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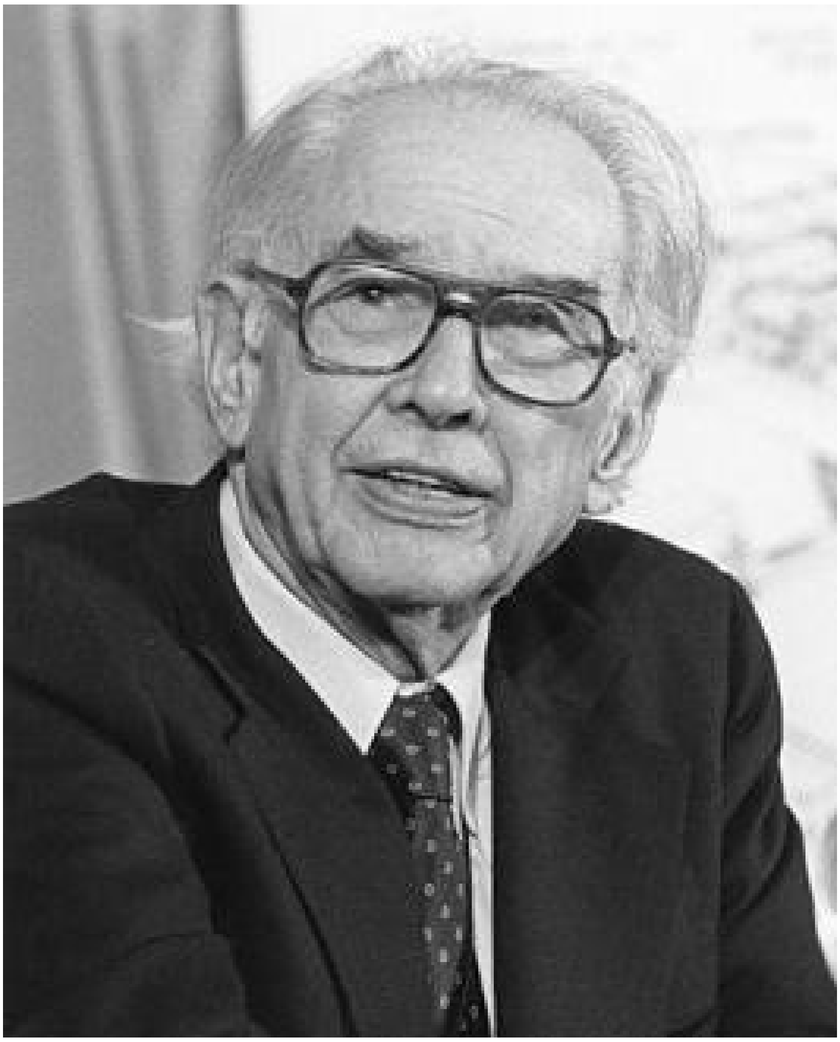

JOHN ATANASOFF SOCIETY OF AUTOMATICS AND INFORMATICS

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ON COMPUTERS, INFORMATION TECHNOLOGIES AND AUTOMATICS

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State Controller with Improved Response Speed for Linear Discrete SISO Systems

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***Abstract* — This paper presents an opportunity to create a linear discrete system (LDS) with a modal state controller for Single Input Single Output objects control. The created controller has an integrating element and a relationship between the set point (SP) and the control object (CO), implemented with an inverse model on the object. The proposed system guarantees handling of the perturbances and providing an improvement in the system performance as in PID-controller systems. In structure proposed, an LQR state controller could be used instead of the MSC.**

Keywords—*modal state controller - MSC, LQR state controller, state space, state observer, direct connection, inversion model, PID-control law*

I. Introduction

It was accepted in [1, 3] and also in [2, 4] that when control in a system is realized by feedback on the state of the object (represented by the state vector (SV)), the controller in this system is called a state controller (SC).

If an LDS is represented in the state space (SS), a necessary condition for the LDS to be led to a desired state is that the state elements are measured or can be estimated [1,2,3] using a state observer.

