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Design and analysis of robust adaptive control for twin rotor MIMO systems using neuro-fuzzy inference techniques

Konstrukcja i analiza systemów niezawodnego adaptacyjnego sterowania dwuwirnikowym systemem wielowejściowym i wielowyjściowym (MIMO) z zastosowaniem techniki wnioskowania neuro-rozmytego

***Abstract**. This paper presents an adaptive Neuro-Fuzzy inference system conception for in controlling twin rotor multi-input multi-output System (TRMS). The control of the TRMS was very challenging because the rotor interacts badly at the beam between yaw and pitch angle. In consequence, it is considering as multi-input and multi-output (MIMO) with nonlinear dynamic behaviour. By combining the fuzzy logic and neural network, the hybrid ANFIS algorithm is developed. Fuzzy logic concept was used to adaptation of the learning algorithm to improve the robustness of learning and operating of the neural network. In order to be able to verify the performance and to test behaviour of the proposed ANFIS control algorithms, the numerical simulation is realized. The simulation results showed a good system stabilization and very good tracking performance of the proposed control system.*

***Streszczenie.** W artykule przedstawiono koncepcję adaptacyjnego systemu wnioskowania neuro-rozmytego do sterowania dwuwirnikowym systemem wielowejściowym i wielowyjściowym (TRMS). Sterowanie TRMS było bardzo trudne, ponieważ wirnik źle oddziałuje na belce między odchyleniem a kątem pochylenia. W związku z tym rozważa się go jako wielowejściowy i wielowyjściowy (MIMO) o nieliniowym zachowaniu dynamicznym. Łącząc logikę rozmytą i sieć neuronową, powstaje hybrydowy algorytm ANFIS. Koncepcja logiki rozmytej została wykorzystana do adaptacji algorytmu uczenia się w celu poprawy niezawodności uczenia się i działania sieci neuronowej. Aby móc zweryfikować wydajność i przetestować zachowanie proponowanych algorytmów sterowania ANFIS, przeprowadzana jest symulacja numeryczna. Wyniki symulacji wykazały dobrą stabilizację systemu i bardzo dobrą wydajność śledzenia proponowanego systemu sterowania.*

Keywords: Adaptive Neuro Fuzzy Inference System (ANFIS); Twin rotor multi-input-output System (TRMS); Nonlinear Control; Neuro-Fuzzy Controller;
Słowa kluczowe: System wnioskowania rozmytego (ANFIS); dwuwirnikowy system wielowejściowo-wyjściowy (TRMS); sterowanie nieliniowe; sterownik wnioskowania neuro-rozmytego.

Introduction

The last few years, there has been an increased interest from researchers in developing the intelligent control for unmanned aerial vehicles [1, 2]. One of the most commonly used vehicles in this area is helicopter. However, the helicopter is of a more complex design than an airplane. It represents an unstable system [3]. The design of a control capable to stabilizing and controlling all the movements of the helicopter becomes an extremely difficult task. The twin rotor multi input multi output system (TRMS) is a helicopter-like system that is restricted to two degrees of freedom, pitch and yaw. It is a complicated, nonlinear and coupled system used for the verification of control methods and observers. The TRMS has attained popularity amongst control researcher due to nonlinearity present in it and significant cross coupling effect which makes it difficult and challenging to design control schemes [3, 4]. It presents the main characteristics of the real helicopter, i.e., intrinsic instability, nonlinearity, and the cross-coupled dynamics [5, 6]. The TRMS is composed of two propellers which are perpendicular to each other and joined by a beam pivoted on its base.

The system can rotate freely in both vertical and horizontal direction. The DC motor drive the boat propellers by changing the voltage supplied to beam, which allow us control the speed of propellers [7]. Recent work showed that conventional control for the TRMS, resulting in a poor performance. The objective is to design an intelligent control scheme to overcome the limitations of conventional control [8].

The fuzzy logic and neural network have shown great ability in solving complex control of nonlinear system. Many applications have been devised using the fusion of artificial neural network and fuzzy logic through adaptive neuro-fuzzy inference system (ANFIS) [9, 10, 11, 12, 13].

