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Adaptive True Proportional Navigation Guidance based on Heuristic Optimisation Algorithms

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ABSTRACT

The PN-guidance (Proportional Guidance) still continues to be improved, because it is the simplest, cheapest and most reliable algorithm. One of the most important techniques to improve PN-guidance is to adapt the navigation constant depending on time. In this study, first, the entire adaptation methods for PN-guidance are classified, then the adaptation process is online achieved by using heuristic optimisation during guiding the missile. The novelty of this study is that the heuristic optimisation approach is used at the first time to update the navigation constant of PN-guidance. It is considered that having short program code, fast convergence speed and just simple algebraic computations without derivative are vital advantages of heuristic algorithms using into missile systems. In this scope, an Adaptive True-PN (ATPN) guidance algorithm is designed by optimising navigation constants varying according to the target behaviour. The results show that while the acceleration gap of the pitch axis decreases 21.8%, the acceleration gap of yaw axis reduces 39.68%. These reductions mean that while the missile guided by ATPN is maneuvering, it is exposed to less acceleration and less strain.

Keywords: True proportional navigation guidance; Heuristic optimisation algorithm; Adaptation; Effective navigation constant; Tactical missile

1. INTRODUCTION

Although it is an issue which has been studied almost since 1940s, the subject of tactical missile guidance still remains a current research area. Actually, only a few main guidance approaches have been suggested theoretically since these dates [1-2]. But it can be seen that the most preferred guidance approach is still PN-guidance (Proportional Guidance) and versions due to its many advantages such as having a simple scheme and easy implementation. Of course, PN-guidance has been tried to transform to the optimal or adaptive forms by being applied different additional techniques so far in the time. For example, US patent for predictive PN-guidance approved in 1985 is an important mile-stone providing adaptive PN-guidance[3]. Additionally, Shukla[4], *et al.* suggested to carried out optimal biased PN-guidance by optimising bias parameters analytically. Yang[5], *et al.* proposed optimal PN-guidance based on time-varying navigation gains. The authors made the hypothesis that "under the exact nonlinear formulation of PN guidance, the optimal value of navigation constant may be time varying depending on the initial conditions of engagement, the time-to-go, and/or the range-to-go". As similar to the Shukla's study, Kim[6], *et al.* proposed time-varying biased parameter for optimal PN-guidance. After these pioneer studies, the US patent for adaptive matched augmented PN-guidance approach presented[7]. Dionne and Michalska[8] studied an adaptive PN-guidance law based on the banks of guidance laws selected by an on-line governor in effect at each time instant. Yang[9] suggested three-dimensional adaptive variable structure PN-guidance. Yu[10], *et al.* presented adaptive PN for the missile with the seeker mounted in the side window. Then, the adaptive PN-guidance with a variable coefficient for mortar projectiles is proposed by Zhang[11], *et al*. In addition, they presented a different approach about this subject[12]. After two years, Sharma[13], *et al.* suggested adaptive PN for short range ballistic missile as similar to the Zhang's study[13]. Weiss[14], *et al.* proposed the new adaptation approach for PN-guidance including derivation of a new guidance law via direct implementation of the Simple Adaptive Control algorithm.

In parallel, different nonlinear control methods were suggested for adaptation to the highly maneuvering targets. For example, Huang[15], *et al.* presented the profile-tracking-based adaptive guidance law. Guan and Yi[16] studied adaptive sliding mode guidance rule in the case of input saturation and autopilot lag. At last, after the years of 2000s, artificial intelligence-based methods such as fuzzy logic[17-18] and machine learning[19] have been applied to PN-guidance to provide optimality and adaptability. In addition, the genetic and heuristic optimisation techniques suggested optimising guidance process for the first time at these years [20-21]. Lee[22] proposed to combine PSO (Particle Swarm Optimisation) and PN-guidance so as to obtain optimal PN-guidance. Yaghi[23], *et al.* developed adaptive neural fractional order proportional integral derivative controller to

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optimize PN-guidance. After that, Chauhan[24], *et al.* proposed an optimal navigation constant adjusted according to the heading error and the missile lead angle.

In light of this literature survey, the PN adaptation methods for tactical missiles can be classified as in Fig. 1. On the other hand, it is understood from the date of last studies that the adaptation of PN algorithm is still an open research area. Although, there are many other similar methods in the literature in this area, the heuristic approach is new and excited tool for providing optimal adaptation. For this reason, the novel heuristic-based method is proposed as a new adaptation class. Clearly, heuristic optimisation algorithms have been used successfully in guidance applications for many years. Having short program code, fast convergence speed and just simple algebraic computations without derivative are vital advantages of heuristic algorithms to operate into tactical missile systems which the process speed is largely important.