This paper presents one variant of a LDS for SISO object with steady-state error free (SSEF) modal SC (MSC) with built-in an integrating element and a relationship between the SP and the control object, implemented with an inverse model on the object. The proposed system guarantees handling of the perturbations and providing an improvement in the system performance as in PID-controller systems. In the structure proposed, an LQR state controller could be used instead of the MSC.

II. Problem Formulation

In fig.1 is shown the scheme of a LTI discrete system with SSEF SC with built-in scaling factor k_0 for SISO objects and in fig.2 is shown the scheme of a discrete system with SSEF SC with built-in integrating element. In this case, the variables of state are not directly measurable, and to determine the SV x(k) a state observer (SO) is used.

In fig. 1 is shown a system for which the set point is different from zero and the sampling period is T_0=1. In this case, equations (1) and (2) are valid [5,6,7]:

$$u(k) = k_0 y_{sp} - \mathbf{k}^T \hat{\mathbf{x}}(k),\ \ k = 0,1,2,... \quad (1)$$

$$\hat{\mathbf{x}}(k+1) = \mathbf{A}\hat{\mathbf{x}}(k) - \mathbf{b}\mathbf{k}^T\hat{\mathbf{x}}(k) + \mathbf{b}y_{sp},\ k = 0,1,2,... \quad (2)$$

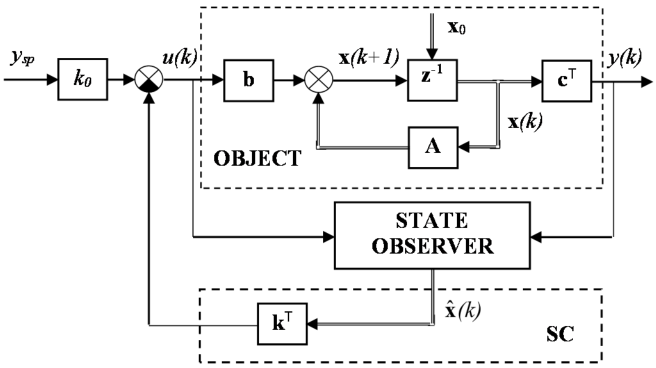

Fig. 1. SC based on a scaling factor k_0

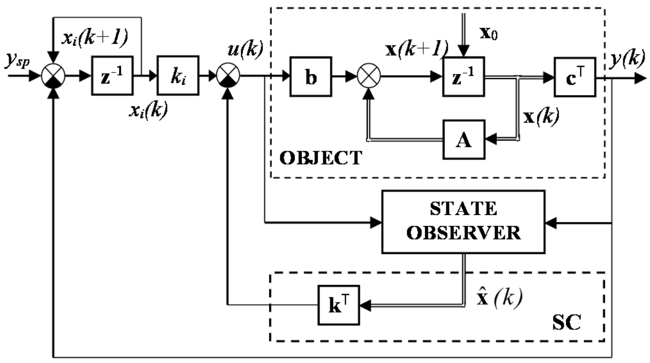

Fig. 2. SC based on an integral component

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The following equations can be written for the system with built-in integral component (fig.2) [3]:

$$\hat{\mathbf{x}}(k+1) = \mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{b}u(k), \quad k = 0, 1, 2, \ldots \tag{3}$$

$$y(k) = \mathbf{c}^{\mathrm{T}}\hat{\mathbf{x}}(k), \quad k = 0, 1, 2, \ldots \tag{4}$$

$$u(k) = k_i x_i(k) - \mathbf{k}^{\mathrm{T}}\hat{\mathbf{x}}(k), \quad k = 0, 1, 2, \ldots \tag{5}$$

$$x_i(k+1) = x_i(k) + y_{sp} - y(k), \; k = 0,1,2,\ldots \tag{6}$$

$$\begin{bmatrix} x_i(k+1) \\ \hat{\mathbf{x}}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & \mathbf{c}^{\mathrm{T}} \\ 0 & \mathbf{A} \end{bmatrix} \begin{bmatrix} x_i(k) \\ \hat{\mathbf{x}}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{b} \end{bmatrix} u(k) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} y_{sp}, \tag{7}$$

$$u(k) = \begin{bmatrix} k_i & -\mathbf{k}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} x_i(k) \\ \hat{\mathbf{x}}(k) \end{bmatrix}, \quad k = 0, 1, 2, \ldots \tag{8}$$

