MIXED REALITY WITH HYPER-BONDS - A MEANS FOR REMOTE LABS

F. Wilhelm Bruns, Heinz - H. Erbe

Artec Research Center, University of Bremen
Center of Human-Machine Systems, Technische Universität Berlin

Abstract: The paper presents a learning environment where on-site and remote components merge into a cooperative learning process. The envisaged system allows working together with complex real and virtual systems, consisting of parts which may be remotely distributed. The learning environment includes a supportive web-database with multimedia learning sequences providing theoretical background information, exercises and help to handle training tasks. Hardware equipment can be connected to the virtual environment with a special bi-directional sensor-actor coupling called Hyper-Bond. The learning environment smoothly integrates equipment and supports full hardware-in-the-loop functionality, allowing to build up real systems from subsystems of complex virtual systems.

Keywords: bond graphs, hyper bonds, e-learning, simulation, remote experiments

1. INTRODUCTION

Engineering education is confronted with the need to develop theoretical integrated with practical learning sequences to fulfill the demands for multi-skilled engineers and also skilled technicians. Tasks and problem solving in complex technical systems requires cognitive and operational knowledge and practical experience about generating systems, diagnosis- and maintenance-techniques. However, a significant challenge is that these tasks are essentially characterized by the use of tele-medial systems. Service staff of the professional field needs the ability to achieve their aims in (tele) collaboration with others, and they should be able to collaborate in virtual and distributed forms of work. Concepts concerning pedagogical, technical and organizational aspects to meet these requirements in education and training are in development. Cultural differences and similarities concerning learning and collaboration styles have also to be considered regarding curricula, courseware and teaching methods.

Computers are now used in the classroom and at the job as multimedia tools to provide alternative sources of learning material, to provide interactive learning situations and to provide simulation of systems that cannot for reasons of cost, size or safety be used in reality. The use of the Internet is rapidly increasing and is being seen by some people as the greatest source of knowledge available for learning. The use of simulation tools has some benefits for education. The learner is not exposed to the hazards of the real world. The learner is able to explore a range of possible solutions easily and quickly. The learner is able to use the tools that will be available in industry. The cost of simulation tools is significantly less than the real world components and allows more participation and interaction than a limited demonstration. An added benefit is that learners today, enjoy using computer based technology and this enthusiasm fosters the learning process. The question is indeed to what extend real experience can be replaced by learning with simulations? The internet makes it possible for e-learners to have access to remote laboratories. They could change control parameters to study the effect on the performance of a plant. Before doing this they can experiment with the virtual equipment in a computer-simulation to save time when remote experimenting with the real equipment.

Remote laboratory applications are not new. With respect to learning support there are however still many open questions:

- How to synchronize multiple remote actions on one lab-object to support collaboration,
- How to handle feedback from the process: visual, sound, haptics or more general: how to sense all interesting physical phenomena
- How to handle action into the process: electrical, mechanical, thermodynamic or more general: how to generate all interesting physical phenomena
- How to represent learning content, scenarios, prerequisites, tools etc. in a standardized Learning Object Module (LOM) to support a modular, open, easy and flexible use
- How to administrate the learning session running on original critical equipment, supported by an on-line expert?

Goldberg & Chen (2001) and Song & Goldberg (2003) fruitfully address the problem of collaborative control of robotic cameras to observe a remote laboratory and the distribution of video-streams. On their web-page it is also shown how they face the learning object module problem.

Ferreira et al (2002) and Cooper et al (2002) demonstrate the use of remotely controlled experiments of biochemistry, fundamental physics, automatic visual inspection and digital electronics in the EU-project PEARL (2003). Mueller & Ferreira (2003) report about remote-lab development of the EU-project MARVEL – a mixed reality learning environment for vocational training in mechatronics.

However, up today, all remote-lab developments strictly separate reality and virtuality, energy and information. One can sense the remote process, view specific parameters, control them by changing parameters and observe the process by video-cameras. The process, as a flow of energy controlled by signals and information is either in reality or completely modeled in virtuality by simulation. Going one step further, we suggest a distributed environment where the process-model of energy and information flow can cross the border between reality and virtuality in an arbitrary bi-directional way. Reality may be the continuation of virtuality or vice versa. This bridging or mixing of reality and virtuality opens up some completely new perspectives not only for learning environments but also for evolutionary systems design and service work. To make this possible, Bruns (1999) developed a concept of *Complex Objects* being a unit of various closely coupled virtual and real representations and *Hyper-Bonds*, a universal interface type. This name has been chosen because of its relation to bond graph representations.

Bond-Graphs are it selves a very powerful representation for dynamic systems.

2. BOND-GRAPHS AND HYPER-BONDS

Hyper-Bonds combine the unified abstract systems representation of bond graphs with an implementation of “hyper-connections” between physical phenomena of the computer-external environment and the logical structure of computer-internal representations, a blend of physical systems with their virtual counterparts.

