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Optimization of PID Controllers for UAVs Using SPSA Algorithm for Enhanced Flight Performance

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Abstract

This paper presents the design and optimization of a longitudinal control system for a fixed-wing Unmanned Aerial Vehicle (UAV). The study focuses on the development of a state-space model based on the UAV's aerodynamic parameters. The system matrices (A and B) are derived from the vehicle's physical properties and aerodynamic coefficients, allowing for an accurate representation of the UAV's response to control inputs. A PID controller was used to regulate the pitch angle, and its parameters are optimized using the Simultaneous Perturbation Stochastic Approximation (SPSA) method. This optimization approach proves to be effective in fine-tuning the control gains by minimizing the error in the pitch response under realistic flight conditions. The study emphasizes the robustness of SPSA, particularly in high-dimensional and noisy environments.The results demonstrate the improved autonomous performance of the UAV, with the PID controller successfully achieving the desired pitch angle control.

1. Introduction

The control systems of Unmanned Aerial Vehicles (UAVs) have become a significant research area in recent years. PID (Proportional-Integral-Derivative) controllers are commonly used in this domain, however, more efficient performance can be achieved through optimization techniques. PID controllers are widely used in dynamic systems such as UAVs because of their simplicity and adaptability, and they can be optimized for better performance. However, for UAVs to adapt to more complex and variable flight conditions, more sophisticated optimization methods are required (Sonny et al., 2023; Erkol, 2018). Erkol (2018) investigated the optimization of PID gains for a quadrotor UAV using methods such as Ziegler-Nichols, PSO (Particle Swarm Optimization), and SPSA, showing that SPSA is an effective optimization method. SPSA, particularly in noisy and nonlinear systems, has proven to be an effective optimization algorithm due to its ability to find optimal solutions with minimal function evaluations (Sonny et al., 2023). This algorithm has the advantage of significantly reducing both the optimization time and cost. Moreover, Çantaş and Akbulut (2021) compared PID and LQR (Linear Quadratic Regulator) based control systems for fixed-wing aircraft and noted that PID controllers are successful in optimizing nonlinear systems. In studies involving the integration of SPSA with PID, it has been demonstrated that combining these methods can significantly improve flight performance. Muliadi and Kusumoputro showed that optimization using genetic algorithms led to better results compared to traditional methods in the design of PID-controlled UAV speed control systems. They also noted that PID optimization helped minimize the impact of external disturbances during flight (Muliadi and Kusumoputro, 2018). Amelin and Maltsev, (2021) applied the SPSA algorithm to optimize the speed and position control of UAVs, finding that SPSA offered performance improvements and was effective under both stable and variable flight conditions. Shehryar (2019) used SPSA to optimize the aerodynamic performance of UAVs and demonstrated that its combination with PID enhanced aerodynamic efficiency. These studies show that combining PID and SPSA control techniques can help improve the flight efficiency of UAVs (Shehryar, 2019). The improved particle swarm optimization method for UAV PID parameter tuning achieves better control performance indicators and shorter adjustment time, leading to better dynamic performance [Guo et. Al., 2022). Mao et. Al, (2017) stated that PID and Kalman filters can be integrated for UAV speed and direction control. Optimization using the SPSA algorithm also highlighted that more control over aerodynamic parameters and system behavior could be achieved (Mao et. Al, 2017). Optimizing PID gains using SPSA results in reduced position error and improved balancing response in unmanned surface vehicles (Singh and Bhushan, 2020). Furthermore, Kaba (2020) compared adaptive control systems and PID controllers, noting that adaptive systems performed better. However, it was also observed that PID controllers could outperform in some cases (Kaba, 2020). Çoban (2019) designed a tailplane for small UAVs alongside an autopilot system, aiming to improve flight stability and control performance. This study emphasizes the importance of effective system integration in small UAVs to achieve better flight characteristics and control responsiveness (Çoban, 2019). In another significant study, Çoban and Oktay (2018) proposed a simultaneous design of a small UAV flight control system and a lateral state-space model. This model provides a robust solution for controlling the dynamic behavior of UAVs, particularly in lateral motion, and highlights the advantages of an integrated control approach (Çoban & Oktay, 2018). Furthermore, Çoban, Bilgiç, and Oktay (2019) focused on the dynamic modeling and simulation of the ISTECOPTER, a specific UAV. This research contributed to enhancing the understanding of the dynamic behavior of UAVs through comprehensive simulations and experimental validation (Çoban, Bilgiç, & Oktay, 2019). In conclusion, the combination of PID and SPSA-based optimization methods for UAVs facilitates faster and more efficient flight performance (Abdelmaksoud et al., 2020; Mobarez et al., 2019). These optimization approaches provide more flexible and dynamic response times during flight, minimizing the effects of noise and external disturbances.The studies indicate that these methods contribute to improving not only the speed and position control but also the aerodynamic efficiency of UAVs (Amelin and Maltsev, 2021).