In the presence of measurable perturbances in the system or in the absence of any perturbances, it is advised to use the SC with built-in scaling factor (fig.1) because the speed of the system is greater. If unmeasurable perturbances are present in the system, a SC with built-in an integral component is recommended (fig.2). If perturbances occur in the control process, the structure in fig. 2 handles with them very well, but its performance is significantly lower.

In the current development, the goal is to propose a system based on SC with a built-in integral component, which provides forcing of the transient process at its beginning (analogous to the action of the differentiating constituent in standard PID-controllers).

III. Steady State Error Free State Controller Synthesis with Improved Response Speed for Linear Discrete SISO Systems

Fig. 3 shows the type of a classic control system with an inverse model.

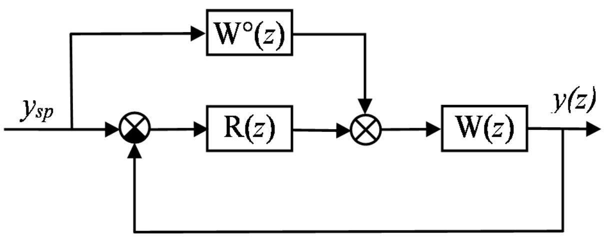

Fig. 3. Control system with an inverse model

W(z) denotes the CO, W°(z) is its inverse model, and R(z) is the system controller. The relationship between the object and its inverse model is given by the following equation:

$$W^{\circ}(z).W(z)=1 \tag{9}$$

$$W(z) = \mathbf{c}^{\mathrm{T}}\left(z\mathbf{I} - \mathbf{A} + \mathbf{b}\mathbf{k}^{\mathrm{T}}\right)^{-1}\mathbf{b}, \text{ then} \tag{10}$$

$$W^{\circ}(z) = \left[\mathbf{c}^{\mathrm{T}}\left(z\mathbf{I} - \mathbf{A} + \mathbf{b}\mathbf{k}^{\mathrm{T}}\right)^{-1}\mathbf{b}\right]^{-1} \text{ or} \tag{11}$$

$$W^{\circ}(1) = \left[\mathbf{c}^{\mathrm{T}}\left(\mathbf{I} - \mathbf{A} + \mathbf{b}\mathbf{k}^{\mathrm{T}}\right)^{-1}\mathbf{b}\right]^{-1} = k_{dc} \tag{12}$$

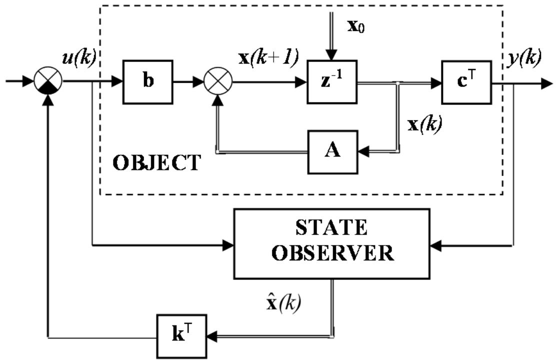

Fig. 4. Feedback closed loop system

For approximation of the inverse model equation (12) could be used and it could be assumed that k_{dc} is a scalar for SISO systems that could be called "direct connection factor".

