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FAULT DIAGNOSIS on AIRCRAFT LONGITUDINAL FLIGHT CONTROL USING OBSERVERS

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ABSTRACT

In this study, a model-based FDI (fault detection isolation) technique is proposed for sensor fault detection and isolation on an aircraft longitudinal flight control system. Fault detection and isolation process has a vital importance especially in aerospace. In this sector, health fault diagnosis can prevent systems from abnormal situations and also provides operational continuity of the aircraft system. In this work, the detection and isolation of sensor faults are carried out through the use of UIO (Unknown Input Observer) – GOS (Generalized Observer Scheme) structures respectively. According to the various MATLAB simulations, it can be said that proposed structure gives satisfactory results.

INTRODUCTION

Fault detection and isolation process has a vital importance in aerospace. Sensor, actuator, component or plant failures may change the system behavior and cause catastrophic failures [Jiang et al., 2011]. Health fault diagnosis can prevent systems from abnormal situations and also provides operational continuity of the aircraft system. Fault tolerant control systems are designed to guarantee the operational continuity of the related systems in spite of faults and failures.

Fault detection and isolation methods are seperated into two parts: Model-free methods and model-based methods [Hajiyev and Caliskan, 2003]. Observer usage is one of the model-based FDI method. It's different applications can be seen in various areas of aerospace. Aircraft sensor fault detection, isolation and reconfiguration studies [Yazar et al., 2017; Yazar and Kiyak, 2013a; Yazar and Kiyak, 2013b], aircraft flight control studies [Castaldi et al., 2014; Kiyak and Kahvecioglu, 2006; Kiyak and Kahvecioglu, 2007; Kiyak 2015; Rosa et al., 2010] are some examples of observer-based works in this area.

In this study, UIO and GOS cascade structure is used for detecting and isolating related sensor faults in the system. Using UIO methodology, unknown inputs are decoupled from system and by means of GOS, residual values are calculated for all system sensors. For various fault scenarios, the designed system is tested and the success of system is presented. In the following sections, theory of observers and simulations with different scenarios are shown respectively. At last, as a conclusion, the short brief of work and future plan are mentioned.

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METHOD

Fault Detection

The system uncertainty can be summarized as an additive unknown disturbance term in state space representation of a dynamic system described as Equation (1) [Chen and Patton, 1999]:

$$\dot{x}(t) = Ax(t) + Bu(t) + Ed(t)$$
$$y(t) = Cx(t)$$
(1)

Where,

$x(t)$ ϵ $R^{n\times1}$ is the state vector,

$y(t)$ ϵ $R^{m\times1}$ is the output vector,

$u(t)$ ϵ $R^{r\times1}$ is the known input vector,

$d(t)$ ϵ $R^{q\times1}$ is the unknown input vector (or disturbance).

A, *B*, *C* and *E* are known matrices with appropriate dimensions respectively. The structure for a full-order observer is described as Equation 2 [Chen and Patton, 1999]:

$$\dot{z}(t) = Fz(t) + TBu(t) + Ky(t)$$
$$\hat{x}(t) = z(t) + Hy(t) \quad (2)$$

Where,

$\hat{x}(t)$ ϵ $R^{n\times1}$ is the estimated state vector,

$z(t)$ ϵ $R^{n\times1}$ is the state of this full-order observer.

F, T, K, H are matrices to be designed for achieving unknown input de-coupling and other design requirements.The estimation error is calculated by using Equations (1-2) as follows [Chen and Patton, 1999]:

$$e(t) = x(t) - \hat{x}(t) \quad (3)$$

Dynamic form of error vector is governed by the following Equation 4 [Chen and Patton, 1999]:

$$\dot{e}(t) = (A - HCA - K_1C)e(t) - (F - (A - HCA - K_1C))z(t) - (K_2 - (A - HCA - K_1C)H)y(t) -$$
$$(T - (I - HC))Bu(t) + (I - HC)Ed(t) \quad (4)$$

Where

$$K = K_1 + K_2 \quad (5)$$

If one can make the following Equations (6-9) hold true [Chen and Patton, 1999]:

$$(HC-I)E=0 \tag{6}$$
$$T=I-HC \tag{7}$$
$$F=A-HCA-K_1C \tag{8}$$
$$K_2=FH \tag{9}$$

