ENERGY INTERFACES FOR MIXED REALITY

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Abstract: A general concept of interfaces between physical and virtual systems based on a continuity of energy-flow, introduced as *hyper-bonds*, will be extended. Power (effort × flow) can be bi-directionally transferred from the physical energy-level to the virtual signal/information-level and vice versa. In mixed reality systems, using these hyper-bonds, power connections of relevant phenomena can be described by bond graph theory. Two improvements of the hyper-bond concept are presented: 1. the explicit description of both, continuous-time dynamics of real subsystems and discrete-time dynamics of virtual subsystems in bond graphs and 2. the definition of a hyper-bond subsystem in terms of bond graphs and control-block diagrams, which can perform a power connection and conversion of continuous-time/discrete-time signals between real/virtual subsystems. An example of modeling mixed reality systems with energy interfaces (haptic ball manipulator) is demonstrated, showing the potentiality for low cost automation.

Keywords: mixed reality, haptic, bond graphs, hyper bonds, interface.

1. INTRODUCTION

Mixed reality is a field of modern technology mixing physical and virtual spaces. It is supported by

- image integration technology, mixing computer generated images with recorded video images,
- tracking technology to recognize the position of real objects, and
- interface technology to sense and generate various physical phenomena being exchanged between real and virtual objects.

Previous research classifies mixed reality as the unification of various concepts and technologies: reality, augmented by virtuality (AR), virtuality, augmented by reality (AV), tangible objects as handles for virtual object manipulation (tangible bits), and the floating shift of attention in a continuum of mixed physical and virtual phenomena (Pridmore et al., 2004). Virtual reality is experienced in an immersive way via HMD (head-mounted displays) or CAVEs (Cruz-Neira et al. 1992). Augmented virtuality attaches real objects or their video images to the virtual environment (Milgram and Kishino 1994). Shared spaces constitute a floating point in the real/virtual continuum (Benford et al. 1996). Augmented reality overlays the real world (or images of it) with digital data (Billinghurst et al. 1996). *Tangible bits* bridge the gap between the virtual space and the physical environment by providing graspable physical representations, which can be used to manipulate digital data (Ishii and Ullmer 1997).

We will present an energy interface for mixed reality, supporting a unified view on the interaction between real and virtual spaces: *hyper-bonds*. All measurement of physical phenomena and all human perceptions are based on energy exchange. However the level of involved energy might differ considerably. On a semiotic level, energy is the carrier of signs and signals, on an action level, energy is the driving force. *Tangible bits* and *hyper-bonds* both bridge the gap between real and virtual environments, but in a different way. Tangible bits operate on a semantic level, whereas hyper-bonds operate on an energetic level.
The key characteristics of tangible user interfaces are summarized in that digital information (model) is represented by graspable physical objects which are coupled with digital information, mechanisms for interactive control, and digital representations (Ullmer and Ishii 2000). However, the key of energy interfaces is to bi-directionally transfer energy into signals/information. Energy interfaces do not aim at graspable physical representations of virtual objects.

They provide energy transfers to keep energy balances between real and virtual objects.

One of the challenging problems in the energy interfaces is that physical phenomena are described in various domains in different notations — e.g., mechanical domain, electric domain, hydraulic domain. Bond graphs are suited to overcome this manifold. They give effective insights in how a mixed reality system can be designed as a whole, reusable, and easily extendible model. Thus, they contribute to cost efficient design.

A universal energy interface between real and virtual objects was first introduced by Bruns (2001) as *hyper-bonds*. The concept can be summarized as follows,

Hyper-bonds are hardware- and software implementations of a mechanism to sense and generate physical phenomena at the leading edge of an energy-connection of two subsystems (real or virtual) in a way which preserves the behavior of a comparably connected real system. Power (effort × flow) can be bi-directionally transferred from a real energy-level into a virtual signal/information-level and vice versa. Real systems, virtual systems and hyper-bonds can be described by bond graphs and analyzed according to classical control theory.

