International Journal on Engineering, Science and Technology
Volume 2, Issue 1, 2020 ISSN: 2642-4088

Bus-Approach for Engineering and Design of Feedback Control

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Abstract: A new method of design of closed control loops with one or more controlled variables is proposed. A feedback control system, represented with traditional transfer functions, will be described in the non-traditional way as a bus. It is not a real fieldbus used in the industry communications, but a symbolic one, which could be calculated for engineering purposes and also simulated with MATLAB/Simulink. For a simple control loop with only one controller and one plant the bus-approach has not many advantages against traditional block diagram. But the application of the bus-approach for the systems with many controllers or many plants, also for MIMO-Control (*Multi Input Multi Output*) has many significant advantages, which are shown in proposed paper.

Keywords: Closed Loop Control, Transfer Function, Redundant Control, Cascade Control, MIMO-Control

Basics of Bus-approach

The simple example of a closed loop for feedback control is shown in Figure 1. The loop consists of a plant with the transfer function $G_S(s)$ and the controller with the transfer function $G_R(s)$, where s is the Laplace-Operator. The variables are:

$x(s)$ – process variable PV
$w(s)$ – set point SP
$y(s)$ – actuating variable
$e(s)$ – error

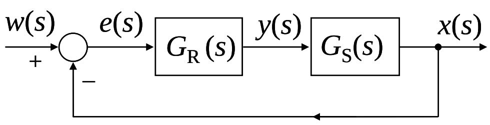

Figure 1. Block Diagram of a Feedback Control as a Closed Loop

The bus-approach means that the controller and the plant are connected as local devices between two buses-wires (see Figure 2). The bus is not a real fieldbus with protocols, telegrams and so on, but a symbolic connection, a virtual bus, which links the blocks of the feedback control together. It is supposed, that there is a connection between two bus wires on the left and on the right sides. Both wires are called $x(s)$. On this way is mentioned the feedback, which is not shown in Figure 2 to simplify the block diagram.

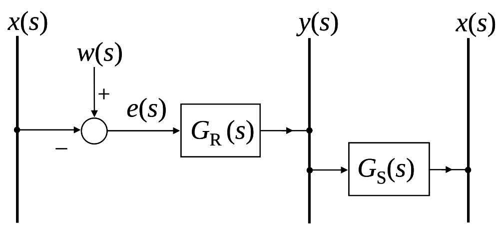

Figure 2. Block Diagram of a Feedback Control as a Virtual Bus ([1], p. 1)

This feedback is clearly seen in the MATLAB/Simulink-model, given in Figure 3. Two kinds of standard blocks of the library "Signal Routing" are implemented, namely: "Bus Creator" and "Bus Selector". All inputs and outputs of the bus, which are not used for actual control, should be connected to the terminator or to constants.

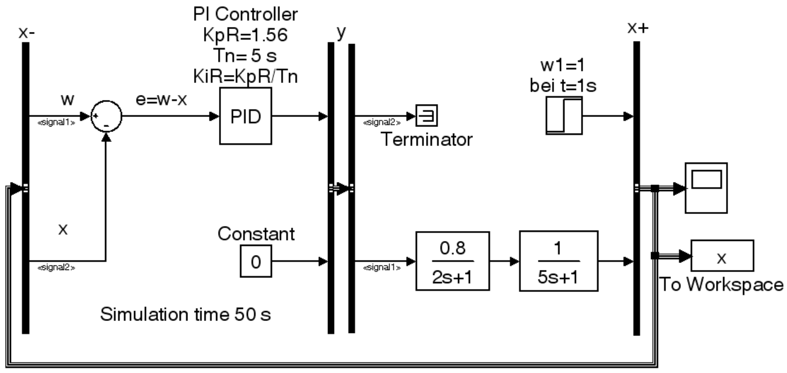

Figure 3. MATLAB/Simulink Model of bus-approach for a feedback control ([1], p. 3)

On the same way, as shown in Figure 1 and Figure 2, we can apply the bus approach for any kind of feedback control. An example of both block diagrams for common case with the set point $w(s)$ and the disturbance $z(s)$ as classical loop and as virtual bus is given in Figure 4.