As similar to Yang's hypothesis, using heuristic optimisation at the first time to optimize the navigation constant for each sample time of the PN guidance process is presented as the novelty of this study. This new type of adaptation method is offered at the classification depicted in Fig. 1, as different from the literature. In this way, the PN-guidance finds an opportunity to adapt its navigation parameters depending on time according to changing maneuvers of the target. For this purpose, well-known PSO algorithm is selected due to its proved superiority. In addition, the dynamic performance of the proposed ATPN-guidance is compared with that of TPN guidance by using both the standard maneuvers which were specified in[22] and the more aggressive maneuver offered for the target in this study.

The article is organised as follows: first, brief information about PN and TPN-guidance is given. Second, the proposed ATPN-guidance based on heuristic approach is explained. Then, modelling of missile and target, and the simulations are summarised. After that, results and the discussion are presented. Finally, the conclusion includes suggestions for further studies.

2. CLASSIC PN AND TPN GUIDANCE

Guidance is defined as directing an object toward a target. To perform this process successfully, a natural rule called parallel navigation which is commonly used by both humans and animals is applied. PN-guidance algorithm is defined as the implementation of parallel navigation rule. The algorithm is based on automatic control loop which minimises the LOS (Line-Of-Sight) rate between the target and missile by producing lateral acceleration command[1-2]. According to the collision triangle, the rates of change of LOS distance (V_R) and angle (V_θ) are defined as;

$$V_R = R = V_T \cos(\alpha_T - \theta) - V_M \cos(\alpha_M - \theta) \tag{1}$$

$$V_\theta = R\dot{\theta} = V_T \sin(\alpha_T - \theta) - V_M \sin(\alpha_M - \theta) \tag{2}$$

The collision mathematically depends on two circumstances[2]. First, the rate of change of LOS distance should be negative, and second the rate of change of LOS angle should be zero;

$$V_R < 0 \Rightarrow V_T \cos(\alpha_T - \theta) < V_M \cos(\alpha_M - \theta) \tag{3}$$

$$V_T = 0 \Rightarrow V_T \sin(\alpha_T - \theta) = V_M \sin(\alpha_M - \theta) \tag{4}$$

The first condition can be easily provided by keeping speed of missile high. Second, the perpendicular components of speeds of missile and target should be equal, and this can only be provided by applying an external acceleration command to the missile. The acceleration command proportional to the speed, V_M, in (5) is applied as perpendicular to this velocity.

$$a_M = N V_M \dot{\theta} \tag{5}$$

where N is the ratio $\dot{\alpha}$ and $\dot{\theta}$ and is a navigation constant. It must be greater than 1 in order for the missile to catch the target. The practical region of the constant is between 2 and 6, so the missile can be turn faster than the LOS[2]. On the other hand, the exact measurement of V_M is impractical if there is no on-board inertial sensor in the missile, but the LOS rate can be easily and precisely measured by seeker. So, the lateral acceleration command for the actual implementation of PN-guidance is generated as;

$$a_M = N' V_M \dot{\theta} \tag{6}$$

where N' is called effective navigation constant. From (6), the acceleration command depends on the missile-to-target closing velocity, V_{cl}. The command is applied perpendicular to the LOS vector as different from PN-guidance[2]. The actual

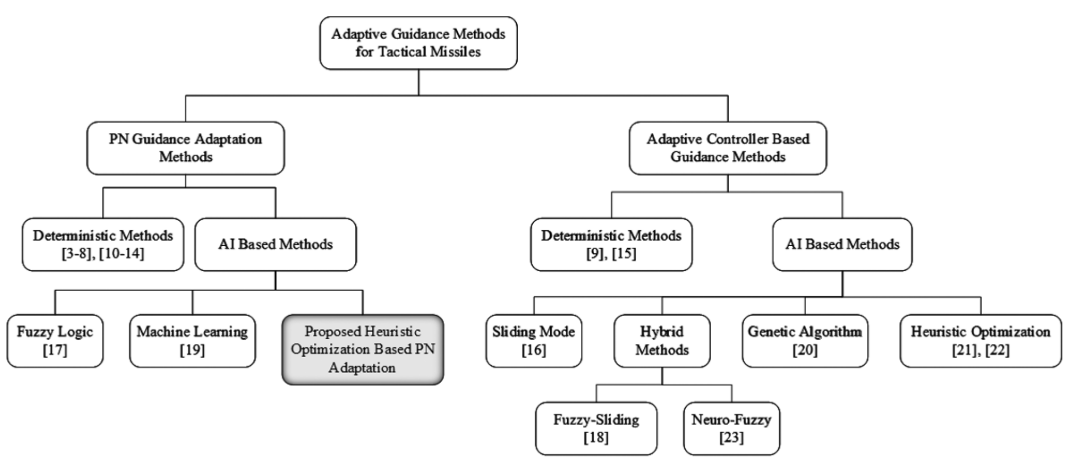

Figure 1. Classification for adaptation guidance methods for tactical missiles.