2. Method

The UAV's longitudinal dynamics are modeled in terms of its state-space representation. The following parameters are used in the calculations.

Table 1. Calculation parameters of UAV

Air density (ρ)	1.225 kg/m³
Vehicle mass (m)	1.7 kg
Airspeed (u_0) =	60 km/h
Wing span (b)	1.38 m
Wing chord (c)	0.23 m
Reference area (S) = b * c	0.2835 m²
Coefficient of drag at zero angle of attack	(C_{ko}) = 0.01323
Coefficient of lift at zero angle of attack	(C_{lo}) = 0.45021
Lift curve slope ($C_{l}\alpha$)	5.721 rad⁻¹
Aspect ratio (AR)	b²/S
Distance from the center of gravity to the aerodynamic center (x_{∞})	0.07 m
-Moment of inertia around the y-axis (I_{YY})	0.078387 kg·m²

The force components along the three axes (x, y, z) are expressed in relation to the aircraft's weight, linear accelerations ($\dot{u}, \dot{v}, \dot{w}$), linear velocities (u, v, w), angular velocities (p, q, r), and heading angles (ϕ_A, θ_A) as demonstrated below:

$$F_A = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} M_a(\dot{u} + qw - rv) + M_a g \sin(\theta_A) \\ M_a(\dot{v} + ru - pw) - M_a g \cos(\theta_A)\sin(\phi_A) \\ M_a(\dot{w} + pv - qu) - M_a g \cos(\theta_A)\sin(\phi_A) \end{bmatrix} \tag{1}$$

To formulate the moment equations, the Law of Conservation of Angular Momentum has been employed as commonly referenced in the literature. This principle is represented in Equation 2:

$$^{I}\dot{\vec{h}} = \frac{\partial}{\partial t}{}^{I}\vec{h} + {}^{I}\vec{\omega}^{A} \otimes {}^{I}\vec{h} \tag{2}$$

The components of the moment on the three axes (L, M, N) expressed in terms of the aircraft's inertia properties (I_{xx}, I_{yy}, I_{zz}, I_{xz}),angular velocities (p, q, r) and angular accelerations ($\dot{p}, \dot{q}, \dot{r}$) as shown below:

$$M_A = \begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx}\dot{p} - (I_{yy} - I_{zz})qr - I_{xz}(pq + \dot{r}) \\ I_{yy}\dot{q} - (I_{zz} - I_{xx})pr + I_{xz}(p^2 - r^2) \\ I_{zz}\dot{r} - (I_{xx} - I_{yy})pq - I_{xz}(\dot{p} - rq) \end{bmatrix} \tag{3}$$

The kinematic equations are found using the 3-2-1 axis rotation order commonly used in aviation.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \dot{\phi}_A - \dot{\psi}_A sin(\theta_A) \\ \dot{\psi}_A cos(\theta_A) sin(\phi_A) + \dot{\theta}_A cos(\phi_A) \\ \dot{\psi}_A cos(\theta_A) cos(\phi_A) - \dot{\theta}_A sin(\phi_A) \end{bmatrix} \tag{4}$$

The UAV's longitudinal state-space equations are expressed as:

$$\delta\dot{x} = A\,\delta x + B\,\delta u \tag{5}$$

Where:
- x is the state vector, including the UAV's position, velocity, and orientation,
- u is the control input, such as the throttle or elevator deflection,
-A and B are the system matrices.

