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Robust UAV Interception Using Hybrid Guidance Laws: A Comparative Study with Pure Pursuit and Proportional Navigation

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Abstract:

This study addresses the increasing need for effective counter-drone strategies due to the rapid proliferation of Unmanned Aerial Vehicles (UAVs), including their misuse in hostile applications. A comparative evaluation of four guidance laws—Pure Pursuit (PP), Proportional Navigation (PN), Hybrid One (H1), and Hybrid Two (H2)—is conducted using a two-dimensional simulation framework implemented in Python. The system dynamics are numerically solved using the fourth-order Runge–Kutta (RK4) integration method.

The performance of each guidance law is assessed across six distinct target maneuver scenarios, including deterministic and stochastic motion profiles. Evaluation metrics include miss distance, interception time, path length, and root mean square (RMS) lateral acceleration. Results demonstrate that Hybrid Two consistently achieves successful interception in all scenarios, outperforming other methods in overall ranking and robustness. Specifically, Hybrid Two yields the lowest cumulative score and superior interception efficiency in highly maneuvering target conditions.

The findings suggest that Hybrid Two, with a blending coefficient of $\alpha = 0.5$, provides a balanced and reliable guidance strategy, making it a strong candidate for real-world UAV interception systems, particularly for net-based capture mechanisms.

Keywords — Pure Pursuit, Proportional Navigation, Runge–Kutta (RK4) integration, UAV interception systems, Unmanned Aerial Vehicles, Hybrid Guidance Laws.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are aircrafts with no human pilot, crew, or passengers on board, but rather is controlled remotely or is autonomous. UAVs were originally developed for military operations that were too hard or too dangerous for humans. By the 21st century UAVs became important assets to most militaries. As technology improved and costs fell, UAVs had found their way into civilian hands for non-militaristic purpose such

as aerial photography, agriculture, environmental monitoring, etc. Unfortunately, the growth and ease at which people could get UAVs caused a negative side effect where criminal or terroristic organizations could use the UAVs for nefarious and malicious means [1], [2]. Corrupt organizations and people have exploited UAVs for drug trafficking, arms trafficking, detonating explosives in conflict zones, etc. UAVs flown near airports have also caused disruption in civilian lives showing that the direct negative effect of UAVs apply to both military and civilian personnel.

In an effort to combat this many counter-drone solutions have been thought of. One of these solutions is using interceptor UAVs/drones to pursue and intercept the target UAV/drone. The interceptor achieves this by using a guidance law. Guidance Laws are laws which guide the UAV and tells which direction to steer their nose in. The 2 main guidance laws are Pure Pursuit (PP) and Proportional Navigation (PN). Pure Pursuit tells the interceptor to steer in the direction the target is currently at and is considered least efficient for a target using a near straight line manoeuvre while at the same time demanding high lateral acceleration near the end of the chase. Proportional Navigation attempts to predict where the target will be in the future and steers the interceptor towards that point. It does this by commanding acceleration proportional to the LOS rotation rate in order to drive that rotation rate to zero [3], [4]. The collision triangle condition is what guarantees interception. While this guidance law is better than PP and more effective when targets fly in a near straight line, its effectiveness reduces when it comes to manoeuvring targets. There is a third option called Hybrid Guidance Laws, which aims to combine the effectiveness of both PP and PN. It does this by adding a weight blend parameter (α) to the formulas of PP and PN and combining them to find a middle ground. While hybrid guidance formulations have been proposed in the literature, the literature surrounding their effectiveness compared to pure guidance laws is limited when it comes to UAVs. This paper compares the effectiveness of two hybrid guidance laws (Hybrid One and Hybrid Two) against each other and against PP and PN. It does this with the help of a simulation-based comparative analysis of the 4 guidance laws (PP, PN, Hybrid One, and Hybrid Two) applied across multiple target scenarios. The simulation is run in Python in a two-dimensional framework using the 4th order Runge-Kutta (RK4) method. Performance is assessed from time taken to interception [5].

This paper contributes a multi-scenario multi-metric comparison of Pure Pursuit, Proportional Navigation, Hybrid One, and Hybrid Two across six target manoeuvre scenarios, including both a smooth and an aggressive random walk profile, identifying the conditions under which hybrid blending provides genuine advantages over pure Proportional Navigation. Section 2 reviews the relevant literature. Section 3 describes the methodology. Section 4 presents the results. Section 5 concludes the paper.

2. LITERATURE REVIEW

2.1. Pure Pursuit Guidance Law

The Pure Pursuit (PP) guidance law is one of the most fundamental and intuitive approaches used in interception problems. It operates by continuously aligning the velocity vector of the pursuer with the instantaneous line-of-sight (LOS) direction toward the target. As a result, the pursuer always steers toward the target's current position rather than predicting its future trajectory. This simplicity makes Pure Pursuit straightforward to implement in real-time systems [6], [7].

According to Shneydor [1], the lateral acceleration command for Pure Pursuit is expressed as:

$$a_{PP} = K * V_{Pursuer} * \epsilon \quad (1)$$

where K is the proportional gain, V_{Pursuer} is the pursuer velocity, and ϵ is the heading error (LOS angle – pursuer heading). Shneydor [1] also showed that Pure Pursuit suffers from high lateral acceleration needs towards the end of its chase.

2.2. Proportional Navigation Guidance Law

Proportional Navigation (PN) is a widely used guidance strategy that improves upon the limitations of Pure Pursuit by incorporating predictive behavior. Instead of directly chasing the target's current position, PN aims to maintain a constant LOS angle. For non-maneuvering targets, this condition ensures interception if the range between the pursuer and target is continuously decreasing [8], [9].

The lateral acceleration command for PN, as described by Guelman [2] and Zarchan [3], is given by:

$$a_{\text{PN}} = N \cdot V_c \cdot \dot{\lambda} \quad (2)$$

where N is the navigation constant, V_c is the closing velocity, and $\dot{\lambda}$ is the rate of change of the LOS angle. Guelman [2] established that for non-maneuvering targets, a navigation constant $N > 2$ guarantees interception in finite time, while $N = 3$ provides energy-optimal performance. Zarchan [3] further extended this analysis, suggesting that values of N between 3 and 5 yield optimal interception performance across a broader range of scenarios. Based on this established range, a value of $N = 4$ is adopted in this study.

2.3. Hybrid Guidance Laws

Hybrid guidance laws have emerged as a response to the inherent limitations of both Pure Pursuit and Proportional Navigation. While Pure Pursuit offers rapid responsiveness, it often produces inefficient trajectories. In contrast, Proportional Navigation provides smoother and more efficient interception paths for predictable target motion but struggles against highly maneuvering targets.

To address these limitations, hybrid approaches combine the characteristics of both methods. Ghosh et al. [4] investigated blended guidance strategies and demonstrated that appropriately tuned combinations of PP and PN can outperform either method individually. Their study also highlighted that the optimal blending coefficient is scenario-dependent, meaning that no single value is universally optimal across all engagement conditions.

In this context, Hybrid One follows a convex blending formulation: [10]

$$a_{\text{H1}} = \alpha \cdot a_{\text{PN}} + (1 - \alpha) \cdot a_{\text{PP}} \quad (3)$$

where α is the blending coefficient. This formulation ensures a weighted balance between predictive and reactive behaviors. In contrast, Hybrid Two, evaluated in this study, adopts a non-convex augmented structure that emphasizes Proportional Navigation while retaining a partial contribution from Pure Pursuit, thereby enhancing responsiveness under aggressive target maneuvers.

2.4. UAV Interception and Performance Metrics

The effectiveness of UAV interception strategies is often evaluated using multiple performance metrics. Ryoo et al. [6] demonstrated that longer and more curved trajectories result in higher energy consumption, thereby establishing path length as a critical performance indicator.

Furthermore, Rajasekhar and Sinha [7] showed that interception performance is highly dependent on the nature of the target's maneuver, reinforcing the need to evaluate guidance laws across diverse scenarios. This scenario dependency motivates the multi-case analysis conducted in this study. [11]

Additionally, Palumbo et al. [8] emphasized the importance of Root Mean Square (RMS) lateral acceleration as a key metric, particularly for small UAVs where actuator limits and energy efficiency are critical. Consequently, this study incorporates RMS lateral acceleration alongside interception time and path length to provide a comprehensive evaluation of guidance law performance.

2.5 Research Gap

Prior studies on guidance laws have predominantly focused on performance evaluation within a single engagement scenario, which limits their applicability to real-world situations where target maneuvers are uncertain and variable. Moreover, existing literature lacks a comprehensive comparison of guidance laws under both smooth and highly aggressive random walk target profiles within a unified framework. To address these limitations, the present study conducts a systematic comparison of Pure Pursuit, Proportional Navigation, Hybrid One, and Hybrid Two across six distinct maneuvering scenarios. These scenarios include both smooth and aggressive stochastic motion profiles, and the evaluation is performed using four key performance metrics with a fixed blending coefficient of $\alpha = 0.5$.

3. METHODOLOGY

3.1. Simulation Framework

A two-dimensional simulation was implemented in Python using NumPy and matplotlib.pyplot to evaluate the performance of the four guidance laws (PP, PN, Hybrid One, Hybrid Two) over six target maneuvers scenarios. The pursuer and target are modelled as point masses moving at constant speed with no aerodynamic drag. It is assumed that the pursuer knows the correct position of the target at each timestep. The fourth order Runge-Kutta (RK4) method is used to integrate the equations of motion at a fixed timestep of $DT = 0.01$ and for a maximum time of 100 seconds. The simulation terminates under one of two conditions. The first condition is if the distance between the pursuer and the target is less than 3 meters, which means the interception was successful and a net was deployed by the pursuer to catch the target. The second condition is if the simulation time reaches 100 seconds which means interception has failed. The initial range between the pursuer and the target is 424.26406 meters. The constant speed of the pursuer is 30 m/s and the constant speed of the target is 20 m/s. The initial location of the pursuer is at the origin (0,0) and the heading of the pursuer is 45 degrees (to directly face the target). The initial location of the target is (300,300) and the target's heading is 180 (facing left). The maximum time of 100 seconds was chosen so that every guidance law has enough time to intercept the target. [12], [13]

The engagement dynamics are governed by relative motion equations between the pursuer and target:

The equations represent the relative position of the target with respect to the pursuer in the Cartesian coordinate system. Δx : horizontal separation and Δy : vertical separation

$$\Delta x = x_T - x_P \text{ and } \Delta y = y_T - y_P \quad (4)$$

This equation gives the Euclidean distance (range) between the pursuer and the target. It is a key parameter used to determine interception conditions.

$$R = \sqrt{(\Delta x)^2 + (\Delta y)^2} \quad (5)$$

The LOS angle λ defines the direction from the pursuer to the target relative to the horizontal axis. It is a crucial variable in guidance laws, as it determines where the target is located from the pursuer's perspective.

$$\lambda = \tan^{-1} \left(\frac{\Delta y}{\Delta x} \right) \quad (6)$$

The heading error ϵ represents the difference between the LOS angle and the pursuer's current heading angle θ_p

$$\epsilon = \lambda - \theta_p \quad (7)$$

If $\epsilon = 0$: the pursuer is directly pointing at the target

If $\epsilon \neq 0$: the pursuer must adjust its direction.

