

# HYPER-BONDS

## – DISTRIBUTED COLLABORATION IN MIXED REALITY –

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A concept of mixing distributed real and virtual worlds through a unified human-machine interface, connecting logical to physical phenomena, will be introduced. This approach allows the extension of ubiquitous computing and image oriented mixed reality to ubiquitous physical action. It is shown, how distributed collaboration between two or more locations and environments can benefit from this technology. Relations to control-theory and modeling are presented.

### Mixed Reality and Ubiquitous Computing

Research fields like *Mixed Reality* and *Ubiquitous Computing* beside their special orientations, deal with the problem how to connect real physical phenomena to virtual, computer internal control or simulation models. More often than not, this connection is restricted to an information projection into the real scene or into a video-capture of the real scene and to ubiquitous computing, not action and reaction. Concepts of *Embedded Systems* and *Cybernetics* have not yet been introduced into these disciplines in a unified way. There are several well developed unified 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 are available to 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 electrical phenomena (Bruns, 1999, 2001), fig. 1, opens up promising perspectives of further research to merge existing knowledge and tools from various other fields. Bond-Graph Theory is a powerful candidate because of its 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). However, there is still a high demand for interactive on the fly real time modeling and for hybrid systems with analog/discrete and real/virtual interfaces (see

control theoretical aspects at Mostermann, 1997 and Melchiorri, C., 2003, tangible media aspects at Ishii, 1997 and image-centered mixed reality work of Ohta & Tamura 1999).

No comparable approach is known to the author where it is possible to duplicate and continue the real to the virtual and vice versa on a high semantic level.

### Motivation for Hyper-Bonds and Bond-Graphs

Driven by a need of simulation experts and pedagogues to closely bring together simulation and real world phenomena, we developed several solutions to support the modeling process in mechatronics by systems specifications through concrete demonstration of the desired dynamic behavior (programming robot and conveyor systems by hand gestures and object movements). In a further development, it was possible to connect a real model to its virtual representation by image-recognition of user actions in a work- and learning-space, enabling learners and system designers to easily switch between real concrete and abstract virtual representations of the same system. Meanwhile first prototypes have been evaluated in several European Engineering and Vocational Schools, confirming our approach. A next step was, to expand this interface to a bidirectional connection, providing the user with electrical and air-pressure connectors on a real modeling desk and correspondingly in a virtual modeling world enabling him/her to connect a real pressure tube/electric wire coming from a pressure/voltage source to the interface and continue this phenomenon on a signal level in virtuality to drive a virtual component. This same process can be reversed, extending virtual signals into real physical phenomena. Using the internet for a distribution of multi-user virtual worlds then opens up new ways of distributed real-virtual co-operation. First results of a running project were we offer remote mechatronics laboratory services for European schools can be seen at <http://www.labfuture.net>. A 24 h running remote laboratory can be visited at <http://lab.artec.uni-bremen.de>.

These projects developed and evaluated hyper-bonds for low speed and discrete event driven systems. The theory of *bond-graphs* has been useful for insight into the similarity of processes from different domains, but there was no need to go into detailed modeling of the interface itself. This changes however, if we turn to high speed and continuous processes, like driving 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. A low cost solution and experiences with users for the former problem have been presented (Yoo & Bruns, 2004), fig. 2. Another scenario usable in remote maintenance, remote human-human or human-robot collaboration could be a pneumatic push through the internet, fig 3. These applications require a sound theoretical background to handle real-time problems namely the stability and quality of control of dynamic systems.

