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HARDWARE-IN-THE-LOOP APPLICATIONS IN THE ROBOTIC HAND CONTROL DEVELOPMENT

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Abstract. *The purpose of this work is the study and the application of the Hardware-in-the-Loop technique as a support tool in the artificial robotic hand control development process. The efforts concentrate on the development of a computational and experimental environment to work together and simultaneously. In the computational environment, the simulated system model was developed in real-time. In the experimental environment, prototype parts of the robotic hand were implemented. In both cases, a multivariable controller was developed and utilized. By adopting this approach, parts of the system simulated in real time can be substituted – according to the needs - by physical parts, such as: sensors, actuators, and new control hardware, allowing a considerable investment reduction in hardware and in time of project.*

Keywords*: Control System, Hardware-in-the-Loop, Robotics, Mechatronic, Dynamic Simulation*

1. INTRODUCTION

The interdisciplinarity of mechatronics product requires engineering tools and approaches to enable the simultaneous and concurrent development of different parts of the system associated with the individual knowledge areas. Because of the growing complexity and interdependency between the design of the mechanical and the design of the control system, computer aided methods for designing, modeling and off-line and real-time simulation are increasingly being applied. A consequence of such approaches and tools application is the reduction of the development time as well as the achievement of increased quality, reliability and safety.

During the course of the system design in a mechatronic project the modifications of the mechanics and the controller must be done in close collaboration. While a well-designed controller can allow the use of a simpler (and cheaper) mechanical construction, a badly designed mechanical system can never yield good performance even when using sophisticated control. Consequently, it is important that during the preliminary project stages an appropriate choice, with respect to the necessary mechanical properties, is made to obtain a good performance of the overall system.

The complete realization of many modern products and processes encompasses the integration of digital control systems which can be split in two phases – hardware and software integration. In the hardware integration phase, the actuator, sensors, control and power electronics are developed or selected. These components should be tested, analyzed and validated as systematic as the mechatronic project demands. In the software integration phase, the inputs and outputs measured supply the multiple levels of a distributed control system. Typically this includes: low level controllers, high level control (e.g. advanced feedback control strategies), supervision and the optimization level.

Nowadays, Real-Time Simulation techniques offer significant benefits by minimizing the difficulties associated with the hardware and software integration phases of mechatronic system development. Usually the following three approaches (R. Iserman at al., 1999) can be distinguished which explicitly include the most commonly encountered situations:

1. Control Prototyping: A physical prototype of the plant is used in the experiment and the dedicated control hardware is replaced by a simulated model of the controller running on general-purpose computer.
2. Hardware-in-the-Loop: The dedicated hardware is used in the experiment and the physical prototype of the plant replaced by the simulated model.
3. Software-in-the-loop: The simulated process is run with the controller simulated in real-time. This may be required if the final hardware is not available or as a preliminary design step before running hardware-in-the-loop simulations.

Each one of these approaches could be applied in a mechatronic products development process. It depends on the specific necessity in each of then. This work will explore the Hardware-in-the-Loop approach and will point out the benefits, gains and even the risks of the use of this technique.

Hardware-in-the-Loop (HIL) simulations are usually performed at system level when the physical components can be modeled with high fidelity, potentially including many degrees of freedom and high complexity of the system. Frequently, a dynamic plant is simulated in real-time because the physical counterpart is not available, or because experiments with the real process imply high costs in terms of time and money. Furthermore it is important to avert risks in critical plant processes.

The combination of the two more usual Real Time Techniques: Hardware-in-the-loop and Control Prototype is defined here as hybrid HIL approaches (Fig. 1). In general, the system consists of actuators, the plant and sensors, each of which can be fully or partially simulated.

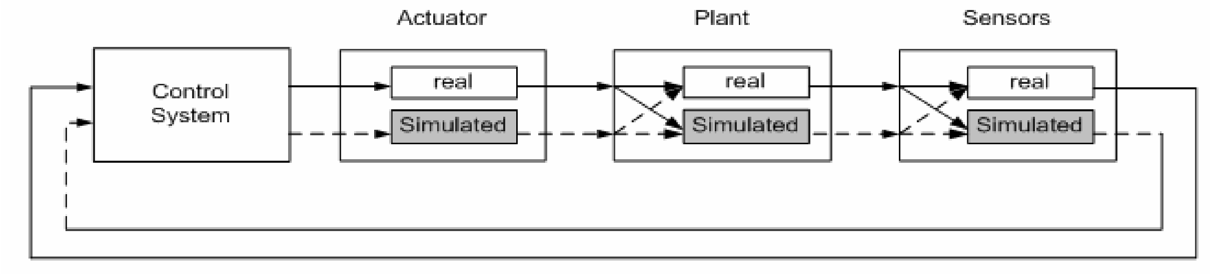


Figure 1. Possible hybrid combinations of physical and simulated structures in the Hardware-in-the-Loop approach

In the hybrid HIL approach, frequently some parts of the system are real physical components while others are simulated in real-time. Considering the complete plant as a system, it is typically composed of multiple subsystems which again can be decomposed hierarchically down to the component level. Importantly, not only the entire plant can be replaced in HIL simulations but any level of hierarchy to study lower level interactions down to the level of individual components.