This term is especially important in Pure Pursuit guidance.

The below equations (8) and (9) resolve the velocities of both the pursuer and target into horizontal (x) and vertical (y) components. This decomposition is necessary for calculating relative motion. [14]

$$v_{xp} = V_p \cos(\theta_p), v_{yp} = V_p \sin(\theta_p) \text{ – for the pursuer} \quad (8)$$

$$v_{xt} = V_t \cos(\theta_t), v_{yt} = V_t \sin(\theta_t) \text{ – for the target} \quad (9)$$

Relative velocity equations (10) represent how the target is moving with respect to the pursuer.

$$v_{x,rel} = v_{xt} - v_{xp}, v_{y,rel} = v_{yt} - v_{yp} \quad (10)$$

Positive/negative values indicate direction of motion difference

These components are used in computing closing velocity and LOS rate

Closing velocity V_c represents the rate at which the distance between the pursuer and target is decreasing.

$$V_c = \frac{\Delta x \cdot v_{x,rel} - \Delta y \cdot v_{y,rel}}{R^2} \quad (11)$$

If $V_c > 0$: the pursuer is approaching the target

If $V_c < 0$: the target is moving away

It is essentially the projection of relative velocity along the line of sight.

The LOS rate $\dot{\lambda}$ measures how quickly the LOS angle is changing over time. [15]

$$\dot{\lambda} = \frac{\Delta x \cdot v_{y,rel} - \Delta y \cdot v_{x,rel}}{R^2} \quad (12)$$

A zero LOS rate implies a constant bearing, which is the condition for collision in Proportional Navigation. A non-zero LOS rate indicates that the pursuer must maneuver to correct its path. This parameter is fundamental to Proportional Navigation guidance.

All four guidance laws utilize the previously defined engagement geometry parameters to compute the required lateral acceleration commands throughout the simulation. To comprehensively evaluate their performance, six distinct target maneuver scenarios are considered, representing both deterministic and stochastic motion patterns. In the straight flight scenario, the target moves in a constant direction with zero lateral acceleration, i.e., $a_T(t) = 0$. In the sinusoidal weave scenario, the target applies a time-varying lateral acceleration defined by $a_T(t) = 15\sin(2\pi t/4)$, resulting in a periodic oscillatory motion; due to continuous heading changes, the trajectory evolves diagonally rather than strictly along a single axis. The turn scenario models constant curvature motion with a fixed lateral acceleration of 12 m/s^2 , producing a circular path. In the step maneuver, the target initially travels in a straight line for the first 5 seconds ($a_T(t) = 0$), after which it abruptly applies a constant lateral acceleration of 20 m/s^2 . Two stochastic scenarios are also included: the smooth random walk, where the target acceleration follows a random process with a standard deviation of 7.5, and the aggressive random walk, characterized by a significantly higher standard deviation of 100; both are generated using a fixed random seed of 42 to ensure reproducibility. [16]

The study evaluates four guidance laws: Pure Pursuit (PP), Proportional Navigation (PN), Hybrid One (H1), and Hybrid Two (H2). In all cases, the commanded lateral acceleration is constrained within the physical limits of the pursuer, specifically between $\pm 30 \text{ m/s}^2$. The Pure Pursuit law, following Shneydor [1], computes acceleration as $a_{PP} = K \cdot V_{Pursuer} \cdot \epsilon$, where the proportional gain K is set to 4 and the pursuer velocity V_p is 30 m/s. Proportional Navigation, based on Guelman [2] and Zarchan [3], is defined as $a_{PN} = N \cdot V_c \cdot \dot{\lambda}$, with the navigation constant $N = 4$. Hybrid One adopts a convex blending approach, combining both laws as $a_{H1} = \alpha a_{PN} + (1 - \alpha) a_{PP}$, while Hybrid Two uses a non-convex formulation given by $a_{H2} = a_{PN} + (1 - \alpha) a_{PP}$. In this study, the blending coefficient α is fixed at 0.5, ensuring equal weighting between PP and PN in Hybrid One, while giving PN relatively greater influence in Hybrid Two.

Performance is evaluated using four key metrics. Miss distance represents the separation between the pursuer and target, with values below 3 meters indicating successful interception; otherwise, the final separation at the maximum simulation time is reported. Interception time measures the duration required to achieve this condition, with unsuccessful attempts labeled as failures if interception does not occur within 100 seconds. Path length, as highlighted by Ryoo et al. [9], quantifies the total distance traveled by the pursuer and serves as an indicator of energy efficiency. Additionally, RMS lateral acceleration, following Palumbo et al. [8], reflects the control effort required and is particularly relevant for UAV systems with actuator constraints.

The simulation is initialized with the pursuer positioned at the origin (0,0) and the target at (300,300), corresponding to an initial separation of approximately 424.3 meters. The pursuer travels at a constant speed of 30 m/s, while the target moves at 20 m/s, representing a realistic interception scenario with a speed advantage. The initial heading of the pursuer is set to 45° , aligning with the initial LOS angle to eliminate heading error at the start, whereas the target begins with a heading of 180° . The simulation uses a fixed timestep of 0.01 seconds and runs for a maximum duration of 100 seconds. Additional parameters include acceleration limits of 30 m/s^2 for the pursuer and 20 m/s^2 for the target, along with the predefined gains and random walk characteristics described earlier [17], [18]. These settings ensure a consistent and realistic framework for comparing guidance law performance across all scenarios.

3.2 Simulation Flow charts

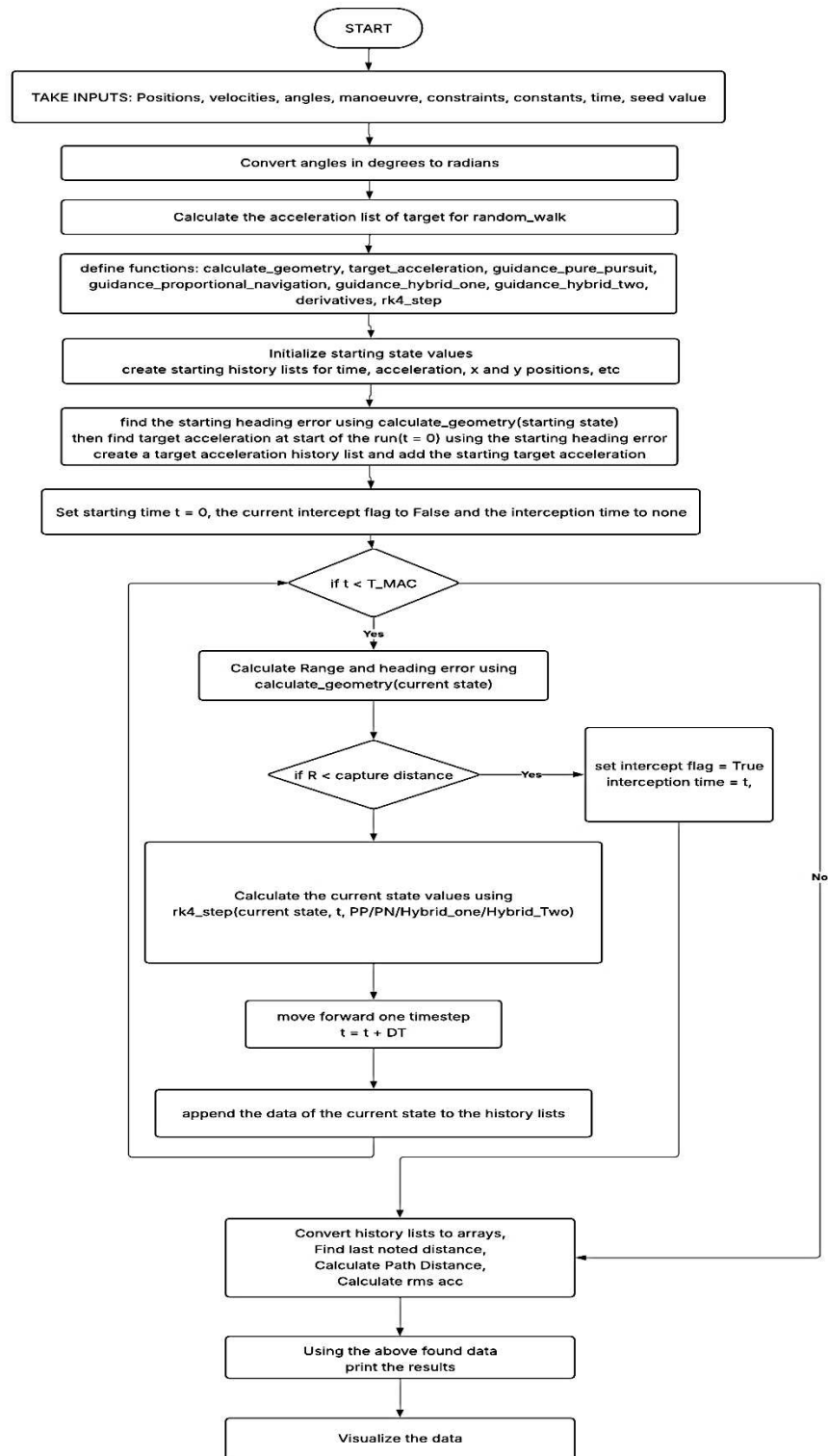


Fig.1. Flowcharts

The simulation flow (from Figure 1) follows a structured iterative process: [19], [20]

1. Initialization Stage
Initial positions, velocities, headings, and parameters are defined.
2. Time Loop Execution
At each timestep: Relative geometry is computed (distance, LOS angle, velocities), Guidance law generates lateral acceleration command and Acceleration is clipped to physical limits.
3. Numerical Integration (RK4)
The RK4 method updates position and heading with high accuracy.
4. Target Motion Update
Target acceleration is applied based on scenario definition.
5. Termination Check: If distance < 3 m $\rightarrow$ interception and If time > 100 s $\rightarrow$ failure
6. Data Logging
Metrics such as trajectory, acceleration, and time are recorded.

