setup, that is, RTOS, RT Simulation, electric power generating system (i.e., Siemens PLC & Motor drive system), test-hardware (i.e., E-H system,) and control & network system. In this experiment, xPC target is selected as the RT platform satisfying the requirements of the
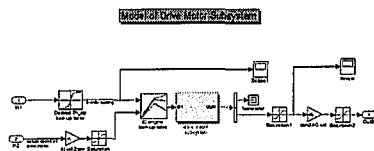
4

Figure 8. DCV-Control Module

research purpose, and all of RT models are built and compiled by Simulink and RTW and, then downloaded to the target PC which has a Pentium 4 CPU of 2.4GHz speed and 512 Mbyte RAM. In case RT-models need multiple processors, QNX RTOS can be considered. The sampling time is set to 0.001 sec., which means all real-time tasks such as RT simulations and input/output signal-interfacing, etc. have to be done in less than the given sampling time. Total run-time is 15 sec, and the complete real-time system for this experiment is shown in figure 9.

The experiment is performed in the following procedures: Given throttle_opening profile shown in figure 10, the drive model computes the model-commanded speed of the drive servomotor. This speed input is sent to the motor-drive through analog ports between target PC to PLC, and via profibus from PLC to motor-drive. Then, the motor starts running in idle mode. The actual speed signals of motors measured by the built-in encoders of motors are fedback to the RT-models of target PC in the reverse order of sending desired speed signal to motor-drive. When 2 seconds lapse, the DCV control logic changes the on/off status of solenoids so that the fluid power generated by hydraulic pump drives the hydraulic motor which is governed by the RT-load model representing the simple excavator. During the run-time (i.e., 15 seconds), the virtual excavator is lifted up from downward position to upright one with respect to the joint.

Figure 11 shows measured speed and model-commanded speed of the drive model, respectively while figure 12 does those of load model. For first 4 seconds, the speed of drive motor keeps tracing the model-commanded one, and then it tries to keep constant one with occasional drop to zero, which comes from the interaction with the behavior of the load motor. In figure 13, measured speed of drive & load model with angular displacement of load model are presented. The model-commanded speed of load model is very close to zero over whole operating time due to the load model given (i.e., gravitational term, friction terms). The load motor keeps tracing the model-commanded speed so that the virtual excavator is lifted up to upright position at the end of operating time. The pressure signals measured by transducers

are shown in figure 14. And figure 15, all measured signals are presented for the comparisons.
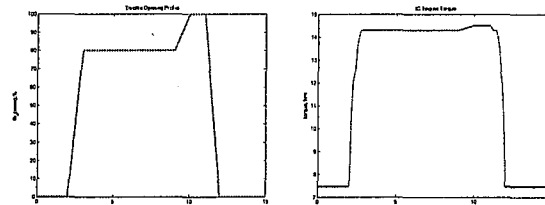

Figure 10. Input throttle-opening profile (left side) and the generated torque curve of IC Engine model (right side)
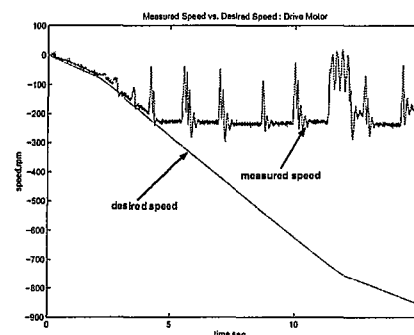

Figure 11. Measured speed vs. model-commanded speed (desired speed) of drive model

Future Works and Conclusions

This paper describes a HIL simulation facility developed in order to test hydraulic and other drive components under a virtual RT environment. Due to the PC-based HIL simulator, this facility provides more computational power and more flexibility in RT-modelling and programming. Furthermore, in case new test-hardware is targeted in the HIL simulator, whole hardware set-ups can be easily reconfigured to meet the new experimental objective.

In this paper, the experiment has been performed on the E-H system of figure 4 to validate the HIL testbed. It is noted that the behavior of test-hardware is completely affected and controlled by the virtual environments of given RT-models. The experiment results also show that this HIL technology can enable research institutions, particularly academic institutions, to
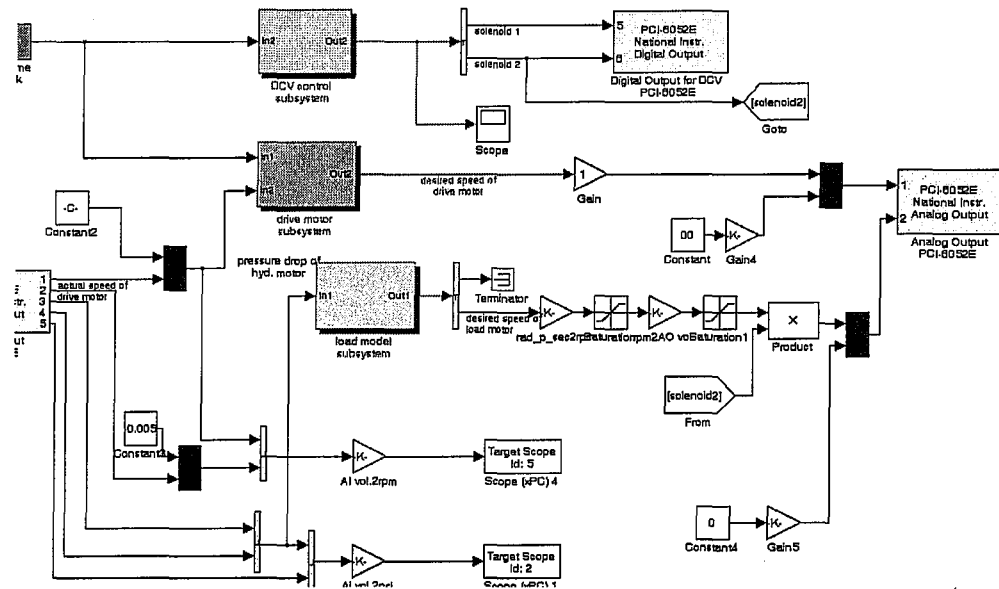
5