In previous research of implementing the hyper-bond concept, three methods were introduced. First, *a sensing and generating mechanism* which can switch between source and sink, generate and sense voltage/current- or pressure/volume-flow was introduced by Bruns (2001). This mechanism aims only at *discrete event* systems. Second, *Virtual Equivalence*, introduced by Yoo (2004), is an electric hyper-bond, which can replace an arbitrary virtual electric circuit by an *equivalence electric circuit* connected with a real circuit. An equivalence circuit can be used as a bi-directional power interface allowing interactions between real/virtual circuits. The necessary technology for a full R-L-C virtual circuit is, however, not yet available. Third, hyper-bond implemented as *analog subnet* is a theoretical construct running in 20-sim, presented by Bruns (2004). Given an arbitrary system, any energy connection can be replaced by a subnet hyper-bond conserving the overall behavior and providing a mechanism to separate two physical subnets connected via hyper-bond, a network of sensors and generators of effort and flow.

The following improvements of the hyper-bond concept are discussed.

- *The mixed reality bond graph modeling* — a way to describe and interpret *together* continuous-time dynamics of real subsystems and discrete-time dynamics of virtual subsystems in bond graphs; traditional bond graphs are continuous descriptions, while virtual signals/systems are discrete-time dynamics within the computer.
- *The definition of hyper-bond subsystem* — a hyper-bond must be able to be defined with the causality from continuous-time dynamics to discrete-time dynamics and vice versa because bond graphs are mathematically analyzed via derivations of causality.

Note that our research is slightly different from the concepts of switching bonds, introduced by Broenink and Wijbrans (1993), or hybrid bond graphs, introduced by Mosterman (1997): these concepts are focused on extending traditional bond graphs for modeling abrupt power changes in structure, such as breaks in pipes and wires, and overflow from tanks, causing discontinuity in system behavior.

2. MIXED REALITY BOND GRAPH MODELING

In mixed reality, real systems show continuous-time dynamics and they can be represented as *differential equations*, while virtual systems are of discrete-time dynamics running on the computer and they can be represented as *difference equations*. Continuous-time signals can be converted to discrete-time signals by sampling, and discrete-time signals can be transformed to continuous-time signals via ZOH (*Zero-Order-Hold*).

Bond graphs are continuous descriptions which contain all information needed to derive *differential equations*. In a strict sense, bond graphs for discrete-time dynamics are incomplete representations because they do not contain sampling information.

For modeling mixed reality systems using bond graphs, it is necessary to model *together* continuous-time dynamics for real subsystems and discrete-time dynamics for virtual subsystems and to couple both. Therefore, we use *two distinct bond graph notations*: bond graphs for real subsystems (using traditional notation) and bond graphs for virtual subsystems (using new notations). The new bond graph notation is marked with the sign '*'—e.g., they will be notated such as R*, I*, C*, 1*, 0*, Se* and so on. The interface between continuous-time/discrete-time dynamics is achieved by a *hyper-bond subsystem* (HB). Note that the new bond graph notation does not means a modification of the bond graph itself, but means the transformation from a bond graph modeling of virtual subsystems to discrete-time dynamics (difference equations).

Such descriptions serve the designer for

- effective insight into holistic design: real and virtual subsystems in a mixed reality system can be modeled together as a whole system using two types of bond graph notations.
- modeling and simulation with practical information for implementing the system: sampling rate, core algorithms (difference equations for virtual subsystems and hyper-bond), and hardware structures (for real subsystems and hyper-bond).

Fig. 1 shows our concept of mixed reality bond graph modeling. Power is transferred from real to virtual or vice versa via a hyper-bond subsystem.