The Neuro-fuzzy logic have gained great important and witnessed a rapid growth in industrial applications. They proved that such control can achieve satisfactory results in control of systems whose behaviour is difficult to describe mathematically or is highly nonlinear [14]. In this study, two ANFIS (Adaptive Neuro Fuzzy Inference System) controllers are deployed for the two axes; pitch, and yaw in order to control the to the speed vertical and horizontal direction and track the desired trajectories of a TRMS [6]. This paper is divided into following sections. Section 1 provides the dynamic model of the TRMS. Section 2 gives the details about the Neuro–Fuzzy control system and its structure. Section 3 has the results along with discussion and section 4 gives the conclusion.

Mathematical modeling of the TRMS

The mathematical model is developed by making some simplifications; it is assumed that the dynamics of the motors can be converted into first-order equations. The rotation can be said in principle as the movement of a pendulum. According to the diagram presented in Fig. 1, the nonlinear equation can be translated through the equations of moments of forces and inertia. The parameters of TRMS are shown in Table 1 [15, 16, 17, 18, 23].

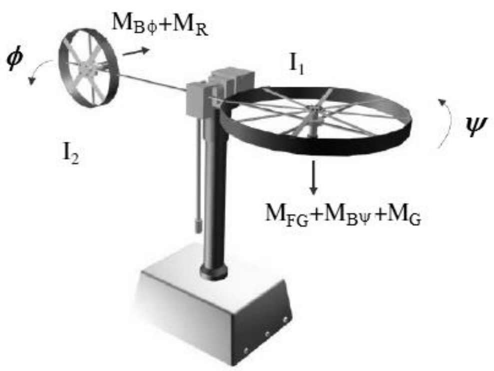

Fig. 1. Rotor multi-input-output System (TRMS).

Table 1. Physical parameters of the TRMS

Symbol	Quantity	Value
I_1	Moment of inertia of vertical rotor	I_1, 6.8×10^{-2} kg m^2
I_2	Moment of inertia of horizontal rotor	2×10^{-2} kg m^2
a_1	Static characteristic parameter	0.0135
b_1	Static characteristic parameter	0.0924
a_2	Static characteristic parameter	0.02
b_2	Static characteristic parameter	0.09
M_g	Gravity momentum	0.32
$B_{1\psi}$	Friction momentum parameter	6×10^{-3} Nms/rad
$B_{1\phi}$	Friction momentum parameter	1×10^{-1} Nms/rad
k_{gy}	Gyroscopic momentum parameter	0.05 s/rad
k_{gx}	Gyroscopic momentum parameter	0.0163 s/rad
k_{11}	Motor 1 gain	1.1
k_{22}	Motor 2 gain	0.8
T_{11}	Motor 1 denominator parameter	1.2
T_{10}	Motor 1 denominator parameter	1
T_{21}	Motor 2 denominator parameter	1
T_{20}	Motor 2 denominator parameter	1
T_p	Cross reaction momentum parameter	2
T_0	Cross reaction momentum parameter	3.5
k_c	Cross reaction momentum gain	-0.2

Main rotor model

The following momentum equation can be derived for the vertical movement:

(1) $$I_1 \ddot{\psi} = M_1 - M_{FG} - M_{B\psi} - M_G$$

where, M_1 is the nonlinearity caused by the rotor and can be estimated as second order polynomial and due to this the torque is induced to the TRMS as given below.

(2) $$M_1 = a_1.\tau_1^2 + b_1.\tau_1$$

The gravitational torque about the pivot point, which is described by the following equation:

(3) $$M_{FG} = M_g.\sin(\psi)$$

The frictional torque can be estimated as following equation:

(4) $$M_{B\psi} = B_{1\psi}.\dot{\psi} + B_{1\psi}.sign(\dot{\psi})$$

The gyroscopic torque occurs due to coriolis force. This torque is resulted when moving main rotor changes its position in azimuth direction, and describes as in (5) given below.

(5) $$M_G = K_{gy}.M_1.\dot{\phi}.\cos(\psi)$$

The motor and the electrical control circuit are approximated by a first order transfer function, given in Laplace space by:

(6) $$\tau_1 = \frac{k_{11}}{T_{11}s + T_{10}} u_1$$

where, u_1 is the input voltage of the DC motor, T_{11} is the time constant of the main rotor and k_{11} is the static gain DC motor.

Tail rotor model

Similar equation is developed for the horizontal plane motion. The net torques produced in horizontal plane motion is described by the following equation.