This structured pipeline ensures numerical stability and consistent comparison across scenarios.

Table 1: Simulation Parameters

Parameter	Symbol	Value	Description
Pursuer Initial Position	$(X_{\{P0\}}, Y_{\{P0\}})$	(0, 0)	Origin
Target Initial Position	$(X_{\{T0\}}, Y_{\{T0\}})$	(300, 300)	Initial separation
Pursuer Speed	(V_P)	30 m/s	Constant
Target Speed	(V_T)	20 m/s	Constant
Initial Heading (Pursuer)	$(\theta_{\{P0\}})$	45°	Aligned with LOS
Initial Heading (Target)	$(\theta_{\{T0\}})$	180°	Opposite direction
Max Acceleration (Pursuer)	$(A_{\{max\}})$	$\pm 30 \text{ m/s}^2$	Saturation limit
Max Acceleration (Target)	$(A_{\{T,max\}})$	20 m/s ²	Maneuver limit
PN Constant	(N)	4	Navigation gain
PP Gain	(K)	4	Proportional gain
Blending Coefficient	(α)	0.5	Hybrid weighting
Time Step	(dt)	0.01 s	Integration step
Max Simulation Time	(T_{max})	100 s	Termination
Capture Radius	—	3 m	Interception threshold
Random Walk Std (Smooth)	—	7.5	Low variability
Random Walk Std (Aggressive)	—	100	High variability

Table 1 summarizes the simulation parameters used for evaluating the hybrid missile guidance algorithm involving Pursuit (PP) and Proportional Navigation (PN) techniques. The pursuer starts from the origin while the target begins at a distance of 300 m in both X and Y directions, with constant velocities of 30 m/s and 20 m/s respectively. Guidance performance is controlled using a PN navigation constant of 4, PP gain of 4, and a blending coefficient of 0.5 to equally combine both guidance laws. Acceleration limits are imposed on both pursuer and target to represent realistic maneuvering capabilities, while the simulation runs with a fine integration step of 0.01 s up to a maximum of 100 s.

Two different random-walk standard deviations are considered to model smooth and aggressive target maneuvers, and interception is declared when the pursuer reaches within a 3 m capture radius of the target.

IV. RESULTS

Interceptor and target trajectories for the straight-flight scenario

The straight flight scenario provides a baseline in which the target travels in a straight line in a non-evasive manner.

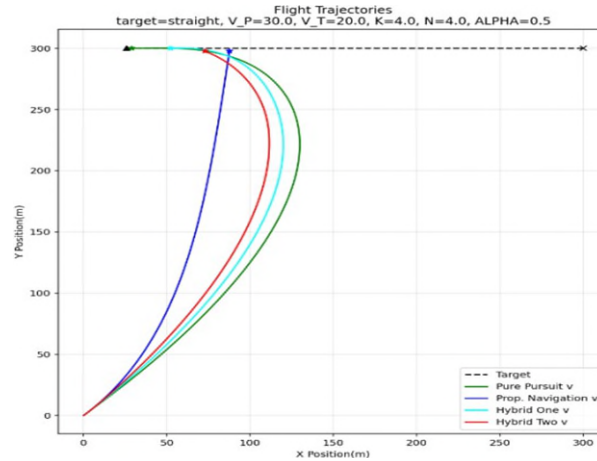


Figure 1. Trajectories (Straight)

Figure 1 illustrates the interceptor and target trajectories for the straight-flight scenario. Since the target moves without evasive manoeuvres, all four guidance laws successfully achieve interception. Pure Pursuit (PP) follows a noticeably curved path because the pursuer continuously aims toward the target's current position. Proportional Navigation (PN) produces a smoother and more direct interception trajectory by predicting future target motion through LOS rate minimization. Hybrid One (H1) combines characteristics of PP and PN, resulting in moderate curvature, while Hybrid Two (H2) generates the most balanced and efficient trajectory with reduced deviation and smoother convergence toward the target.

Variation of miss distance with time for the straight-flight scenario

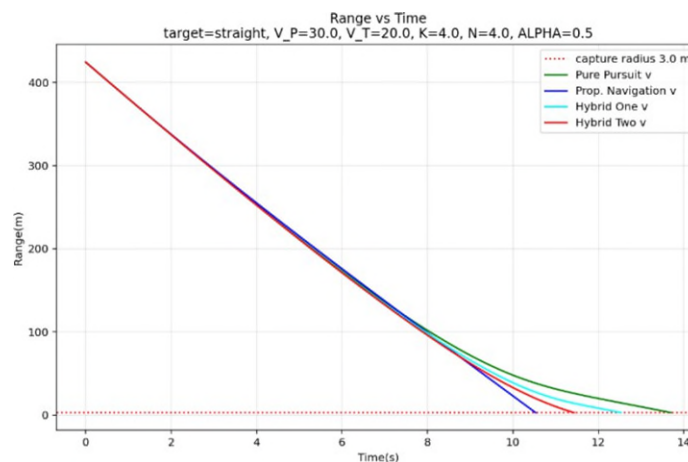


Figure 2. Range vs Time (Straight)

Figure 2 presents the variation of miss distance with time for the straight-flight scenario. The range decreases steadily for all guidance laws, confirming successful interception within the simulation time. PP shows a comparatively slower reduction in range because of its indirect pursuit trajectory. PN reduces the range more rapidly due to its predictive interception capability. H1 improves upon PP by incorporating PN characteristics, while H2 demonstrates the fastest and smoothest convergence toward the target. The graph highlights the superior interception efficiency of H2 in terms of engagement time.

Lateral acceleration commands generated by the pursuer during interception

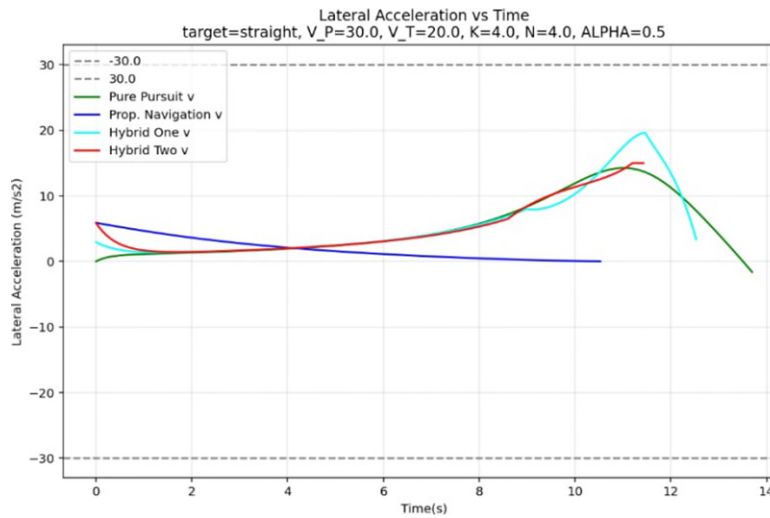


Figure 3. Lateral acceleration of pursuer (straight)

Figure 3 shows the lateral acceleration commands generated by the pursuer during interception. PP exhibits high acceleration peaks near the terminal phase because the pursuer must make sharp corrections as it directly chases the target position. PN maintains smoother acceleration profiles with lower peaks due to its LOS-based predictive control. H1 reduces the aggressive acceleration behaviour of PP but still shows moderate oscillations. H2 demonstrates balanced acceleration behaviour with smoother control effort while maintaining rapid interception capability.

Target lateral acceleration during the straight-flight scenario

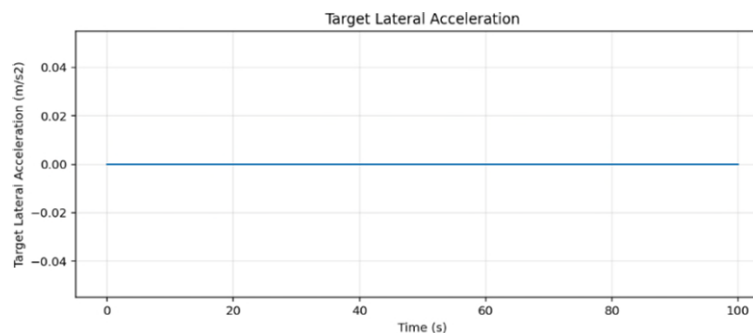


Figure 4. Lateral Acceleration of Target (straight)

Figure 4 represents the target lateral acceleration during the straight-flight scenario. Since the target travels in a straight path without evasive manoeuvres, the lateral acceleration remains zero throughout the simulation. This

confirms that the scenario serves as a baseline condition for evaluating the fundamental performance characteristics of the guidance laws without target-induced disturbances.