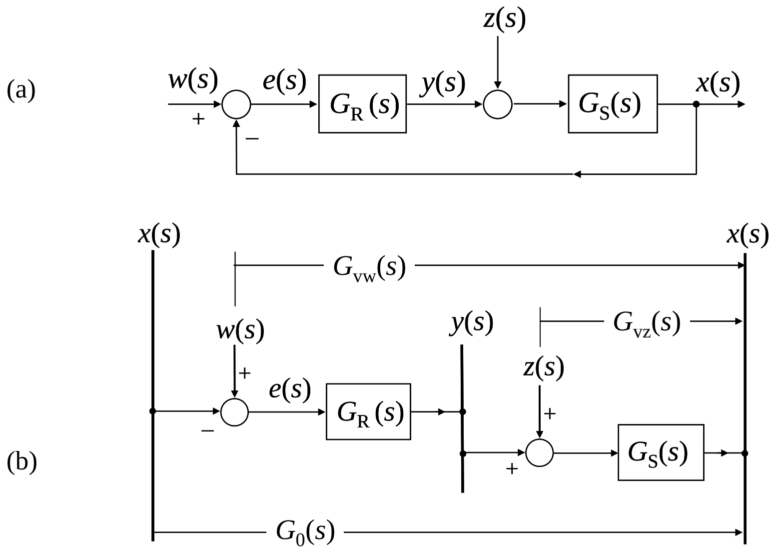

Figure 4. Classical Closed Loop (a) and Bus-approach (b) for the Same Feedback Control ([1], p. 6)

With the bus-approach is easier to define the transfer functions as on the classical way with the closed loop. According to the block-diagram of Figure 4(b) the transfer function of an open loop G_0 is the signal way from the left bus wire $x(s)$ to the right wire $x(s)$. The transfer functions $G_{vw}(s)$ and $G_{vz}(s)$, which are called “forward-transfer functions” will be defined as the signal way from signal source, accordingly from $w(s)$ or $z(s)$, untill output $x(s)$. It results to transfer functions of reference behaviour $G_w(s)$ and of disturbance behaviour $G_z(s)$ as given in the Table 1.

Table 1. Transfer Functions of a Feedback Control According to Figure 4

Transfer function	*Reference behaviour*	*Disturbance behaviour*
Forward transfer function	$G_{vw}(s) = G_R(s)G_S(s)$	$G_{vz}(s) = G_S(s)$
Open loop transfer function	$G_0(s) = G_M(s)G_R(s)G_S(s)$	
Closed loop transfer function	$G_w(s) = \dfrac{G_{vw}(s)}{1+G_0(s)}$	$G_z(s) = \dfrac{G_{vz}(s)}{1+G_0(s)}$

Application of the Bus-approach for Simple Loops

All kinds of classical closed loops could be performed and simulated with bus-approach as described below.

Separate Control for Many Plants

Using bus-approach it is possible to simulate many separated closed loops with one bus as it is given in Figure 5.

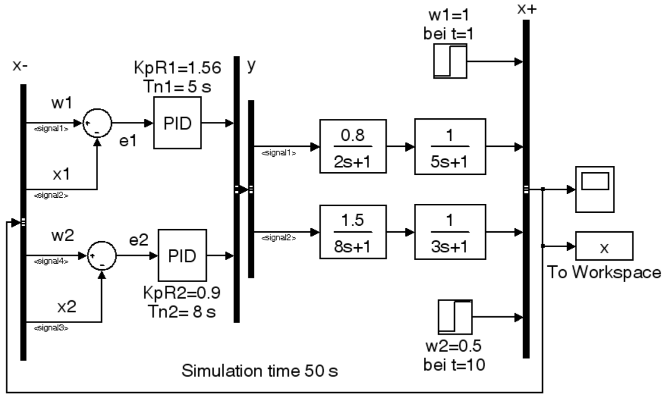

Figure 5.Bus-approach for Two P-T2-plants, Each Controlled with its PI-controller ([1], p. 10)

Disturbance Compensation

With the disturbance compensator $G_{Rz}(s)$, shown in Figure 6, it is possible to completely eliminate the influence of the disturbance z. The compensator $G_{Rz}(s)$ is calculated so, that after a step of disturbance z = 2 by t =30 s the condition $x(s)$ = 0 will be fulfilled. In this example is needed the condition $G_{vz}(s) = G_S(s)$, which results to the following transfer function of the compensator:

$$G_{Rz}(s) = \frac{1}{G_R(s)} \quad \Rightarrow \quad G_{Rz}(s) = \frac{1}{K_{PS}} = \frac{1}{0{,}94}$$

