HARDWARE-IN-THE-LOOP SIMULATION RIG FOR INVESTIGATION OF FRICTION COMPENSATION AND CONTROL SYSTEMS

Teodor DUMITRIU, Nicolaos Antonio CUTULULIS, Emil CEANGA

"Dunarea de Jos" University of Galati, Faculty of Electrical Engineering
111 Domneasca str, 800201 Galati, ROMANIA
Phone/Fax: (+40)236 46 01 82; E-mail: teodor.dumitriu@ugal.ro

Abstract: Friction is to be considered an essential process for micrometer scale tracking servo systems. Therefore, a high performing and robust control of friction becomes an important issue in mecatronics and robotics field of research. This paper is a contribution to the development of a real time friction simulator (RTFS) using Matlab/SIMULINK® and DS1103 PPC Controlled Board. The simulator is designed to generate friction torque on its mechanical shaft and to provide the static and/or dynamic characteristics of a given friction model for further friction behavior test and simulation in order to implement different friction compensation strategies.

Keywords: hardware in the loop, model-based compensation, limit cycles, real time system, friction simulator , digital signal processor, electromechanical tracking system.

1. INTRODUCTION

Friction is responsible for several servomechanism problems and their removal is always a challenge for control engineers. Tracking errors, limit cycles and undesired stick-slip motion are the most known phenomena that friction can lead to. Control strategies that attempt to compensate for the effects of friction inherently require a suitable friction model to predict and to compensate for the friction. An approach for studying friction behavior, in order to validate a model or a model based scheme of compensation as part of high precision servo system control is a real time friction simulator (RTFS) built around the Hardware-In-the-Loop (HIL) structure presented hereafter.

The modern controlled systems' development is based on the use of HIL simulation techniques, for physical emulation of the systems, with which the investigated equipment interacts (Hanselman, 1993). HIL systems contain a physical sub-system, which is controlled in closed loop by a real time software simulator, built on the basis of the emulated system's mathematical model. This physical sub-system, connected to the investigated equipment, offers static and dynamic characteristics, practically identical with the ones of the emulated system.

An example of a HIL system is the friction torque simulator, connected to an AC servo-motor. The simulator "offers" a mechanical shaft, where the static and dynamic behavior of the friction is obtained, according to the conditions yielded by the model took into account. In this case, the investigated equipment is the following assembly: electrical actuator (AC servo-drive) + power electronic circuit + electrical network + associated control systems. However, HIL systems allow experimental investigation of high precision control algorithms required in positioning servo systems such those used in robotics and emulate friction behavior for different kind of applications.

This paper aims to present the HIL technique (conceiving a methodology for HIL configuration) in connection with the performance evaluation of a positioning tracking servo-system with friction implemented by using an experimental setup based on dSPACE 1103 board. Moreover, a library of friction models and observers is presented herein. All included models provide a way to structure a new Matlab/SIMULINK® toolbox for control design of systems with friction.

2. THE PRINCIPLE OF THE HIL SYSTEM

In the following, these definitions are used:
- the equipment whose static and dynamic characteristics are emulated throughout HIL is called Simulated Physical System (SPS);
- the equipment that simulates SPS is called Real Time Physical Simulator (RTPS):
- the equipment connected to RTPS is called Investigated Physical System (IPS);
- the assembly SPS + IPS is called Basic Physical System (BPS);
- the assembly RTPS + IPS forms the HIL system, which allows the experimental studies of IPS in the emulated environment, created by RTPS.

SPS and IPS are interacting. This implicates the existence of at least two common physical variables, called inter-connection variables. The steady state dependency between these variables defines the external characteristics of SPS and IPS. Evidently BPS's steady state regime is being at the intersection of these external characteristics.

Let us consider a tracking servo-system with friction, in which the AC servo-motor, the power electronic circuit, the electrical network and the control system form an IPS. In this case, the HIL system contains RTPS as a friction torque simulator, which emulates the real friction, offering a mechanical shaft, to which IPS is coupled. The interaction variables are the shaft speed Ω and the shaft torque, $T_{friction}$.

Let us consider a BPS with the state model:

$$\begin{cases} \dot{x} = F(x,u) \\ y = G(x,u) \end{cases} \qquad (1)$$

The dynamic system (1), marked with S in Figure l.a, can be simulated throughout usual off-line numerical procedures. The system S is structured in two interactive sub-systems, S1 and S2 (Figure l.b), so that its interaction variables, z_1 and z_2, correspond with the interaction variables between SPS and IPS. Normally, S1 includes the model of SPS and S2 includes the model of IPS and $\dim z_1 = \dim z_2$.