Compare the total path length travelled by the pursuer under each guidance law

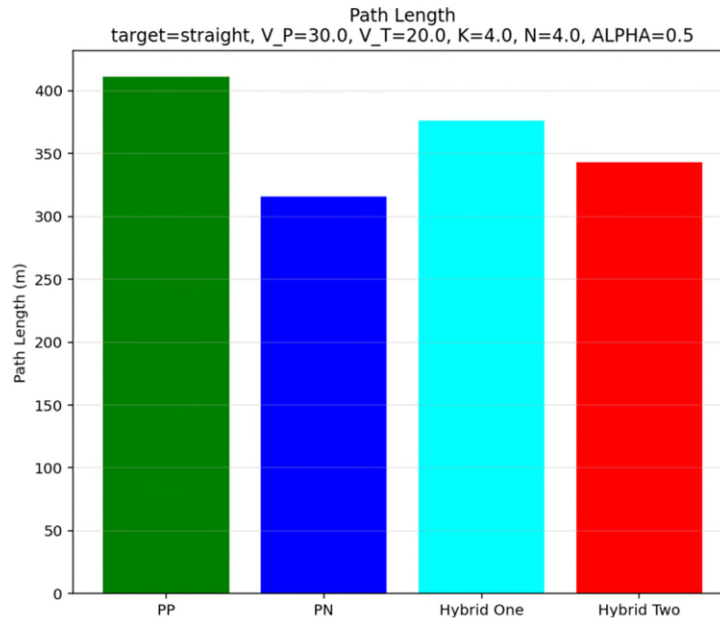


Figure 5. Path Length of each guidance law (straight)

Figure 5 compares the total path length travelled by the pursuer under each guidance law. PP results in the longest path because the curved chasing trajectory increases travel distance. PN achieves a shorter path length by steering more directly toward the predicted interception point. H1 reduces the path length relative to PP but still remains less efficient than PN. H2 achieves one of the shortest path lengths, indicating improved interception efficiency and lower energy expenditure for the interceptor UAV.

RMS lateral acceleration values for the pursuer under different guidance laws

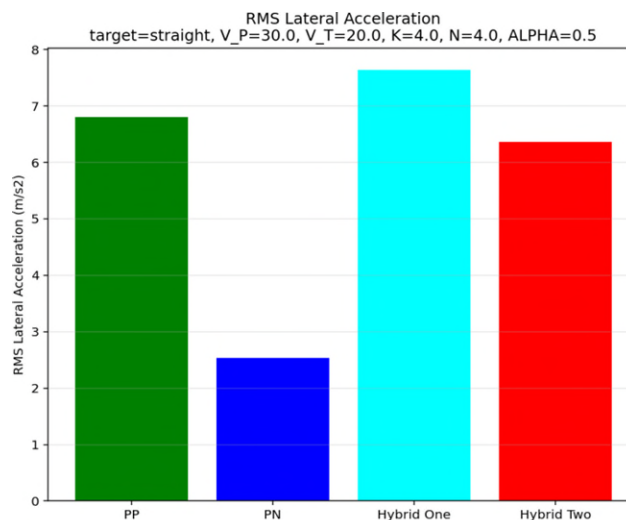


Figure 6. RMS lateral acceleration of each guidance law (straight)

Figure 6 presents the RMS lateral acceleration values for the pursuer under different guidance laws. PP produces the highest RMS acceleration due to its aggressive terminal manoeuvres and continuous heading corrections. PN shows the lowest RMS acceleration because of its smoother and more stable control behaviour. H1 achieves moderate RMS acceleration values by blending PP and PN characteristics. H2 maintains relatively low RMS acceleration while still providing fast interception, demonstrating a strong balance between agility and control smoothness.

Weave Flight Scenario- Interception trajectories for the sinusoidal weave target manoeuvre scenario

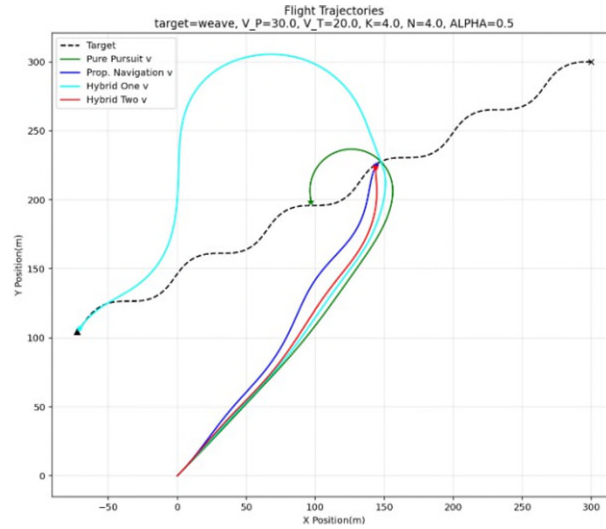


Figure 7. Trajectories (Weave)

Figure 7 illustrates the interception trajectories for the sinusoidal weave target manoeuvre scenario. The target continuously changes direction, making interception more challenging. PP produces a highly curved trajectory because it reacts directly to the target's instantaneous position. PN performs better by anticipating target motion, resulting in smoother interception paths. H1 combines both behaviours but still experiences moderate curvature. H2 demonstrates the most stable and efficient interception trajectory, maintaining smoother convergence despite continuous target manoeuvres.

Variation of miss distance with time during the weave scenario

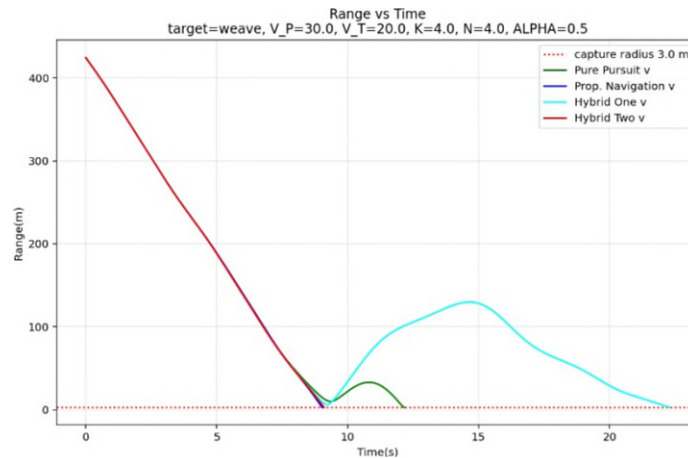


Figure 8. Range vs Time (Weave)

Figure 8 shows the variation of miss distance with time during the weave scenario. The oscillatory motion of the target causes fluctuations in the range reduction profiles. PP takes longer to intercept because it continuously adjusts to the weaving target motion. PN reduces the range more efficiently through predictive guidance. H1 improves interception performance relative to PP, while H2 achieves the fastest and smoothest reduction in range, indicating superior robustness against oscillatory target manoeuvres.

Pursuer lateral acceleration profiles during the weave manoeuvre scenario

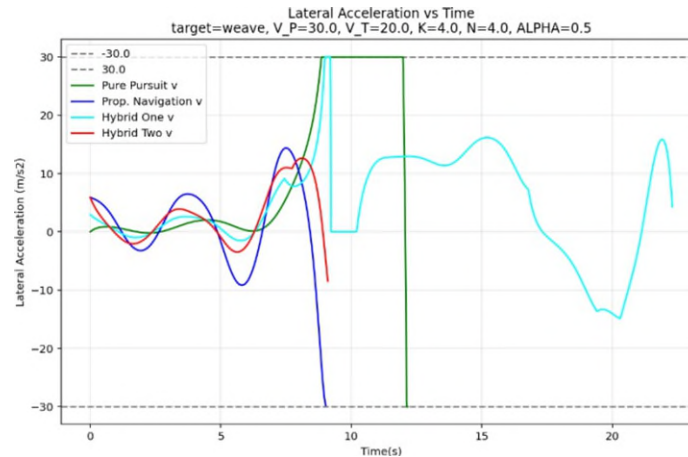


Figure 9. Lateral Acceleration vs Time (Weave)

Figure 9 presents the pursuer lateral acceleration profiles during the weave manoeuvre scenario. PP exhibits strong oscillatory acceleration commands because it reacts directly to the target's changing direction. PN generates smoother acceleration responses with lower fluctuations. H1 reduces excessive oscillations but still experiences moderate acceleration variations. H2 demonstrates the most balanced acceleration profile by effectively combining rapid responsiveness with smoother control action.

Sinusoidal lateral acceleration applied to the target during the weave scenario

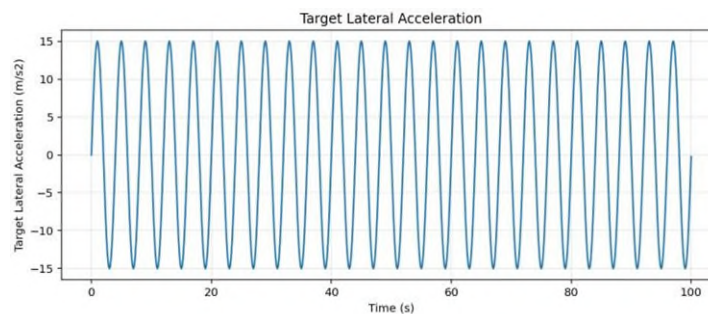


Figure 10. Lateral Acceleration of target vs time (Weave)

Figure 10 illustrates the sinusoidal lateral acceleration applied to the target during the weave scenario. The acceleration oscillates periodically, creating continuous directional changes in the target trajectory. This manoeuvre increases interception difficulty and tests the adaptability and responsiveness of the different guidance laws under dynamic target conditions.

Path lengths travelled by the pursuer in the weave scenario

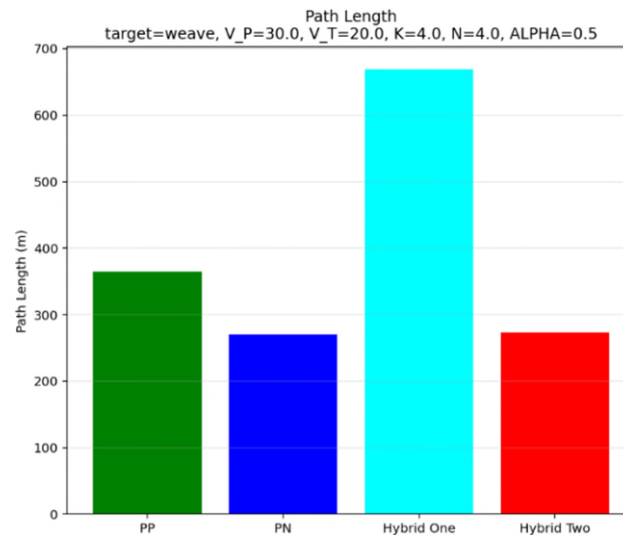


Figure 11. Path Length of each guidance (Weave)

Figure 11 compares the path lengths travelled by the pursuer in the weave scenario. PP results in the longest path because of repeated heading corrections while chasing the weaving target. PN produces shorter trajectories through predictive interception. H1 improves efficiency relative to PP but remains less optimal than PN. H2 achieves the shortest and most efficient trajectory, confirming its ability to handle manoeuvring targets with reduced travel distance and improved energy efficiency.