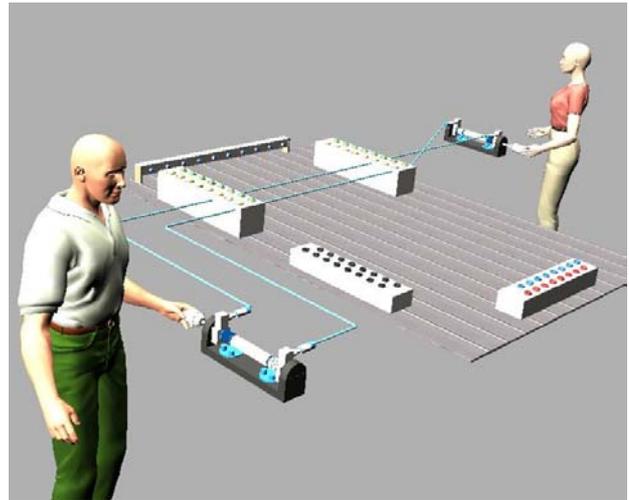


Fig. 3: Pneumatic pushing via hyper-bonds

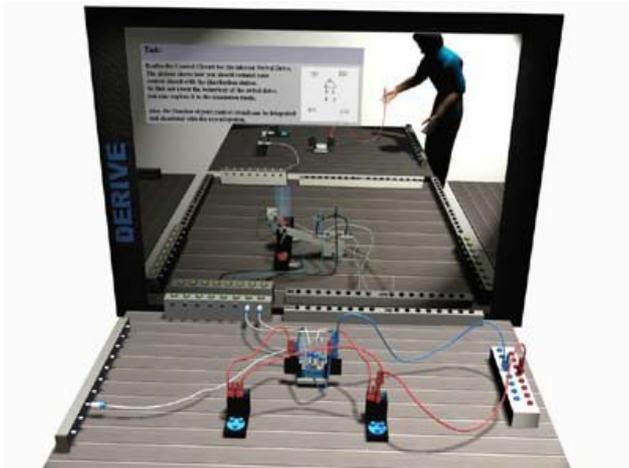


Fig. 1: Connecting real and virtual worlds

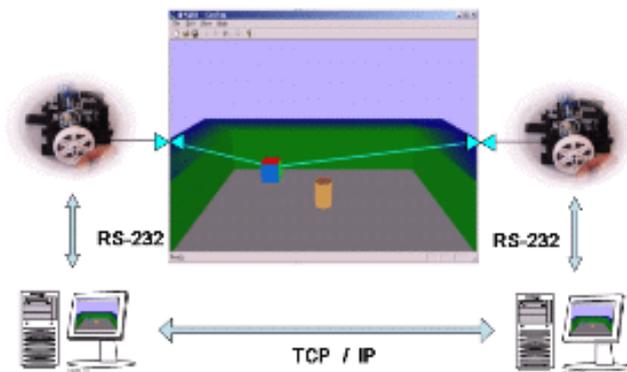


Fig. 2: Distributed Collaboration

We imagine as a far reaching perspective the ultimate hyper-bond as an extension of the famous *ultimate display* envisioned by E Sutherland (1965), who thought about a display room, where “a bullet displayed in such a room would be fatal”. From a control perspective we are not only interested in projected chairs to sit on or bullets not being hit by, but in a bi-directional action, 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, would again be converted into its virtual continuation. This scenario requires some second thoughts, but I am rather convinced that most engineers find many useful and joyful applications of this rather utopian scenario. 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.

Yoo (2004) has shown, that having some knowledge about one part of a mechatronic effort/flow network, this part can be replaced by a simple equivalent network of resistor, inductor and capacity, implemented as a real interface, thus connecting a known virtual network to an unknown real mechatronic network. This certainly is a most useful approach to connect virtuality with reality, except that necessary interface components for a full R-I-C network, are modulated capacities, which are not yet available to build a real universal hyper-bond. Furthermore, this concept might run into problems if both parts of the system are unknown. We therefore present a completely local implementation with the advantage of no necessary knowledge about the connected subsystems.

## 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, which means that it is not necessary 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.