The following system structure with improved response speed is proposed (fig. 5):

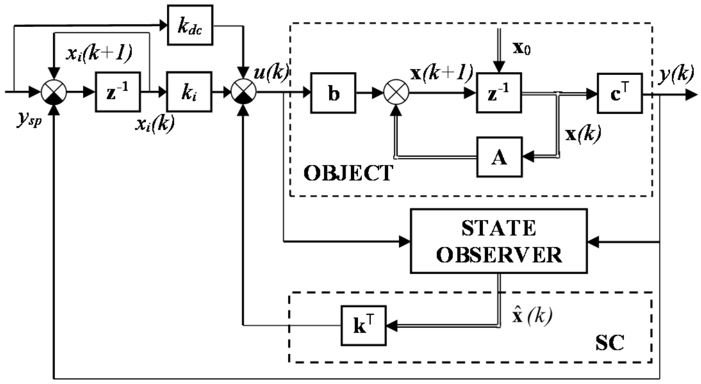

Fig. 5. Proposed system structure with improved response speed

For the control signal of the structure in fig.5, where the set point is different from zero and the sampling period is T_0=1, could be written the equation (13):

$$u(k) = k_i x_i(k) - \mathbf{k}^{\mathrm{T}}\hat{\mathbf{x}}(k) + k_{dc}y_{sp}, \; k = 0,1,2,\ldots \tag{13}$$

Considering equations (6) and (7), for the control signal of the proposed structure, we get:

$$u(k) = \begin{bmatrix} k_i & -\mathbf{k}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} x_i(k) \\ \hat{\mathbf{x}}(k) \end{bmatrix} + k_{dc}y_{sp}, \quad k = 0,1,2,\ldots \tag{14}$$

IV. Experimental Scheme of the System with Improved Response Speed

In order for the experiment to be possible, the system must be controllable. The feedback vector $\mathbf{k}^{\mathrm{T}}$ is calculated by an algorithm for modal control via the SV $\hat{\mathbf{x}}(k)$ calculated through an adaptive state observer SO. In all the reasoning presented above, it is assumed that when the SC starts operating, the adaptive SO has already collected the necessary input-output data and has estimated $\hat{\mathbf{x}}(k)$. However, it is important to clarify how the object will be controlled during the adaptive observation process.

This problem can be solved in the following ways:

- ✓ to use information from input-output data about the object that has been accumulated before the start of the experiment;
- ✓ to identify the object in advance by conducting an offline experiment;
- ✓ to use an auxiliary (additional) controller to control the object until the necessary input-output data is collected.

This additional controller must possess the following capabilities:

- ✓ to implement a change of the control signal within set limits until the moment of switching on the main SC;
- ✓ to be able to set its parameters without having to identify the object;
- ✓ to send to the object an informative control signal to ensure reliable operation of the observation algorithm.

For solving the problem mentioned above in the present work an auxiliary relay-pulse controller (ARPC) is used which output control signal depends not only on the control error (see fig.6). The ARPC is set so that if for n - clocks the controller output $u(k)$ is only at a high value or at a low value, the output of the ARPC for one clock is switched to an alternative value. Therefore the signal at the object input is quite informative. If the auxiliary controller keeps $u(k)$ on one and the same value for more than n clocks, the information matrix will fill up with linearly dependent rows. This will happen because each row contains n consecutive values of the input signal, and adjacent rows differ by only one value.

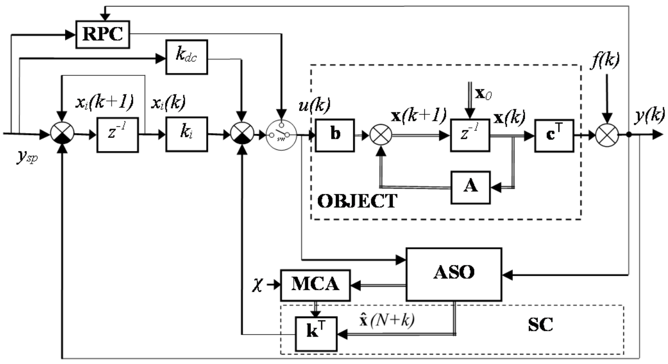

Fig. 6. SC with improved response speed for linear discrete SISO systems

Taking into account the assumption above the equation (14) can be presented in the following way:

$$u(N+k) = \begin{bmatrix} k_i & -\mathbf{k}^T \end{bmatrix} \begin{bmatrix} x_i(N+k) \\ \hat{\mathbf{x}}(N+k) \end{bmatrix} + k_{dc} y_{sp},\ k = 0,1,2,... \quad (15)$$

Here N is the number of the input-output measurements which are required for SV estimation.