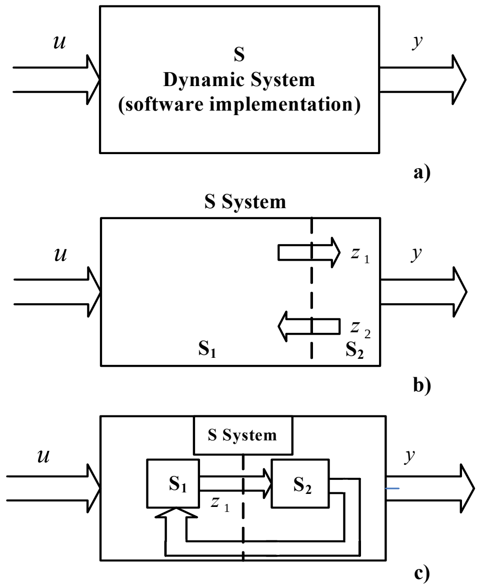

Fig. 1. BPS as a dynamic system: a) basic scheme: b) structure of system; c) SIL.

The scheme of Figure l.b can be drawn in Figure l.c where S1 and S2 are connected in closed loop. In this loop, IPS and SPS are simulated by software. This is why the structure in Figure l.c is called Software-In-the-Loop simulation (SIL). Of course, it can not achieve the experimental studying of IPS. In the HIL structure, the sub-system S2 has physical implementation, according to the principle scheme shown in Figure 2.

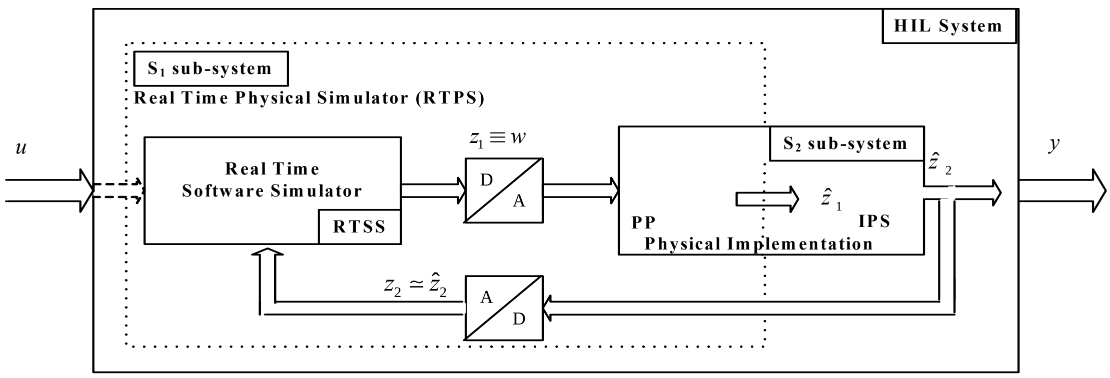

Fig. 2. The HIL system structure

The HIL system contains IPS (S2 sub-system) and S1, implemented as RTPS, which emulates the physical environment of IPS. The RTPS has two main components: RTSS (Real Time Software Simulator) and the physical part (PP) of the RTPS, which offers the "natural" environment for IPS. The inter-action variables, z_1 and z_2, have special signification. The variable z_1 is called Piloting

Variable (PV) and represents the set points for the physical variables of PS, which form the $\hat{z}_1$ vector.

So, the $\hat{z}_1$ vector's components are brought to the desired values, imposed by RTSS throughout the piloting variable z_1. The variable $\hat{z}_2 \simeq z_2$, transferred from the sub-system S2 towards RTSS will be called Response Variable (RV). The simulation structure represented in Figure 2, in which sub-system S2 is in physical implementation, containing the physical part of RTSS and IPS, is named HIL system.

3. HIL STRUCTURE FOR RTFS

The conditions for HIL systems achievement are illustrated in case when SPS is a friction torque simulator. A real time friction simulator (RTFS) is conceived to generate the friction torque on its shaft, providing the static and dynamic characteristics for a given friction model selected from Simulink® library developed by authors. It enables the modifying of parameters which alter the friction process.