RMS Lateral Acceleration of Each Guidance Law (Weave)

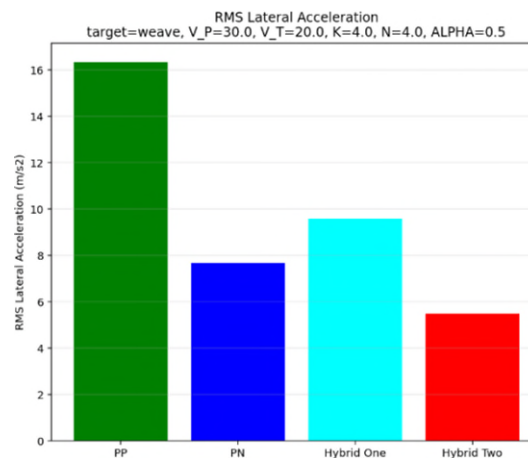


Figure 12. RMS lateral acceleration of each guidance law (Weave)

Figure 12 presents the RMS lateral acceleration values during the weave scenario. PP exhibits the highest RMS acceleration because of frequent and aggressive manoeuvre corrections. PN maintains lower RMS acceleration due to smoother control dynamics. H1 produces moderate RMS acceleration levels, while H2 achieves comparatively lower RMS acceleration despite maintaining rapid interception performance. This demonstrates the ability of H2 to balance interception efficiency with reduced control effort.

Turn Scenario

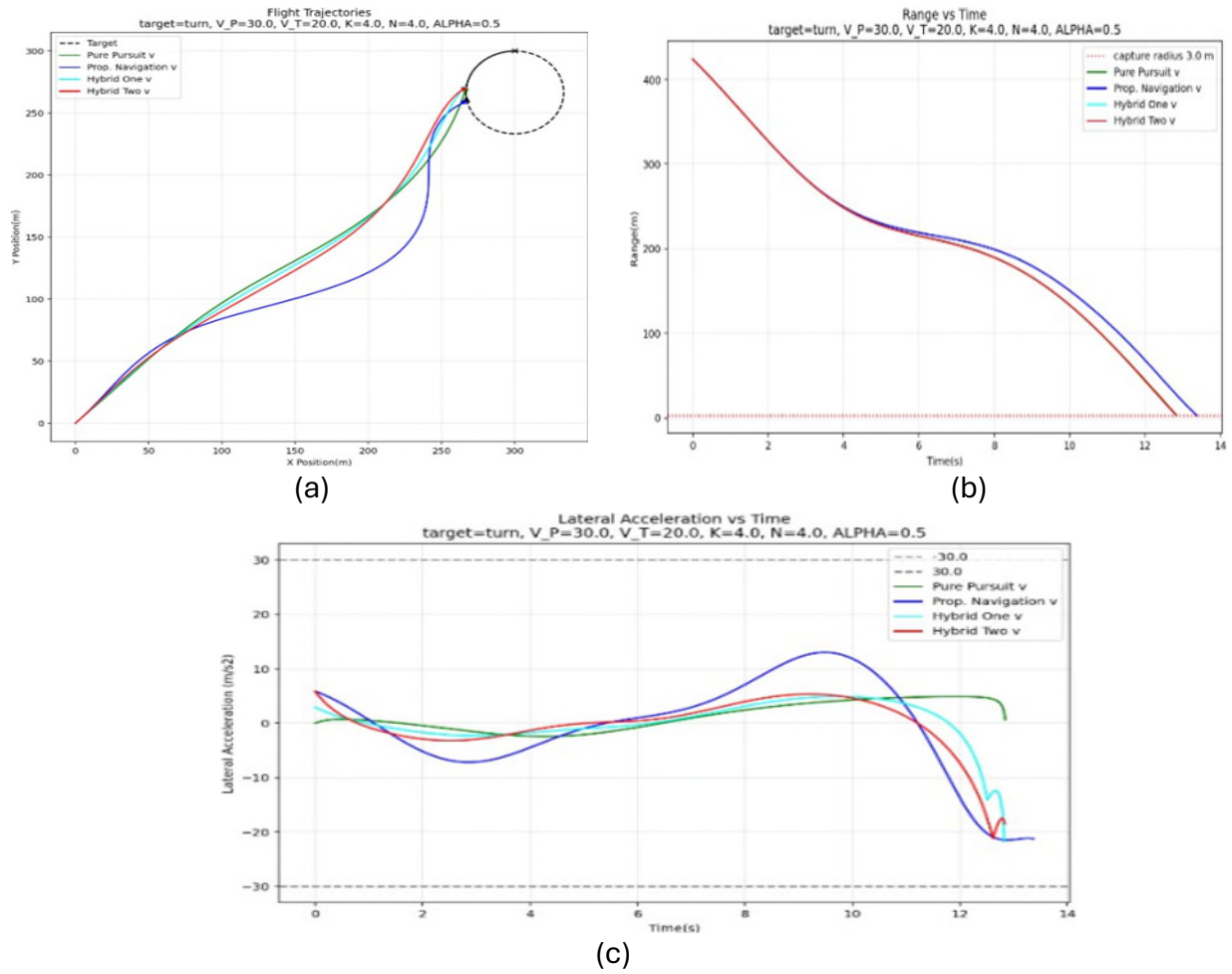


Figure 13. (a) Interception trajectories for all guidance laws under constant turn manoeuvre (b) Range versus time comparison during turn manoeuvre (c) Pursuer lateral acceleration response during turn manoeuvre

Figure 13 presents the trajectories of the pursuer and target during the constant-turn manoeuvre scenario. The target continuously applies a fixed lateral acceleration, producing a circular turning path that significantly increases interception difficulty. Pure Pursuit generates a delayed and highly curved pursuit trajectory because the interceptor continuously chases the instantaneous target position. Proportional Navigation performs better by steering toward the predicted target path; however, large target heading changes reduce its efficiency. Hybrid One improves interception stability through blended guidance, while Hybrid Two demonstrates the most stable interception trajectory with smoother convergence and better adaptation to continuous turning motion.

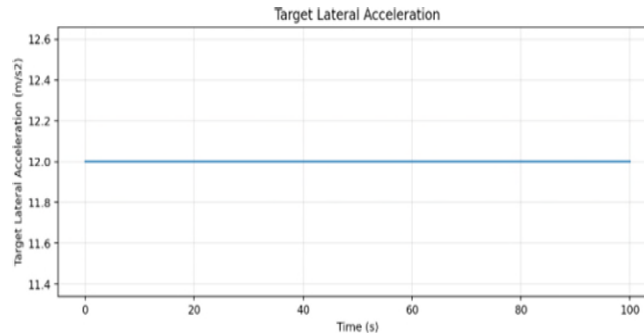


Figure 14. Target Lateral Acceleration Profile for Turn Scenario

Figure 14 illustrates the variation of range with time during the turn manoeuvre. Pure Pursuit shows slower convergence because the pursuer repeatedly lags behind the turning target. Proportional Navigation reduces the range more rapidly by anticipating the target's future position. Hybrid One achieves improved convergence relative to PP, whereas Hybrid Two demonstrates the fastest and smoothest reduction in miss distance, confirming superior interception efficiency in continuously turning engagements.

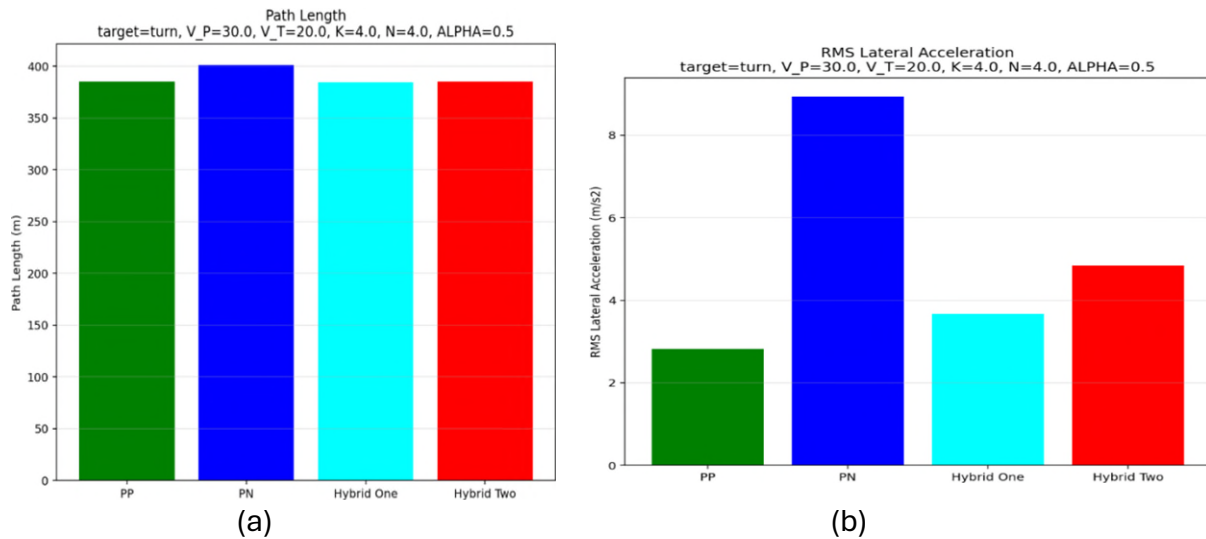


Figure 15. (a) Path length comparison of all guidance laws and (b) RMS lateral acceleration comparison of all guidance laws

Figure 15 compares the path length and RMS lateral acceleration values for the four guidance laws. Pure Pursuit results in the longest path and highest RMS acceleration because of aggressive terminal corrections. Proportional Navigation produces improved path efficiency and lower acceleration demand, although performance degrades under continuous turning motion. Hybrid One demonstrates moderate performance improvements, while Hybrid Two achieves the best compromise between shorter path length and reduced acceleration demand.