application of PN-guidance is named TPN-guidance. The three-dimensional acceleration commands for the pitch (a_{pc}) and yaw (a_{yc}) controls are given below[22];

$$a_{pc} = N_p V_{cl} \dot{\theta} + g \cos(\gamma_M) \tag{7}$$

$$a_{yc} = N_y V_{cl} \dot{\theta} \tag{8}$$

where N_p and N_y are the effective navigation constants for the pitch and yaw controls, respectively. Also, $\dot{\phi}$ and $\dot{\theta}$ are the vertical and the horizontal LOS rates, and γ_M is the flight path angle of the missile.

3. HEURISTIC OPTIMISATION BASED GUIDANCE

3.1 Heuristic Optimisation and PSO

Heuristic optimisation is an algebraic optimisation approach that provides fast solutions by avoiding derivatives. It uses mathematical models of natural optimum behaviours or phenomena that exist in nature, such as searching food of living things or vortex event etc. Actually, although a lot of different heuristic optimisation algorithms have been derived since 1980s, some basic algorithms like PSO or genetic algorithm, are still preferred as reference by researchers, due to their powerful convergence abilities.

PSO algorithm which is a swarm intelligence-based optimisation approach was first introduced in 1995[25]. Swarm intelligence is a part of evolutionary computation which has the capability of fast convergence and near-optimal solutions with its short and algebraic program code without derivatives. It basically models the food searching action of bird flocks. Mathematically, it uses particles whose positions represent possible solutions of the problem and each particle flies in search space at a particular speed that can be adjusted in light of previous flight experiences. The positions of the particles are updated by the equations below;

$$v_i^{t+1} = w.v_i^t + c_1.r_1.(p_i^t - x_i^t) + c_2.r_2.(g_i^t - x_i^t) \tag{9}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{10}$$

where, $i = 1, \ldots, n$, and n is the size of swarm, w is inertia weight decreased linearly at each iteration, c_1 and c_2 are positive constants for weighting to search, r_1 and r_2 are random numbers distributed uniformly between 0 and 1, superscript t is the iteration number, p_i is the best previous position of the i^{th} particle and g is the best particle position among all the particles. The last position of g is defined as optimum solution of the problem. The simple pseudo code of PSO can be written as below;

Initialisation
Repeat
Evaluate the fitness values of particles
Compare the fitness values to determine the p and g
Change velocity and position of the particles as to Eqns (9) and (10)
Until (requirements are met)

3.2 PSO Based Adaptive TPN-Guidance

The constants N_p and N_y belonged to TPN-guidance is generally applied fixedly although there are some adaptation studies in literature. However, they largely affect the missile's ability to follow targets, because these constants directly determine the speed of missile's rotation relative to LOS. For example, catching the target is to be impossible for the missile if the constants are less than 1, since its velocity is less than LOS rate. The theoretical value is computed as 3 so as to guarantee target capture[2]. But when the constants are larger than 3, the collision course errors can be corrected earlier in flight. Indeed, increasing of effective navigation ratio,

- Decreases the heading error,
- Requires higher initial acceleration to the missile,
- Reduces the terminal-phase acceleration required to intercept the target[2].

In this scope and the Yang's hypothesis, it is clear; the adaptive adjustment of the navigation constants in each time-step of the guidance process will increase the missile's tracking capability. Additionally, having short program code, fast convergence speed and only simple algebraic calculations without derivative are superior advantages of heuristic algorithms to use into missile systems, since fast completion of calculations in each time-step of the guidance process is vital. Hence, ATPN-guidance (Adaptive True-PN) approach based on heuristic PSO algorithm is suggested at the first time.

At this new approach, effective navigation constants which belong to pitch and yaw axes of TPN-guidance are optimised with the well-known Particle Swarm Optimisation (PSO) algorithm for each time-step according to feedbacks of the previous acceleration commands and missile's flight path angle. PSO has been selected due to its short program code and fast convergence speed, due to need fast completion of calculations in each time-step of the guidance process[25]. On the other hand, the researchers can choose a more powerful and recent heuristic optimisation algorithm to improve performance of the proposed ATPN-guidance. The scheme of the proposed ATPN-guidance is presented in Fig. 2.