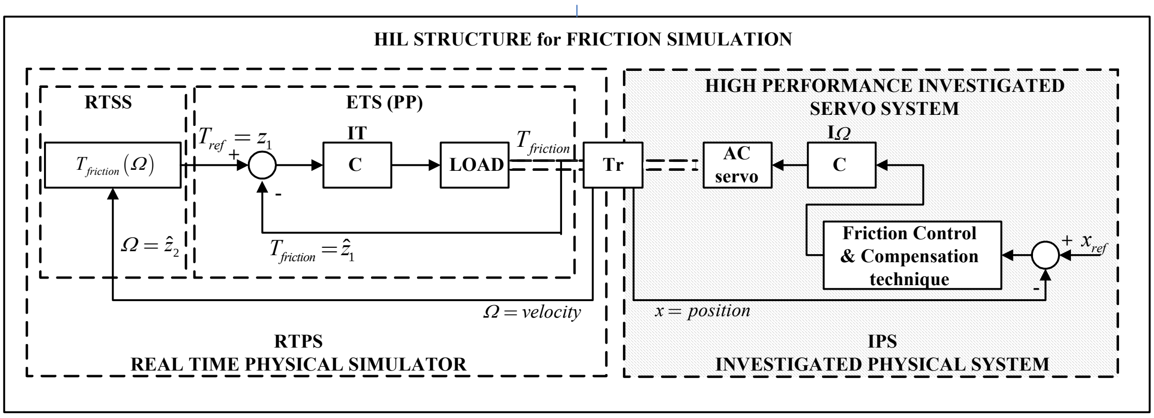

Figure 3. HIL system architecture for friction simulator

The structure proposed for friction simulator (figure 3 the clear part) consist in two sub-systems:

- a real time software simulator (RTSS), that implements the static and/or dynamic model of the friction torque - z_1 becomes T_{ref};
- an electromechanical tracking system (ETS), which receives the reference signal (set point - $z_1 = T_{ref}$) from the RTSS and provides a shaft which has the static and dynamic characteristics of the typical friction torque load ($\Omega(T)$ - where $\Omega = \hat{z}_2 \simeq z_2$); the ETS controller imposes that the feedback $T_{friction} = \hat{z}_1$ to be equal with T_{ref}.

The IPS part of the HIL structure (shading filled part in figure 3) includes beside the speed strategy inverter controller, a block featuring a soft implemented strategy for friction control later presented in this paper.

In the simplified block diagram, illustrating the HIL's architecture for friction simulator (Figure 3), the symbols are: Ω, x - measured angular velocity and position, T_{ref} - reference variable as numerical imposed torque via friction model, $LOAD$ - torque controlled AC machine simulating the friction torque ($T_{friction}$), $AC\,servo$ - servo-tracking electric drive tested with the simulator (the mechanical actuator coupled with induction machine $LOAD$ emulating the friction torque), T_r - transducer for mechanical variables measured on the shaft (position, angular velocity), **CIT** – torque strategy inverter controller, **CI** Ω **-** speed strategy inverter controller.

3.1. RTSS configuration

The RTSS is based on mathematical models of the friction. The main models used on RTSS configuration and included in friction models library developed by authors are: classical static models or KFM (Kinetic Friction Model) and 2 dynamic models (Bliman-Sorine and LuGre) most used recently in literature (Armstrong-Helouvry, B. *et al.*, 1994).

Static models. Friction static models have evolved from the simplest relay approach of Coulomb friction, F_C, to a generalized mathematical description which includes viscous term, F_v, stiction, F_S (short for static friction – friction at rest) and Stribeck friction. These classical friction components can be combined in different ways and any such combination is referred to as a classical KFM i.e.:

$$F = \begin{cases} F(v) & if\ v \neq 0 \\ F_e & if\ v = 0\ and\ |F_e| < F_S \\ F_S\,\mathrm{sgn}(F_e) & otherwise(v = 0\ \ and\ |F_e| > F_S) \end{cases} \qquad (2)$$

F_e is the external force and $F(v)$ is an arbitrary function. A number of parameterization of $F(v)$ have been proposed. For example, the Tustin's model of friction depict this term as:

$$F(v) = F_C + (F_S - F_C)e^{-|v|/v_s} + F_v v \qquad (3)$$

where v_s is called the Stribeck velocity. The Simulink® Tustin friction model is presented in figure 4.

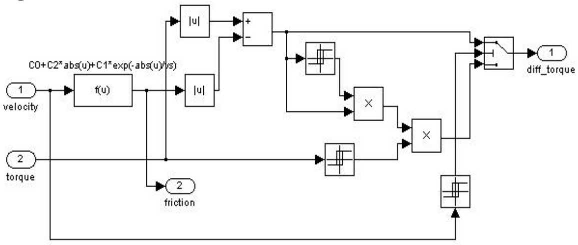

Figure 4. The Simulink Tustin friction model

4 others different static models are included in friction library (see paragraph 4).