Paynter (1961) introduced the theory of bond graphs as a unifying view on physical phenomena from a continuity of power-flow perspective. Power flows through system components and connections by way that the product of effort and flow is continuous, following typical laws of energy conservation. Effort (e) is the driving force for flow (f) and can be a pressure difference, force and torque, electrical potential difference, temperature difference etc. Flow (f) can be a flow of material, momentum, electric current, entropy. The bond graph theory has been further developed by Karnopp et al (1990). Pairs of effort and flow (e,f) are for example in mechanical systems force (F) and velocity (v), in electrical systems voltage (V) and current (i), in pneumatic/hydraulic systems pressure (P) and volume flow rate (dQ/dt).

Bond graphs use half arrows connecting elements and junctions. The arrows indicate the direction of power (e*f). Strokes at the arrows indicate the causality.

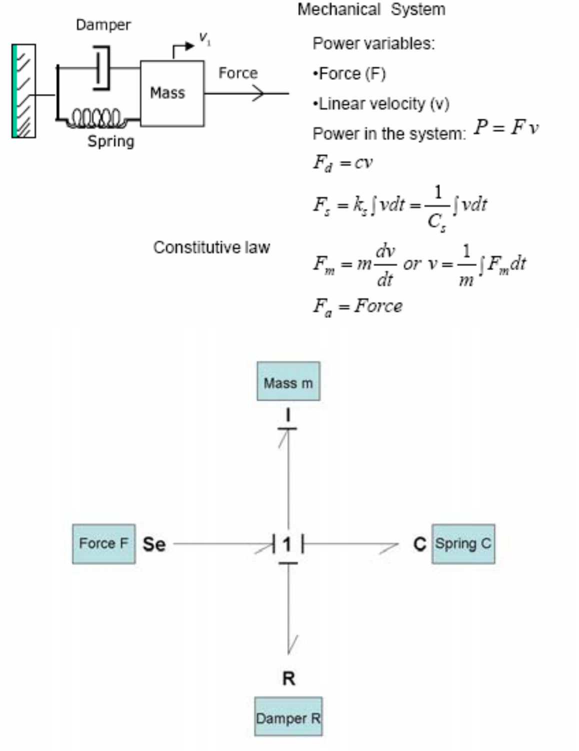


Fig.1. Bond graph of a simple mechanical system.

The effort-source **Se** in figure 1 imposes an effort on the system independent of the flow f. Inertial type elements **I** receive effort and generate flow. A capacitive element **C** receives flow and generates effort. Resistive or dissipative elements **R** do not have a time-integral form of the constitutive law.

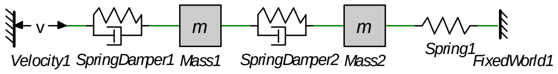
Therefore the arrows can have strokes on one or the other end depending of the structure of the system. I, R and C-elements have only one port to be connected. Transfer (TF) and Gyrator (GY) elements have two ports. These elements transform power, but conserving it. The so called junctions, 1 and 0, have more ports for connections. Bonds at 1-junctions have all the same flow f, and the algebraic sum of the effort is zero. For 0-junctions the opposite is valid. From the simple example of figure 1 one derives:

effort imposing element I:

$$d/dt\,(m*v) = Se - c*v - k \int v\,dt$$
$$dx/dt = f1 = f2 = f3 = f4 = v$$

$$m\,d^2x/dt^2 = F - r\,dx/dt - k\,x$$

a damped vibration differential equation.
20-sim, a powerful tool developed by v. Amerongen and his group (2000), simulates bond graph structures directly, and calculates transfer functions, state space descriptions analyses stability with Bode, Nyquist, zeros/poles. The tool will be used in what follows.
Now let us consider the hyper bond concept. As an example a mass-spring-dashpot network (Fig. 2) was modeled with bond graphs (Fig. 3). When cutting off the network the device connecting it has to secure the power continuation. Figure 4a shows this connecting device, called hyper bond. Flow on both sides has to be sensed. The difference of both efforts is used to generate two new sources of effort in a control-loop. The example shows that the hyper bond preserves the networks continuity (Fig. 4b).



20-sim3.5 Viewer (c) CLP 2004

Fig. 2. Mass-spring-dashpot network.

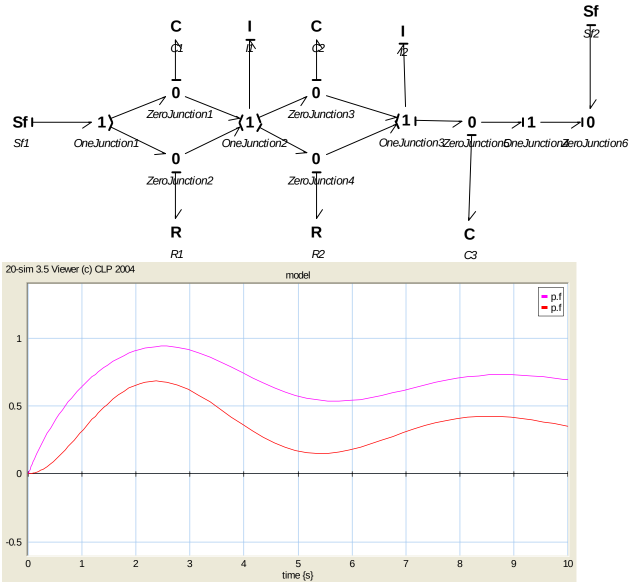


Fig. 3. The network modeled with 20-sim, Sf imposes flow.