PSO is run together with the guidance algorithm in each time-step. PSO parameters can affect to the results of the simulations. Some of these parameters are also constant or no change. The numbers of iterations and the particles have been chosen as minimum values by trial and error method in order to obtain maximum convergence speed. The number of particles of PSO is selected 40 by trial and error. The other parameters are given in Appendix. The cost function, J, is based on the vertical and the horizontal LOS rates in (10)[22]. The parameters presented in (12) and (13) are computed for each time-step in accordance with (7) and (8). The N_p and N_y constants create each particle of PSO and the best constants are computed by the algorithm in each iteration.

$$J = \sqrt{\dot{\phi}^2 + \dot{\theta}^2} \tag{11}$$

$$\dot{\phi} = \frac{r_1\left(a_{pc} - g\cos(\gamma_M)\right)}{N_p V_{cl}} \tag{12}$$

$$\dot{\theta} = \frac{r_2 a_{yc}}{N_y V_{cl}} \tag{13}$$

where r_1 and r_2 are numbers from 0 to 1 randomly generated in each iteration so as not to fall into a local-optima. The flow

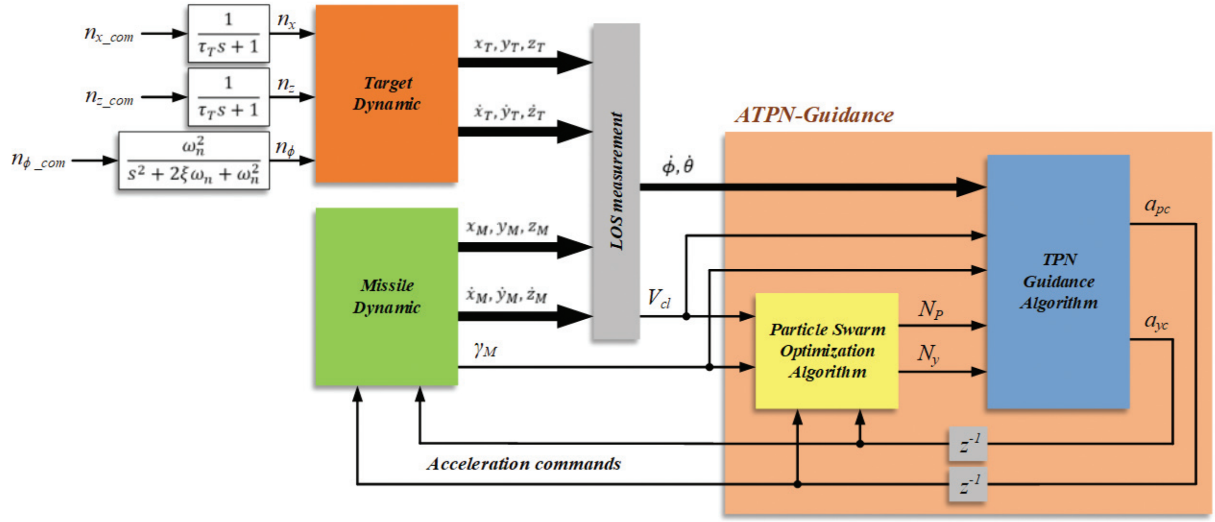

Figure 2. The scheme of the proposed ATPN-guidance.

chart of ATPN-guidance is depicted in Fig. 3 (upper). Finally, the optimum N_p and N_y navigation constants calculated by PSO in each time-step are summarised in Table 1 as an example. The adjustment range is chosen from 3 to 5 so as to improve tracking ability of the algorithm. The changes of the navigation constants are given in Fig. 3 (below).

4. MODELLING AND SIMULATION

Point-mass models of the missile and target have been used because they are sufficient for kinematic analysis. Their aerodynamic vectors are illustrated in the Cartesian coordinate frame presented in Fig 4. In addition, the model dynamics are summarised below[22]. In these models, γ is flight path angle, ψ is azimuth angle and φ is roll angle.

4.1 Missile Modelling

Point-mass model of the missile is presented as;

$$\dot{x}_M = V_M \cos(\gamma_M)\cos(\psi_M) \tag{14}$$

$$\dot{y}_M = V_M \cos(\gamma_M)\sin(\psi_M) \tag{15}$$

$$\dot{z}_M = V_M \sin(\gamma_M) \tag{16}$$

$$\dot{V}_M = \frac{T_M - D_M}{m_M} - g\sin(\gamma_M) \tag{17}$$

$$\dot{\gamma}_M = \frac{a_p - g\cos(\gamma_M)}{V_M} \tag{18}$$

$$\dot{\psi}_M = \frac{a_y}{V_M \cos(\gamma_M)} \tag{19}$$

$$\dot{a}_p = \frac{a_{pc} - a_y}{\tau_M} \tag{20}$$

$$\dot{a}_y = \frac{a_{yc} - a_y}{\tau_M} \tag{21}$$

$$D_M = k_1 V_M^2 + k_2 \frac{a_{pc}^2 + a_{yc}^2}{V_M^2} \tag{22}$$

Table 1. Optimum N_p and N_y navigation constants for each sample-time

Time steps (s)	N_{p_best}	N_{y_best}	Status
0.00	0	0	Initial step
0.02	4.2407	4.1814	Optimal navigation constants for guidance steps
0.04	4.5293	4.3945	
0.06	3.9099	3.7706	
0.08	3.3214	4.8186	
0.10	3.9837	4.3122	
0.12	3.8723	3.4103	
0.14	4.1792	3.9208	
0.16	4.4944	3.8887	
0.18	3.9564	3.9476	
.	.	.	
.	.	.	
.	.	.	
.	.	.	
8.48	4.2666	4.1027	
8.50	4.3082	4.3623	
8.52	3.8363	3.7082	
8.54	4.3321	4.1697	Interception (final) step