The longitudinal system is linearized around a steady flight condition, and the state-space matrices A and B are derived from the UAV's aerodynamic parameters. The state-space model is as follows:

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}}Z_w & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} X_{\delta_T} & X_{\delta_e} \\ Z_{\delta_T} & Z_{\delta_e} \\ M_{\delta_T} + M_{\dot{w}}Z_{\delta_T} & M_{\delta_e} + M_{\dot{w}}Z_{\delta_e} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_T \\ \Delta\delta_e \end{bmatrix} \tag{6}$$

Where:
-Xu, Xw represent the forces in the longitudinal direction, -Zu, Zw represent the forces in the vertical direction, -Mw, Mw represent the moments around the body axes,

-g is the gravitational acceleration.

This formulation is derived based on flight stability models, including aerodynamic force and moment coefficients (Nelson, 2007).

For the control design, a PID controller is implemented to manage the UAV's pitch angle and maintain the desired trajectory. The PID gains are optimized using the SPSA method, which is particularly effective in high-dimensional, noisy environments. The PID controller is designed with the following gains:

$K_p = 50 * x_5$
$K_i = 5 * x_6$
$K^d = 50 * x_7$

Where x_5, x_6, and x_7 are parameters obtained from the SPSA optimization. These parameters are adjusted to minimize the error in the UAV's pitch angle response, with the optimization process iterating to find the best control gains (Spall, 2005).

To improve the autopilot and improve the design performance of the UAV, an optimization method called Simultaneous Perturbation Stochastic Approximation was applied. This method was developed by Prof. Dr. James Spall in 1987 and is briefly referred to as the SPSA optimization method in the literature. This optimization method is a step-by-step change of the adjustable parameters from the initial estimated values to the values that will give the minimum of the objective function.

Our autopilot system is dependent on the PID and aircraft parameters and the optimum values of its parameters are determined according to the system responses such as settling time, rise time and overshoot. Finding an analytically defined relationship between the system responses and the desired parameters is quite difficult and demanding. The objective or cost function is expressed as a function of the settling time, rise time and overshoot values and is determined by J.

$$J = \sum g(T_{st} - T_{st_u})^2 + T_{rt} + g(\%OS^2) \quad (7)$$

The optimum values of the estimated adjustable parameters correspond to the parameter values that give the minimum objective function or the derivative of the objective function zero. In other words, the values that will give the minimum objective function are the most suitable values for our system and the values we want to find when performing optimization [Spall, 1992].

Ψ represents the vector of optimization variables. In traditional SPSA, if $\Psi_{[k]}$ is estimated at the Ψ kth iteration, then the estimate in the next step can be expressed as: $\Psi_{[k+1]} = \Psi_{[k]} - \Psi_k g_{[k]}$ where:

$$g_k = \left[\frac{\Gamma_+ - \Gamma_-}{2d_k\Delta_{[k]_i}} \cdots \frac{\Gamma_+ - \Gamma_-}{2d_k\Delta_{[k]_p}}\right]^T \quad (8)$$

a_k and d_k are the payoff sequences, and $g_{[k]}$ is the estimate of the gradient of the target at $\Psi_{[k]}$.

The SPSA optimization method is applied to fine-tune the PID controller's parameters. SPSA is an iterative method that estimates the gradient of the cost function using random perturbations. The SPSA method is particularly useful in the presence of noise and for systems with a large number of variables. The optimization results in the selection of optimal PID gains that improve the UAV's autonomous performance (Spall, 2005).