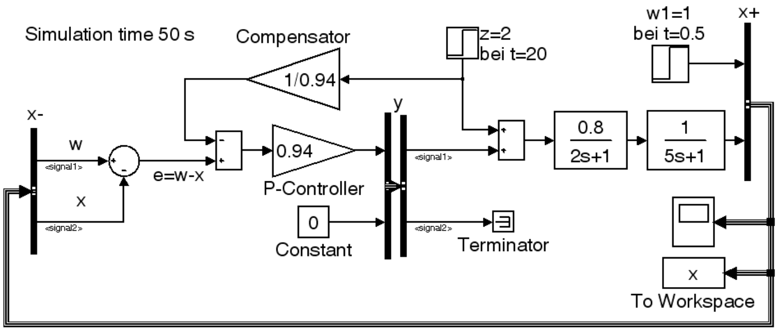

Figure 6. Disturbance compensation with Bus-approach ([1], p. 9)

Cascade Control

A cascade control (Figure 7) is also no exception for the use of bus-approach. The relations between main controlled variable $x(s)$ and its set point $w(s)$ are well known. The same about the internal variable $x_1(s)$:

$$G_{01}(s) = \frac{x_1(s)}{e_1(s)} \quad \Rightarrow \quad G_{w1}(s) = \frac{x_1(s)}{w_1(s)} = \frac{G_{01}(s)}{1+G_{01}(s)}$$

$$G_0(s) = \frac{x(s)}{e(s)} \quad \Rightarrow \quad G_w(s) = \frac{x(s)}{w(s)} = \frac{G_{w1}(s)}{1+G_{w1}(s)}$$

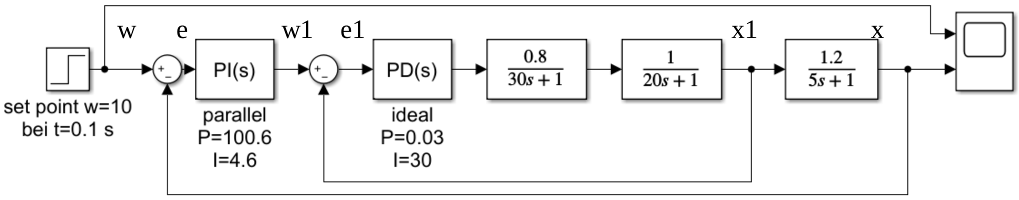

Figure 7. Classical Cascade Controls

The loop of Figure 7 is simulated in Figure 8 with bus-approach. It has the same transfer functions as above.

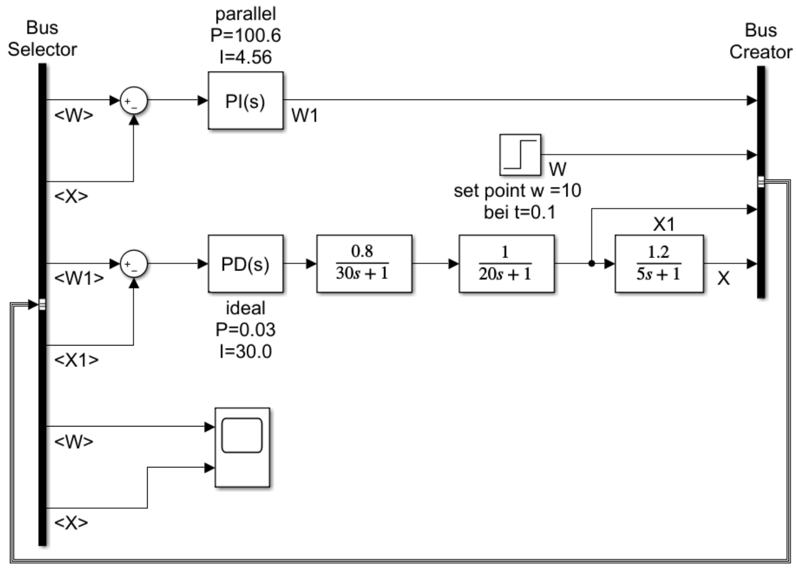

Figure 8. Cascade Control with Virtual Bus

Redundant Control

The P-T2 plant given in Figure 9 is controlled with the main PI-controller with actuating value “control”. Another PI-controller with actuating value “safe”, called *redundant controller*, has the same parameters as the first controller and is connected to the same bus. If a disturbance occurs, the “safe” and “control” variables will differ one from another and the redundant switch will connect the redundant controller instead of main controller.