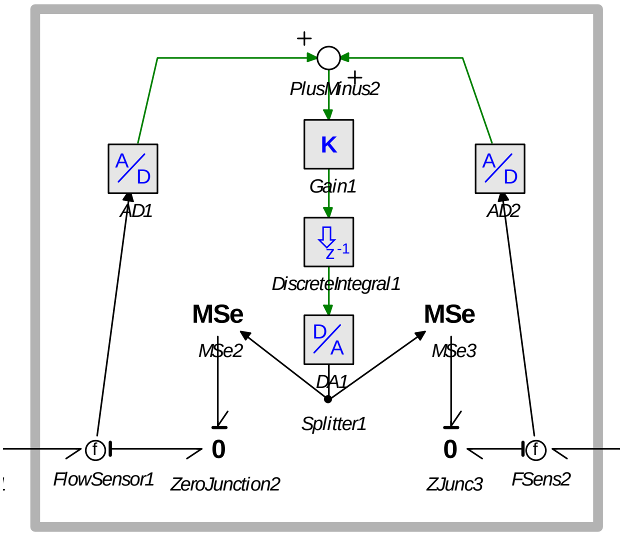


Fig. 4a. Hyper bond (sensing flow, generating effort)

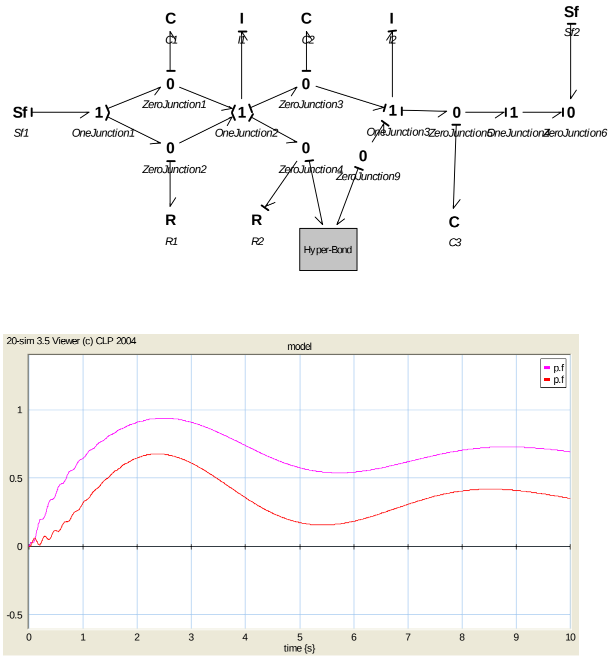


Fig. 4b. The network cut off and connected again with a hyper bond (sample frequency: 35 Hz).

The hyper bond concept can be summarized in two statements Bruns (2004):

Statement 1:
Given an arbitrary system S described by a bond-graph BG with effort-flow elements: MSe (modulated source of effort), MSf (modulated source of flow), R (resistor), C (capacity), I (induction), 0 (constant effort node), 1 (constant flow node), energy and signal arcs, sensors of effort and flow, we can replace any energy connection by a subnet HB (Hyper-bond) conserving the overall behavior and providing a mechanism to separate two physical subnets S1 and S2 connected via HB, a network of sensors and generators of effort and flow.

Statement 2:
Given a separation of two physical networks S1 and S2 connected via HB, an arbitrary implementation of S1 and S2 as real or virtual system is possible, restricted only by signal transmission time and sensor/generator characteristics.

Two types of HB are possible:

1. HBF senses the flow into or out of the connected subnets and generates two equal real or virtual efforts until both flows are equal,

2. HBE senses the effort and generates two equal but opposite flows

Two major problems can be identified so far:

1. To integrate hyper-bond simulation functionality into interactive virtual components representing real objects is still an open issue. Tools like 20-sim support C-code exportation and dll-interfacing, but it is not a trivial problem to merge various time characteristics of numerical integration methods within a stiff or discontinuous system.
2. The adequateness and quality of the hyper-bond implementation depends on the dynamics of the connected systems. Although it is not necessary to have full knowledge about the connected systems, it is necessary to have some boundary values of relevant frequencies. Or in other words, having a certain hyper-bond implementation, a certain class of behaviors can be translated.

For a deeper understanding of hybrid bond graphs and how to handle discontinuities, boundary cuts and transfer between power flow, signal flow and logic switches see Mostermann (1997).

3. DISCRETE HYPER BONDS

3.1 Realization of simple hyper bond

Figure 5 shows a simple connection of a real pneumatic valve, to a pressure source (not seen on the left side) and a hyper-bond below the screen. The valve is under real pressure. If pushed, the tube connecting the valve and the hyper-bond is under pressure and triggers an input signal to generate virtual pressure in the virtual tube-continuation. The simulated cylinder drives out. If the pushbutton is released, the valve opens a pressure release, the real pressure drops and the virtual pressure driven by the back-spring of the cylinder causes an outflow of air through the hyper-bond. This demonstrates the bi-directional character of the hyper-bond.

