HYPER-BONDS
SUPPORTING DISTRIBUTED COLLABORATION IN ENGINEERING WORKSPACES

Wilhelm Bruns

Bremen University, Germany
Research Center for Work, Environment and Technology (artec)
bruns@artec.uni-bremen.de

Abstract: A concept of mixing distributed real and virtual worlds through a unified human-machine interface connecting logical to physical phenomena will be introduced and shown how this can be used for distributed collaboration if two or more physical locations and environments are involved. Relations to control-theory and modeling are presented.

Keywords: human-machine interface, multi-modal interactions, interactive control, multisensor integration, engineering workspaces

1. INTRODUCTION

Mixed Reality deals with the problem how to connect real physical phenomena to virtual, computer internal control algorithms or simulation models. There are several well developed concepts to describe discrete and continuous physical processes (Petri-Nets, Bond-Graphs), however there is a gap between control theory and its application to general and easy to use human-machine interfaces. Only few concepts bridge the real and virtual world in a *unified way*. The introduction of *Hyper-Bonds*, first demonstrated for quasi-static discrete event applications of pneumatic and electric phenomena (Bruns, 1999, 2001), fig. 1, opens up promising perspectives for further research, but is still in its early stage. Bond-Graph Theory based on a unified view on effort/flow driven systems of mechatronics (Paynter, 1961), now being integrated into various simulators as modeling language (see 20sim, van Amerongen, 2000, and Modelica) can be used to support and implement adequate multi-modal mixed-reality interfaces. Control Theory may improve interactive on the fly real time modeling and hybrid systems design with analog/discrete and real/virtual interfaces (see control theoretical aspects at Mostermann, 1997 and Melchiorri, 2003, tangible media aspects at Ishii, 1997 and image-centered mixed reality work of Ohta & Tamura 1999).
Mixed Reality, if not only considered from an image-processing point of view, but from a point of view of sensing and generating a broad variety of physical phenomena, may provide a technology for a new type of collaborative systems design and distributed systems service and maintenance, thus enriching engineering workspaces.

2. MOTIVATON FOR HYPER-BONDS

It is a well known desire of systems engineers to bring together simulation and real world phenomena. Not only should the simulation model be an adequate representation of some real phenomena in focus, it is also of considerable advantage to ease the modeling process and fasten the iterative cycle of modeling, experimentation, evaluation by coupling the virtual model with real representations or continuations. Supporting the modeling process can be done in various ways: by systems specifications through concrete demonstration of the desired structure or the dynamic behavior through hand-movement or object recognition. Programming a robot and conveyor system or specifying an electro-pneumatic circuit, are examples of this approach (Schäfer et al, 1997, Schäfer & Bruns, 2001). Connecting a real model with its virtual representation by image-recognition of user actions in a work- and learning-space, allows learners and system designers to easily switch between real concrete and abstract virtual representations of the same system. This interface has then been extended to a bidirectional connection, providing the user with electrical and air-pressure connectors on a real modeling desk and corresponding virtual connectors in the virual modeling world enabling him to connect a real pressure tube/electric wire from a real pressure/voltage source to the interface and continue this phenomenon on a signal level in virtuality to drive a virtual component. The process can be reversed, extending virtual signals into real physical phenomena. Using the internet for the distribution of a multi-user virtual world then opens up new ways of distributed real-virtual co-operation. A running remote mechatronics laboratory can be experienced at http://lab.artec.uni-bremen.de, fig. 1.