The state estimation error will then be [Chen and Patton, 1999]:

$$\dot{e}(t)=Fe(t) \tag{10}$$

If all eigenvalues of F are stable, *e(t)* will approach zero asymptotically, i.e. $\hat{x}\rightarrow x$

Necessary and sufficient conditions for Equation 2 to be a UIO for the system defined by Equation 1 are:

rank(CE)=rank(E)
(C,A_1) is detechable pair

Where,

$$A_1=A-E((CE)^T CE)^{-1}(CE)^T CA \tag{11}$$

Considering the necessary and sufficient conditions, F and K can be calculated using following equations:

$$F=A_1-K_1C \tag{12}$$
$$K=K_1+K_2=K_1+FH \tag{13}$$

Fault Isolation

The system equations that all actuators are assumed to be fault-free can be expressed as [Chen and Patton, 1999]:

$$\begin{aligned}\dot{x}(t)&=Ax(t)+Bu(t)+Ed(t)\\ y^j(t)&=C^j x(t)+f_s^j(t) \qquad \text{for j=1,2,….m}\\ y_j(t)&=c_j x(t)+f_{s_j}(t)\end{aligned} \tag{14}$$

Where,

c_j ϵ $R^{1\times n}$ is the j_{th} row of the matrix C,

C^j ϵ $R^{(m-1)\times n}$ is obtained from the matrix C by deleting j_{th} row c_j.

y_j is the j_{th} component of y,

y^j ϵ $R^{(m-1)\times 1}$ is obtained from the vector y by deleting j_{th} component y_j

According to this description, *m* UIO-based residual generator can be expressed as [Chen and Patton, 1999]:

$$\begin{aligned} \dot{z}^j(t) &= F^j z^j(t) + T^j Bu(t) + K^j y^j(t) \\ r^j(t) &= (I - C^j H^j) y^j(t) - C^j(t) z^j(t) \end{aligned} \qquad \text{for } j=1,2,,\dots,m \qquad (15)$$

The following equations must be satisfied by the parameter matrices [Chen and Patton, 1999]:

$$\begin{aligned} H^j C^j E &= E \\ T^j &= I - H^j C^j \\ F^j &= T^j A - K_1^j C^j \\ K_2^j &= F^j H^j \\ K^j &= K_1^j + K_2^j \end{aligned} \qquad \text{for } j=1,2,\dots..,m \qquad (16)$$

According to Generalized Observer Scheme, each residual generator is driven by all inputs and all but one outputs. All actuators are assumed to be fault-free and a fault occurs in the j_{th} sensor, the residual will satisfy the following isolation logic [Chen and Patton, 1999]:

$$\begin{aligned} \left\| r^j(t) \right\| &\langle T_{SFI}^j \\ \left\| r^k(t) \right\| &\geq T_{SFI}^k \end{aligned} \qquad \text{for } k=1,\dots..,j-1,j+1,\dots\dots,m. \qquad (17)$$

Where,

T_{SFI}^j are isolation threshold values for j=1,…….m.

$r^j(t)$ is the norm of the residual

SIMULATIONS

In simulation part, the longitudinal model of a F2B Bristor Fighter is preferred [Fossen, 2011]. The linearized mathematical model consists of 4 states – namely *p*(roll rate), *r*(yaw rate), ϕ(roll angle), ψ*(yaw angle)* and a control input δ_A(aileron deflection). All actuators are assumed to be fault free during the simulations. The known input is modelled using a unit step function and the unknown input is presented using random signal function changes between the values of 1 to 3.The mathematical model can be described by:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Ed(t) \\ y(t) &= Cx(t) \end{aligned}$$

(18)

$$A = \begin{bmatrix} -7.1700 & 2.0600 & 0 & 02.0600 \\ -0.4360 & -0.3410 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0.2330 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 26.1 \\ -1.6600 \\ 0 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Due to unstable structure of the system matrix, LQR method is used for calculating the feedback gain vector G in the simulations to make the system stable. The new system matrix and gain vector are as follows:

$$A_{new} = \begin{bmatrix} -28.2187 & 4.3400 & -35.3365 & -26.1000 \\ -0.9027 & -0.4860 & 2.2475 & 1.6600 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0.2330 & 0 \end{bmatrix}$$
(19)

$$G = [0.8065 \quad -0.0874 \quad 1.3539 \quad 1.000]$$
(20)

Simulation 1: No fault case

The system outputs and residuals of no fault case can be seen in Figure 1.