(7) $$I_2 \ddot{\phi} = M_2 - M_{B\phi} - M_R$$

where the tail propeller thrust M_2 is a nonlinear function of the DC motor momentum described by:

(8) $$M_2 = a_2.\tau_2^2 + b_2.\tau_2$$

(9) $$M_{B\phi} = B_{1\phi}.\dot{\phi}$$

(10) $$M_R = \frac{k_c(T_0 s + 1)}{T_p s + 1} M_1$$

Again, the D.C. motor with electrical circuit is estimated as the first order transfer function and given by the following equation.

(11) $$\tau_2 = \frac{k_{22}}{T_{21}s + T_{20}} u_2$$

Where u_2 is the input voltage of the DC motor, T_{21} is the time constant of the main rotor and k_{22} is the static gain DC motor.

The dynamics of the TRMS system are described as follows:

(12) $$\ddot{\psi} = \frac{1}{I_1}\left(-M_g.\sin(\psi) - B_{1\psi}.\dot{\psi} + k_{gx}\dot{\phi}^2.\sin(2\psi) - \left(a_1\tau_1^2 + b_1\tau_1\right)\left(k_{gy}\dot{\phi}.\cos(\psi)\right)\right)$$

(13) $$\ddot{\phi} = \frac{1}{I_2}\left(-B_{1\phi}.\dot{\phi} - \frac{k_c(T_0 s + 1)}{T_p s + 1}\left(a_1\tau_1^2 + b_1\tau_1\right) - \left(a_2\tau_2^2 + b_2\tau_2\right)\right)$$

The block diagram of TRMS system, that includes the main and the tail rotors, is presented in Fig. 2, this figure show the dynamics cross couplings of the system. The TRMS is controlled by two inputs (u_1, u_2).

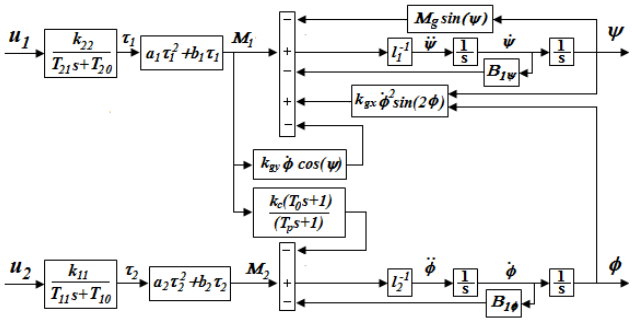

Fig. 2. Block diagram of TRMS system.

Neuro–Fuzzy control system

This section presents the control techniques using Neuro-Fuzzy (ANFIS). The ANFIS controllers are implemented by the majority of automatic control designers. They are used in processes whose characteristics as high order and non-linearities [19, 20].

ANFIS structure

Combining the learning power of neural network with knowledge representation of fuzzy logic gives Neuro-Fuzzy control (NFC). In this work, the development of the control strategy for control of the TRMS such as the u1 and u2, are presented using the concepts of ANFIS control scheme, the block diagram of ANFIS which is shown in the Fig. 3.

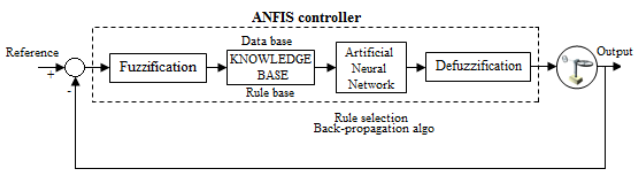

Fig. 3. Block diagram of the ANFIS control scheme.

The resulting Sugeno fuzzy reasoning system is shown in Fig.4. The rule base block of fuzzy controller is connected to the neural network block. It is incorporates several IF–THEN rules in the following form:
Rule 1: IF x_1 is A_1 AND x_2 is B_1 THEN $y_1 = p_1 x_1+q_1 x_2+r_1$
Rule 2: IF x_1 is A_2 AND x_2 is B_2 THEN $y_2 = p_2 x_1+q_2 x_2+r_2$

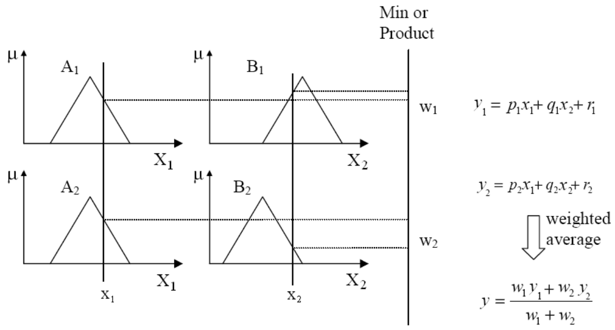

Fig. 4. Two-input first-order Sugeno fuzzy model with two rules.