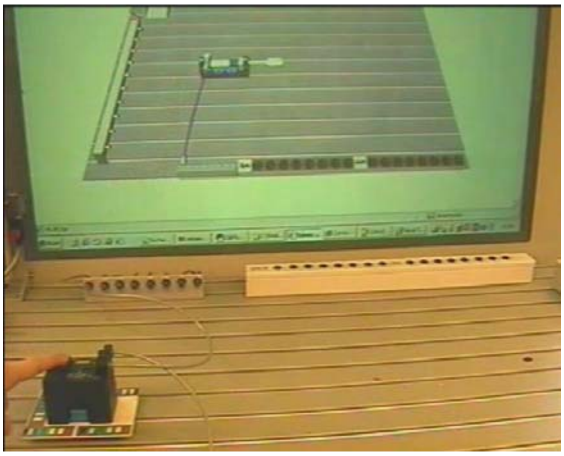


Fig. 5. Pneumatic equipment: single acting cylinder and valve split into reality and virtuality.

Figure 6 explains the correlation of pressure p, fluid flow q with force F, velocity v and mass/inertia I, compressibility C of the fluid and friction R in a simple pneumatic equipment. In many automation systems, electro-pneumatic circuits are considered as state automata and the elements can be represented as simple off/on switches like the valve and in/out positioning like the cylinder. These state automata do not require a bond-graph representation, but if one is interested in a more detailed dynamic behavior, then this can be described by graphs shown in figure 6.

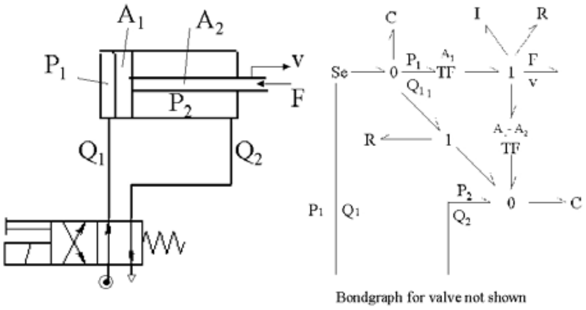
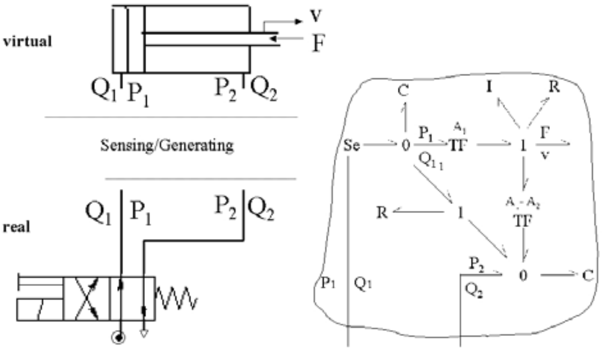


Fig. 6. 4/2 way valve controlling a double-acting cylinder and a bond graph of the cylinder alone

Components (valves, cylinders, etc.) are always connected by bonds having the value pair e and f. Knowing e and f at one connection, resulting from calculation or measurement, allows a cutting of the system in two parts and a separate investigation.

In mechanics one learns the principle of cutting a system at well defined boundaries and replacing the external influences by some observable and measurable relevant variables, reducing the investigation to the internal dynamics of the rest. In laboratory work this principle is used to construct reproducible experiments, but also mentally it is used to think about systems in hypothesis and mental experiments. Today, as more and more labs are permeated by computers, a free and easy distribution of a system between reality and virtuality has some advantage. Certain well known aspects of a system can be represented in a formal way by algorithms in the computer, others to be investigated in more detail are represented in reality, but coupled to a dynamic surrounding. This allows completely new forms of easy experimental work and learning. Here Hyper Bonds comes into play.



Bondgraph for valve not shown

Fig. 7. Cutting of the system of Figure 6 by a sensing/generating mechanism (hyper-bond)

In order to provide arbitrary boundary conditions, we must have a mechanism to switch between a source of effort and a sink of effort, and to generate and sense phenomena. Figures 7 and 8 show the boundaries between reality and virtuality and its realization with a special sensor/actuator coupling.

Hyper Bonds are of course also possible for pairs like voltage V and current i, Temperature T and heat flow dQ/dt and mass M and velocity v. Figures 7 and 8 are only simplified examples for use of discrete hyper-bonds. The hardware implementation of figure 8 is simple. For every supported physical phenomenon, there must be two sensors (pressure-meter and volume-flow meter for pneumatics) and a controllable source (air-flow and air-pressure). Analog sensor-signals are converted into digital values and then available for the software side of a hyper-bond. The opposite direction requires digital values from the software being converted into analog signals to drive a generating mechanism (force and speed for mechanics).

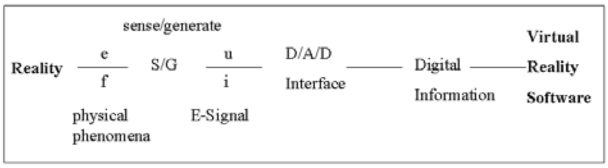


Fig. 8. Discrete Hyper-Bond

3.2 A learning environment

The European project "Distributed Real and Virtual Learning Environment for Mechatronics and Tele-service" (DERIVE) used the concept of hyper bonds to describe electro-pneumatics (Bruns et al, 2002) in a unified and didactically expandable way as well as to have a link to several powerful simulation tools supporting bond graph modeling.