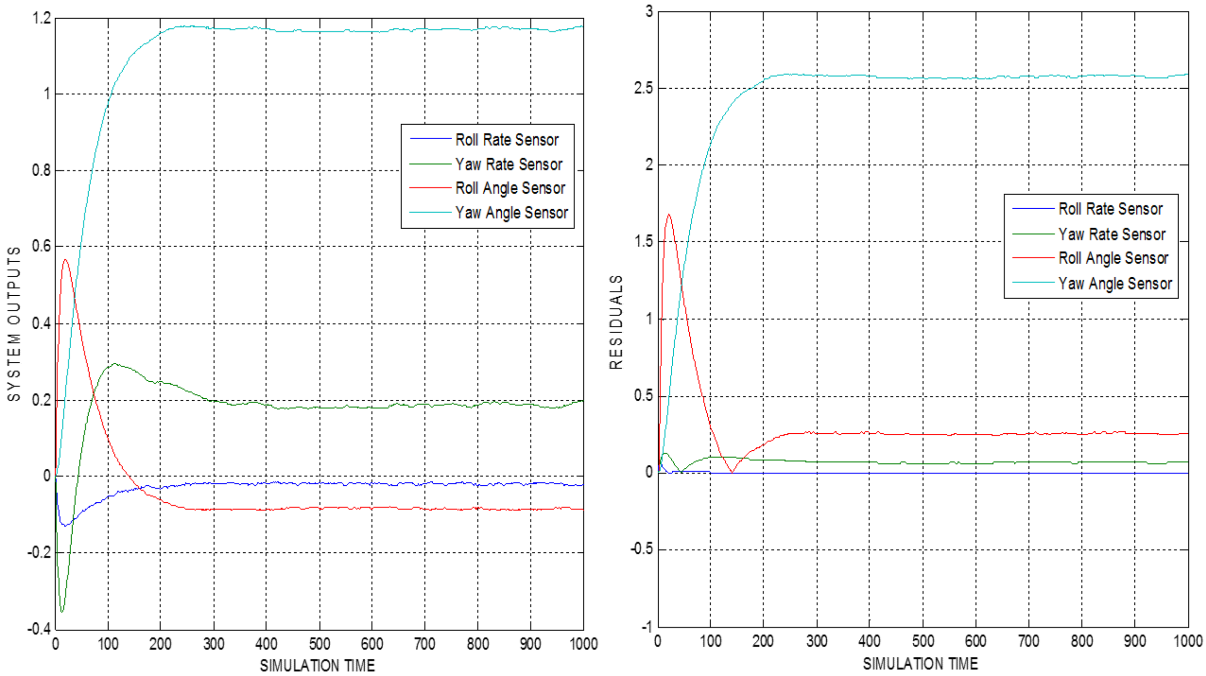

Figure 1*:* System outputs and residuals for no fault case

Simulation 2: Roll rate sensor failure case

In simulation 2, at 200th second according to simulation time, a fault occurs on roll rate sensor. The residuals are calculated for each sensors. Considerable increases are seen in every residual norms except the residual norm belongs to roll rate sensor. It originates form GOS theory. Sensor failure can be easily isolated using GOS structure considering residual values from Figure 2.