Dynamic models. The static friction models briefly described before have considered friction only for steady velocities. No attention is paid to the behavior of friction as the velocity varied. Therefore, an significant interest must be focused on dynamic friction modeling required for precision servos and advanced hardware implementation of friction compensators. There are 2 dynamic models to be taken into account: Bliman-Sorine and LuGre models.

Bliman-Sorine friction model. The model can be viewed as a parallel connection of a fast and a slow Dahl model (figure 5). Bliman and Sorine stress rate independence. The magnitude of the friction depends only on $\operatorname{sgn} v$ and the space variable s is defined as:

$$s = \int_0^t |v(\tau)| d\tau \qquad (4)$$

Thus, in the Bliman-Sorine model, friction is then a function of the path only (velocity independent). The 2 Dahl models mentioned above are expressed as linear system in the space variable s.

$$\frac{dx_S}{ds} = Ax_S + Bv_S \qquad (5)$$
$$F = Cx_S$$

where x_s is the displacement and $A = \begin{pmatrix} -1/(\eta\varepsilon_f) & 0 \\ 0 & -1/\varepsilon_f \end{pmatrix}, B = \begin{pmatrix} f_1/(\eta\varepsilon_f) \\ -f_2/\varepsilon_f \end{pmatrix}, C = \begin{pmatrix} 1 & 1 \end{pmatrix}$ are the second order model matrix with $f_1 - f_2$ corresponding to kinetic friction reached exponentially as $s \to \infty$ and $f_1 = F_C$, and stiffness $\sigma = f_1/\varepsilon_f$.

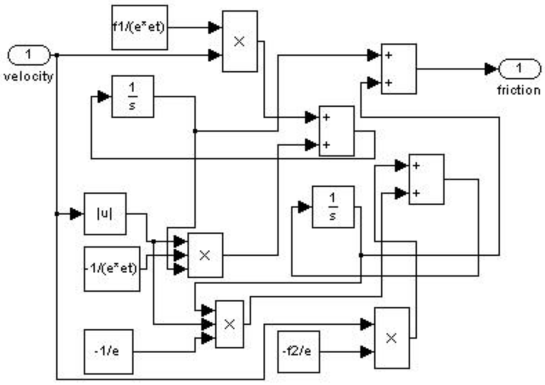

Figure 5. The Simulink Bliman-Sorine friction model

LuGre friction model. The model is related to the bristle interpretation of friction. It includes Stribeck effect, rate dependent friction phenomena such as varying break-away force and frictional lag.

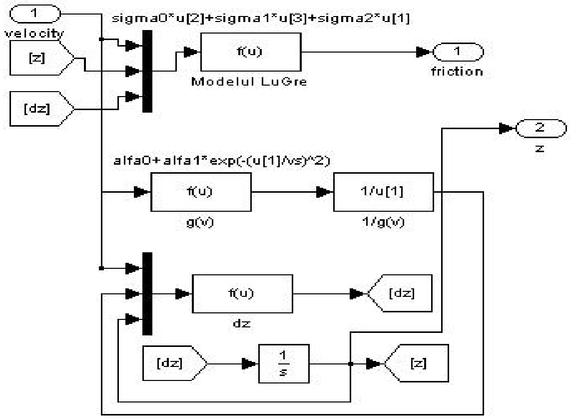

Figure 6. The Simulink LuGre friction model

The model (illustrated in figure 6) has the form:

$$\frac{dz}{dt} = v - \frac{\sigma_0 |v|}{g(v)} z \qquad (6)$$

$$F = \sigma_0 z + \sigma_1 \dot{z} + \alpha_2 v \qquad (7)$$

where z is the pre-sliding displacement or, more accurate, the average deflection of the bristles, σ_0 and σ_1, are the stiffness of bristle and, respectively, the damping, α_2 is viscous friction. The function $g(v)$ is the function describing Stribeck's effect. A parameterization proposed for $g(v)$ is given hereafter:

$$g(v) = F_C + (F_S - F_C)e^{-(v/v_S)^2} \qquad (8)$$

3.2. ETS (PP) configuration and control

The Physical Part (ETS in HIL architecture) of friction simulator is based on the current control of an AC motor (*LOAD* in figure 3). This current is considered as the electrical image of the torque developed on the shaft. The set point of the loop is obtained according to a mathematical model that includes different friction characteristics (depending on which model has been chosen from friction library). The state description of the friction model is

$$T_{ref} \simeq T_{friction} = F(\Omega) \qquad (9)$$

The output variable T_{ref} is a mechanical variable, which characterizes the friction modeled behavior on its shaft. Depending on this reference variable, the simulator has been be used with a torque control strategy, when T_{ref} is the shaft torque reference and *Tr* is a speed transducer (or a speed estimator).