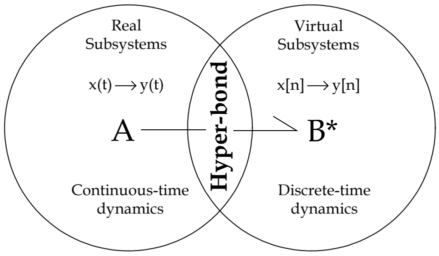

Fig. 1: The concept of mixed reality bond graph modeling

3. HYPER-BOND SUBSYSTEM AND CAUSALITY

The bond in bond graphs means a power connection in which power (effort × flow) flows from one subsystem into another. Bond graphs are mathematically analyzed by causality reasoning. Causality reasoning is a process of determining the computational direction of the bond variables, effort and flow. At each port, we have two variables: effort and flow, but only one of them can be controlled (Fig. 2a and Fig. 2c).

Such power connections and causality are unavailable in the traditional computer interface (e.g., A/D or D/A converters). That is, the traditional computer interface cannot absorb or discharge real power from or to real environments. It merely provides unidirectional-electric-conversions at extremely low power.

We therefore introduce a *hyper-bond subsystem* to overcome this difficulty. It can perform a power connection and conversion of continuous-time and discrete-time signals between real and virtual subsystems. Its *causality* is a process of determining the computational direction of the continuous-time and discrete-time variables. Fig. 2b and Fig. 2d show symbol, causality, and constructs of the hyper-bond subsystem. It consists of effort/flow samplers T, connection-impedance Z, effort or flow generator (MSe or MSf) MS, a zero-order-hold ZOH, and a gain K—PI, PD, or PID controllers may be used for improving transient response and steady-state error.

MS absorbs or discharges real power—it may be an electric power supplier, air-compressor, etc. Z includes elements to physically connects a real subsystem and a generator MS. Note that MS and Z should be selected on the condition of connecting to the real subsystem. Sampling rate for virtual modeling is decided by sampler T of the hyper-bond subsystem and it is propagated to all virtual subsystems.

There are two combinations of the hyper-bond causality. One is that the *effort* from a real subsystem determines the input signal of a virtual subsystem via a hyper-bond subsystem and the flow signal from a virtual subsystem generates the input flow into a real subsystem via a hyper-bond subsystem (Fig. 2b). The other is that the *flow* from a real subsystem determines the input signal of a virtual subsystem via a hyper-bond subsystem and the effort signal from a virtual subsystem generates the input effort into a real subsystem via a hyper-bond subsystem (Fig. 2d).

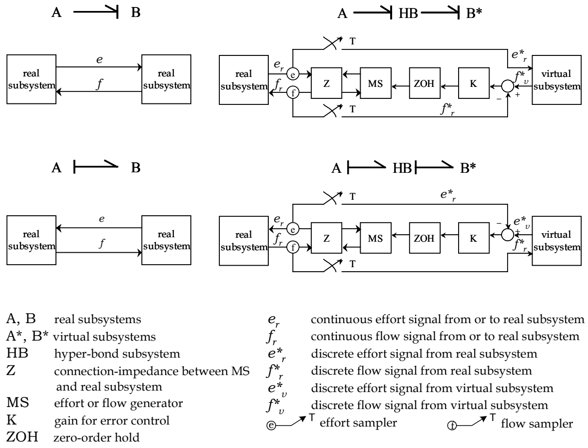

Fig.2: (a) and (c) are bond graph symbol/causality, and (b) and (d) are hyper-bond symbol/causality

4. HAPTIC BALL MANIPULATOR — AN EXAMPLE OF MIXED REALITY BOND GRAPH MODELING

According to their input/output behavior, haptic interfaces can be characterized as impedance haptic, if position or velocity is sensed and the force is generated or as admittance haptic, if the force is sensed and the position or velocity is generated. Impedance-type architectures are most common, because they measure only position or velocity, while admittance-type architectures require measuring both position or velocity, and force. Although many haptic interfaces are of the impedance-type, admittance type offer distinct advantages, such as high damping and stiffness behavior, particularly in applications requiring precise motion control. (ref. Adams and Hannaford 1999 or Ueberle and Buss 2004).