Table 2: Comparative Analysis – Turn Scenario

Guidance Law	Interception Success	Interception Time	Path Length	RMS Lateral Acceleration	Overall Observation
Pure Pursuit (PP)	Successful	Slow	Long	High	Delayed response to turning target
Proportional Navigation (PN)	Successful	Moderate-Fast	Moderate	Moderate	Effective but affected by continuous turn
Hybrid One (H1)	Successful	Moderate	Moderate	Moderate	Improved adaptability
Hybrid Two (H2)	Successful	Fastest	Shortest	Low	Best robustness against turning motion

In table 2 shows the comparative analysis demonstrates that PP experienced delayed interception because the pursuer lagged behind the turning target and generated highly curved pursuit paths. PN improved interception efficiency by steering toward the anticipated target location, although continuous target turning reduced predictive accuracy. H1 provided improved adaptability by blending PP responsiveness with PN prediction. H2 achieved the best overall performance, producing the fastest interception, shortest path length, and lowest RMS acceleration. These results indicate that H2 is highly effective in engagements involving sustained turning manoeuvres because it maintains both predictive capability and reactive responsiveness.

Step Scenario

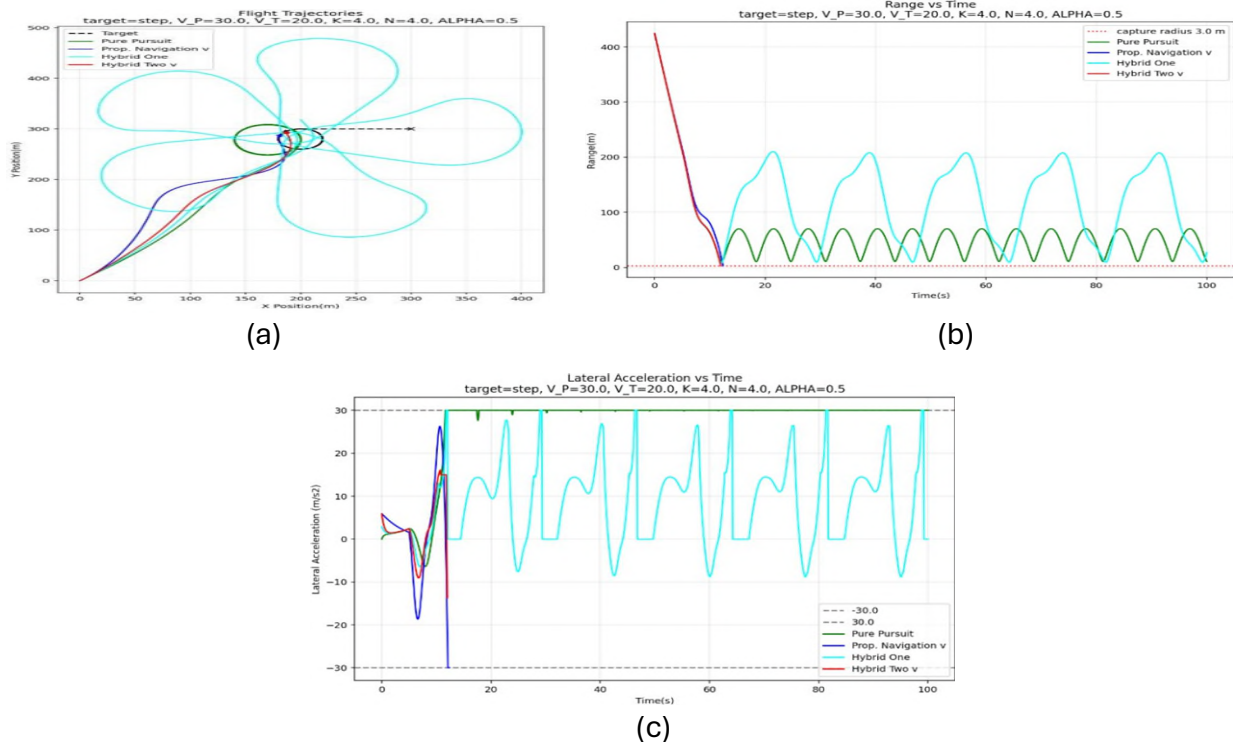


Figure 16. (a) Interception trajectories for step manoeuvre target motion (b) Range versus time comparison during step manoeuvre (c) Pursuer lateral acceleration response during step manoeuvre

Figure 16 illustrates the interception trajectories when the target suddenly changes manoeuvre after an initial straight flight segment. The abrupt acceleration change introduces significant interception difficulty. Pure Pursuit struggles to rapidly adapt to the sudden target motion, resulting in large trajectory deviations. Proportional Navigation initially performs effectively but experiences degradation after the step manoeuvre because the sudden LOS rate change causes delayed corrective action. Hybrid One exhibits partial adaptation but may fail to maintain stable interception in severe cases. Hybrid Two demonstrates the best adaptability by rapidly responding to the abrupt manoeuvre while maintaining stable convergence.

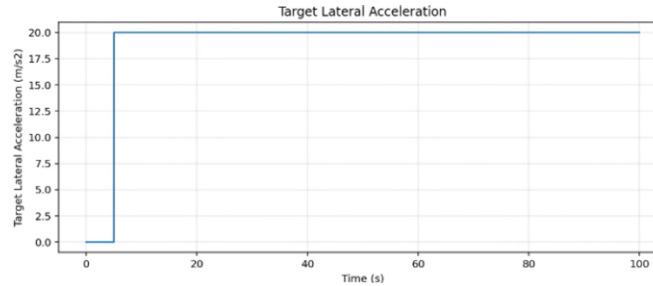


Figure 17. Target Lateral Acceleration Profile for Step Manoeuvre Scenario

Figure 17 shows the miss distance variation for the step manoeuvre case. The sudden target acceleration introduces fluctuations in the range profiles. Pure Pursuit exhibits slower convergence and may experience temporary increases in miss distance. Proportional Navigation shows improved response but may struggle to maintain continuous convergence after the step input. Hybrid One demonstrates better adaptation than the pure laws, while Hybrid Two maintains the smoothest and most reliable reduction in range.

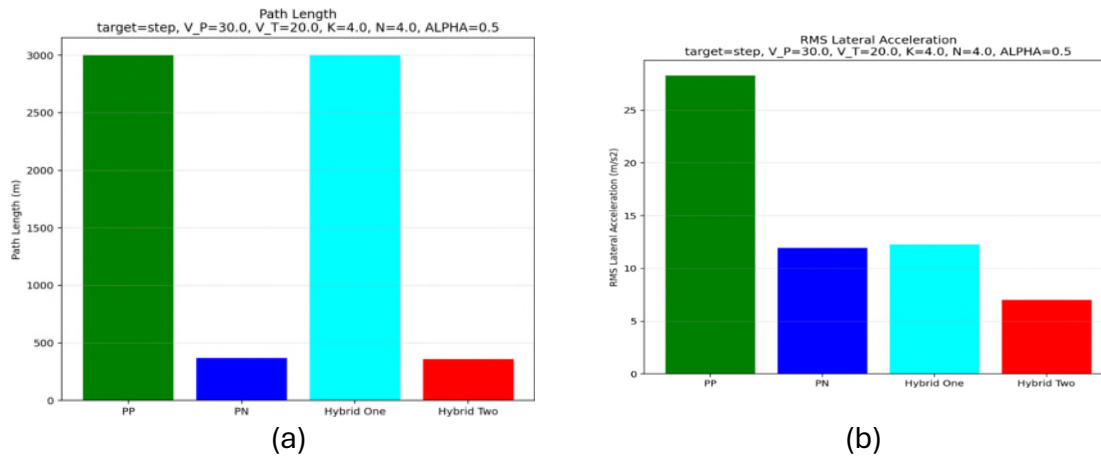


Figure 18. Comparative Performance Metrics for Step Manoeuvre Scenario: (a) Path length comparison of all guidance laws (b) RMS lateral acceleration comparison of all guidance laws

Figure 18 compares the path length and RMS acceleration for all guidance laws during the step manoeuvre. Pure Pursuit produces large acceleration peaks and extended path lengths because of delayed corrective action. Proportional Navigation reduces the path length but experiences increased control effort during sudden target changes. Hybrid One demonstrates moderate improvement, whereas Hybrid Two achieves superior interception performance with reduced path length and lower RMS acceleration.

Table 3: Comparative Analysis – Step Manoeuvre Scenario

Guidance Law	Interception Success	Interception Time	Path Length	RMS Lateral Acceleration	Overall Observation
Pure Pursuit (PP)	Fail/Delayed	High	Long	High	Weak response to abrupt manoeuvre
Proportional Navigation (PN)	Moderate	Moderate	Moderate	Moderate	Predictive but sensitive to sudden changes
Hybrid One (H1)	Fail/Moderate	Moderate	Moderate	Moderate	Improved but insufficient robustness
Hybrid Two (H2)	Successful	Fastest	Shortest	Low	Most adaptable to abrupt manoeuvres

In table 3 shows the step manoeuvre scenario represented a sudden and abrupt change in target acceleration, making it one of the most demanding deterministic cases. PP showed poor adaptability because it reacted slowly to the sudden target manoeuvre, leading to increased path length and higher acceleration demand. PN initially performed effectively but its performance degraded after the abrupt target acceleration because sudden LOS rate changes reduced prediction accuracy. H1 improved adaptability compared with the pure laws but still lacked sufficient robustness under abrupt manoeuvre conditions. H2 achieved the best interception performance by rapidly adapting to the target's sudden manoeuvre while maintaining stable convergence and lower control effort. The comparative analysis confirms that the augmented hybrid guidance structure in H2 significantly enhances responsiveness to sudden target behaviour changes.