The Hardware-in-the-Loop has increasingly become an interesting approach in several areas. Until now it has been most thoroughly applied in the automotive industry. This is due to the fact of the automotive industry being one of the most competitive market segments at present, with buyers of vehicles expecting high levels of quality, safety and functionality accompanied by a pressure to decrease costs and time of development (Kenji Hagiwara et al., 2002).

At several stages during the design of a new vehicle, the construction of prototypes is required. Usually each prototype is built carefully, however, when the tests begin, problems frequently appear and they must be communicated to the supplier of the items or equipment, causing the difficulties. This can lead to alterations of either the hardware or software project. These alterations, in turn, end up generating a constant restructuring of the project coordination, leading to the construction of an entire fleet of prototypes before successfully reaching the desired system.

To reduce the dependence on the vehicle prototypes, mainly in the preliminary stages of the project, HIL techniques are applied. As a consequence, a complete prototype of the vehicle is only gradually built in the course of the development process and is targeted at eliminating any remaining necessary modifications before beginning the large-scale production (Kenji Hagiwara et al., 2002). For example in Isermann et al. (1999), engine dynamics are simulated by using a software module on a host computer. An engine control unit (ECU) is integrated with the dynamics simulation module through an interface. The simulated responses of the engine dynamics are transmitted to the ECU from the host computer. After the execution of the computations in the embedded algorithm, the ECU generates control commands which are sent back to the dynamics simulation module.

The automation industry is another area that is slowly showing interest in the HILS approach. In (M. Linjama et al., 2000) the possibility of substituting the hydraulic parts of a production line by models simulated in real-time is analyzed. The objective is to test the control hardware with the simulated model that includes the servo actuator dynamics as well as the feedback of the sensor and the amplifying cards. In this work, the HILS technique is pointed out as a promising method to reduce development costs in industrial plants.

The space industry has also frequently been using HIL techniques. An example of this is the work by Carufel et al. (2000), where HIL Simulations are used to simulate space hardware. Further, the dynamic contacts between the space hardware and its intended environment during the space missions are simulated by using an industrial robot to artificially generate the required forces. The objective of that study was to train operators for skilled handling of robot manipulators during space station missions.

The Hardware-in-the-Loop Simulation technique has also been used in the development of autonomous underwater vehicles (AUV). Feijum Song et al. (2001) present a concrete implementation as well as general considerations about HILS for underwater vehicles. The use of HILS is highly profitable in this application field due to the complexity of the development of autonomous underwater vehicles caused by the hostile operation environment.

HILS techniques have been used to streamline the test procedures for new elevator configurations in (Büchler et al. 2005). Various components of an overall elevator system are simulated in real-time. In one setup the elevator door mechanism, including toothed-belts and cogwheels, is simulated by using a rigid-body dynamics engine and connected to the real control hardware. The photoelectric barrier is also simulated in the same software to test controller responses to such sensor input. In the largest setup a complete multistory building containing the elevator shaft and multiple lift doors interacts with the lift control unit.

Many others mechatronic system developments nowadays are using HIL techniques in some situations, even to improve the integration process in different phases of development or to test new control algorithms in a specific hardware. In the present work, the HILS technique is demonstrated by using the example of the development of an artificial robot hand, called BRAHMA (Brazilian Anthropomorphic Hand), cp. Fig.2. This example will be used to illustrate various aspects of Hardware-in-the-Loop technique.

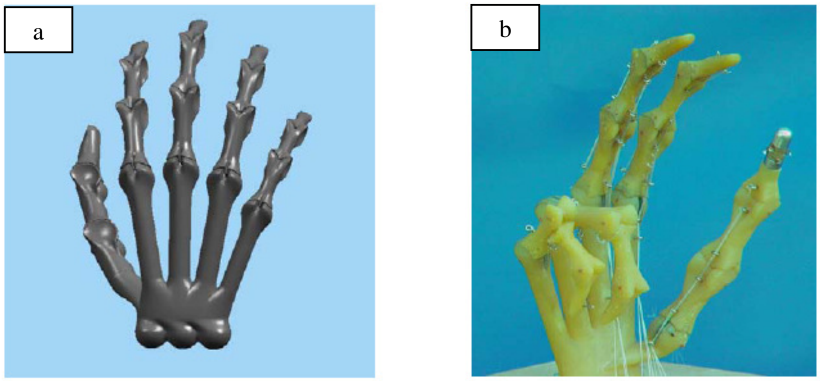
In the BRAHMA setup, a classical and hybrid combination of physical and simulated structures in the Hardware-in-the-Loop strategy were chosen to be applied in Albuquerque, 2007a, where the dedicated control hardware and some parts of the plant are placed in the loop. The possible advantages of using such a HIL approach in these situations are detailed in the application section.