The backpropagation algorithm will train the neural network to determine the rule bases. The ANFIS controller inputs are fuzzy sets.

The proposed ANFIS structure of Sugeno type with five layer. This structure is a combination of gradient descent and least squares estimator techniques. Fig. 5. shows the corresponding ANFIS architecture.

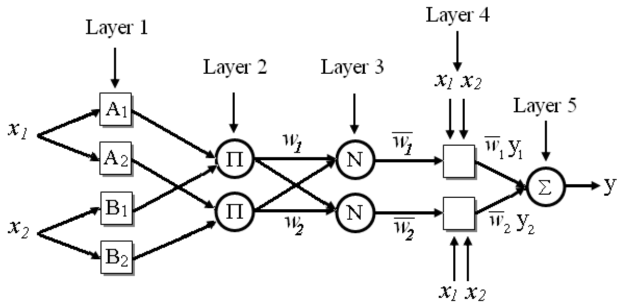

Fig. 5. Equivalent ANFIS architecture

It is composed of five functional blocks (rule base, database, a decision making unit, a fuzzification interface and a defuzzification interface) which are generated using five network layers [21, 22]:

Layer 1: Each input node in this layer corresponds to the specific input variable *(x=e(k);y=Δe(k)).* Every node *i* at this layer is an adaptive node with the following function:

(14)
$$O_{1,i} = \mu\, A_i(x) \qquad \text{for } i = 1,2, \text{ or}$$
$$O_{1,i} = \mu\, B_{i-2}(y) \qquad \text{for } i = 3,4$$

where x (or y) is the input to the i^{th} node and A_i (or B_{i-2}) is a linguistic label (such as ''low'' or ''high'') associated with this node. In words, $O_{l,i}$ is the membership grade of a fuzzy set *A* (=A_1,A_2,B_1, or B_2) and it specifies the degree to which the given input *x* (or *y*) satisfies the quantifier *A*.

Layer 2. Each node performs a membership function that can be referred to as the fuzzification procedure. This layer is represented by the following function:

(15)
$$O_{2,i} = w_i = \mu A_i(x)\, \mu B_i(y) \qquad i = 1,2$$

Layer 3. It's a rule layer. Each node in this layer computes the activation level of each fuzzy rule. Each node calculates the weights that are in this normalized layer. The nodes labeled *N* calculates the ratio of the ith rule's firing strength to the sum of all rules' firing strengths.

(16)
$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2} \qquad i = 1,2$$

Layer 4. This layer acts as a defuzzifier. The single node is denoted by Σ and sums all incoming signals with node functions.

(17)
$$O_{4,i} = \overline{w_i} y_i = \overline{w_i}\left(p_i x_1 + q_i x_2 + r_i\right)$$

Where wi is the output of layer number 3, and p_i,q_i,r_i are the parameter set.

Layer 5. It is an output layer, it gathers all the inputs coming from layer 4 and transforms the fuzzy classification results into a net (binary) result.

(18)
$$O_{5,i} = y = \sum_{i=1} \overline{w_i} y_i = \frac{\sum_i w_i y_i}{\sum_i w_i}$$

ANFIS control system description

Fig. 6 shows the global structure of the system control block diagram incorporating the proposed Neuro–fuzzy approach, for control of TRMS equipped with ANFIS controller [23].

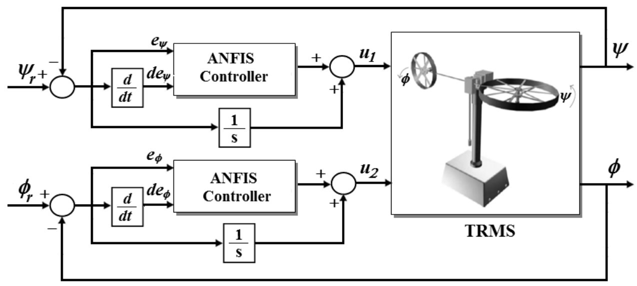

Fig. 6. Block diagram of the proposed ANFIS control scheme of TRMS.