DERIVE provides a new learning environment that supports schools for technicians to deliver courses in mechatronics. The support for the learning process will be reflected in a graduation from local real to local virtual to remote virtual to remote real, taking the student from basic knowledge to the full implementation in industry.

The tele-cooperation functionality in the learning environment will allow enterprises to use the training facilities in order to update the knowledge of their employees. With new equipment being more complex and requiring more complex maintenance, the training requirements for workforce and engineers increases. The new environment will allow groups of employees at remote locations to take part at the same training using the same equipment (either simulated or real). This staff will be able to work in a collaborative way to solve problems and explore learning situations. This new kind of interaction will allow the systematic support of skilled workers and engineers. Also, the learning environment is an appropriate tool to realize project orientation in technical training, providing a platform for self-managed and collaborative learning.

A learning session could be as follows:

1. Modeling Task:
Build a circuit for a welding operation.
First activate a clamping cylinder with the push of a left button, after this first cylinder has reached its end-position (clamps a work-piece), a second cylinder, the welder is automatically activated. On pressing a right button, the process is terminated and the clamping and welding cylinders move in, releasing work-piece and welding process.
Solve the task by using virtual parts and real parts of the platform at the remote lab as preferred. Consider the problem definition and suggest improvements.

2. Modeling means:
You may use in "virtuality":
Double Acting Cylinder with Magnetic Proximity Switch,
Single Acting Cylinders,
3/2-way valves with push button, normally closed,
3/2-way solenoid valve, normally closed,
5/2-way solenoid valve,
Sources of pressure and voltage,
Hyper-Bond connectors between real and the virtual,
Tubes and wires,
You can use in "reality" (observable by video camera):
Hyper-Bond connectors between real and the virtual,
Real single Acting Cylinders,
3/2-way solenoid valve, normally closed,
Tubes and wires.
First try a virtual solution with double acting cylinder 1 upper half, a 5/2 way solenoid valve, a single acting cylinder 2 (left lower side) and a cylinder 3 (right lower side),
(Figures 9 – 10).