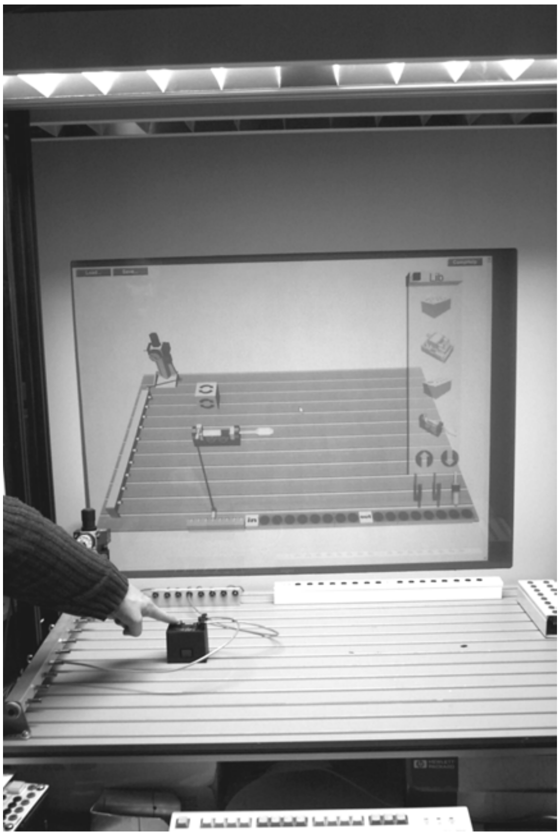

Fig. 1: Connecting real and virtual worlds

So far, these interfaces are for low speed and discrete event driven systems. If we want to turn to fast reacting continuous processes, like the control of a remote work-load wheel by a local hand-wheel through an internet-connection or continuation of an analogue pressure-change from a real source via internet to a real target, then a deeper insight into the control-loop is necessary and a unified view derived from Bond-Graph Theory is helpful. A low cost solution for the former problem has been demonstrated (Yoo & Bruns, 2004), fig. 2, allowing two users to cooperatively solve a force-related virtual task from two different locations. Another scenario usable in remote maintenance, remote human-human or human-robot collaboration could be a pneumatic pressure invocation on a remote double acting cylinder through the internet, fig 3. Of course, the pressure is converted into a signal at one side, possibly changed in the virtual modeling world, transmitted via Internet to the remote side and converted back to real pressure, sensing and reflecting the outside pressure and resistance of the other side. These applications require a sound theoretical background to handle real-time problems namely the stability and quality of control of dynamic systems.

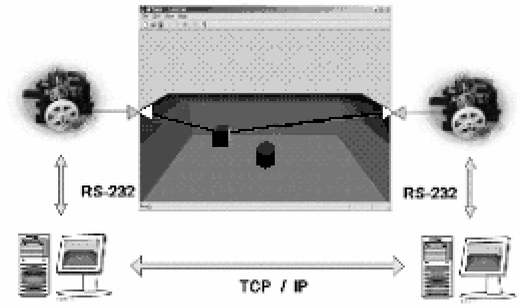

Fig. 2: Distributed Collaboration

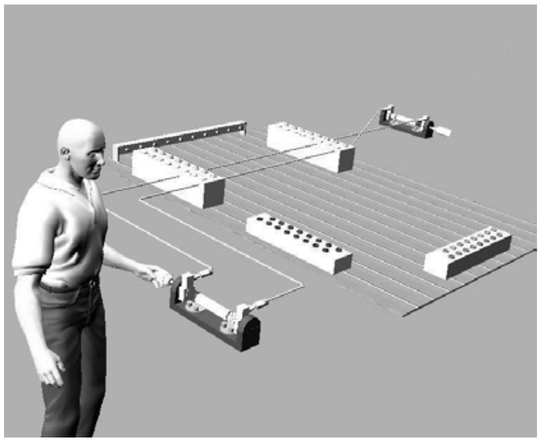

Fig. 3: Pneumatic action via hyper-bonds

From a control perspective we are interested in a bi-directional action and reaction, crossing the boarder between the real and the virtual. The real pendulum coming out of a "magic" hyper-bond wall as an extension of the virtual pendulum having the same, translated and generated characteristics as the virtual pendulum, experiencing some changes in reality and then, swinging back, at the entrance into the hyper-bond wall, again being converted into its virtual continuation. This scenario requires some second thoughts. With such an interface, able to convert real physical phenomena, even masses, into their virtual representation and vive versa, we could not only realize the utopian “holodeck” or other tele-presence and tele-operation applications, but also have an interesting means to validate our virtual simulation models against real practice. However, considered from a cybernetic point of view, this poses a major theoretical and practical challenge.

We demonstrate how modeling of the complete real-virtual-real hyper-bond system with a simulator supporting bond-graphs (20sim), can give some insight into problems, possibilities and limitations.

Theory of Hyper-Bonds

Theorem 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 behaviour 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.

Theorem 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.

The advantage of Theorem 1 is its local specification, overcoming the necessity to know anything about the structure of systems S1 and S2. This locality is a valuable property for implementing distributed mixed reality. Theorem 2 provides the basis for the continuation of virtual simulation phenomena into reality and the continuation of physical phenomena into virtual models. Together they provide a powerful means to design and handle mechatronic systems.