SV $\hat{\mathbf{x}}(N+k)$ is estimated by ASO (adaptive state observer). By using a modal control algorithm (MCA), the feedback vector $\mathbf{k}^T$ is obtained, according to the state vector $\hat{\mathbf{x}}(N+k)$. The closed-loop eigenvalues position is defined by the number χ. An unmeasurable, constant in value perturbance $f(k)$, influents the system output.

V. Computer Simulation

The model used for the computer simulation is a model of a steam super-heater and is presented by the transfer function [1] given bellow:

$$W(p) = \frac{(1+13.81p)^2(1+18.4p)}{(1+59p)^5} \quad (16)$$

The model (16) is presented in the SP after discretization (with T_0=40s) according to the following equations:

$$\begin{aligned} &\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{b}u(k), \\ &y(k) = \mathbf{c}^T\mathbf{x}(k) + f(k), \quad k = 0,1,2,... \end{aligned} \quad (17)$$

where

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \vdots & \mathbf{I}_{n-1} \\ \cdots & \cdots & \cdots \\ & \mathbf{a}^T & \end{bmatrix},\ \mathbf{a} = \begin{bmatrix} 0.0062 \\ -0.0856 \\ 0.4732 \\ -1.3082 \\ 1.8085 \end{bmatrix},\ \mathbf{b} = \begin{bmatrix} 0.0273 \\ 0.1193 \\ 0.1897 \\ 0.1990 \\ 0.1658 \end{bmatrix},\ \mathbf{x}_0 = \begin{bmatrix} 1.1000 \\ 1.1500 \\ 1.0500 \\ 1.0000 \\ 1.0700 \end{bmatrix} \quad (18)$$

A MATLAB script for computer simulation is developed based on the structure given in fig.6. For collection of the data required for the initial state vector estimation the first $N=15$ steps ($N=3n$, and n is the order of the object) are used. During this data acquisition the process is controlled by the ARPC, because the SC is not working due to the lack of input-output data.

For the simulations is assumed that the object is noise influence free. The control process is started in the absence of an unmeasurable perturbance for P steps, i.e. $f(k)=0$ and $k=0, 1, 2, ..., P$. The unmeasurable perturbance which appears at the *70-th* step and has a constant value $f(P+k)=5$, ($P=70,\ k=1, 2, ...$) is simulated and applied at the system output. Until the 40^{-th} step the system set point is $y_{sp}=35$, and after this it becomes *40* (see fig.7).

The process of adaptive observation (the estimation of the vectors **a** and **b**) is performed only at the beginning of the process, and then at each step $\mathbf{x}(k)$ is calculated using an ASO, which is presented in [8]. The feedback vector $\mathbf{k}^T$ is determined by a modal control algorithm (AMC) presented in [9]. The stability region is set to $\chi=0.3$. The integration coefficient has a value of $k_i=0.2$.

Simulations were carried out under the same conditions with the three structures shown above (fig.1, fig.2, fig.5) in order to compare the results. The obtained results are presented in fig.7. For each of the three experiments, $u(k)$, $y(k)$, and y_{sp} are presented.

V. Conclusion

The obtained results show that when SC with built-in scaling factor (the structure in fig.1) is used, the system has the best performance. When the set point changes, the state controller reacts very quickly at the beginning of the process. The problem is that when a perturbance occurs, SC cannot eliminate its influence and a steady-state error occurs and its value is equal to the perturbance.