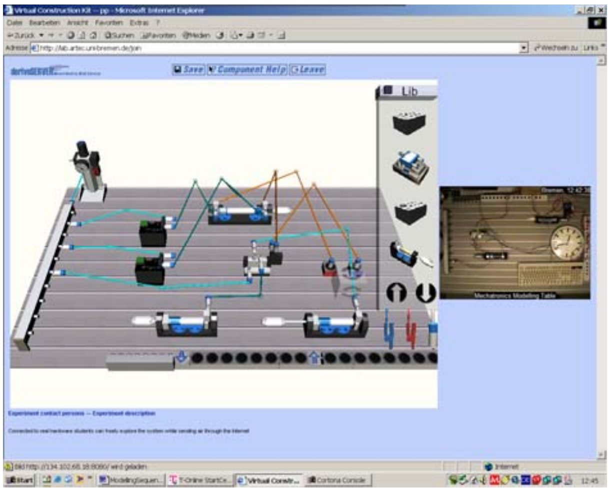


Fig. 9. Pressure supply on -> cylinder 3 moves out

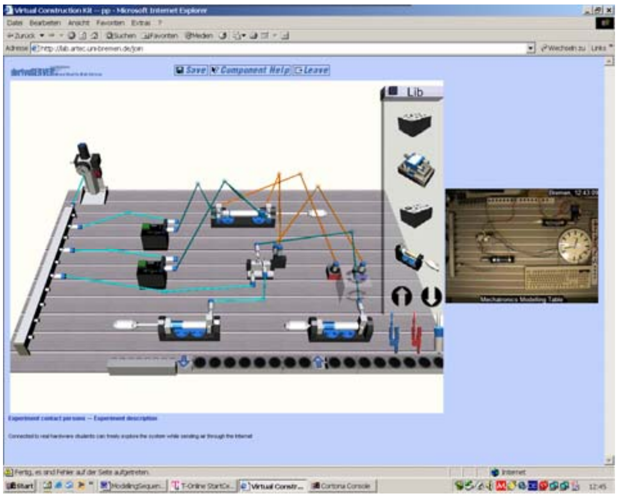


Fig. 10. Virtual circuit in action

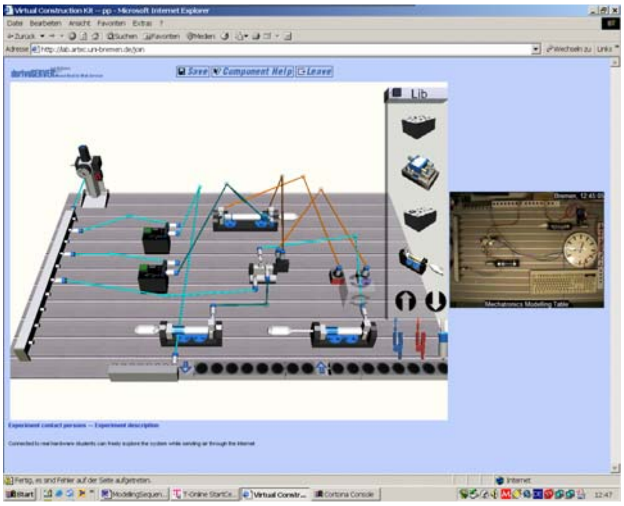


Fig.11. Exporting pressure into the hyper bond

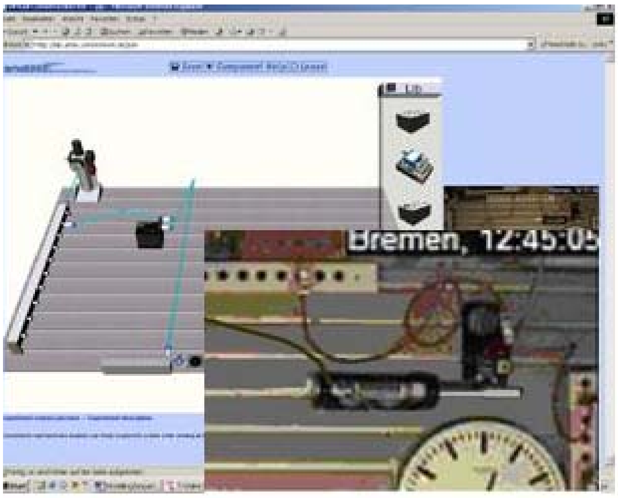


Fig. 12. Most parts exported onto the remote lab

Then export virtual parts into reality!

Connect virtual pressure valve via hyper-bond (first right pneumatic-connector) with a real cylinder seen on video-image upper right, figures 11-12. Press virtual push-button and see the single acting cylinder moving out as long as button is pushed. On release of the button, the air flows back from reality into virtuality and cylinder moves in. In figure 12 most virtual parts are exported. Push the virtual button, highlights active connectors in virtuality and move real cylinders.

The project developed a mixed reality human computer interface. To develop adequate technological and pedagogical concepts for e-learning in future technical training, users need had to be analyzed in depth. The requirements of different user groups (students, teachers, employees) had to be described and consolidated. Acting in an environment, where real world objects and IT-technologies are applied simultaneously, requires new concepts of supporting cooperating local and distributed learning groups. The scientific challenge is to handle physical as well as virtual presence and awareness without confusing side effects for the users. With Hyper-Bonds, a learning environment got realized where on-site and remote components merge into a cooperative learning process. The environment system allows working together with complex real and virtual systems, consisting of parts which may be distributed remotely. The learning environment includes a supportive web-database with multimedia learning sequences providing theoretical background information, exercises and help to handle training tasks. The learning environment smoothly integrates equipment and supports hardware-in-the-loop functionality, allowing to map real systems as subsystems of complex virtual systems.

The environment has been evaluated in 3 European vocational schools and colleges and at one industrial site. In a comparative evaluation of

- traditional teaching with blackboard and teacher learner interaction
- support by simulation only (FluidSim-software of FESTO AG, Germany)
- support by real complex system only (Modular Production System/MPS of FESTO AG, Germany)
- support by real and virtual media (DERIVE)

in 20 hours-courses of mechatronics, Grund and Grote (2004) found some hints that students/ apprentices being trained with DERIVE showed better performances in symbol based fault finding.

The following main tendencies are considered important:

- thinking in abstract categories of structure-behavior-function searching for alternative concrete instantiations (e.g. various structures for one function, or various functions of one structure)
- thinking in categories of information-control-work process and their realization searching for unified system dynamics views (e.g. Petri-Nets and Bond Graphs) for analogous physical phenomena (electricity, pneumatics, force-momentum mechanics …)
- judging about the adequateness or failure of simulation models versus real systems

4. HYPER BONDS REALIZING FORCE FEED BACK IN MIXED REALITY

Hyper-bond is a mechanism based on the translation between physical effort/flow phenomena and digital information like any other analog/digital and digital/analog conversion, however it aims at a unified application oriented solution connecting the physical and its virtual representation and continuation. One of its main features is that the modeler does not have to be aware about the direction of energy-flow. Hyper-bonds are bi-directional and adapt itself to the environment conditions.

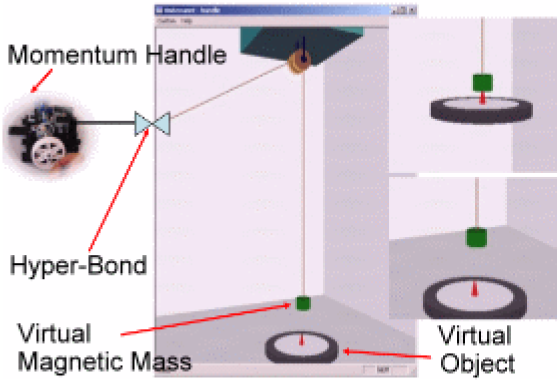


Fig.13. Lifting a virtual weight

To enhancing a learning environment a force feedback should be added to the usual vision feedback. Yoo (2004) together with Bruns developed a low cost momentum handle (Fig. 14), and demonstrated the lifting of a mass in virtuality (Fig. 13) with a feeling of the weight at the handle. The momentum handle senses a force (effort) between a driving pulley and a pulley blocked by a one-directional worm-gear. The force-signal is used within the control program of the virtual world to calculate a resulting force depending on the other virtual processes (in Fig. 15 only represented as a constant). The resulting force signal is then used to drive a motor connected to the second pulley via worm-gear in a flow-controlling way. It is obvious that this closed loop control depends very much on the time characteristics of the application (Se), the network-transport delay-time (A/D to D/A) and various inductivities, resistances and capacities.