As can be verified by simulation, 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

We demonstrate the approach in a stepwise transformation of a simple resistor network into two networks connected by a hyper-bond implementation using 20-sim as simulator.

Fig. 4 shows two connected resistors and two sources of effort in an iconic and a bond-graph representation. Applying a sine-wave generator on the left side and a cosine-wave generator on the right side, would result in a behavior given in fig 5 as the middle (green) line.

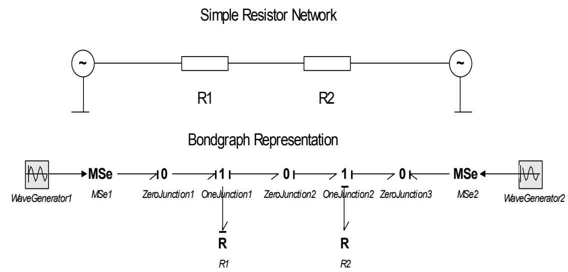

Fig. 4: Resistor Network in Bond-graph Representation
(MSe = modulated source of effort)

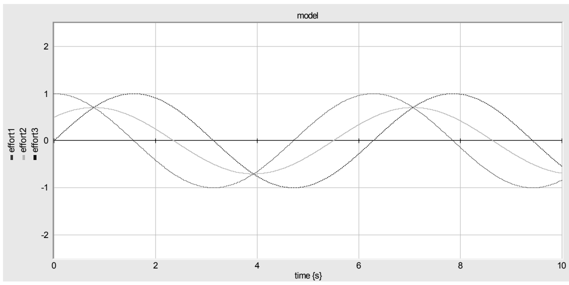

Fig. 5: Result from 20-sim simulation
(…sine wave generated left, --cosine generated right, __measured at the interface)

Fig. 6 presents the empty hyper-bond as a connection between two simple sub-networks. The behaviour of the original system, being cut into two parts, can be preserved by introducing a connecting network, which senses the flow at two boundary points. The difference of both efforts is used to generate two new sources of effort in a typical control-loop. It can be shown, that the result is indeed a preserved behaviour. However, this view is a theoretical one. Real implementations have to take into account the measurement and generation process.

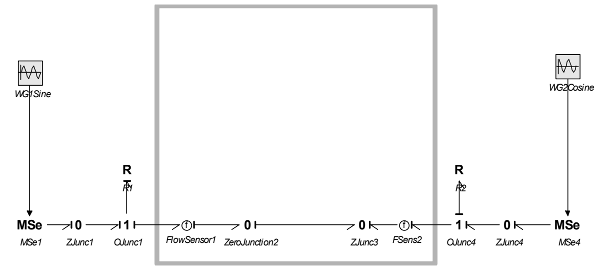

Fig. 6: Empty Concept of Hyper-bond

Introducing A/D-Converters at the measurement side and D/A- Converters at the generator site will result in the implemented hyper-bond of fig 7. The difference between measured flows (currents) at both interface sides is amplified by K and integrated to result in a correcting source of effort (MSe) on both sides. This correction will contribute to an adjustment of the different flows. Depending on the D/A/D sampling rate, it can be seen that also for a network with more components, like inductivity I=0.1, capacity C=0.1 and resistor R=1.0, the overall behaviour can be preserved. In fig 8, again the generating sine- and cosine waves are shown, together with the resulting effort (voltage) and flow (current) at the interface.

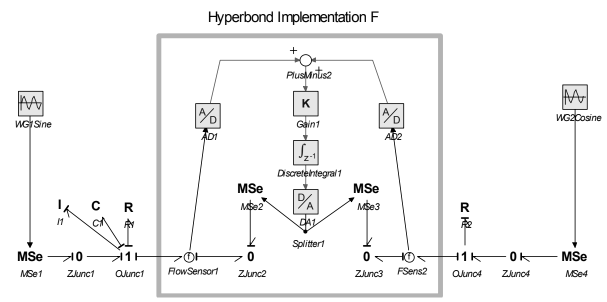

Fig. 7: Implemented Hyper-Bond for Complex System with Inductivity I=0.1, Capacity C=0.1, Resistance R=1.0 and Gain K