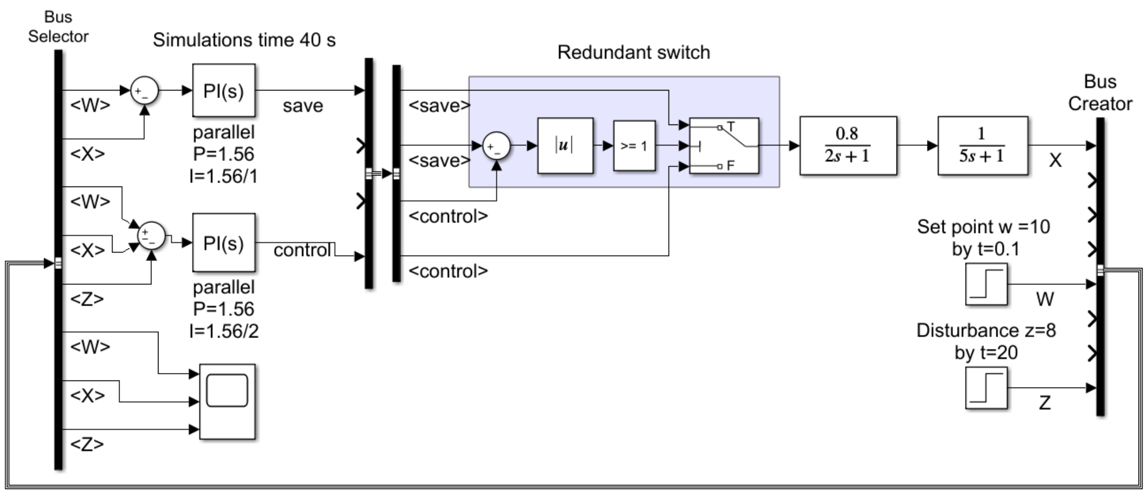

Figure 9. Bus Approach for Redundant Control with Two Identical Controllers

Bus-Approach for MIMO-Control

For simple control loops, discussed above, the bus-approach lets simulate a feedback control comfortably, but has not many advantages against classical closed loop. In opposite the application of the bus-approach for the multivariable feedback control like [3], so called MIMO-Control (*Multi Input Multi Output*), has many significant advantages.

Decoupling Control

The main problems by analysis and design of MIMO systems are dimensionality and interactions. The first problem is known as “curse of dimensionality”, first introduced in [4]. According to MIMO control it means the difficulties to describe such systems with transfer functions. The only known way to avoid this problem is to dispense with transfer functions and to represent a MIMO as state space model.

The interactions are connections between input and outputs of MIMO, which couple the controlled variables. Decoupling is compensation of interactions. Such decoupling is easy to realise by MIMO dimension of n = 2, like described in [1, 2] and shown in Figure 10 (the compensated signal ways are 1-2-3-4).

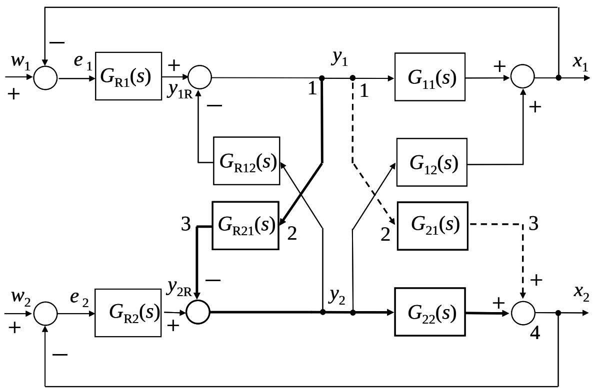

Figure 10. Decoupling Feedback Control by n = 2 ([1], p. 44)

By n < 2 occurs the “curse of dimensionality” and hampers the decoupling. On the classical way it is difficult to represent such systems in a block diagram and to decouple them, like in an example Figure 11 for n = 3.