Figure 9.   Real-Time Model for HIL Simulator
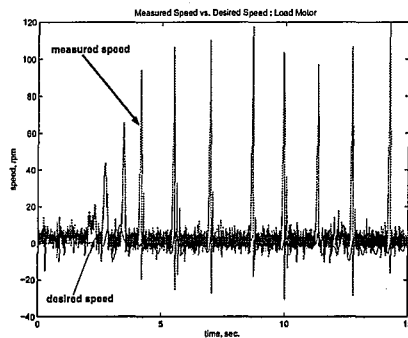

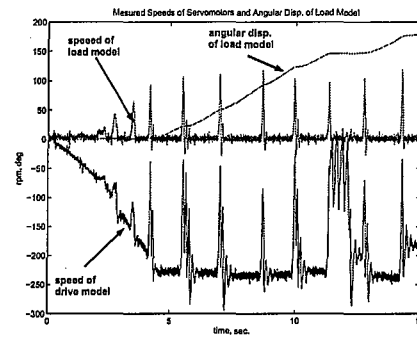Figure 12.   Measured speed vs. model-commanded speed (desired speed) of load model

Figure 13.   Measured speed of drive & load motor and angular displacement of load model

expand their horizons, testing components in realistic simulated environments that would never be available to them in complete hardware form. Prior to experiment, different PC-based RTOS platforms have been verified.

For the next stage, we are targeting a particular hydraulic component, an Electro Hydraulic Poppet Valve (EHPV) with unique and promising characteristics as the research work by this HIL simulator. Also, the novel control algorithms will be developed and verified to control the EHPV. Furthermore, as for the next task of hardware improvements, not only a local bus system like CANBus or Profibus will replace the present analog connections, but also the distributive control system will be appended.
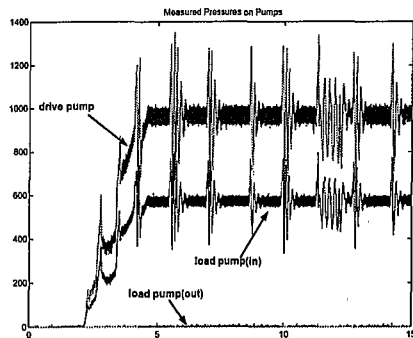
6

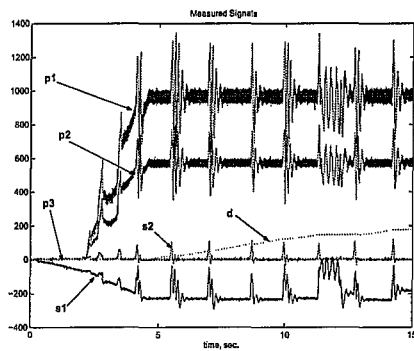Figure 14. Measured pressures

Figure 15. Measured signals in the HIL simulation: s1(measured speed of drive motor), s2(measured speed of load model), d(angular displacement of load model), p1(pressure of drive pump), p2(inlet pressure of load pump), p3(outlet pressure of load pump)

ACKNOWLEDGMENT

REFERENCES

[1] Yamazaki, M., and Brackx, M., 2002. "Analysis of automatically generated vehicle system control software in a HIL environment". In Proc. of the American Control Conference, pp. 3135–3140.

[2] Schaffnit, J., 2000. "Hardware-in-the-loop simulation and rapid prototyping for the development of control functions for diesel engines". In Proc. 1st IFAC Conf. Mechatronic Systems.

[3] Kim, J., and Srinivasan, M. A., 2002. "Computationally efficient technique for real time surgical simulation with force feedback". In Proc. 10th Sym. On Haptic Interfaces For Virtual Envir. & Teleoperator Systs.

[4] Senta, Y., and Okamura, E., 2002. "HIL simulation system for hdd servo firmware". IEEE Transaction on Magnetics, **38** (5) [], pp. 2204–2207.

[5] Zhang, R., 2002. *Multivariable Robust Control of Nonlinear Systems with Application to an Electro-Hydraulic Powertrain.* PhD Thesis, University of Illinois, Urbana, IL, May.

[6] SIEMENS AG, 2003. *Simatic300 Step 7 and General Motion Control Manual,* latest ed. Germany.

[7] MATHWORKS, INC., 2002. *xPC Target For Use with Real Time Workshop,* latest ed. Natick, MA.

[8] OPAL-RT TECHNOLOGIES, 2003. *RT-LAB Real Time Laboratory Users Manual,* latest ed. Montreal, Canada.

[9] MODELICA ASOCIATION, 2002. *Modelica Language Documents, ver. 2.0,* latest ed.