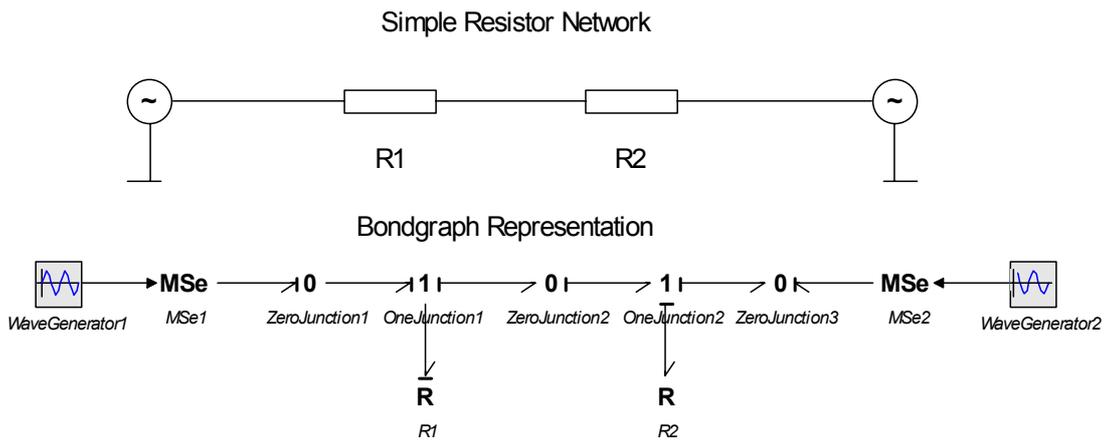


Fig. 4: Resistor Network in Bond-graph Representation

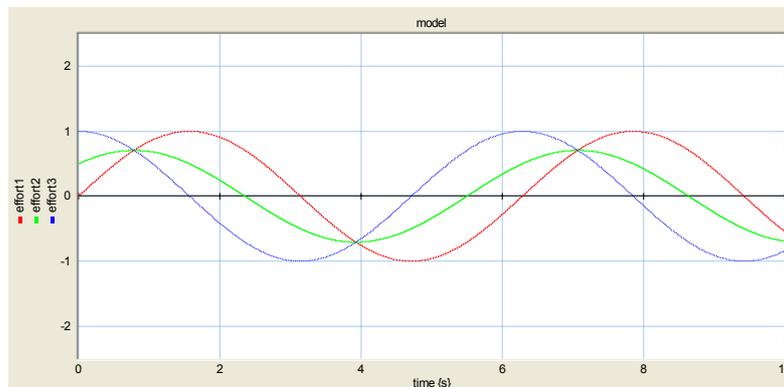


Fig. 5: Result from 20-sim simulation

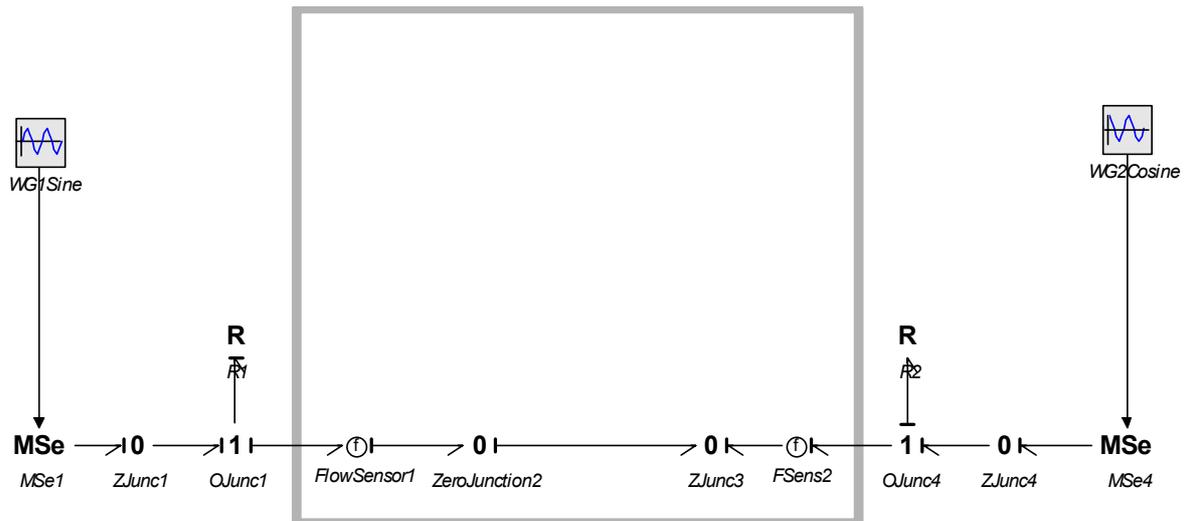


Fig. 6: Empty Concept of Hyper-bond

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. Introducing A/D-Converters at the measurement side and D/A-Converters at the