The definition of the dynamic modeling of the aircraft is important in the development of control systems. High-fidelity models have a great impact on the quality of the designed control algorithms. A tunable autopilot was used using flight observations, and our autopilot system has the classical autopilot structure. As seen in Figure 1, there are three layers for the hierarchical control structure, divided into outer loop, middle loop and inner loop. The inner loop is the attitude compensation loop that controls the pitch and roll of the aircraft. The middle loop balances the direction of progress and altitude of the aircraft. The outer one monitors the x-y positions of the aircraft. Control signals are evaluated in the inner loop. In the outer loop, altitude and yaw errors are corrected. In the middle loop, pitch and roll angles are determined based on these errors. In the inner loop, the position that the control elements should take is determined using roll and pitch.

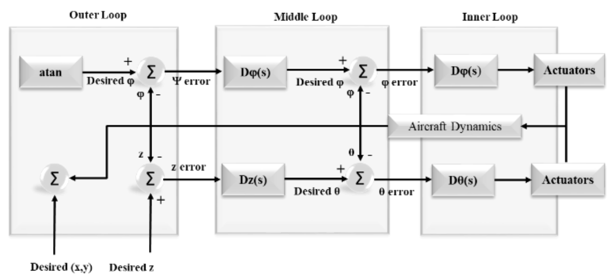

Figure 1. Hierarchical detailed autopilot structure of the UAV

Our autopilot system uses 6 PID controllers to adjust the errors of the throttle lever, elevator angle, height, rudder angle, aileron angle and turning angle.

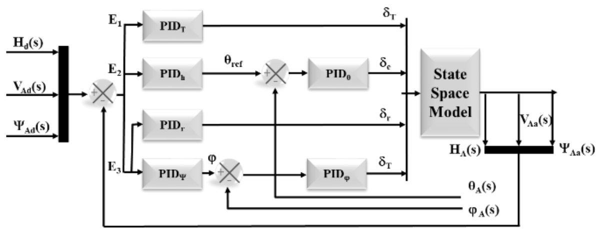

Figure 2. The control structure of autopilot system

The autopilot system can make the aircraft follow the altitude, speed and yaw angle trajectories. The autopilot system needs 5 sensor data. These are altitude, speed, pitch angle, yaw angle, roll angles. Of these, altitude is determined by altimeter and GPS, speed by pitot tube or GPS, and roll, pitch and yaw angle are determined by Gyroscope. If we look at the autopilot in detail, the desired yaw angle and the measured yaw angle difference E3 are multiplied by the yaw PID controller. The obtained signal is subtracted from the measured roll angle and multiplied by the roll PID controller. The resulting signal determines the position of the aileron angle. The other 3 control elements can be obtained similarly using the block diagram. Here, the behavior of the trajectory tracking analysis can be examined as speed, height or yaw angle or their combination. It also uses 5 sensor inputs. In order to facilitate the solution analysis, the trajectory tracking analysis of the pitch angle is considered.

3. Results and Discussion

The figure 3 presents the actual pitch angle, θ, compared to the reference pitch angle of 7.5°. The system demonstrates a fast and smooth rise to the desired angle, with a slight overshoot initially. However, the overshoot is well-controlled, and the system converges to the reference value within a short period. Once stabilized, the actual pitch angle closely tracks the reference, with minimal steady-state error. This result showcases the controller's accuracy in achieving and maintaining the target pitch angle. The system's ability to track the reference input effectively indicates excellent performance and precision.

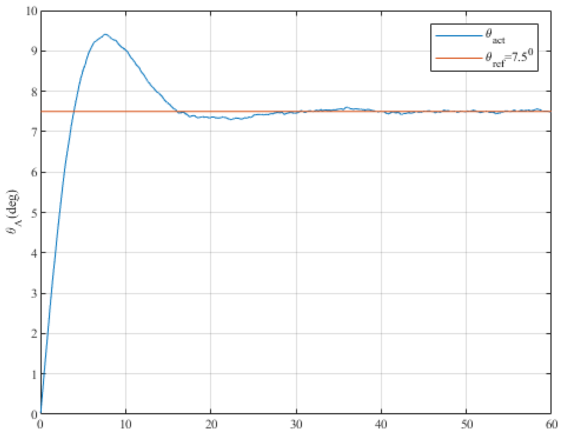

Figure 3. Pitch angle, θ, compared to the reference pitch angle of 7.5°

The figure 4 shows the variation of the elevator deflection angle, δ, over time. Despite the presence of noticeable fluctuations, the signal remains stable without any visible trend toward instability. The system demonstrates that the control inputs are effectively managed throughout the operation. While there is some noise in the signal, this indicates a responsive and active control system that continuously adjusts to maintain stability. Overall, the system's deflection behavior suggests that the control algorithm provides reliable actuation.