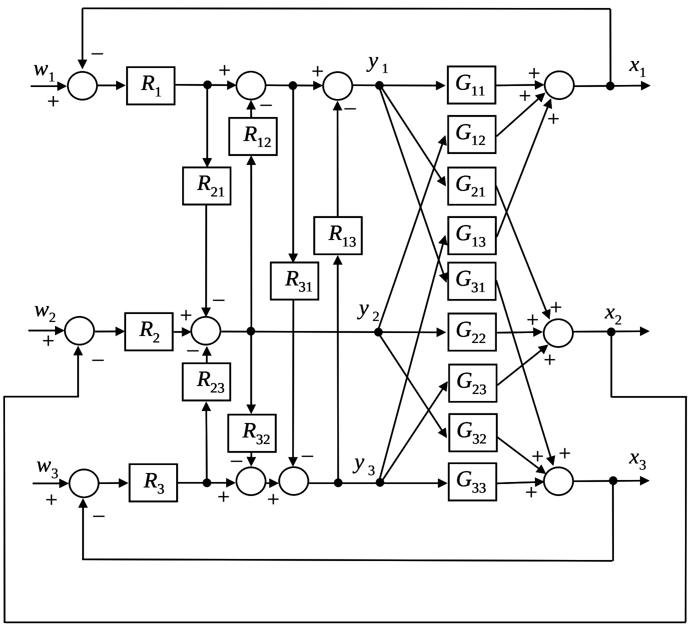

Figure 11. Decoupling MIMO-control as Classical Loop with n = 3 ([1], p. 83)

However it is no problem by bus-approach, like shown in Figure 12 and simulated in Figure 13. In the block diagram of Figure 12 are clearly seen the signal ways, so they are easy to track. The signal way 1-2 or $a_{12}(s)$ will be compensated with the signal way 1-3-4 or $R_{12}(s)$ following with 4-5 or $G_{11}(s)$, which results to the transfer function of the first decoupling controller. Similarly the signal way 6-7 or $a_{21}(s)$ will be compensated with the signal way 6-8 or $R_{13}(s)$ following with 8-3-4-5 or $G_{22}(s)$, which results to the second decoupling controller:

$$R_{12}(s)G_{11}(s) = a_{12}(s) \qquad \Rightarrow \qquad R_{12}(s) = \frac{a_{12}(s)}{G_{11}(s)}$$

$$R_{13}(s)G_{11}(s) = a_{13}(s) \qquad \Rightarrow \qquad R_{13}(s) = \frac{a_{13}(s)}{G_{11}(s)}$$

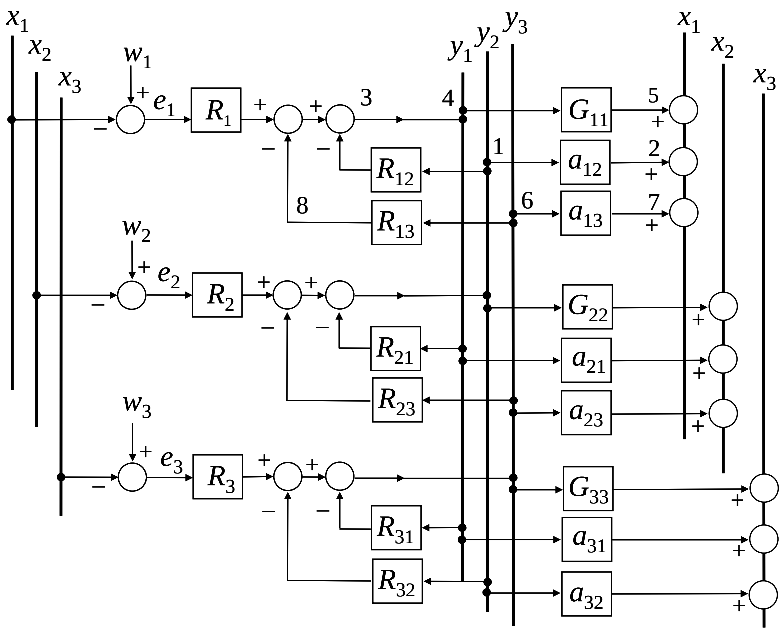

Figure 12. Decoupling MIMO-control with Bus-approach for n = 3 ([1], p. 84)