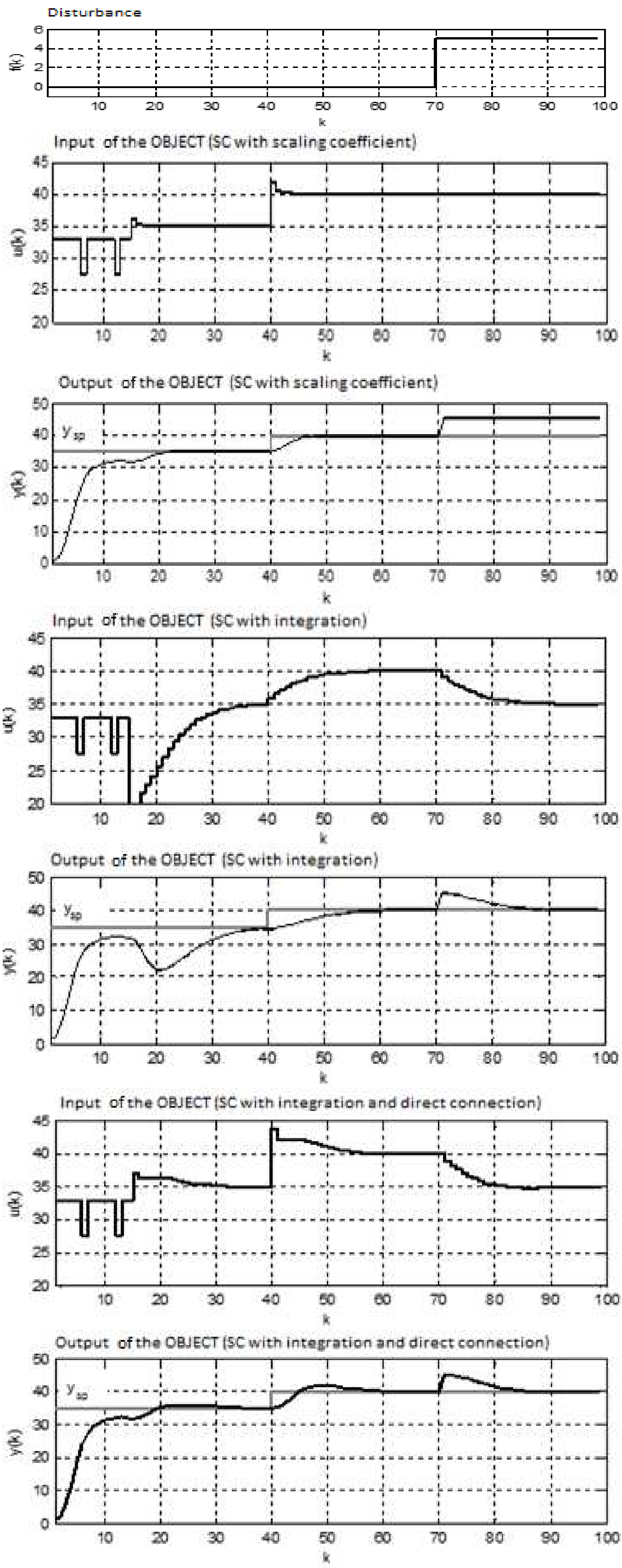

Fig. 7. Computer simulation results

When using a SC with a built-in integral component (fig.2), the influence of the perturbance is eliminated but very slowly. Even when integration starts from the beginning of the observation process (so-called pre-integration) the process is very slow. If the integration process begins after the observation is completed, the process is even slower.

When using SC with built-in integrating element and a relationship between the SP and the CO, implemented with an inverse model on the object (fig. 5), the system has less performance than SC with scaling factor (fig. 1), but is significantly faster than the system with SC with a built-in integral component (fig.2).

Here, the forcing of the process at the initial point in time is observed. This is due to the fact that at the beginning the transfer function of the directly channel is turns out to be equal to unity. This analogous to the action of the differentiating constituent in standard PID-controllers, and the removal of the influence of the perturbance is carried out by the built-in integral component.

The adding of direct connection with inverse model in the state controllers with an integral component gives good results when controlling inert objects or those with high-order. Therefore if the object is too fast it could lead to critical oscillations. The influence of direct connection can be reduced if the scaling factor k_{dc} is multiplied by a constant less than unity.

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