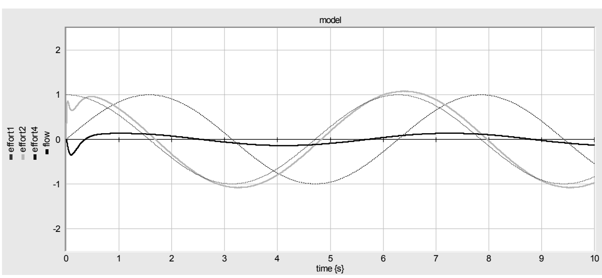

Fig. 8: Implemented Hyper-bond (sine- and cosine-generation and measured effort and flow at the interface)

3. APPLICATIONS

Sensing the effort and generating a real flow may be used to continue one phenomenon from one media into another, just in the sense of a functional continuation as we know it from mathematics of functional analysis, but we also may modify this continuation in an arbitrary sense given by some virtual constraints or boundary conditions. This can be useful for remote operation in flexible virtual-real environments shown in fig. 1-3.

As a bond-graph is a representation in a unified way, we can implement one known stable solution in another physical domain with similar dynamic characteristics if we have adequate sensor/generator devices: in translational movement with force and speed, in pneumatics with pressure and air-flow, in electrical networks with electrical potential and current, in thermodynamics with temperature and heat-flow.

For several examples taken from Karnopp et al (1990) we demonstrated the feasibility of hyper-bonds: electrical networks and mechanical systems (fig 9 and 10).

For engineering workspaces we can use this new modelling and interface technology in various ways:

1. duplicating a real component in virtuality and comparing both behaviours within the corresponding context, would allow an adequate refinement and validation of the simulation model,
2. building a complex real system with many connected components, fig. 11, could be supported by experimenting with connected virtual subsystems first and then exporting the right solution into reality,
3. after verification and validation of a complex virtual model, it can be stepwise exported into reality.
4. engineers at dislocated places can collaborate in testing a virtual system, replacing parts of the design with their own real or virtual components, to find faults or optimise its behaviour, fig. 12-13,
5. physical phenomena at remote places can be sensed and generated, i.e. the fine adjustment of a sensor screw by torque application, while some constraints or guidance of the operation are applied from the virtual system or some external expert,
6. collaboration of two remote experts on a virtual design task can be supported by system generated constraints and phenomena feed-back,
7. collaboration of two remote experts on a real design task can be supported by system generated constraints ad phenomena feed-back,
8. new human-machine interfaces may be introduced in a unified way by interpreting the human action as a modulated source of effort or flow on a dynamic system (fig. 1,2,3,14,15),

9. the interface could even be used to support some hybrid (analogue + digital) calculation: knowing the representing differential equations of a system, one part could be implemented in physical components, being the analogue-computer, the other part in mathematics on the digital computer, both being coupled via this interface,
10. the emerging field of human-robot collaboration might as well benefit from this approach.

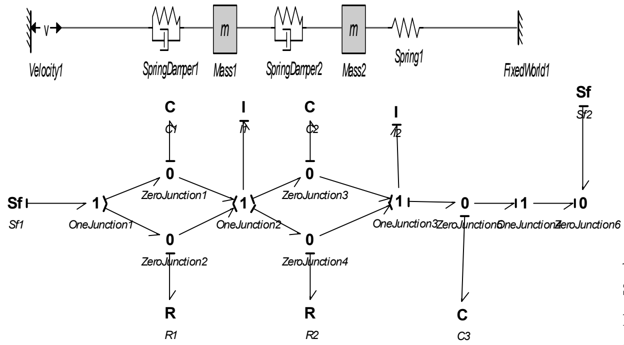

Fig. 9: Two-Mass Spring-Damping System (Example 4.11)