Figure 2. The mechanical structure of the Brazilian Anthropomorphic Hand (BRAHMA)

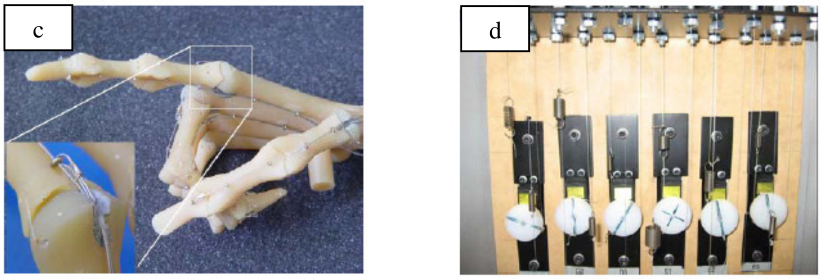
The rest of this document is structured as follows: The Application: Design of Artificial Robot Hand section presents the BRAHMA project. Furthermore, the Model Development section introduces the mathematical representation of dynamic properties of the plant, discusses also various aspects required to perform a simulation of this model and how this could be used as a framework for future HIL simulations implementations. This section also presents the BRAHMA case of study that includes the dynamic coupling between the actuators and the plant; The Control System section shows the importance of control algorithms to emulate a precise dynamic behavior for a well-designed system. These control algorithms have to be developed in accordance to the project constrains and features to be performed. The next step of this section is the requirement to test the performance of a control system in a dedicated hardware. The Hardware-in-the-Loop section is composed of BRAHMA Experimental Environment for HIL Testing presents the experimental hardware and tools used to generate source code and cross-compile on the host and also to perform Real-Time Simulations and after achieving the necessary requirements for performing real-time simulations a classical and hybrid HIL approach is presented and discussed; and finally the Conclusion sub-section analyzes and presents the potentiality of HIL application in a general way as well as the BRAHMA case of study.

2. THE APLICATION: DESIGN OF ARTIFICIAL ROBOT HAND

This section presents how the development of a complex mechatronic system can be improved by using HIL techniques. A five fingers anthropomorphic hand (Fig. 3) was adopted to serve as an implementation example. The artificial hand development by Caurin et al. (2003) has a total of 22 degrees of freedom (d.o.f.), 4 in each of the 5 fingers and 2 additional ones at the wrist. The links are made of a biocompatible polymer (Silvestre, 2001) and, in order to create the rotational joints, a biologically inspired solution is contact proposed. No axes or pins are used; the surface contour and the contact provide the desired movement between the links.



Virtual Model First Prototype



Biologically Inspired Joints and the cable transmission DC Servomotors

Figure 3. Different views of the Brazilian Anthropomorphic Hand (BRAHMA)

The possible advantages of using such a HIL approach (Albuquerque, 2007a) in these situations are:

- The behavior of the whole system can be verified in real-time by using a multitasking controller (Albuquerque, 2004) running on dedicated hardware. Therefore, the system can be validated and tested under a whole range of different conditions.
- Different parts (subsystems) of the mechatronic system can be inserted into the HIL setup, while the rest of the system and the corresponding environment run virtually in computer simulations that are based on mathematical models and the experiments run simultaneously.
- Reduction of the development risks related to the combination of different technologies.
- The overall setup is sufficiently close to the complete physical system to allow the improvement or even the development of new algorithms (e.g. controllers, motion planner) in a straightforward and effective way.
- A flexible interaction between the physical prototype and the simulated model is established. Therefore a user-friendly working platform is established to perform system monitoring, model parameter identification, control system optimization, planning, etc.

The first step required to the development of a HIL setup is the modeling. For new mechatronic products, the technologies integrate from different areas as: mechanical components, electronic circuits and embedded real-time software routines. Mathematically representing these multidisciplinary characteristics is sometimes not a trivial task.

3. MODEL DEVELOPMENT

Modeling is the task concerned with finding a mathematical representation of the kinematic and dynamic properties of the individual entities, subsystems as well as the overall system being developed. Models are developed for the mechanical structure as well as for the sensors and actuators of the system. These models form the framework into which, during the HIL simulation phase, physical components are introduced by replacing parts of the overall modeled system by their physical counterparts. The key feature of HIL hybrid approach is that the interactions between the mathematical models and physical components are a precise reproduction of the interaction occurring in the final system. This requires careful modeling to be performed which accurately reproduces the relevant characteristics of the modeled entity.