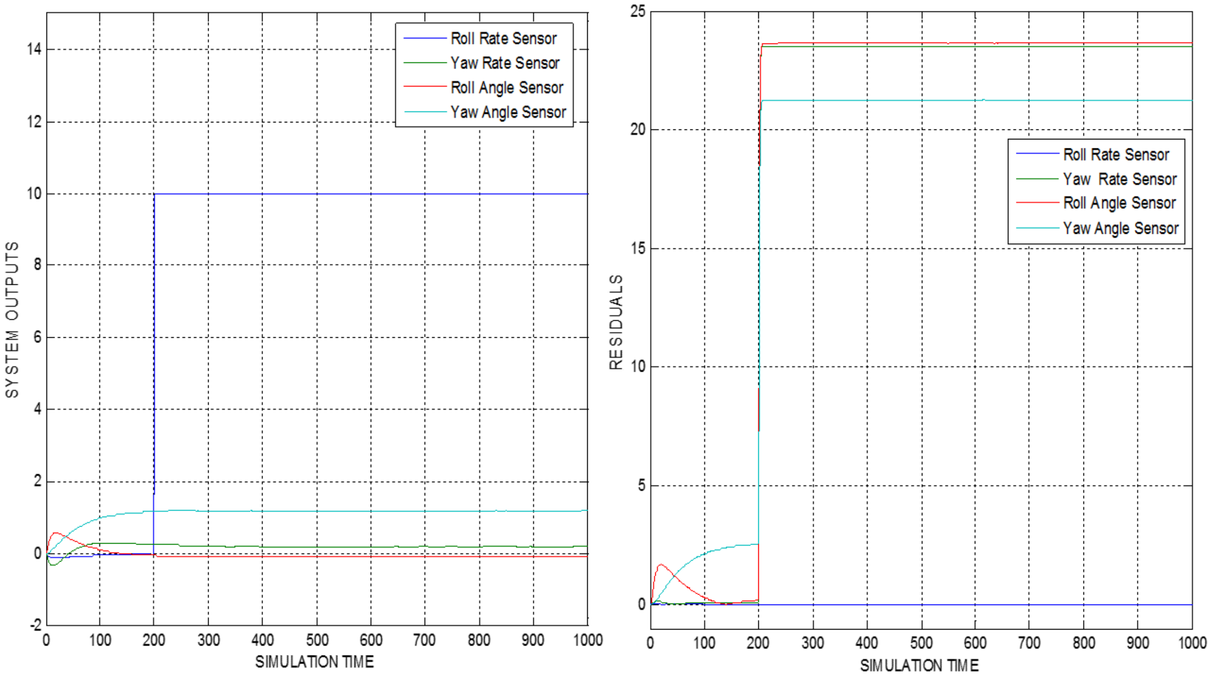

Figure 2*:* System outputs and residuals for roll rate sensor failure case

Simulation 3: Yaw rate sensor failure case

From figure 3, one can be said that simulation results for yaw rate sensor failure can be identified easily using UIO and GOS structures again. 400th second at simulation time, a fault occurs again on yaw rate sensor. The residual norm belongs to yaw rate sensor stays at the same value while the other residual values are increasing. System outputs and residuals are found as displayed in Figure 3.