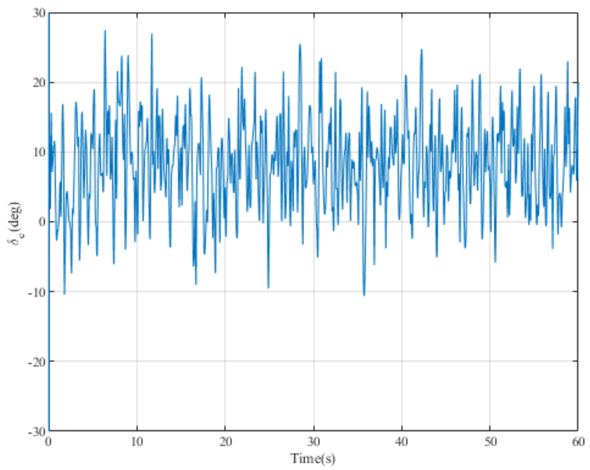

Figure 4. Variation of the elevator deflection angle, δ, over time.

The u value oscillates between +1.5 m/s and -1.5 m/s. This represents the horizontal velocity of the UAV, which shows variability in the forward or backward motion of the vehicle over time. The oscillation within this range indicates that the UAV is capable of adjusting its speed effectively and is able to maintain a certain level of stability. If the UAV's horizontal velocity remains within this range, it can be considered to be operating efficiently in terms of speed control. Small oscillations in u suggest that the flight control system is responding well to any external disturbances or flight path corrections, maintaining an adequate level of control over the UAV's speed.

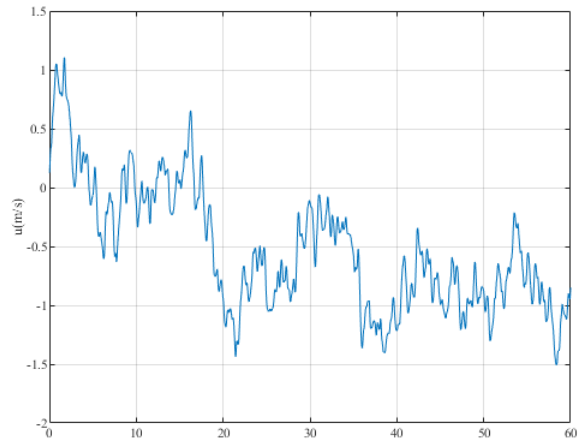

Figure 5. Horizontal velocity of UAV

The w value fluctuates between -0.4 m/s and +0.4 m/s. This represents the vertical velocity of the UAV, or how much it is moving up or down relative to the ground. The small range of fluctuation in **w** indicates that the UAV is maintaining a stable altitude with minimal vertical deviations. It suggests that the UAV's vertical control is quite stable, with effective altitude holding and minimal vertical oscillation. These small oscillations can be attributed to external factors such as minor gusts of wind or small adjustments made by the control system, but they are well within acceptable limits, meaning the UAV is performing its vertical movements efficiently.