The use of programs for modeling and simulation is strongly recommended in this phase of development process. In this work the ADAMS (Albuquerque, 2004) is used as a tool for computer aided modeling.

As a first step in the process of developing a real-time simulation for BRAHMA, the dynamic models need to be established in order to simulate the system behavior and, at a later stage, integrate this model with the electronic control hardware.

In the BRAHMA project, a research effort has been made to observe and accurately reproduce in detail the human hand regarding kinematic and also dynamic characteristics. Initially, the main objectives of modeling for off-line simulations were: parameter evaluation; hand simulation for performance prediction; sensitivity analysis; the understanding of new phenomena and the implementation of a preliminary process for controller development.

The BRAHMA dynamic model (Albuquerque, 2005) can be expressed as nonlinear second-order differential equation:

$$D(\underline{q})\ddot{\underline{q}} + \underline{C}(\underline{q},\dot{\underline{q}})\dot{\underline{q}} + \beta\dot{\underline{q}} + \underline{G}(\mathrm{q}) = \underline{\tau}_c - J^T(\underline{q})\underline{F} \qquad (1)$$

Where: q is the vector of fingers' articulations angular displacement; $D(q)$ is the inertia matrix of the hand's finger; $\underline{\tau}_c$ is the torque vector in the articulations; $C(\underline{q},\dot{\underline{q}})$ is the vector of Coriolis and Centripetal force; β is a positive diagonal matrix of viscose damping; $G(q)$ is the vector of gravitational forces; $\underline{\tau}_c$ is the articulations torque vector; and J is the Jacobian matrix.

The coupling between the output axis and the BRAHMAS joints is realized by cables (Fig. 3b and Fig. 3c). By extending the equation (1) with stiffness and damping due to the coupling, the BRAHMA dynamic can be presented in its complete form:

$$\underline{\tau}_c = D(\underline{q})\ddot{\underline{q}} + \underline{C}(\underline{q},\dot{\underline{q}})\dot{q} + \beta\dot{\underline{q}} + \underline{G}(\underline{q}) + K_c \cdot \left(\frac{\underline{q}_m}{\eta} - \underline{q}\right) + B_c \cdot \left(\frac{\dot{\underline{q}}_m}{\eta} - \dot{\underline{q}}\right) + J^T(\underline{q})\underline{F} \qquad (2)$$

Where: q_m is the vector of actuators' angular displacement; K_c is the positive diagonal matrix of the coupling stiffness; B_c is the positive diagonal matrix of the coupling damping.

The well known accurate dynamic characteristics of joint transmission system are important data for the manipulation of the artificial robot hand with optimal performance and for designing the high quality controller (Albuquerque et. al, 2007b).

4. CONTROL SYSTEM

In all non-trivial mechatronic systems, the mechanical structure and electronic hardware alone are not sufficient to perform the desired task. These components are, to some degree, generic and typically allow a whole range of different tasks to be performed. In a well-designed system, the control algorithms are responsible for causing the mechatronic system to behave in precisely the desired way for the specific task to be solved.

When a motion planner is used, the task of the control system is to generate signals for the actuators of the system which cause the mechanical structure to follow the desired motion plan. The control system can guarantee that the motion plan is followed, since the motion planner takes the constraints into consideration by applying to the kinetic and dynamic properties of the system.

There is a variary of program systems for simulation and control design, such as: MATRIX, ACSL, MATLAB/SIMULINK, and SCILAB. In the present work, MATLAB/SIMULINK is used, which is also suitable for real-time simulation transition thought the use of Real-Time-Workshop toolkit.

In the BRAHMA project, a multiple-input and multiple-output position tracking control system has been implemented in (Albuquerque et. al, 2004). In that work, a three-finger model has been used to develop the initial controller,. Since each finger has 4 d.o.f., the controller operates in a mathematical space containing a total of 12 d.o.f.

Figure 4 presents the block diagram of control system. The K matrices are obtained by selecting the Eigenvalues as well as the associated Eigenvectors of the closed-loop system and by assigning them to the closed loop plant. The values have been selected to yield adequate time response characteristics for the intended manipulation processes.

This controller presented here showed suitable performance for the intended tasks in the off-line simulation tests (Albuquerque, 2004). The diagram (Fig. 4) presents how the hand model follows any set-points values generated by using the state space control system.

Once the virtual prototype, the simulated model and the control system are developed, the next step in this development phase is the hardware and software integration of the robot hand system. In this phase, the Hardware-in-the-Loop is used to make the benefits listed in the Application Chapter.