generator site yields an implemented hyper-bond of fig 7. Depending on the D/A/D sampling rate, it can be seen that even for a more complex network with inductivity  $I=0.1$ , capacity  $C=0.1$  and resistor  $R=1.0$  the overall behaviour can be preserved, fig 8 and 9.

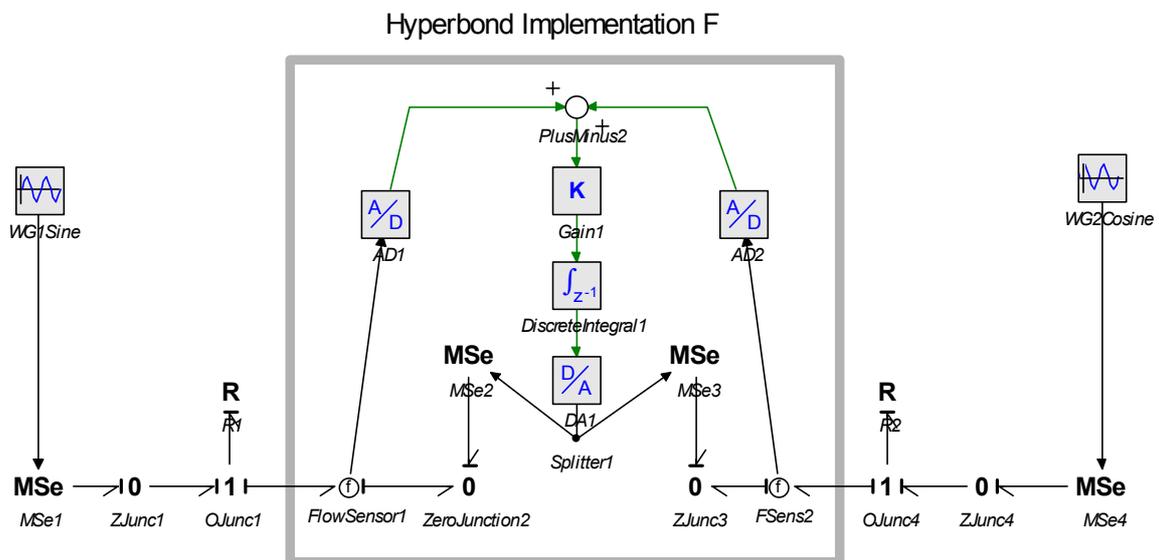


Fig. 7: Implementation of Hyper-bond F (sensing flow, generating effort)