In the following, an admittance-haptic ball manipulator is used for demonstration. Its construction is shown in Fig. 3. Rotational input from the user is changed into translational motion of a virtual ball, while power is transferred from a user's handle to the virtual ball *m*; the user's handle is provided with haptic feedback from a virtual spring and the ball. If the torque imposed on the user's handle exceeds the force of the virtual spring, the ball *m* will be moved. If the virtual ball collides with a virtual object M, collision energy is added to the behavior of the haptic ball manipulator.

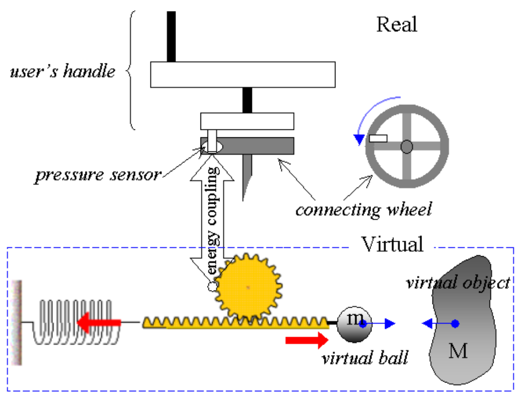

Fig. 3: Structure of haptic ball manipulator

The pressure sensor and the edge of the pinion are energy coupling points (Fig. 3). Thus, a traditional bond graph modeling of ball manipulator which is not considered the haptic interface is shown in Fig. 4. In the real part of Fig. 4, MSe1 is the force imposed on the user's handle; I3 is the inertia of the user's handle. 1/C2 and R3 are the stiffness and the friction of the user's handle. TF1 is a power transformer between the user's handle and the pressure sensor on the connecting wheel. In the virtual part of Fig. 4, e_{portA} is the force imposed on the pressure sensor (i.e., the port A); I2 is the inertia of the virtual pinion; R2 is the friction between the rack/pinion; R1 is the friction of the virtual spring; I1 is the inertia of the virtual ball/rack. 1/C1 is the stiffness of the virtual spring. MSe_2 is the collision force when the virtual ball collides with the virtual object. The behavior of the handle and mass position of the model of Fig. 4 are shown in Fig. 5 : step inputs are imposed for a user's force after 1 sec from the start and a collision force in an opposite direction after 5 sec from the start, R1 = 5 N-m-s, I1 = 1 N-s^2/m, C1 = 0.02 m/N, C2 = 0.0001 m/N, R2 = 5000 N-m-s, R3 = 10 N-m-s, I2 = 0.05 N-s^2/m, I3 = 1 N-s^2/m, TF1 = 0.8.

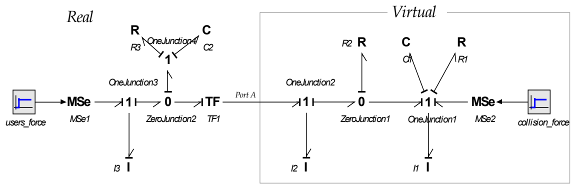

Fig. 4: Traditional bond graph model of ball manipulator (not considered the haptic interface)

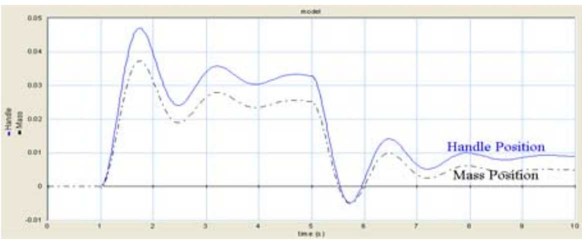

Fig. 5 : Behaviors of handle (I3) position and mass (I1) position of Fig. 4

A mixed reality bond graph modeling to achieve the haptic interface of the ball manipulator is demonstrated in Fig. 6. Real/virtual subsystems are described by two types of bond graph notations, and are connected via a hyper-bond subsystem (mentioned in the parts 2 and 3). The new bond graph notations marked with the sign '*' mean discrete-time dynamics transformed from the traditional bond graph modeling of virtual subsystems of Fig. 4, and their sampling rate is decided by the hyper-bond subsystem. Thus, from the model of Fig. 4, the space-state equations of virtual subsystems can be derived as follows,