where x_M, y_M and z_M are the coordinates of the missile. Also, γ_M, ψ_M, V_M, T_M, D_M, and m_M are the flight path angle, the azimuth angle, the velocity, the thrust, the drag, and the mass of the missile respectively. In addition, k_1, k_2, a_{pc}, a_{yc}, τ_M and g are drag coefficients, lateral accelerations of the pitch and yaw axis and the gravity force, respectively[22]. After the angles and velocity are calculated in accordance with the current status of the missile, then its new coordinates are computed. To increase the reality, the thrust T_M and the mass m_M of the missile is modelled depending on time[26];

$$T_M = \begin{cases} T_0, & t \le 15 \\ 0, & t > 15 \end{cases} \tag{23}$$

$$m_M = \begin{cases} m_0 - \dot{m}t, & t \le 15 \\ m_f, & t > 15 \end{cases} \tag{24}$$

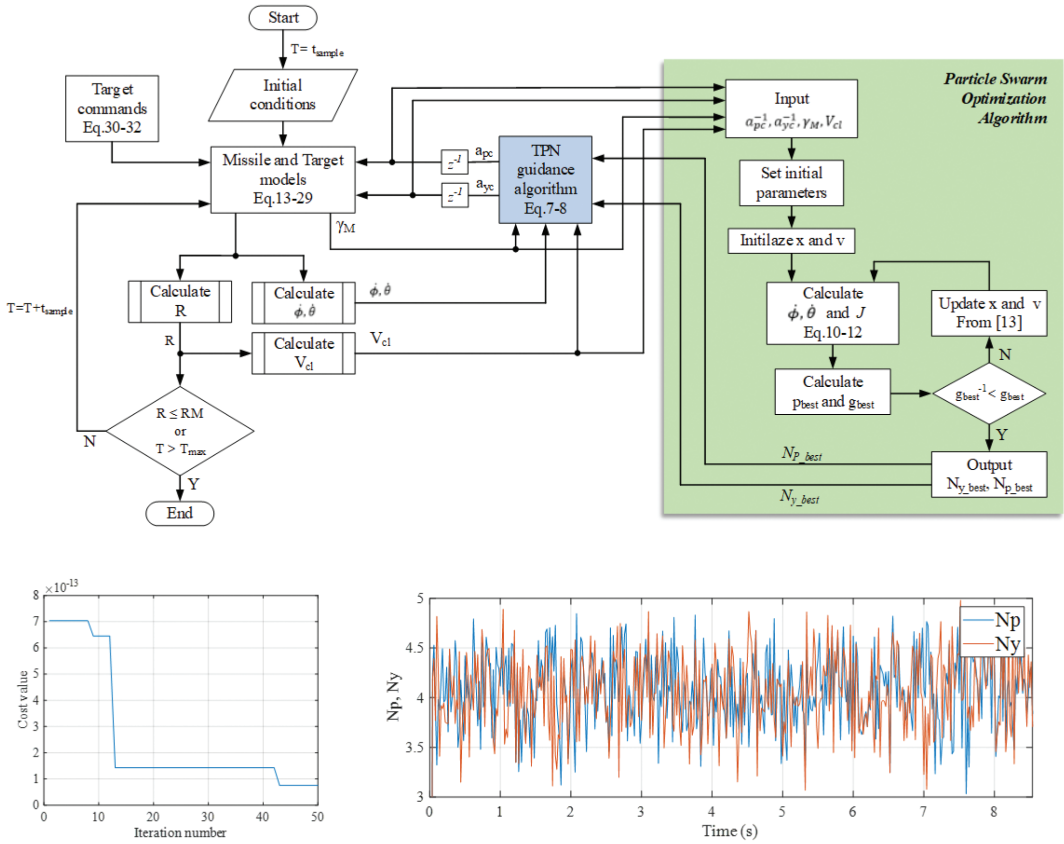

Figure 3. The flow-chart of ATPN-guidance based on PSO algorithm (upper), example convergence curve (below left), changes of navigation constants (below right).