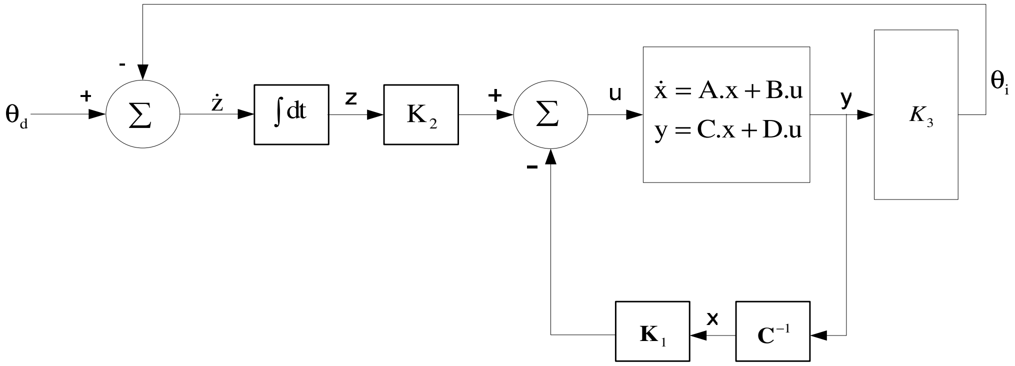


Figure 4. Block diagram representation of the control system

5. HARDWARE-IN-THE-LOOP

The integration of the digital control system and the mechanical system has been done by using the Hardware-in-the-Loop hybrid approach. In this phase it is particularly important to simulate the overall system behavior under real-time constraints in order to be able to connect the control hardware in the loop. This allows testing and validating the control hardware under a range of conditions. Furthermore, part of the physical plant should be included in this setup to be run simultaneously (and hence be coupled) with the other components.

Individual HIL experiments require all the steps described in the previous sub-chapters to be performed for their execution. However, this does not mean that HIL simulations can only be conducted at the end of the overall development cycle. For single components or groups of components within the overall setup it is possible to complete all the above steps and run HIL simulations early on. Such a procedure is even highly advantageous to the development cycle as early HIL experiments can provide crucial information on subsystem behavior on which design decisions about other components can be based.

Conceptually, an individual HIL approach is performed by replacing a part of the model of the complete system by the physical components that section of the model represents. Then the model is simulated in real-time and interacts with the physical entities by using exactly the same mechanisms which will be used in the final setup, i.e. the physical prototype.

6. BRAHMA EXPERIMENTAL FOR HARDWARE-IN-THE-LOOP TESTING

To achieve real-time behavior it was necessary to use dedicated development tools as well as robust hardware architecture. The computational hardware used is based on a MVME162FX microcontroller board mounted on a standard VME bus rack. The microcontroller board is complemented by 4 industrial packages used to handle the set of digital and analog communication interfaces required by the sensors and actuators (Fig. 5).

In the specific case of BRAHMA, automatic code generation was used to produce code for the multitasking VxWorks 5.5 operating system due to the multiple concurrent tasks with real time requirements. For this RTOS the generated code can be efficiently cross-compiled on the host, downloaded and tested for execution and task monitoring.

The currently available lab setup allows free distribution of computation tasks between the host system and the target. Usually, the host is used for code generation and also for off-line computer simulations. On the target, real time tasks, such as sensor signal acquisition and interpretation, motor control, motion planning and online simulation are executed.

The HILS technique is initially used to test and monitor the behavior of BRAHMA for specific input test signals by inserting physical hardware (control hardware and servo-motors) into real-time simulations. The motion planner the controller developed in section Control System is used to perform the manipulation tasks.

First, the system model has to be discretized at a certain sampling rate in order to be transferred to the target afterwards. The next step is to upload the source code onto the target by using Real-Time-Workshop (RTW) from Simulink®. The last step is to start the real-time simulation process, which is managed by tools provided by the RTOS (Fig. 6).