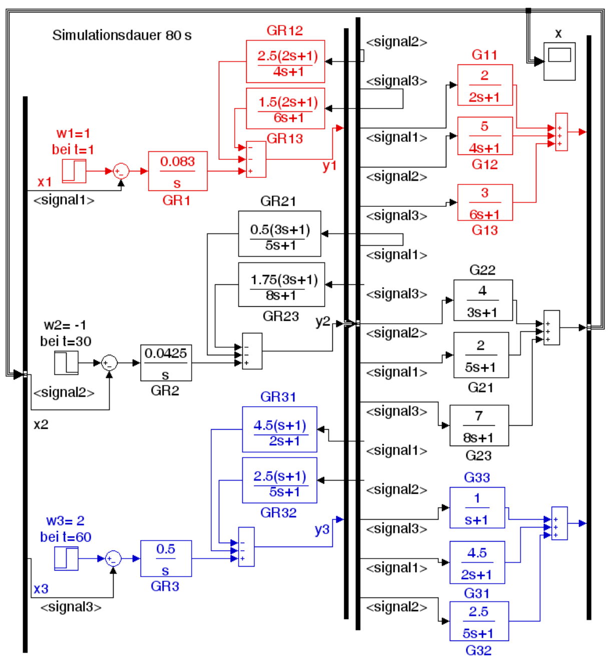

Figure 13. MATLAB/Simulink Model for MIMO-control of Figure 12 ([2], p. 269)

Router Instead of Decoupling

Bus-approach is not only the way to describe the classical closed loops and to simplify the decoupling. The new point of view on MIMO systems lets accelerate the controlling time and eliminate undesired derivative terms (D-terms), as it is done in [1]. Except of this a new element of the virtual bus system, called *Router* in [1], is developed on another principle as a classical decoupled controller (see Figure 14).

A router is a kind of model based filter and consists of transfer functions, which are identical to transfer functions of the main plant (see Figure 15). Due to such construction of router it is easy to tune it, taking in account only transfer function of the main plant. For example the router 1 is adjusted corresponding only to the main plant G_{11} (see Figure 14). The transfer function of coupling plant a_{12} has no meaning for parameters of the router 1. The same is for the router 2, namely, its parameters are depended only of the transfer function G_{22}; the transfer function of coupling plant a_{21} has no meaning for the router 2.

The function of router is not to compensate the interactions of plant, but to distribute the actuating values of main controllers to appropriated parts of plants. Significant is, that a router gets its inputs not from decoupling controllers as by classical MIMO-control, but only from each main controller. The decoupling controllers will be omitted in the loop, which reduces the number of control blocks.

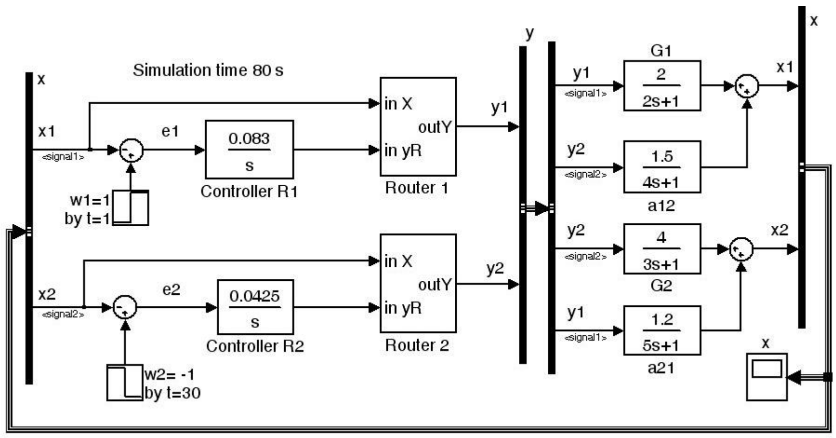

Figure 14. MIMO-control with Two Routers for n = 2 ([1], p. 147)

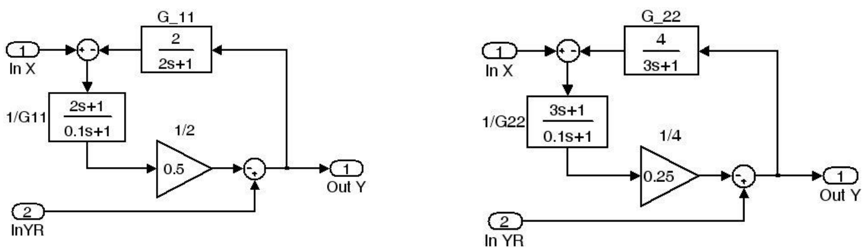

Figure 15. Router 1 (on the left) for Main Variable y_1 und Router 2 for Variable y_2 ([1], p. 148)

With the router becomes the MIMO-control new quality and could be easily extended for plants of any higher order. As an example is shown in Figure 16 the MIMO-control with 4 routers for n = 4 controlled variables.