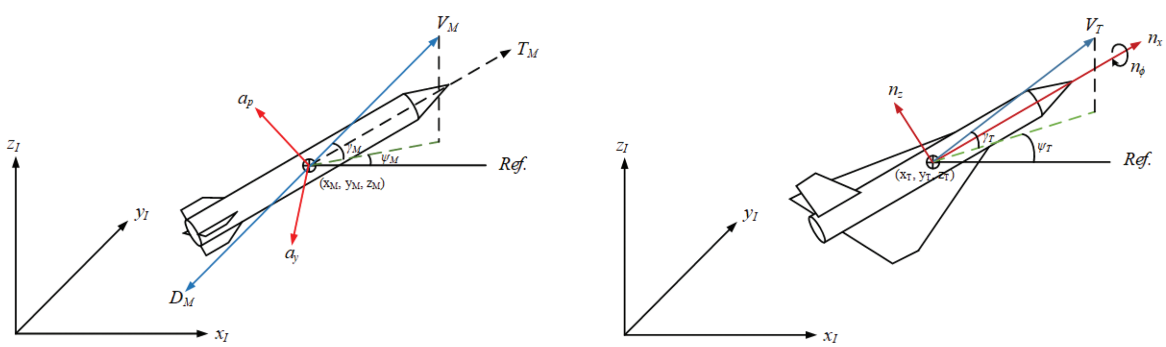

Figure 4. The aerodynamic vectors of a missile (Left) and target (Right)[22].

4.2 Target Modelling

Point-mass model of the target is presented as;

$$\dot{x}_T = V_T \cos(\gamma_T)\cos(\psi_T) \tag{25}$$

$$\dot{y}_T = V_T \cos(\gamma_T)\sin(\psi_T) \tag{26}$$

$$\dot{z}_T = V_T \sin(\gamma_T) \tag{27}$$

$$V_T = g\left(n_x - \sin(\gamma_T)\right) \tag{28}$$

$$\dot{\gamma}_T = \frac{g}{V_T}\left(n_Z \cos(n_\phi) - \cos(\gamma_T)\right) \tag{29}$$

$$\dot{\psi}_T = \frac{g n_z \sin(n_\phi)}{V_T \cos(\gamma_T)} \tag{30}$$

where x_T, y_T and z_T are the coordinates of the target. V_T, γ_T, ψ_T, n_x, n_z, n_φ are the velocity, the flight path, the azimuth angle and the variables which are transformed into the thrust, the pitch force and the rolling angle, respectively. In addition, the dynamic delay model for the variables of thrust, pitch force and rolling angle are given as;

$$n_x = \frac{n_{x\_com}}{1+\tau_T s} \tag{31}$$

$$n_z = \frac{n_{z\_com}}{1+\tau_T s} \tag{32}$$

$$n_\phi = \frac{\omega_n^2}{s^2 + 2\omega_n \zeta s + \omega_n^2} n_{\phi\_com} \tag{33}$$

In these equations, n_{x_com}, n_{y_com} and n_{φ_com} are the control command inputs determining the behaviour of the target[22].

4.3 Engagement Modelling

The engagement model is based upon the initial values presented in Table 2. During simulations, the behaviour of the target is determined by applying the control commands depicted in Table 3. In addition, besides standard maneuvers from[22], an extra aggressive maneuver is chosen to be able to reveal and compare the actual performance of ATPN-guidance.

Table 2. Initial values of missile and target

	x-axis [m]	y-axis [m]	z-axis [m]	Speed [Mach]	ψ [rad]	γ [rad]	Time-step [sec]
Missile	0	0	3000	2	0	0	0.02
Target	6000	4000	3500	0.8	0	0	0.02

Table 3. The control command inputs of the target[22]

Control commands	Maneuvers numbers (MN)							Aggressive maneuver
	1	2	3	4	5	6	7	
n_{x_com} [g]	0	3	0	-3	0	0	0	5
n_{z_com} [g]	9	0	0	0	9	9	-9	3
$\varphi_{\_com}$ [rad]	-π/2	0	0	0	π/2	0	0	5

5. RESULTS AND DISCUSSION

The seven scenarios taken from the literature and the additional new scenario are applied to the simulation. At this new scenario, acceleration of the target is increased, and the missile is provided to perform additional turn maneuver. The control commands of these maneuvers are given in Table 3. For all scenarios, the target was moved to in the air depending on control commands. The algorithms try finding shortest path to meet target and missile. All simulations are run 10 times to avoid stochastic behaviour of the heuristic approach. The trajectories and lateral acceleration curves regarding the maneuver are presented between Figs. 5 and 7. Each figure is consisting of three curves. Three dimensional curves represent paths of the target and missiles in the air and axes of them are as kilometers. The other curves are lateral acceleration value of yaw and pitch. The axis of the "x" represents time as seconds. It is clearly seen that ATPN has more aggressive acceleration to catch target. Thus, its time spent is shorter that classical TPN.