The inputs to the first ANFIS controller are the error (e_ψ) and the change in error (de_ψ) is modelled using the Eq. (19) as;

(19)
$$e_\psi = \psi_r - \psi$$

where ψ_r is the reference pitch angle.

Again, the inputs to the second ANFIS controller are the error and the change in error is modeled using the Eq. (20) as;

(20)
$$e_\phi = \phi_r - \phi$$

where ϕ_r is the reference yaw angle.

The fuzzification block converts the net data into linguistic variables. By using Sugeno method, the input membership functions of the ANFIS uses 25 rules for getting the suitable output. The output from the first ANFIS controller is the u1, and u2 in the second ANFIS controller. The ANFIS network is trained using an off-line learning algorithm.

Results and discussion

This section discusses the simulation results to verify the efficiency of the control strategy proposed in Section 2. To implement the above control techniques, the TRMS is designed through Matlab/Simulink. The responses of reference inputs of the ANFIS controller are presented. For simulation purposes, we consider the parameters listed in Table 1.

For tracking the desired trajectories of TRMS system, the two reference inputs are given to system. The responses of pitch and yaw with step input reference have been illustrated as Fig. 7 and Fig. 8. The results show that the transient response performance was promising. The performance criteria were increase with less overshoot. In ANFIS control, the TERMS has good tracking performance both in horizontal and vertical plane when the reference input is square tracking is shown in Fig. 9. and 10. In sinusoidal signal results for Fig. 11. and 12. showed that ANFIS controller has better response too in pitch and yaw angle.

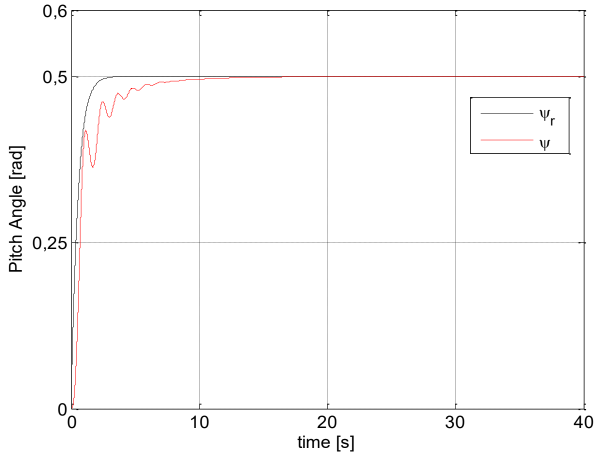

Fig. 7. TRMS pitch angle control system response with step input reference with ANFIS controller.

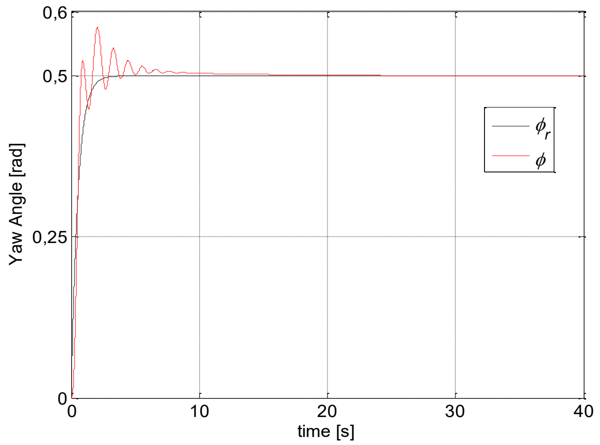

Fig. 8. TRMS yaw angle control system response with step input reference with ANFIS controller.