The typical electric drive dynamic model that governs the HIL investigated physical system is given by its motion equation:

$$J\frac{d\Omega}{dt} = T(\Omega) - T_{load}(\Omega) \qquad (10)$$

where: Ω - the shaft rotation speed, J - the total moment inertia, $T(\Omega)$ - the active torque characteristic, $T_{LOAD}(\Omega)$ - the static characteristic of the load. Considering an electromechanical high performance servo tracking system (IPS in figure 3) working at low velocity and demanding an accurate positioning, the major influence among all components of load torque belongs to friction torque. The quantitative substitute in (10), $T_{LOAD}(\Omega) = T_{FRICTION}$ is fairly well understood. In our experimental studies, the torque control strategy for the *LOAD* AC machine has been adapted by imposing T_{ref} in terms of a friction model. The simplified block diagram of the implemented RTFS is given in figure 7.

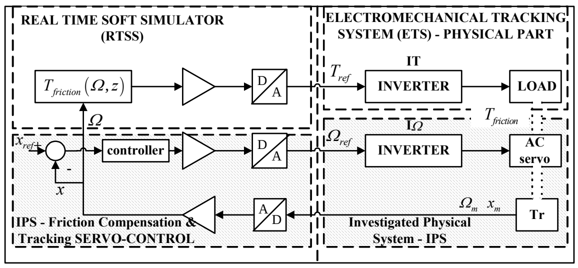

Figure 7. Simplified block diagram of the implemented RTFS

The used symbols are mostly already depicted or well known. The *LOAD* AC machine control is made in closed loop structure, according to the torque imposed to the VLT 5005 FLUX inverter (**IT**). A second VLT 5005 FLUX inverter (**I**Ω) is used to regulate the position of the mechanical shaft by supplying power to AC servo machine controlled also in closed loop structure via a control law imposed by a friction regulation or a model based scheme of compensation.

3.3. RTFS development

The hardware block diagram of the RTFS is presented in Figure 8.

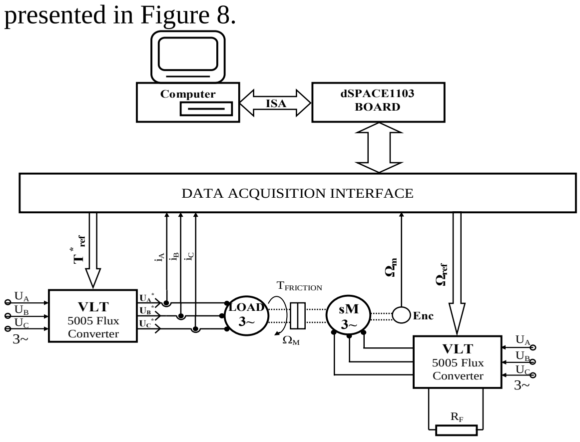

Figure 8. Hardware structure of implemented RTFS

The DS1103 PPC controlled board (dSPACE) is equipped with a Power PC processor for fast floating-point calculation at 400 MHz.

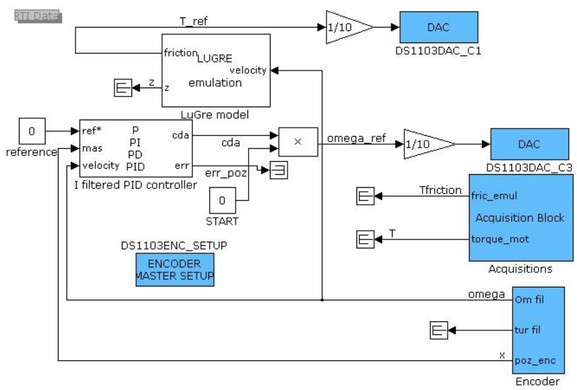

Figure 9. Main Simulink® model for friction RTSS

Programming has been done via Matlab/SIMULINK® in Real-Time Interface (RTI). The control has been entirely developed in SIMULINK® which is a user friendly, block-oriented, dynamic simulation environment. At first, an off – line model was developed, implemented and tested and then with only a few changes the model has been implemented into the dSPACE controller. The ControlDesk panel was used to test the model. In Figure 9 is shown the main SIMULINK® model for an experimental PID positioning system emulating limit cycles (Canudas de Wit, 1995).