The miss-distance and time-to-go values of TPN and ATPN-guidance are compared with each other. In addition, the mean, minimum and maximum values and the gap between them are also computed. The numerical results are summarised in Table 4. In general, it can be seen from the tables that the miss-distance, the time-to-go and the gap values of the ATPN-guidance appear to be significantly better than those of TPN-guidance.

The time-to-go of 3rd and 6th maneuvers are better for the TPN-guidance, but the values for the other five maneuvers are less than TPN-guidance. If the time-to-go of ATPN-guidance are examined, it can be seen that all values are less than those of TPN-guidance. Also, the minimum and the maximum values of the lateral accelerations don't involve any saturation at ATPN-guidance, while the 1th, 2nd, 5th, 6th and 7th maneuvers for TPN-guidance have minimum or maximum saturations. In addition, the gaps between the

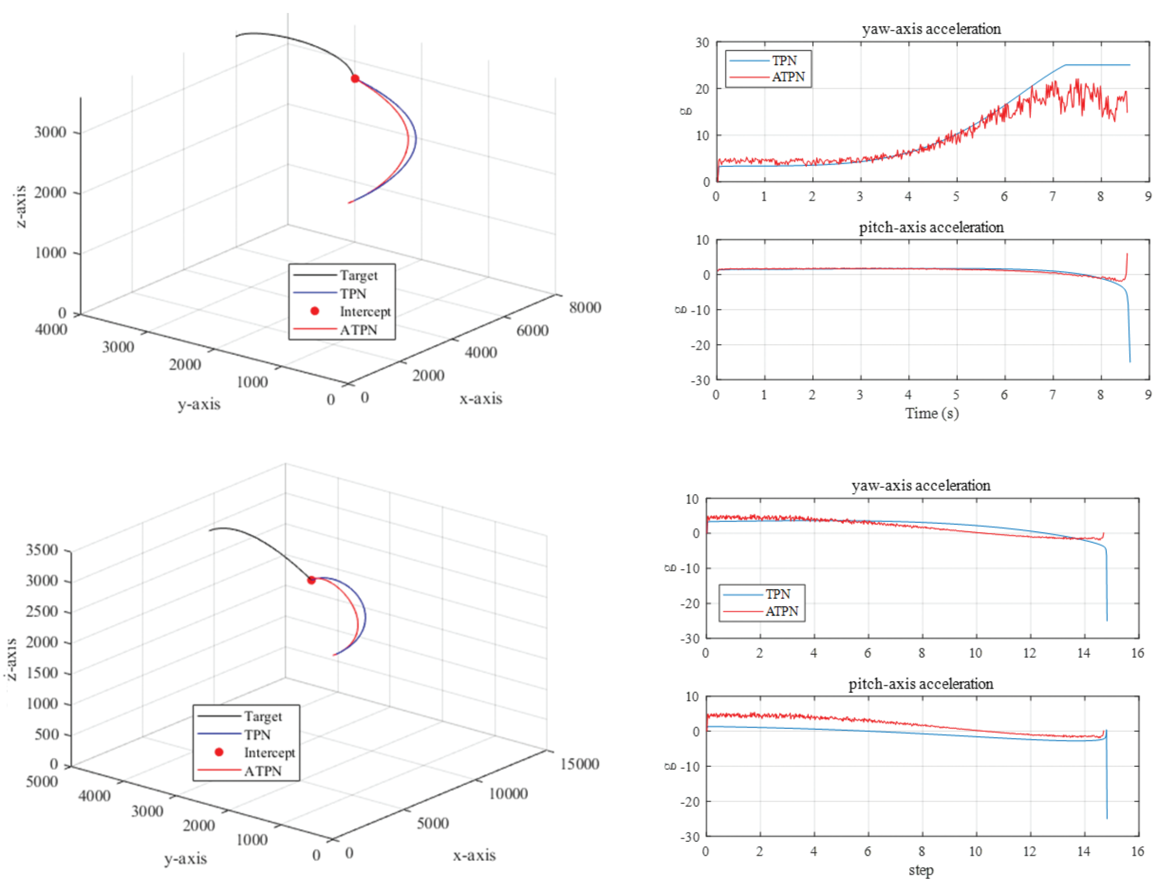

Figure 5. The curves regarding manoeuvre-1 (upper) and 2 (below).