$$\begin{bmatrix} \frac{df_{C1}}{dt} \\ \frac{df_{I2}}{dt} \\ \frac{de_{C1}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_1+R_2}{I_1} & \frac{R_2}{I_1} & -\frac{1}{I_1} \\ \frac{R_2}{I_2} & -\frac{R_2}{I_2} & 0 \\ \frac{1}{C_1} & 0 & 0 \end{bmatrix} \begin{bmatrix} f_{C1} \\ f_{I2} \\ e_{C1} \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{I_1} \\ \frac{1}{I_2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_{portA} \\ MSe_2 \end{bmatrix} \quad (1)$$

$$f_{I1} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_{C1} \\ f_{I2} \\ e_{C1} \end{bmatrix} \quad (2)$$

$$e_{I1} = \begin{bmatrix} -(R_1+R_2) & R_2 & -1 \end{bmatrix} \begin{bmatrix} f_{C1} \\ f_{I2} \\ e_{C1} \end{bmatrix} + MSe_2 \quad (3)$$

$$f_{portA} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} f_{C1} \\ f_{I2} \\ e_{C1} \end{bmatrix} \quad (4)$$

where f_{I1} , e_{I1} are output equations of force and velocity of the virtual ball and f_{portA} is an output equation of velocity in the energy coupling point.
With the sampling rate decided in the hyper-bond subsystem, z-transfer functions of the discrete-time dynamics of Fig. 6 can be transformed from Eq. 1-4. They are described as follows,

$$G_1(z) = Z_{Transform}\left[\frac{E_{I1}(s)}{E_{portA}(s)}\right],\quad G_2(z) = Z_{Transform}\left[\frac{F_{portA}(s)}{E_{portA}(s)}\right],$$
$$G_3(z) = Z_{Transform}\left[\frac{F_{I1}(s)}{E_{portA}(s)}\right],\quad G_4(z) = Z_{Transform}\left[\frac{E_{I1}(s)-E_{collision}(s)}{E_{collision}(s)}\right],$$
$$G_5(z) = Z_{Transform}\left[\frac{F_{portA}(s)}{E_{collision}(s)}\right],\quad G_6(z) = Z_{Transform}\left[\frac{F_{I1}(s)}{E_{collision}(s)}\right] \quad (5)$$

where G_1,G_2, and G_3 are z-transfer functions when $E_{collision}$ is zero and G_4, G_5, and G_6 are z-transfer functions when E_{portA} is zero. If values of parameters of Eq. 1-4 equal those of Fig. 4, and the sampling rate of the hyper-bond subsystem is 0.001 seconds—it is the common servo rate for haptic interfaces (Kenneth el al. 2004)—, the poles of the z-transfer functions will be inside unit circle in the z-plane. Thus, the discrete-time dynamics of virtual subsystems are stable.
We selected the hardware structures of Fig. 7 as the hardware of hyper-bond subsystem for the ball haptic manipulator. In this case, the generator MS is a current supplier (MSf); components of the connection-impedance Z between the current supplier and the connecting wheel are DC motor (GYz), friction and inertia of shafts and gears (Rz and Iz). Position values from the position encoder are changed into velocity values. Fig. 8 shows a hyper-bond modeling in draft and the real load (user's handle).