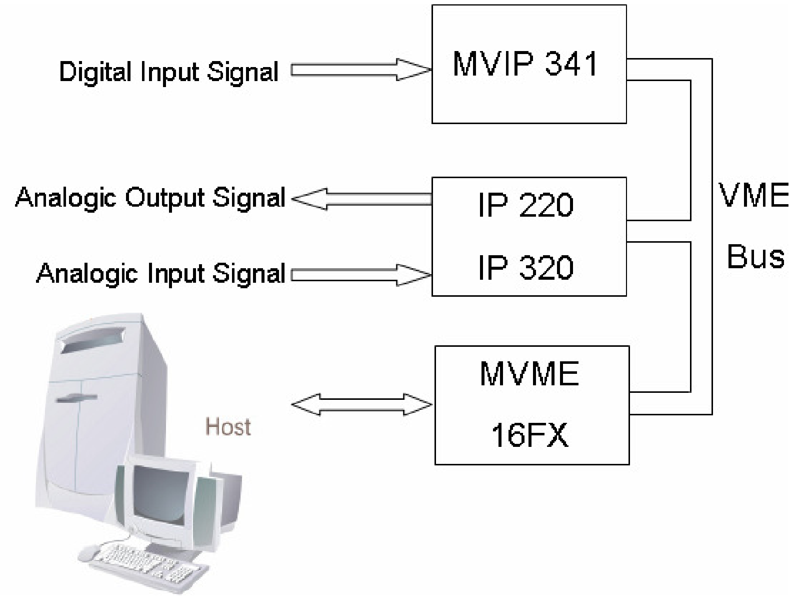


Figure 5. General Structure of Hardware-in-the-Loop System

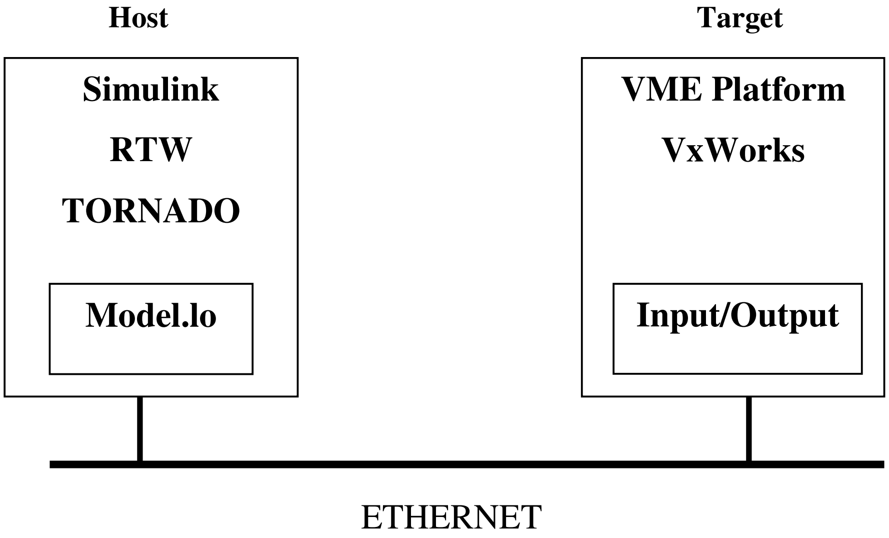


Figure 6. Hardware link sketch (VxWorks is the RTOS chosen)

After achieving the necessary requirements for performing real-time simulations, a classical Hardware-in-the-Loop is implemented (Fig. 7). In this classical setup the behavior of the whole system can be analyzed in real-time by using a multitasking controller running on dedicated hardware for a set of signal tests (Fig. 8).