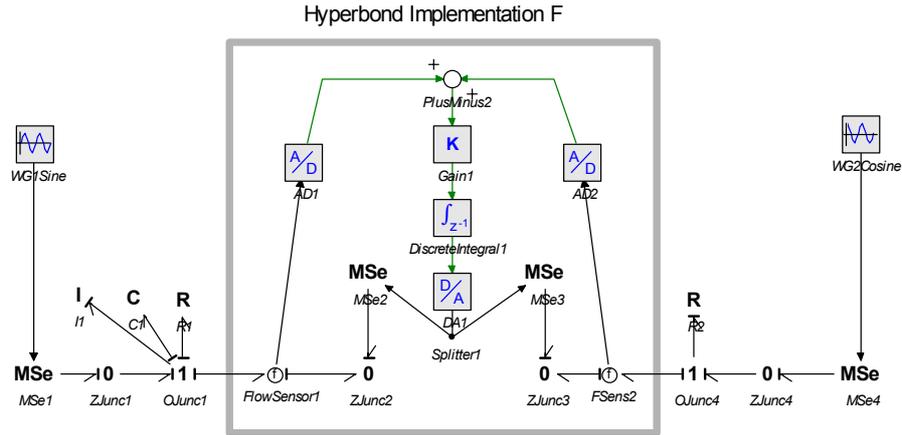


Fig. 8: Implemented Hyper-Bond for Complex System with Inductivity  $I=0.1$ , Capacity  $C=0.1$ , Resistance  $R=1.0$

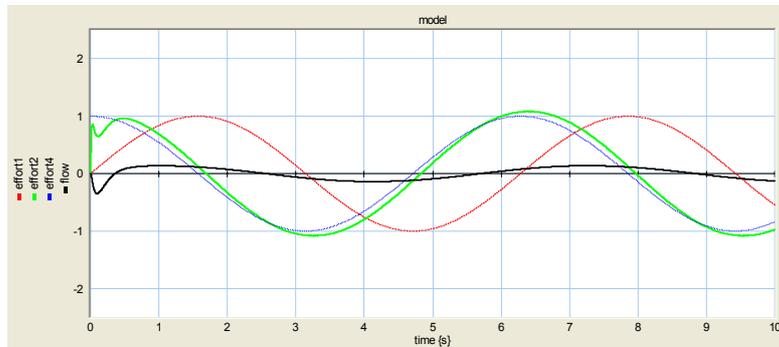


Fig. 9: Implemented Hyper-bond (Sampling Rate 1000 Hz) conformant to theoretical results

### 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 the bond-graph is a representation in a unified way, we can implement this application in other physical domains with the same dynamic characteristics if we have adequate sensor/generator devices: in translational movement with force and speed, in pneumatics with pressure and 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. 10 shows a two-mass spring-damper system and its bond-graph representation, fig 11. If we want to implement parts of the system in reality and experiment on two different levels (reality and virtuality), we only have to apply hyper-bond cuts at the desired boundaries, fig. 12.

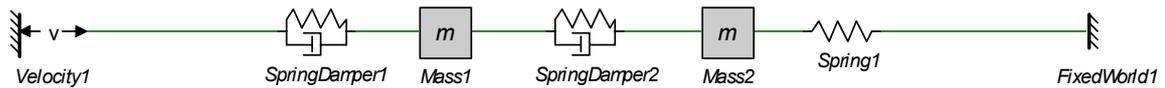


Fig. 10: Two-Mass Spring-Damping System (Example 4.11)

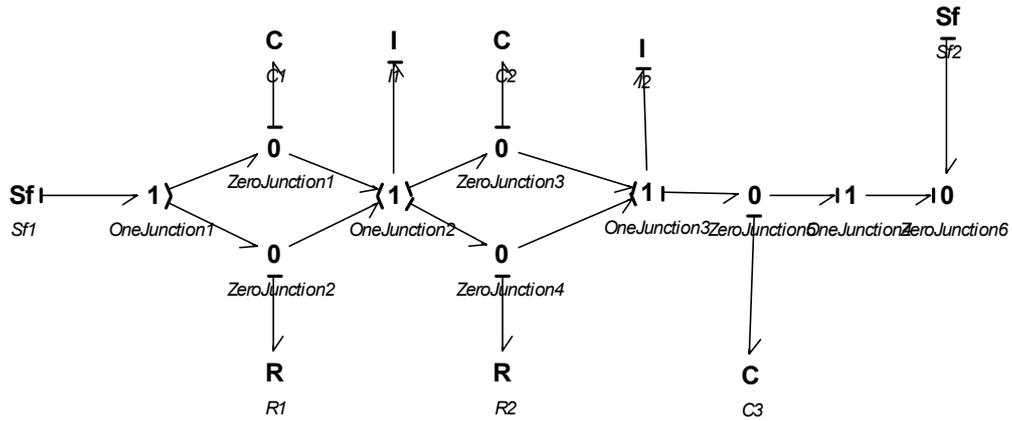


Fig. 11: Bond-graph for Two-Mass Spring-Damping System (Example 4.11)