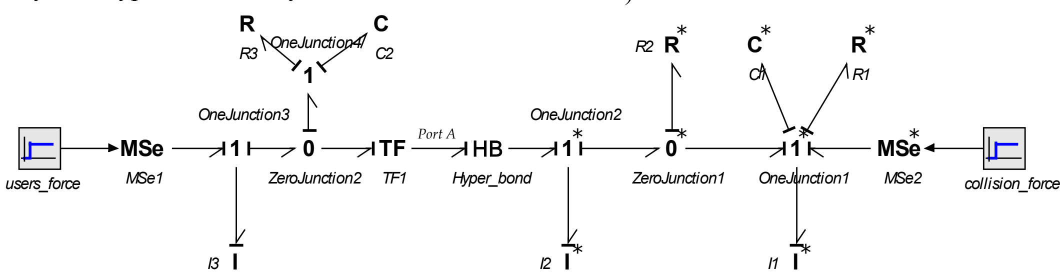

Fig. 6 : Mixed reality bond graph modeling of the haptic ball manipulator

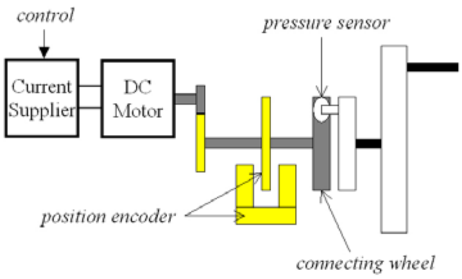

Fig. 7 : Sketch of hardware parts of the hyper-bond subsystem.

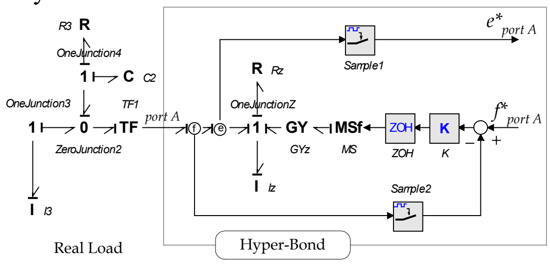

Fig. 8: Hyper-bond subsystem for the haptic interface

Requirements of transient response, stability, and steady-state error (ref. Benjamin 1995) are important keys to select or find parameters of connection-impedance Z and generator MS. Selecting that Rz is 10 N-m-s, Iz is 1 N-s^2/m, r of GY is 1, the forward transfer function $G_{forward}$ between f^*_{portA} and f_{portA} is as follows,

$$G_{forward}(z) = \frac{f_{portA}}{f^*_{portA}} = \frac{K(0.001z^2 - 0.00199z + 0.001)}{z^3 - 2.964z^2 + 2.954z - 0.99} \qquad (6)$$

Root locus of the unity feedback system that has the forward transfer function $G_{forward}$, is sketched as Fig. 9 and the system is stable for K between 0 and 1995. Therefore, K, that ensures to be stable and damping ratio 0.7, is 1060.

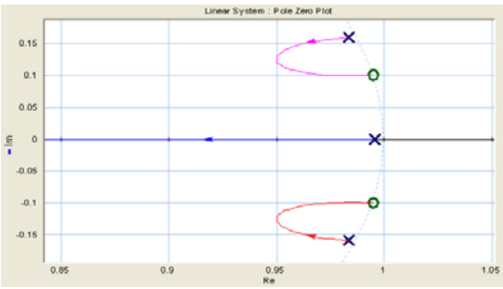

Fig. 9 : Root locus of the unity feedback system that has the forward transfer function $G_{forward}$

Fig. 10 shows behaviors of handle/mass positions when the system has $G_{forward}$ such as Eq. 6 and its K is 1060. Comparing this behaviors with the behaviors of Fig. 5, it shows a steady-state error because of the positive feedback via *sample1*. Such a steady-state error can be reduced by PI (proportional integral) controller.