Smooth Random Walk 42 Scenario

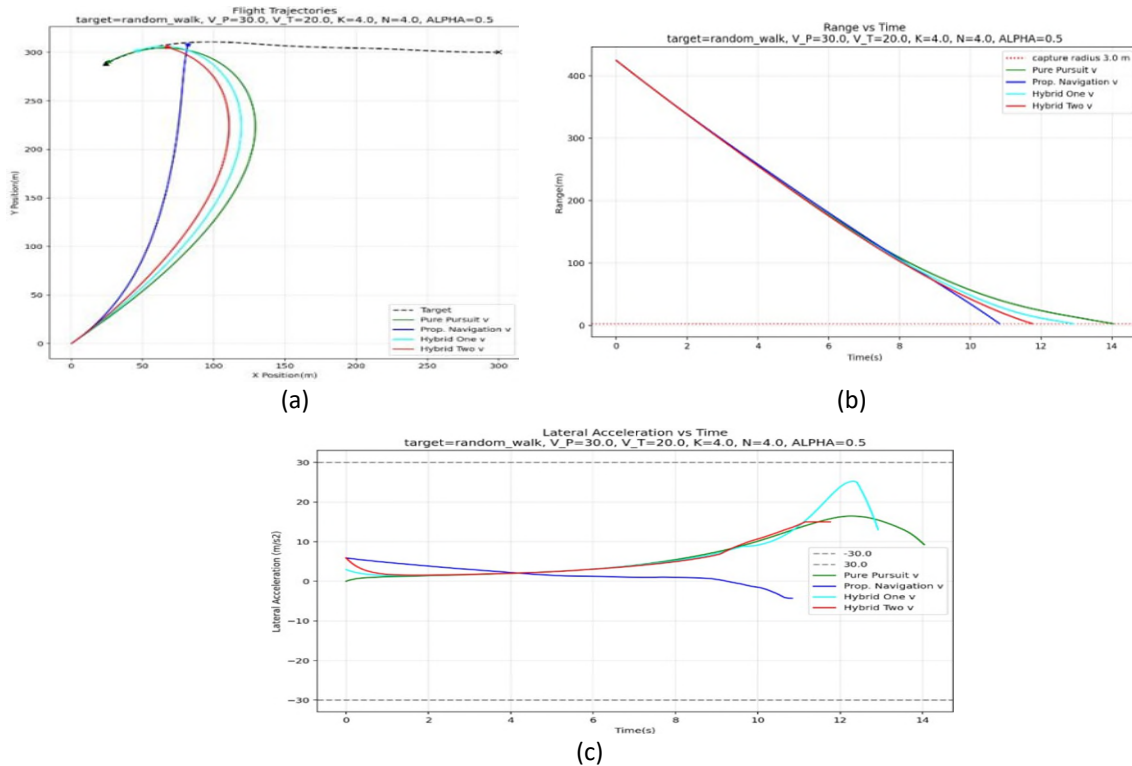


Figure 19. Smooth Random Walk Scenario Performance Analysis: (a) Interception trajectories under smooth random walk target motion (b) Range versus time comparison for smooth random walk scenario (c) Pursuer lateral acceleration response during smooth random walk manoeuvre

Figure 19 illustrates the interception trajectories for the smooth random walk manoeuvre, where the target performs stochastic but low-variability heading changes. Pure Pursuit generates oscillatory pursuit paths because the pursuer continuously responds to random target deviations. Proportional Navigation performs effectively under smooth stochastic motion due to its predictive characteristics. Hybrid One demonstrates improved trajectory smoothness compared with PP. Hybrid Two achieves the most stable and efficient interception path, maintaining smooth convergence despite random target behaviour.

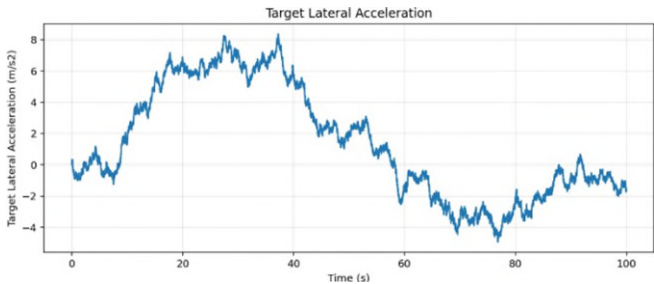


Figure 20 Target Lateral Acceleration Profile for Smooth Random Walk Scenario

Figure 20 presents the variation of miss distance with time during the smooth random walk engagement. All guidance laws successfully reduce the range below the capture radius; however, the convergence behaviour differs. Pure Pursuit experiences noticeable fluctuations due to random target motion, while Proportional Navigation provides smoother convergence. Hybrid Two achieves the fastest and most stable interception profile.

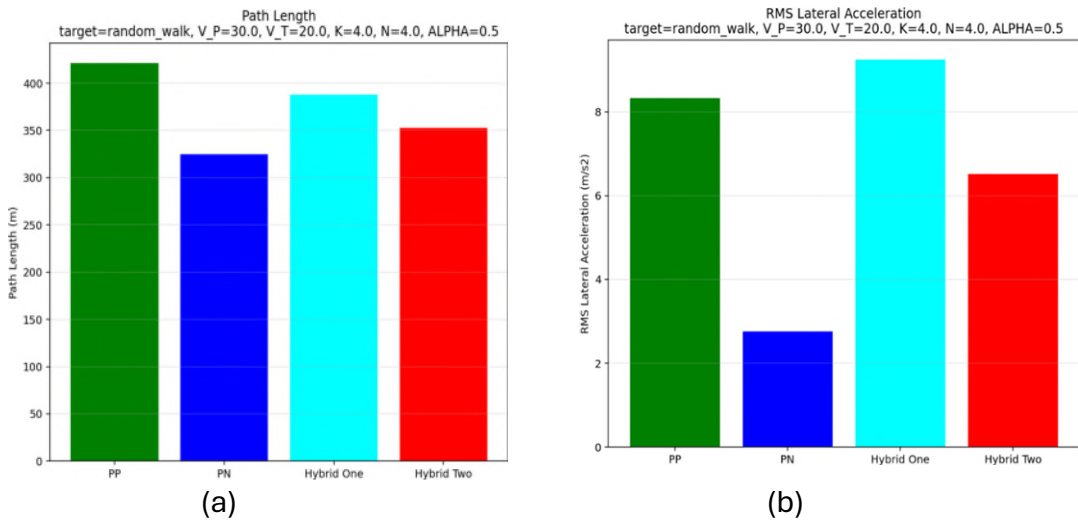


Figure 21. Comparative Performance Metrics for Smooth Random Walk Scenario: (a) Path length comparison of all guidance laws (b) RMS lateral acceleration comparison of all guidance laws

Figure 21 compares the path length and RMS acceleration values for the smooth random walk scenario. Pure Pursuit results in the highest control effort and longest path length. Proportional Navigation achieves lower RMS acceleration and shorter trajectories. Hybrid One improves overall efficiency, whereas Hybrid Two demonstrates the best balance between interception speed, path efficiency, and smooth control response.

Table 4 Comparative Analysis – Smooth Random Walk Scenario

Guidance Law	Interception Success	Interception Time	Path Length	RMS Lateral Acceleration	Overall Observation
Pure Pursuit (PP)	Successful	Moderate	Long	High	Sensitive to random motion
Proportional Navigation (PN)	Successful	Fast	Short	Low	Strong predictive behaviour
Hybrid One (H1)	Successful	Moderate-Fast	Moderate	Moderate	Improved balance
Hybrid Two (H2)	Successful	Fastest	Shortest	Lowest	Most consistent performance

In table 4 the smooth random walk scenario introduced stochastic but low-variability target manoeuvres, simulating realistic UAV disturbances and mild evasive behaviour. PP exhibited fluctuating trajectories and higher RMS acceleration because it continuously corrected its path in response to random target deviations. PN performed effectively in this scenario due to its predictive guidance capability, which smoothed the interception trajectory and reduced unnecessary corrections. H1 improved overall balance between responsiveness and prediction. H2 again demonstrated the best overall performance with the shortest interception time, reduced path length, and lowest RMS acceleration. The table highlights that H2 maintains strong interception consistency even under stochastic target motion conditions.

Aggressive Random Walk Scenario

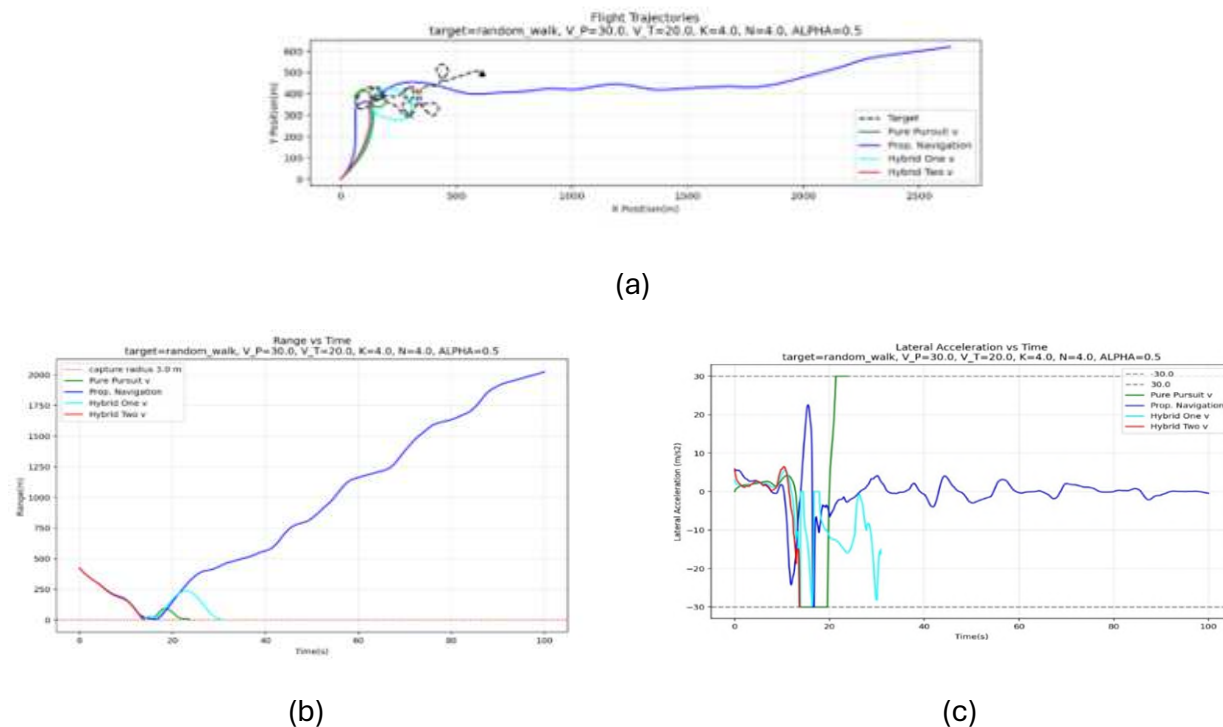


Figure 22. Aggressive Random Walk Scenario Performance Analysis: (a) Interception trajectories under aggressive random walk target motion (b) Range versus time comparison for aggressive random walk scenario (c) Pursuer lateral acceleration response during aggressive random walk manoeuvre

Figure 22 illustrates the interception trajectories for the aggressive random walk manoeuvre scenario. The target performs highly unpredictable and rapidly varying manoeuvres, creating the most difficult engagement condition. Pure Pursuit generates unstable and excessively curved trajectories because it continuously reacts to instantaneous target motion. Proportional Navigation performance degrades significantly due to rapidly changing LOS rates. Hybrid One improves stability but still experiences performance limitations. Hybrid Two demonstrates the highest robustness by maintaining smoother interception behaviour and achieving successful capture despite severe manoeuvring.