4. FRICTION MODELS LIBRARY

In this paragraph the structure of a MATLAB/Simulink® library for servo-systems with friction as a part of a new simulation platform dedicated to model, analysis and control design of friction is presented. A good and readily available friction model allows to perform different analysis, simulation in order to test its influence on system response, as well as to compare various control laws using friction compensation. Subsequently, the development of a library containing the main friction models justifies the idea to extend the ability to simulate the dynamic behavior of friction and to test and compare different models proprieties that are relevant to control design. The conception of the library must take into account the overall model requirements:

- openess;
- ease of parameters determination;
- emphasis on simulation speed;
- literature model coverage (further improvement may be added);
- user friendly: documented, reliable;
- easy to extend.

Moreover, the purpose of friction model database is to offer an educational and research tool able to support a wide range of tasks: lectures concerning the friction phenomena, HIL implementation presented in this paper etc.

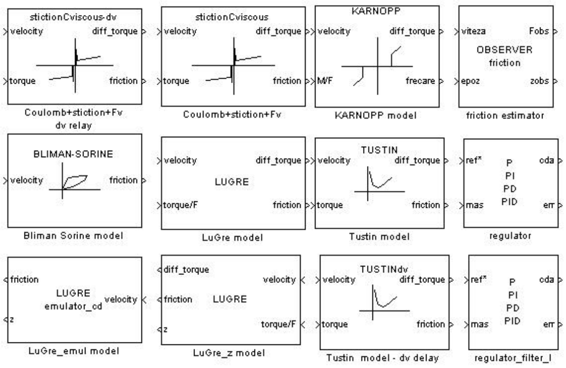

Figure 10. The Simulink® library of friction models

The library contains the following friction models: 2 way approach of a generalized KFM (Coulomb+stiction+viscous), Tustin model, Karnopp model, Bliman-Sorine model and LuGre model. Beside the friction models mentioned above, other control design components are included: a friction observer and 2 PID controllers. The figure 10 illustrate the library content.

5. EXPERIMENTAL RESULTS

As mentioned above, in section 3.3., the whole friction strategy is implemented using a DS1103 dSPACEprototyper. The graphic interface – ControlDesk, offered by DS1103 PPC Controller Board, is an integrated tool to control, monitor and automate SIMULINK® and real time experiments and has permitted the use of virtual instruments and improved control management software. For testing the whole system a virtual control panel was developed in ControlDesk, as shown in figure 11 (captured windows shows some friction characteristics detailed in figure 12).

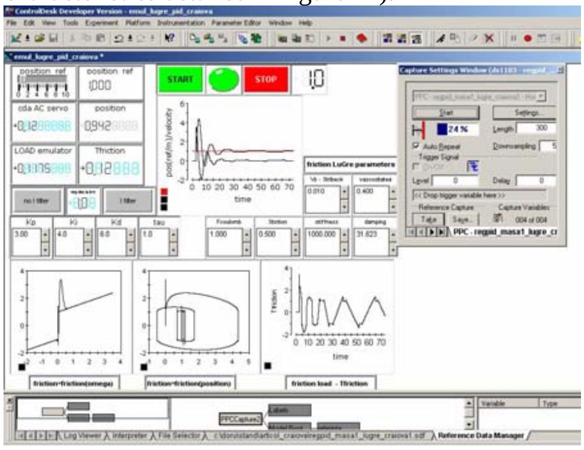

Figure 11. ControlDesk Panel for testing the experimental system

In figure 12 are represented some simulation results concerning PID tracking system application.

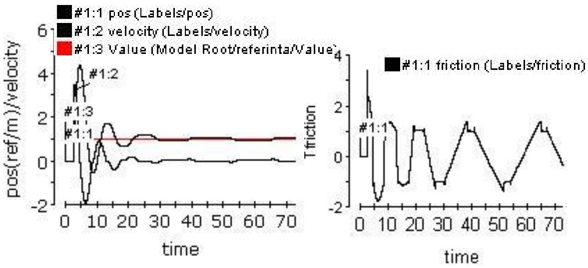

Figure 12. Position and velocity (left) and friction (right) for an emulated stick-slip motion on PID tracking control

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