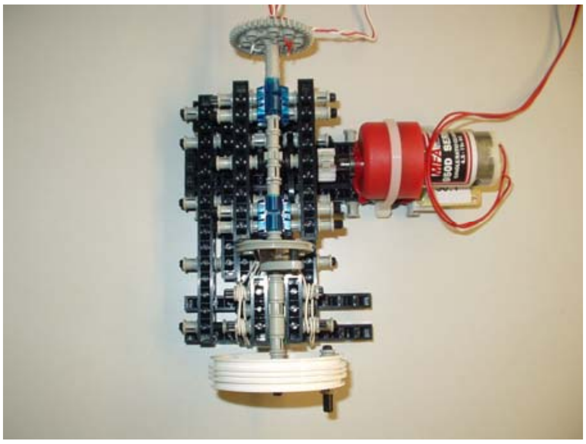


Fig.14 a. Low cost momentum handle.

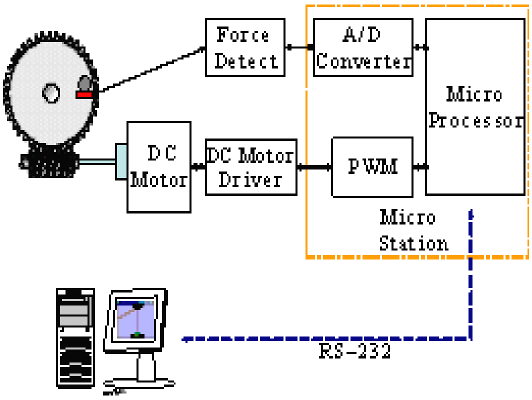


Fig. 14 b. Sketch of the structure of the handle.

The structure can be analyzed with 20-sim in iconographic and bond graph description (Fig.15 and 16).

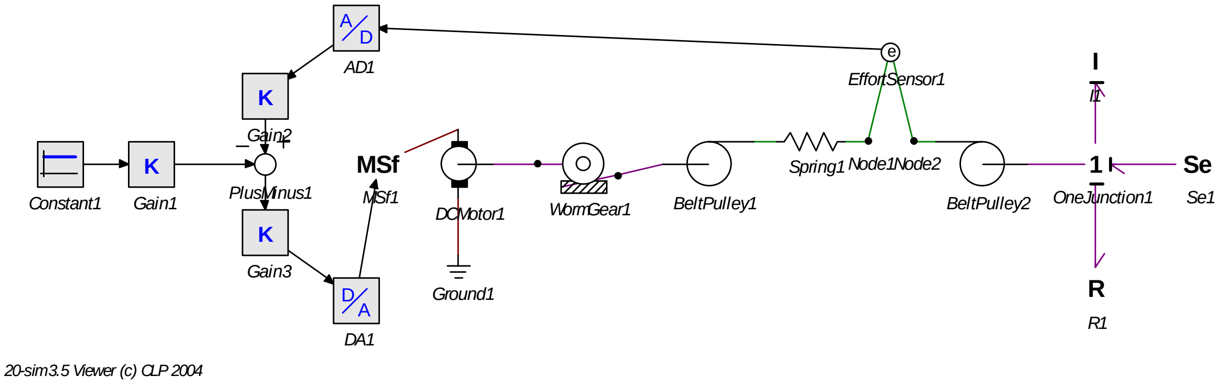


Fig. 15. Iconographic description (with 20-sim) of force feedback with the handle Se on the right, hyper bond in the middle, and a virtual process on the left (here represented only with a constant) and gains.

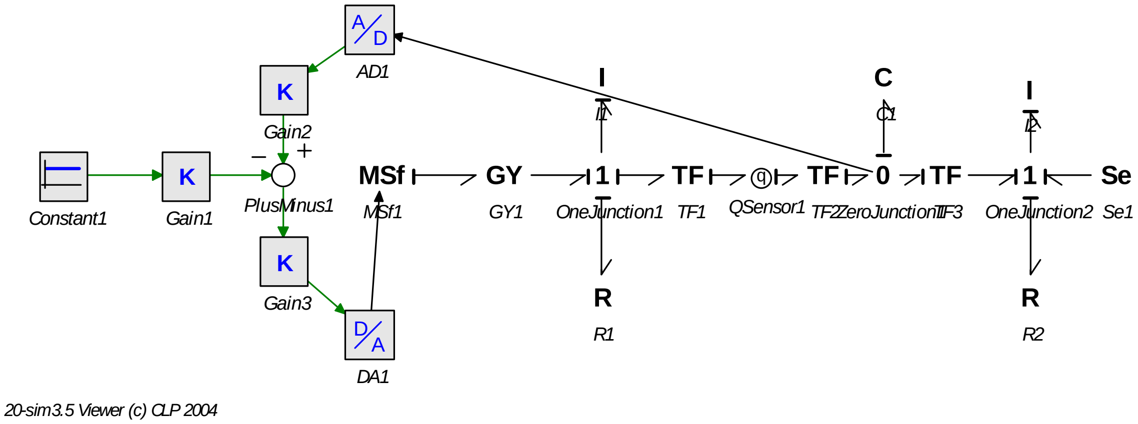


Fig. 16. Bond graph description (with 20-sim)