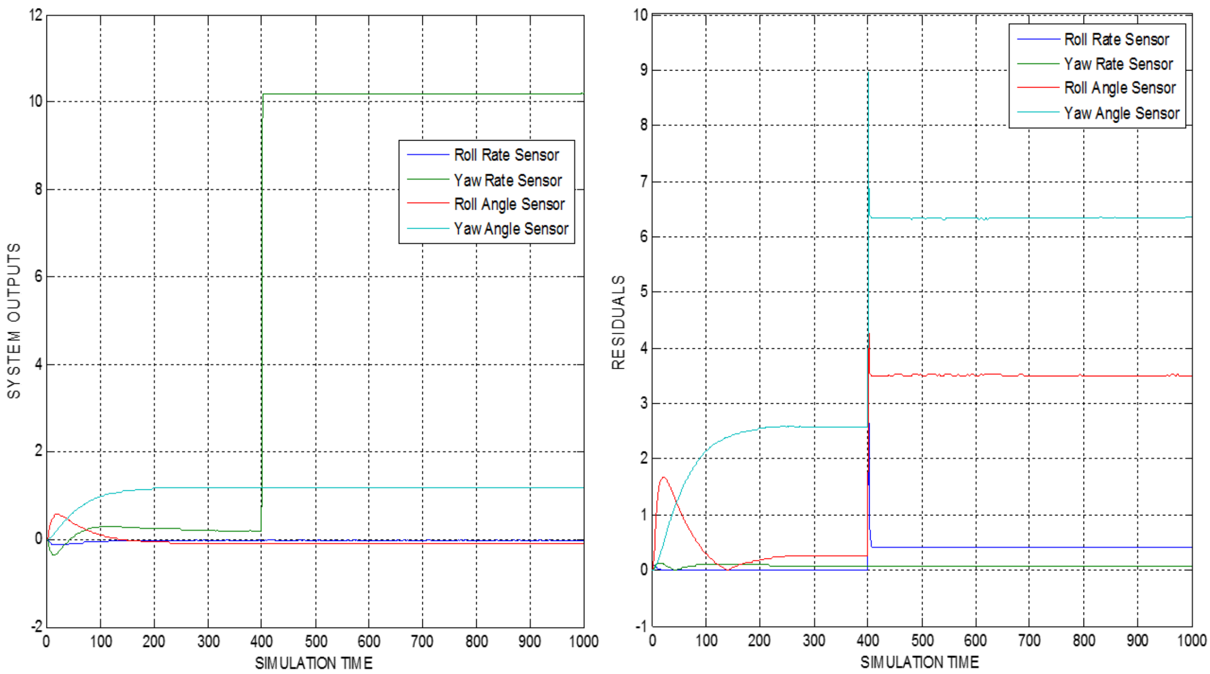

Figure 3*:* System outputs and residuals for yaw rate sensor failure case

Simulation 4: Roll angle sensor failure case

Roll angle sensor fault occurs at 600th second in the simulation. Unknown inputs are decoupled from system by means of UIO structures. Faulty sensor is isolated via GOS methodology. Considerable residual increases are seen again in the system except roll angle sensor residual. All system outputs and residuals are presented in Figure 4.