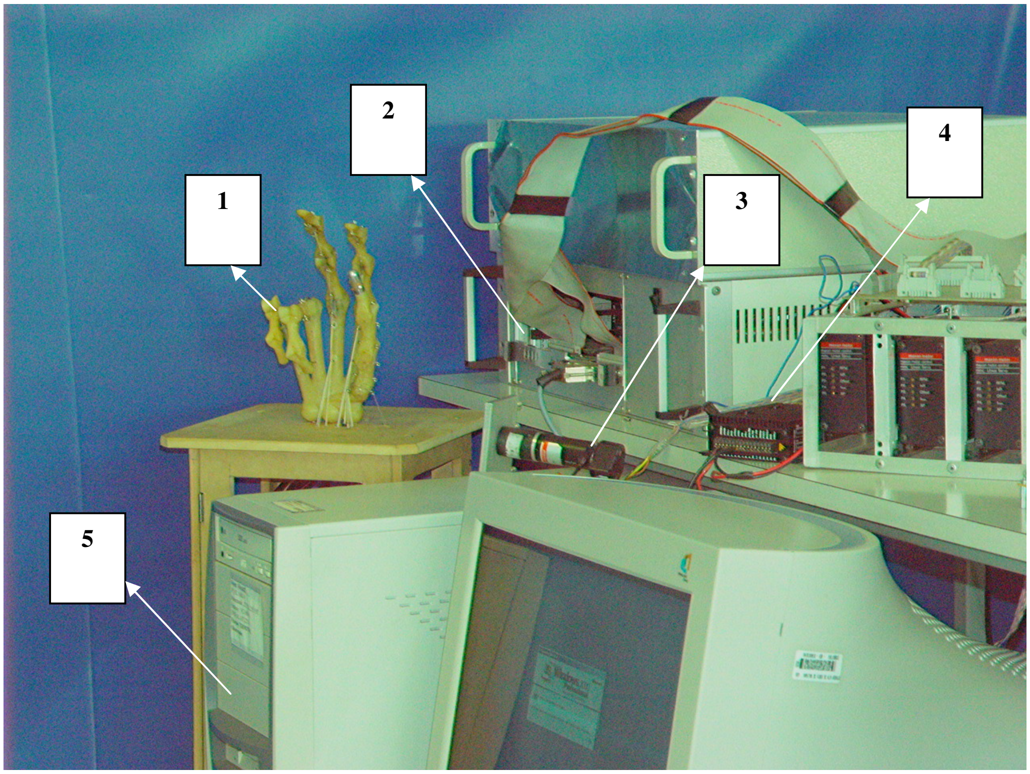


Figure 7. Experimental setup: 1) BRAHMA prototype; 2) Target (dedicated controller); 3) Maxon Servo-Motor; 4) Driver; 5) Host (development environment);

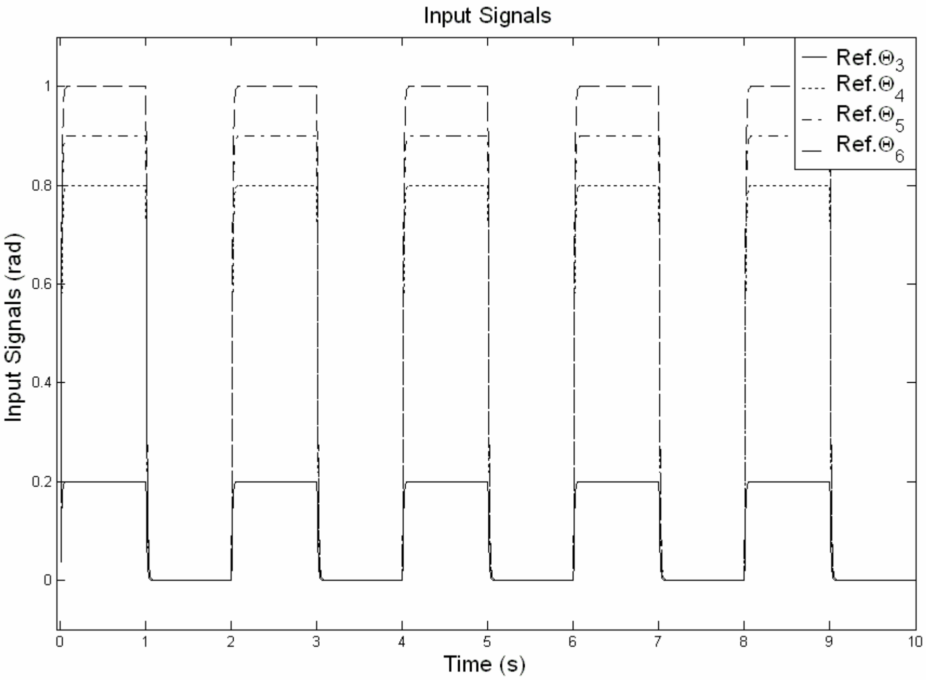


Figure 8. A set of Input Signal Tests

The results of such setup are presented in Fig. 9 and the event monitoring of each task is presented in Fig. 10.