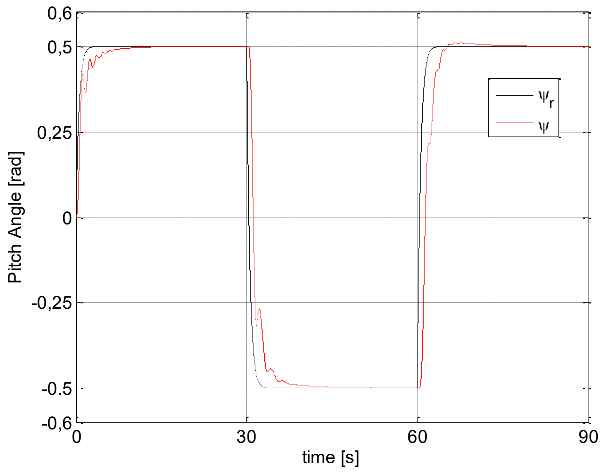

Fig. 9. TRMS pitch angle control system evolution trajectories with square input reference with ANFIS controller.

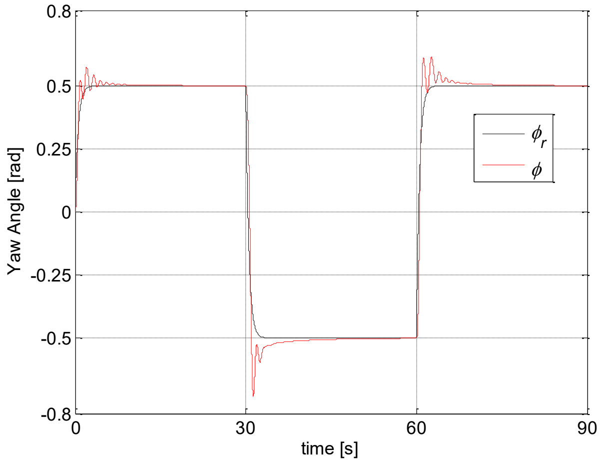

Fig. 10. TRMS yaw angle control system evolution trajectories with square input reference with ANFIS controller.

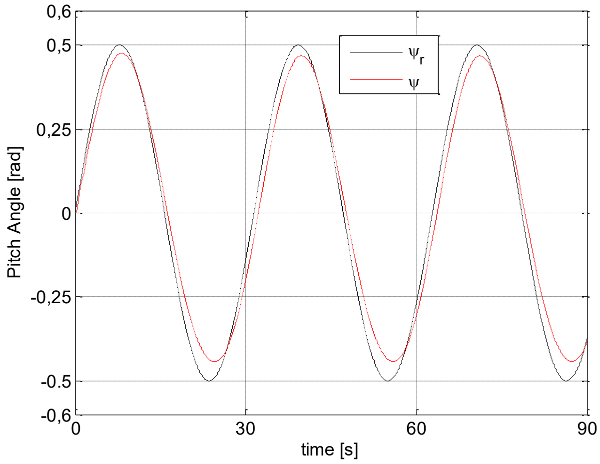

Fig. 11. TRMS pitch angle control system response with sinusoidal input reference with ANFIS controller.

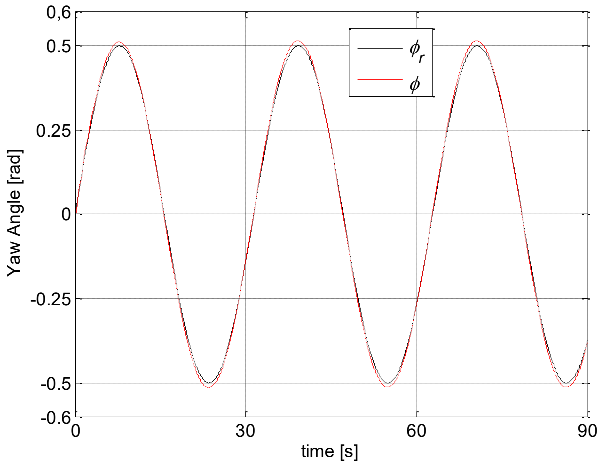

Fig. 12. TRMS yaw angle control system response with sinusoidal input reference with ANFIS controller.

Conclusions

This paper has presented an ANFIS control for pitch and yaw control of TRMS. The system was analyzed and its performances were studied by numerical simulation to validate the theoretical concepts. The twin rotor system is also realised and the controlling of pitch and yaw angles is shown in simulink with the help of matlab. From this study, it can be concluded that Neuro-Fuzzy controller improve greatly the reference tracking and the results demonstrated the effectiveness of the proposed control scheme. In future research, different control scheme also can be implemented in real platform.

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