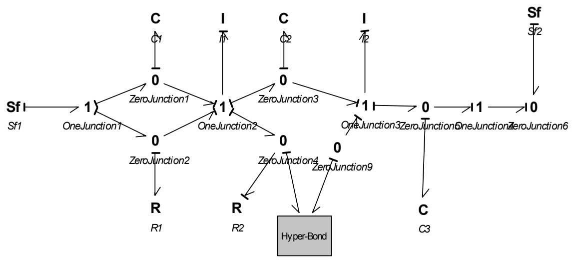

Fig. 10: Cutting and connecting via Hyper-Bond

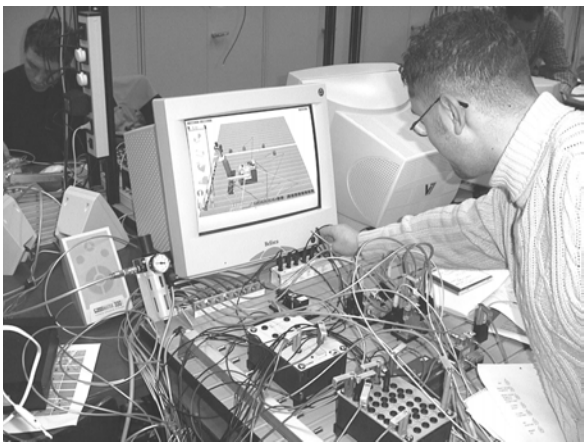

Fig. 11: Modelling in Reality and Virtuality

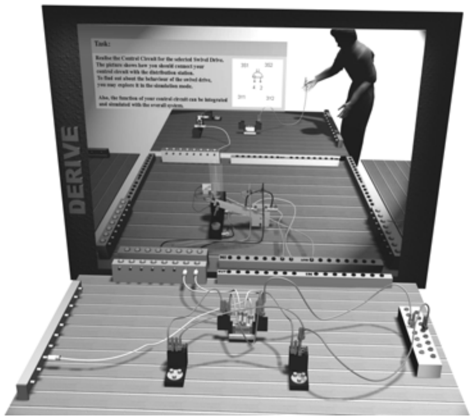

Fig. 12: Modelling in Virtuality

4. RESULTS AND CONCLUSION

A foundation of hyper-bonds has been given and some applications were presented. A general interface concept to merge physical phenomena and information flow as a continuation or modification is a powerful means to design mixed reality environments beyond those approaches which reduce the mixture to an overlay of reality and image-projections.

Several 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 (Mostermann, 1997).
2. Any network-connection induces time-delays into the control-loop, thus contributing to the risk of instability. More control theoretical work has to be done, to improve the loop dynamics (Hirche & Buss, 2003)
3. 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.

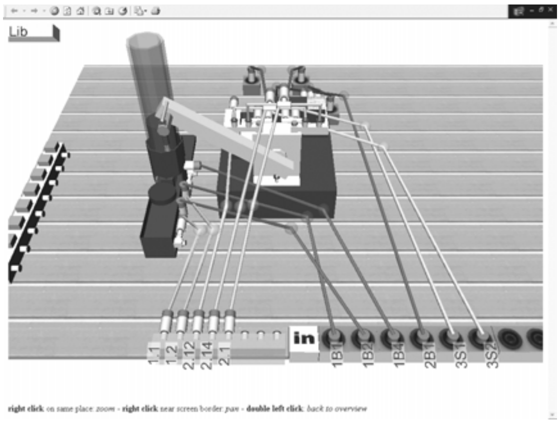

Fig. 13: Virtual Part of a System
(electro-pneumatic distribution station)

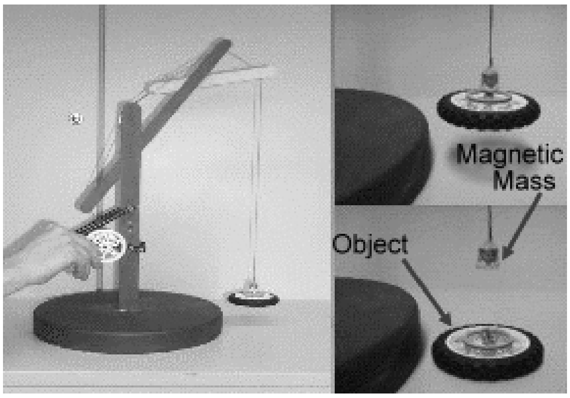

Fig. 14: Real lifter of magnetic weight
(Yoo & Bruns, 2004)

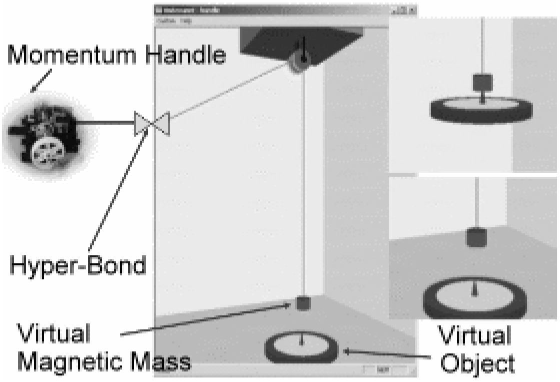

Fig. 15: Force-Feedback lifter of a virtual weight
(Yoo & Bruns, 2004)

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