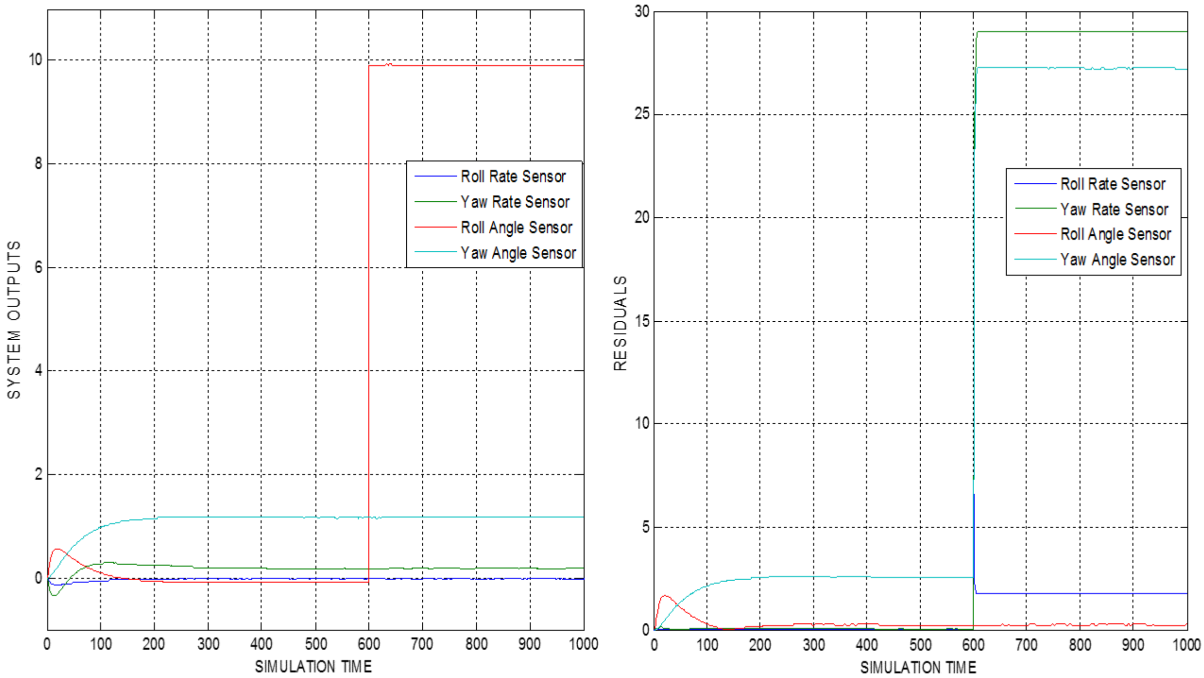

Figure 4 System outputs and residuals for roll angle sensor failure case

Simulation 5: Yaw angle sensor failure case

At last, the simulation experiment is carried to verify the fault detection and isolation ability of UIO and GOS theories on yaw angle sensor. Simulation results in Figure 5 show the same performance for yaw angle sensor failure as well. Fault is detected at 500th second and isolated via residual norm values. The residual norm of yaw angle sensor keeps its same value while the others are affected from the fault.

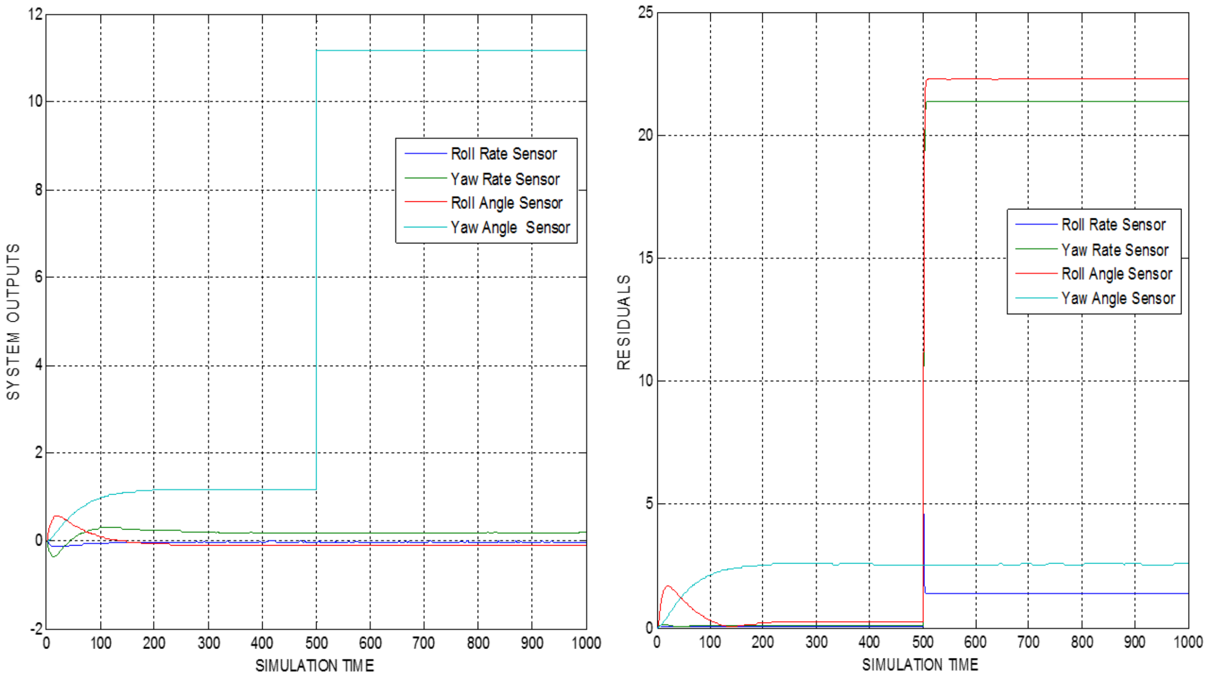

Figure 5: System outputs and residuals for yaw angle sensor failure case

CONCLUSION

In this study, UIO and GOS structures are designed for fault detection and isolation of an aircraft longitudinal flight control system. Using UIO methodology, unknown inputs are decoupled from system and by means of GOS, residual values are calculated for all system sensors. During simulations, a linearized mathematical model of a F2B Bristor Fighter is considered. Various simulations are done under different sensor failure conditions and satisfactory results are achieved. It can be said that the designed system structure is sensitive to a fault without considering its amplitude and insensitive to unknown system inputs. Following study in the subject will be adding a reconfiguration mechanism to the current designed system.

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