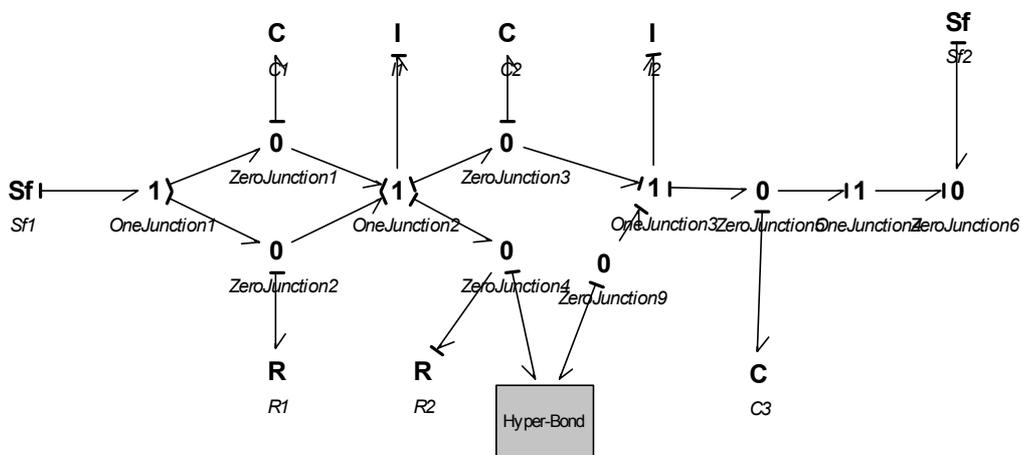


Fig. 12: Hiding the Hyper-Bond in a Sub-model

A distributed system with physical phenomena feed-back, as shown in fig. 1-3 could then be represented and realised by an information connection between two hyperbonds via some virtual model, fig. 13.

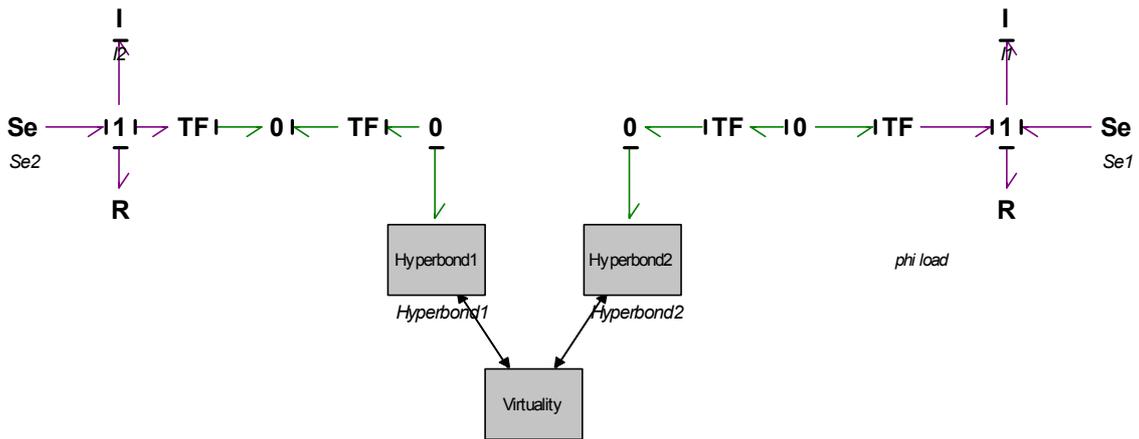


Fig. 13: Distributed Effort-Chain connected via Virtual Model

## 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 flows 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.

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.

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