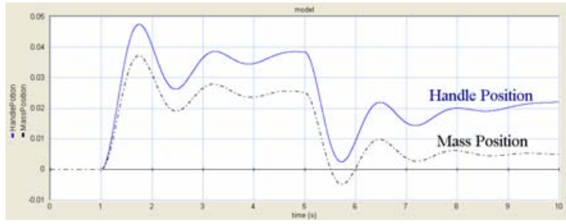

Fig. 10 : Behaviors of handle (I3) position and mass (I1) position when the system has $G_{forward}$ such as Eq. 6 and its K is 1060.

The mixed reality bond graph modeling (Fig. 6) is implemented in 20-sim such as Fig. 12. PI controller has 0.1 as integral gain. *DiscreteDifferential1*, *DiscreteIntegral1*, and *q-sensor* (position sensor) are components to use position input instead of velocity input (*f- sensor*). The simulation of it is shown in Fig. 11 and is in good agreement with Fig. 5.

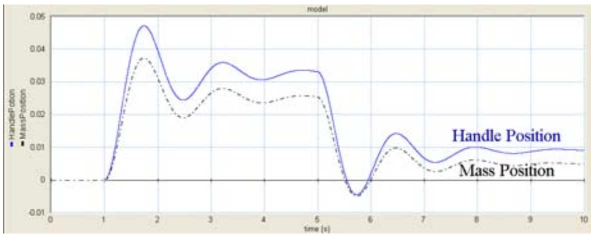

Fig. 11 : Behaviors of handle (I3) position and mass (I1) position of the implementation Fig. 10

6. CONCLUSION

A concept of energy interfaces in mixed reality has been introduced. This concept aims at a complementary view to the semiotic oriented view of tangible bits. For mechatronic systems design, an energetic view has advantages with respect to cost efficiency and reliability, because it supports a holistic approach and provides control-theoretical foundations. The hyper-bond concept for universal energy interfaces, introduced by Bruns (2001), could be improved in two ways: 1. a way was presented to describe and interpret together continuous-time dynamics of real subsystems and discrete-time dynamics of virtual subsystems in bond graphs and 2. the causality of hyper-bonds was elucidated.

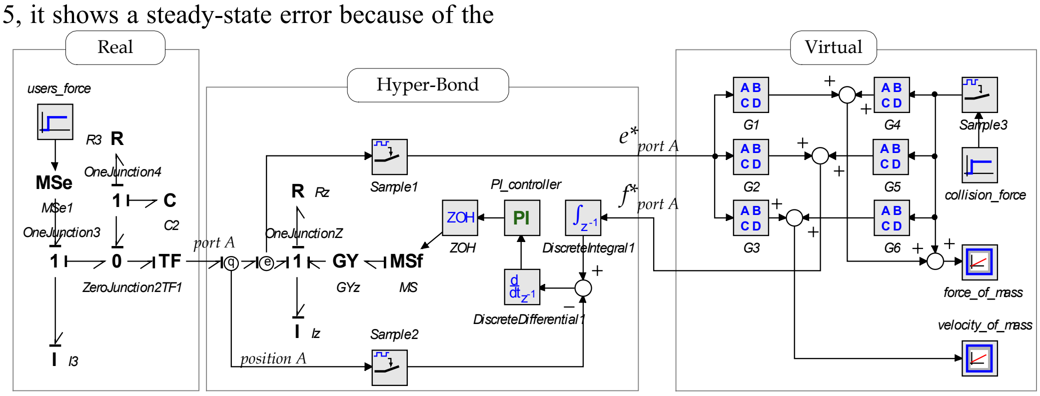

Fig. 12: Implementation of the mixed reality bond graph modeling of Fig. 6 in 20-sim

A practical example of the mixed reality bond graph modeling was demonstrated. In this example, continuous-time dynamics of real subsystems, discrete-time dynamics of virtual subsystems and their energy interface, hyper-bonds, are explicitly described and analyzed using bond graphs. It is shown that the hyper-bond concept can not only be applied to physical phenomena of mixed reality but also to the physical phenomena of the interface itself and the virtual part of the model.

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