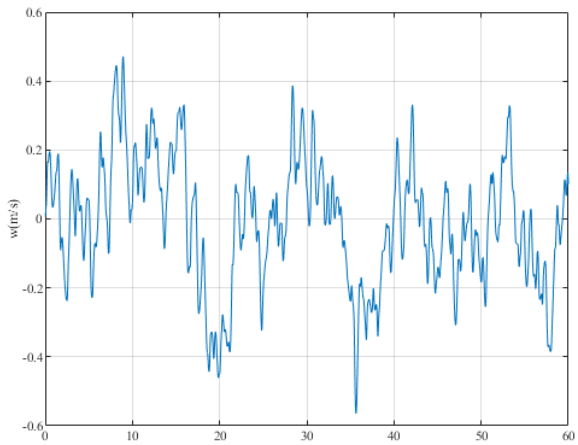

Figure 6. Vertical velocity of UAV

The figure 7 illustrates the pitch rate, q, in response to the applied step input. Initially, the system reacts quickly with a peak pitch rate of approximately 2.5°/s, reflecting its prompt response capability. The pitch rate then settles smoothly within the first 10 seconds, stabilizing near zero. This behavior highlights the system's strong damping performance and its ability to suppress oscillations effectively. The smooth transition to steady-state indicates that the controller successfully mitigates dynamic disturbances and ensures stability in the pitch rate.

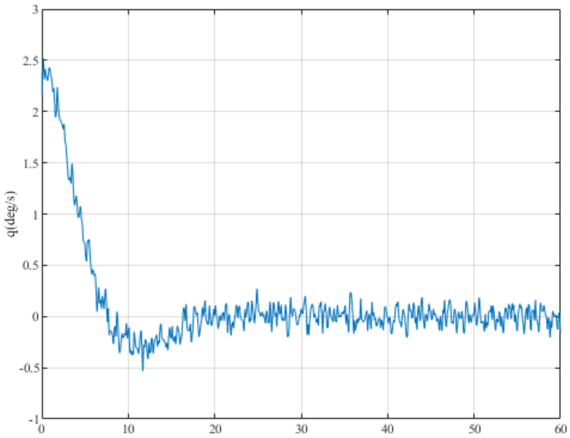

Figure 7. Pitch rate, q, in response to the applied step input

In summary, the results from all three graphs reveal a well-performing control system with fast response times, effective damping, and accurate tracking of the reference pitch angle. The controller successfully stabilizes the pitch dynamics and demonstrates robust performance throughout the test.

In this study, the optimization of PID controllers for unmanned aerial vehicles (UAVs) was carried out using the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. The results demonstrated that optimizing the PID controller gains significantly improved the UAV's flight performance. Specifically, improvements in the control of the pitch angle resulted in the controller providing faster and more stable responses. By using the SPSA optimization technique, the proportional (Kp), integral (Ki), and derivative (Kd) gains were successfully adjusted, making the UAV's flight more precise and efficient. The PID parameters obtained through optimization ensured that the system reached the desired state more quickly, with reduced overshoot. The results show that the PID controller optimization greatly enhanced the UAV's control capabilities and increased flight safety. The use of the SPSA algorithm allowed for effective results even in more complex and noisy systems. The optimization, particularly through increased stability, contributed to more efficient and safer flight. Future studies could investigate how these methods perform in more complex flight scenarios and varying weather conditions. Additionally, comparisons of different optimization algorithms and performance evaluations would be valuable for future research.

4. Conclusion

This study examined the optimization of PID controllers for unmanned aerial vehicles (UAVs), with a focus on the use of various optimization techniques, particularly the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. The results highlighted the significant role of PID controllers in improving UAV performance, while also emphasizing the need for more sophisticated optimization techniques in more complex and variable flight conditions. The SPSA algorithm emerged as an effective method for finding optimal solutions in noisy and nonlinear systems. A review of the literature showed that SPSA has led to notable improvements in UAV flight control, enhancing PID controller performance and thereby increasing flight safety and efficiency. The optimization techniques used in this study, particularly SPSA, proved to be efficient in achieving faster and more effective performance improvements in UAVs. These findings suggest that SPSA could be a valuable tool for enhancing UAV speed, positioning control, and aerodynamic efficiency. Future research could focus on comparing different optimization algorithms and evaluating their performance in more complex flight environments. Additionally, there is a need for further development of such controller optimizations to enable UAVs to operate effectively in broader operational conditions. In conclusion, PID controller optimization is a key tool for improving UAV flight performance, and the application of modern optimization techniques like SPSA enhances controller effectiveness, enabling UAVs to operate more safely and efficiently.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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