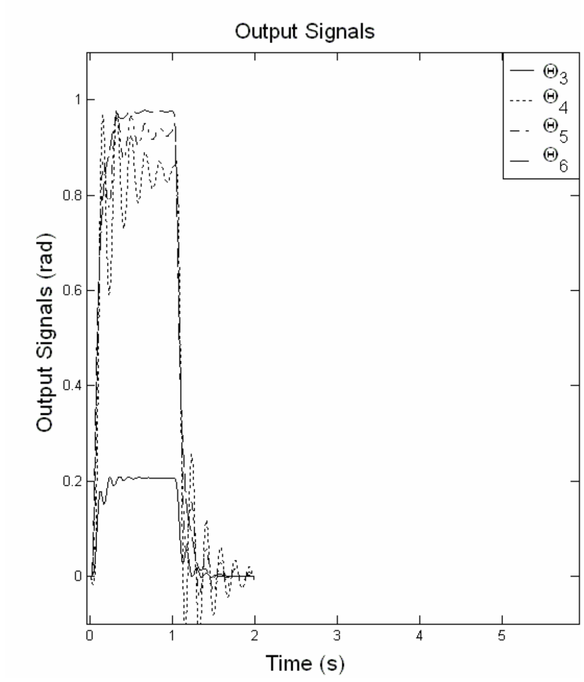
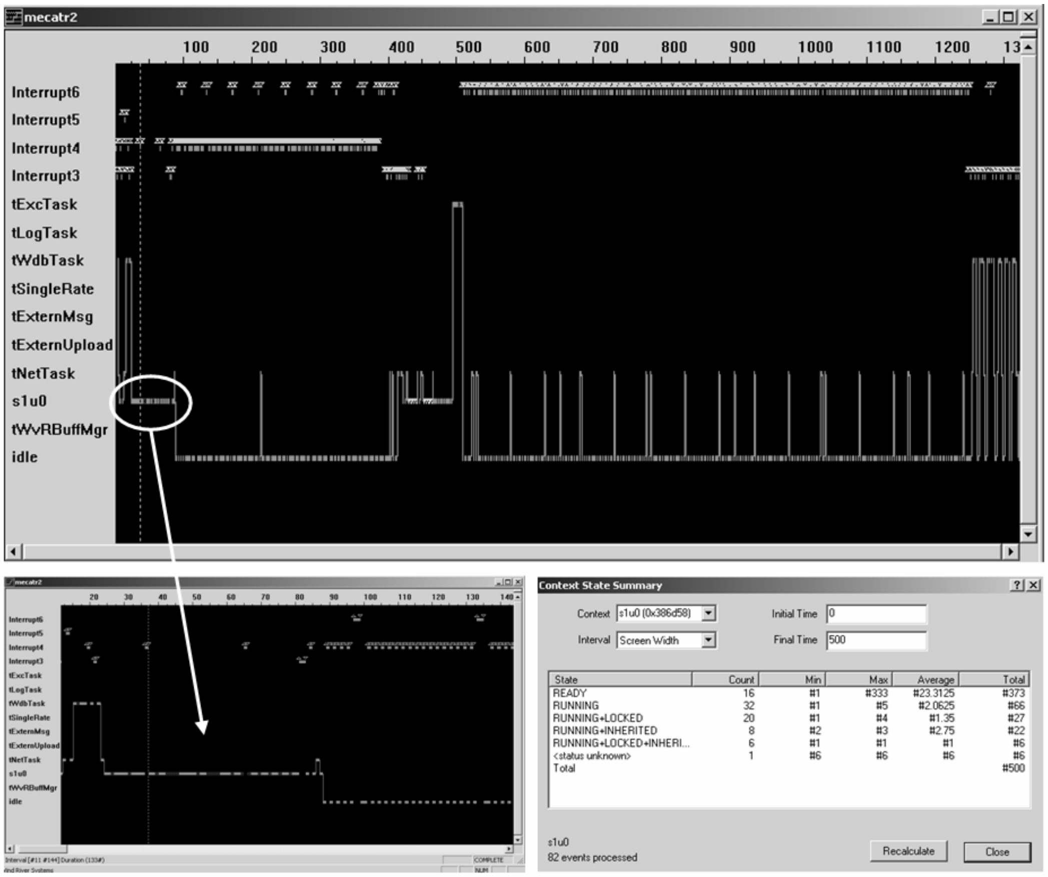


Figure 9. Dynamic Responses at Specific Time Period of Each Finger Joint.



Context: s1u0 (0x386d58)
Interval: Screen Width
Initial Time: 0
Final Time: 500

State	Count	Min	Max	Average	Total
READY	16	#1	#333	#23.3125	#373
RUNNING	32	#1	#5	#2.0625	#66
RUNNING+LOCKED	20	#1	#4	#1.35	#27
RUNNING+INHERITED	8	#2	#3	#2.75	#22
RUNNING+LOCKED+INHERI...	6	#1	#1	#1	#6
<status unknown>	1	#6	#6	#6	#6
Total					#500

s1u0
82 events processed

Figure 10. Using target instrumentation tools in RTOS for monitoring tasks

In Fig. 10 each task is monitoring in Real Time Operation System environment in order to measure the hardware and software performance.

7. CONCLUSION

In this publication Hardware-in-the-Loop simulations were introduced in a theoretical way and illustrated by using an example of a mechatronic development process. It was shown how Hardware-in-the-Loop experiments can be integrated into the mechatronic project development and what benefits can be obtained by doing so. The steps required to perform an individual Hardware-in-the-Loop experiment were explained and illustrated by the development of an artificial robotic hand (BRAHMA) that was used to contextualize the presented approach.

A great benefit of HIL supported mechatronics project development is the possibility to concurrently develop various subsystems in an easy way. An individual HIL experiment within such a parallel development environment is performed by connecting a physical subsystem to the model of the overall system. The physical subsystem replaces the corresponding part of the entire simulated system. As the model of the system is simulated in real-time, its interaction with the physical subsystem can be studied in detail. This interaction reflects precisely the behavior of the real interdependency.

As the development of the mechatronic system progresses, increasingly larger subsystems are included as physical components into the real-time simulation model. Finally, every single component of the simulated system could be replaced and thus the prototype completed.

The example used to contextualize the HIL approaches firstly presents the behavior of the whole simulated plant by using dedicated control hardware in a classical HIL setup and target tasks instrumentation for monitoring every event performance in a specific period of time.

8. ACKNOWLEDGEMENTS

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