Conclusion

Bus-approach is a new representation of closed loops, which allows the use of all known engineering methods for feedback control in time domain, in Laplace-domain and in frequency domain. For simple control loops with only one controlled value the bus-approach has not many advantages against traditional block diagram. But its use for two or more separate closed loops and for redundant control reduces the analyses and design. The engineering of MIMO-Control with bus-approach is much simpler and has many advantages against traditional methods, known in the literature. With bus-approach it is possible to tune controllers avoiding methods of state space control and to realize the MIMO-control without decoupling controllers. For this purpose a new element, called router, is proposed. The actuating values of main controllers will be distributed with router to appropriated parts of MIMO-plant.

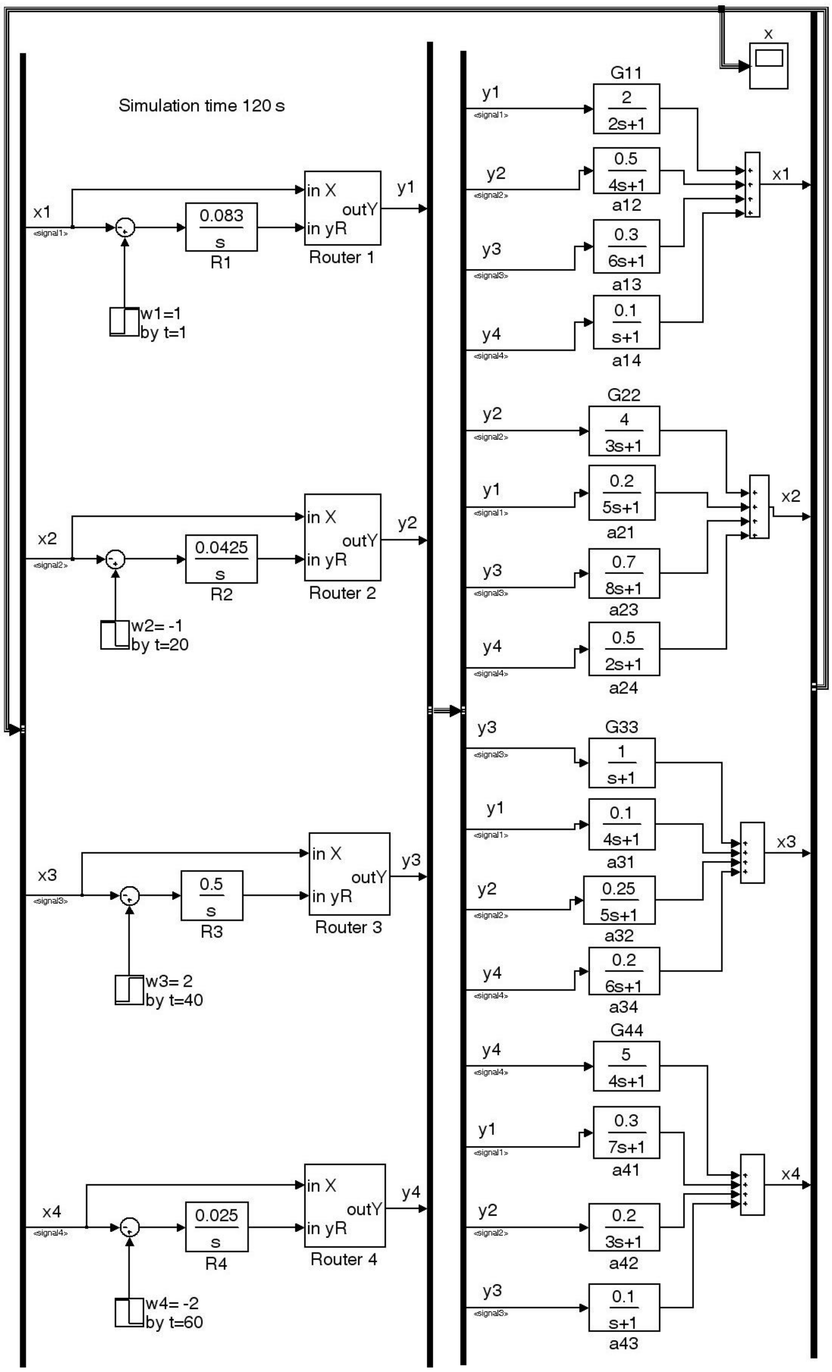

Figure 16. MIMO-control with Routers for n = 4 ([1], p. 151)

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