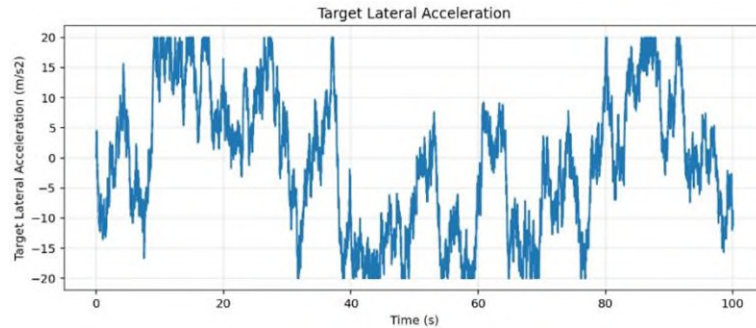


Figure 23. Target Lateral Acceleration Profile for Aggressive Random Walk Scenario

Figure 23 presents the miss distance variation for the aggressive random walk scenario. Pure Pursuit and Proportional Navigation may exhibit unstable convergence behaviour due to rapid target heading changes. Hybrid One demonstrates improved convergence but may still experience oscillatory range profiles. Hybrid Two maintains the most stable reduction in miss distance and successfully achieves interception within the simulation duration.

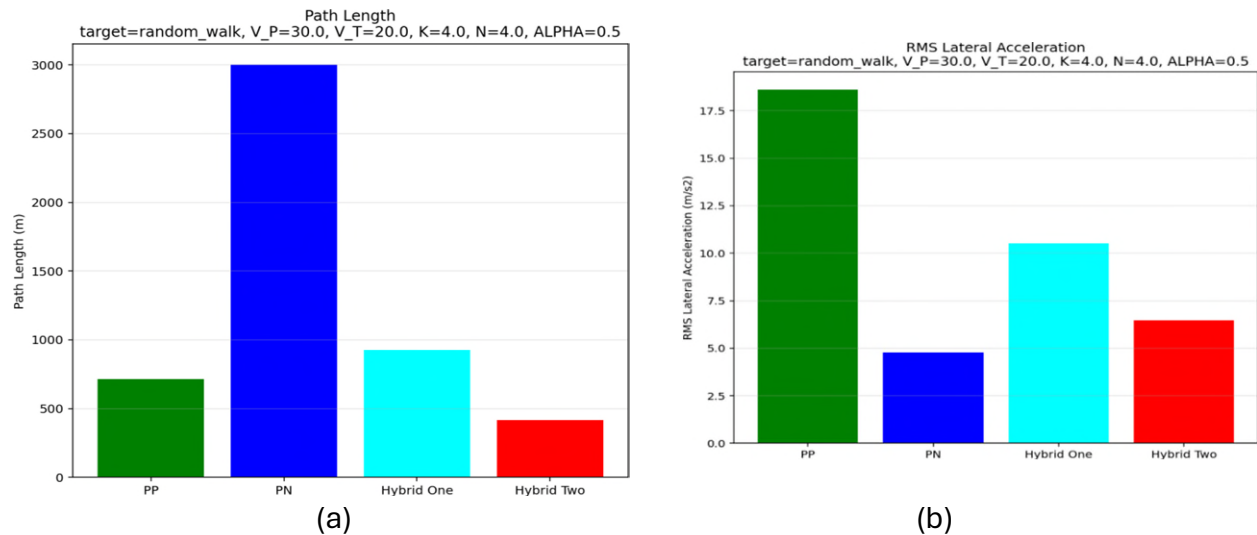


Figure 24. Comparative Performance Metrics for Aggressive Random Walk Scenario: (a) Path length comparison of all guidance laws (b) RMS lateral acceleration comparison of all guidance laws

Figure 24 compares the path length and RMS lateral acceleration for all guidance laws under highly manoeuvring target conditions. Pure Pursuit exhibits extremely high control effort and inefficient trajectories. Proportional Navigation experiences degraded performance because of excessive LOS-rate variations. Hybrid One demonstrates moderate improvement, whereas Hybrid Two achieves the best compromise between interception speed, path efficiency, and control smoothness.

Table 5: Comparative Analysis – Aggressive Random Walk Scenario

Guidance Law	Interception Success	Interception Time	Path Length	RMS Lateral Acceleration	Overall Observation
Pure Pursuit (PP)	Fail/Delayed	Very High	Very Long	Very High	Inefficient against aggressive manoeuvres
Proportional Navigation (PN)	Fail/Moderate	High	Moderate	High	Sensitive to rapid LOS variations
Hybrid One (H1)	Moderate	Moderate	Moderate	Moderate	Better than pure laws
Hybrid Two (H2)	Successful	Fastest	Shortest	Low	Most robust and reliable

In table 5 the aggressive random walk scenario represented the most difficult engagement condition because the target performed highly unpredictable and rapidly changing manoeuvres. PP produced unstable and excessively curved trajectories due to continuous reactive chasing, resulting in very high control effort and inefficient interception. PN performance also degraded significantly because rapidly varying LOS rates reduced the effectiveness of predictive guidance. H1 improved stability compared with the pure laws but still experienced performance limitations under severe manoeuvres. H2 demonstrated the highest robustness and reliability by successfully intercepting the target while maintaining lower path length and reduced RMS acceleration. The comparative analysis clearly shows that H2 is the most suitable guidance law for real-world counter-drone operations involving highly manoeuvring and unpredictable UAV targets.

V. CONCLUSION

This study performed a comprehensive comparative evaluation of four UAV interception guidance laws—Pure Pursuit (PP), Proportional Navigation (PN), Hybrid One (H1), and Hybrid Two (H2)—under six distinct target manoeuvre scenarios using a two-dimensional RK4-based simulation framework. The scenarios included straight flight, sinusoidal weave, constant turn, step manoeuvre, smooth random walk, and aggressive random walk profiles, thereby enabling the assessment of guidance law robustness under both deterministic and stochastic target behaviour. The simulation results demonstrated that Pure Pursuit provides simple and intuitive interception behaviour but suffers from long curved trajectories and high lateral acceleration demand, particularly in highly manoeuvring target scenarios. Proportional Navigation achieved efficient interception for straight and smoothly manoeuvring targets because of its predictive guidance characteristics; however, its performance degraded when the target executed aggressive or abrupt manoeuvres. Hybrid One improved the balance between responsiveness and prediction but was still unable to maintain consistent interception performance in all scenarios. Evaluated guidance laws, Hybrid Two consistently demonstrated the best overall performance. Hybrid Two successfully intercepted the target in all six scenarios while maintaining lower interception times, shorter path lengths, and reduced RMS lateral acceleration compared with the other guidance methods. The augmented hybrid structure enabled the interceptor to retain the predictive advantages of Proportional Navigation while simultaneously improving responsiveness to sudden target manoeuvres through the inclusion of Pure Pursuit characteristics.

The comparative analysis further showed that Hybrid Two provided the most stable interception behaviour in stochastic target conditions, including both smooth and aggressive random walk scenarios. This robustness is particularly important for real-world counter-drone operations where hostile UAV manoeuvres may be unpredictable and rapidly varying. Additionally, the reduced RMS lateral acceleration observed in Hybrid Two indicates lower actuator stress and improved energy efficiency, both of which are critical for practical UAV interceptor systems. Overall, the results confirm that Hybrid Two with a blending coefficient of $\alpha = 0.5$ represents the most effective and reliable guidance strategy among the evaluated methods. Therefore, Hybrid Two is recommended as the preferred

default guidance law for future net-based UAV interception systems and autonomous counter-drone defence applications.

Declarations

I/We hereby declare that the information provided in this manuscript is true and accurate to the best of my/our knowledge. The manuscript titled "**Robust UAV Interception Using Hybrid Guidance Laws: A Comparative Study with Pure Pursuit and Proportional Navigation**" complies with the ethical and publication standards set by the journal. More information on declarations can be found in the journal submission guidelines in the editorial policies section.

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Author contributions

Conceptualization & Research and designed the UAV Interception Using Hybrid Guidance Laws – Defining the research problem, objectives, and methodology and Conducted simulations and experimental validations - Dr. Raja Munusamy

Performed data analysis and evaluated system performance, Data Collection & Interpretation, Analyzing results and Manuscript Writing & Review – Drafting, editing, and refining the research findings for publication --- Sai Avikshith Kadam

Competing interests

The authors have no conflicts of interest to disclose regarding this study.

Ethics approval

This research does not involve any human participants or animals, and thus, ethical approval is not applicable.

Consent to participate

This research does not involve human participants, interviews, or surveys requiring explicit consent. Therefore, consent to participate is not applicable.

If applicable, all contributors have voluntarily participated in the study, and their involvement was based on informed consent.

Consent to publish

All authors confirm that they have reviewed and approved the final version of the manuscript titled "**Robust UAV Interception Using Hybrid Guidance Laws: A Comparative Study with Pure Pursuit and Proportional Navigation**". The authors give their full consent for its publication in Discover applied science.

Furthermore, the authors confirm that the work is original, has not been published previously, and is not under consideration for publication elsewhere. They also acknowledge that the publisher holds the right to edit, format, and distribute the manuscript as necessary for publication.

Data availability

All relevant data supporting the findings of this study are included in the manuscript. Additional data can be provided upon reasonable request.

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