Figure 17 shows the control loop of the momentum handle. It can be analyzed in 20-sim to study stability and other characteristics.

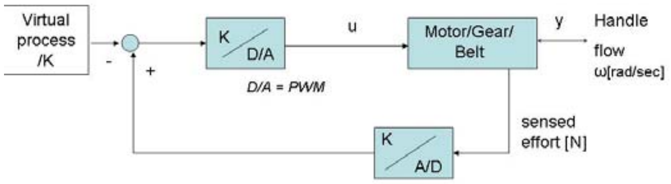


Fig. 17. Control loop of the momentum handle

Yoo, Y. & Bruns, F.W. (2004) also applied the hyper bond concept to demonstrate distributed collaboration. A virtual process, in Figure 18, a virtual weight, at two ropes can be moved, with force feedback, from both sites. These sites could be remote sites connected via internet, if a sufficient quality of service(reaction time) is provided. In general, hyper bonds as a unified interface can be applied to connect and continue real and virtual processes, sketched with 20-sim in Figure 19.

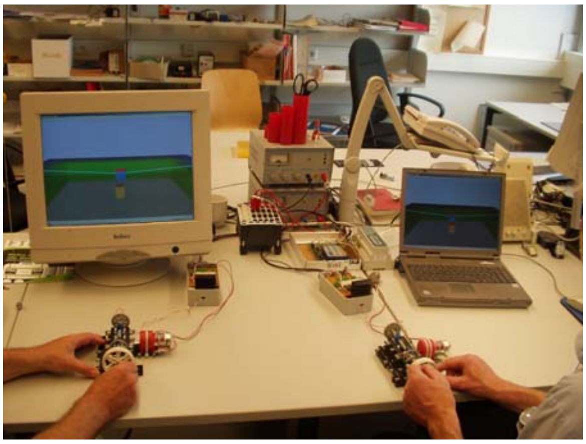


Fig. 18. Distributed collaborative work

These developments will be continued to support remote learning environments for to provide not only the vision and sound when working in remote labs but also a haptic feeling.

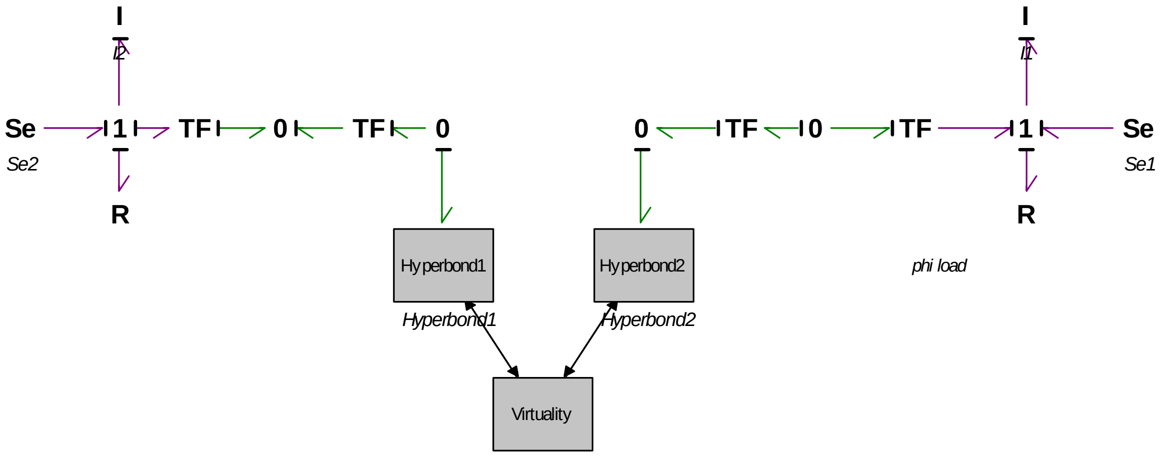


Fig. 19. Distributed effort chain connected with a virtual process

4. CONCLUSIONS

A new interface concept, allowing a flexible and user-friendly modeling in a blended real and virtual environment has been introduced. This concept, suitable for integration into the theory of bond-graphs, allows some learning and working modalities important for training and systems analysis: the stepwise abstraction and concretization of parts of a complex system still within the context of the whole. This feature supports various individual learning styles, systems diagnosis and repair strategies. Further developments and evaluations are undertaken in an EU-project Lab@Future where this interface technology is applied in concepts of future remote laboratories.

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