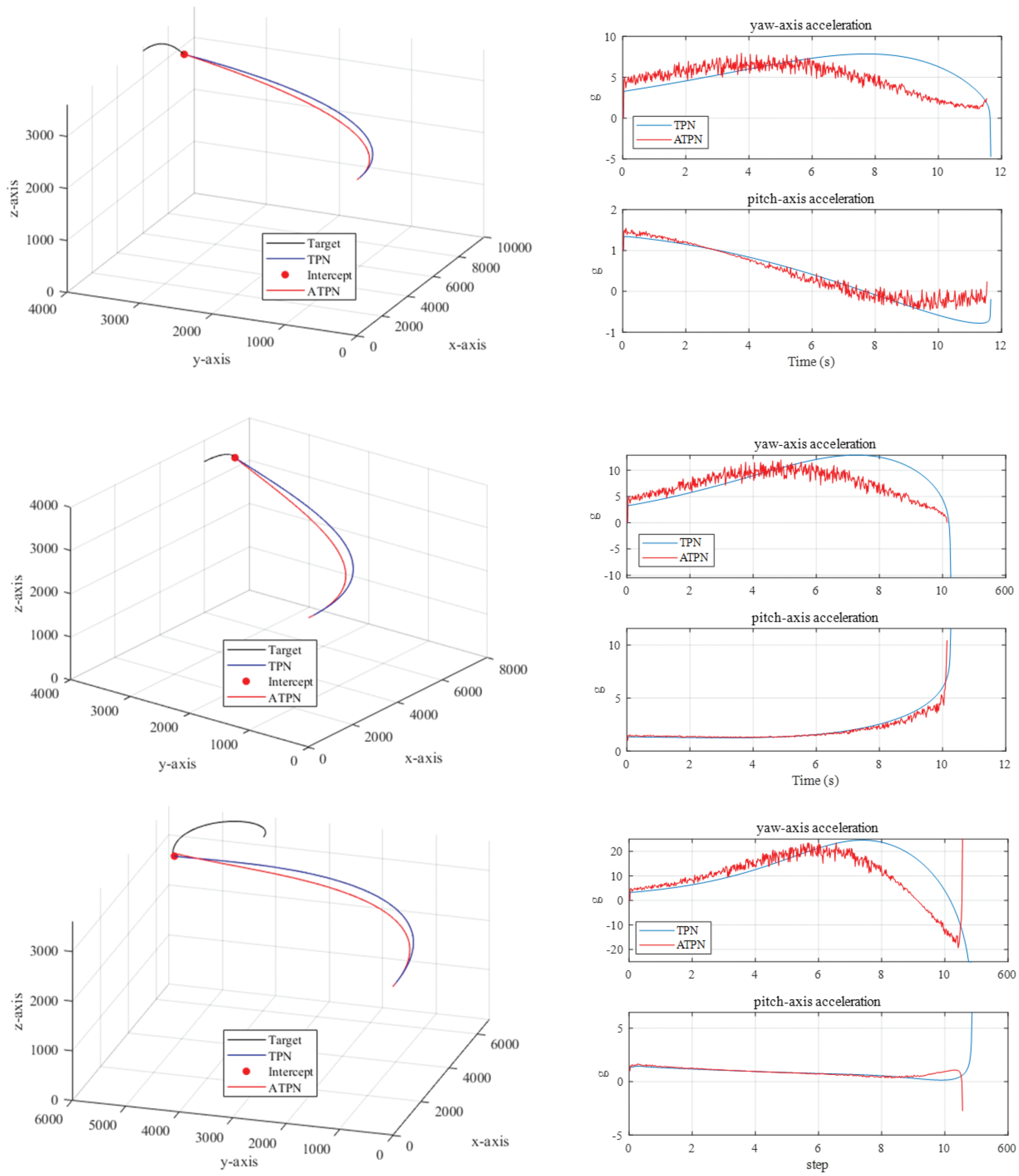

Figure 6. The curves regarding manoeuvre-3 (upper), 4 (middle) and 5 (below).

minimum and maximum lateral accelerations of ATPN-guidance are significantly less than those of TPN-guidance. These results show that although the correct measure of the energy expenditure is not the gap but the integral of the squared acceleration, it can be said with a general acceptation that the kinetic energy consumption is considerably decreased in ATPN-guidance. On the other hand, the jitters occurred on the acceleration curves are considered to cause from the iteration changes of the PSO algorithm. There is no significant effect on the overall performance of the suggested guidance method.

If the average values of the results of standard maneuvers from Table 4 are investigated, it is seen that while the miss-distance increases a little, the time-to-go decreases about the same amount. But the main striking result is the significant reduction in the acceleration gaps. While the gap of the pitch axis decreases 21.8%, the gap of yaw axis reduces 39.68%. These reductions mean that while the missile guided by ATPN is maneuvering at the standard maneuvers, it is exposed to less acceleration and less strain. In addition, although the correct measure of the energy expenditure is not the gap but the integral of the squared acceleration, it can be said with a general acceptation that the kinetic energy consumption is considerably decreased in ATPN-guidance.

Indeed, ATPN-guidance causes some increase in the navigation constants in some time-steps as seen from Table 1.

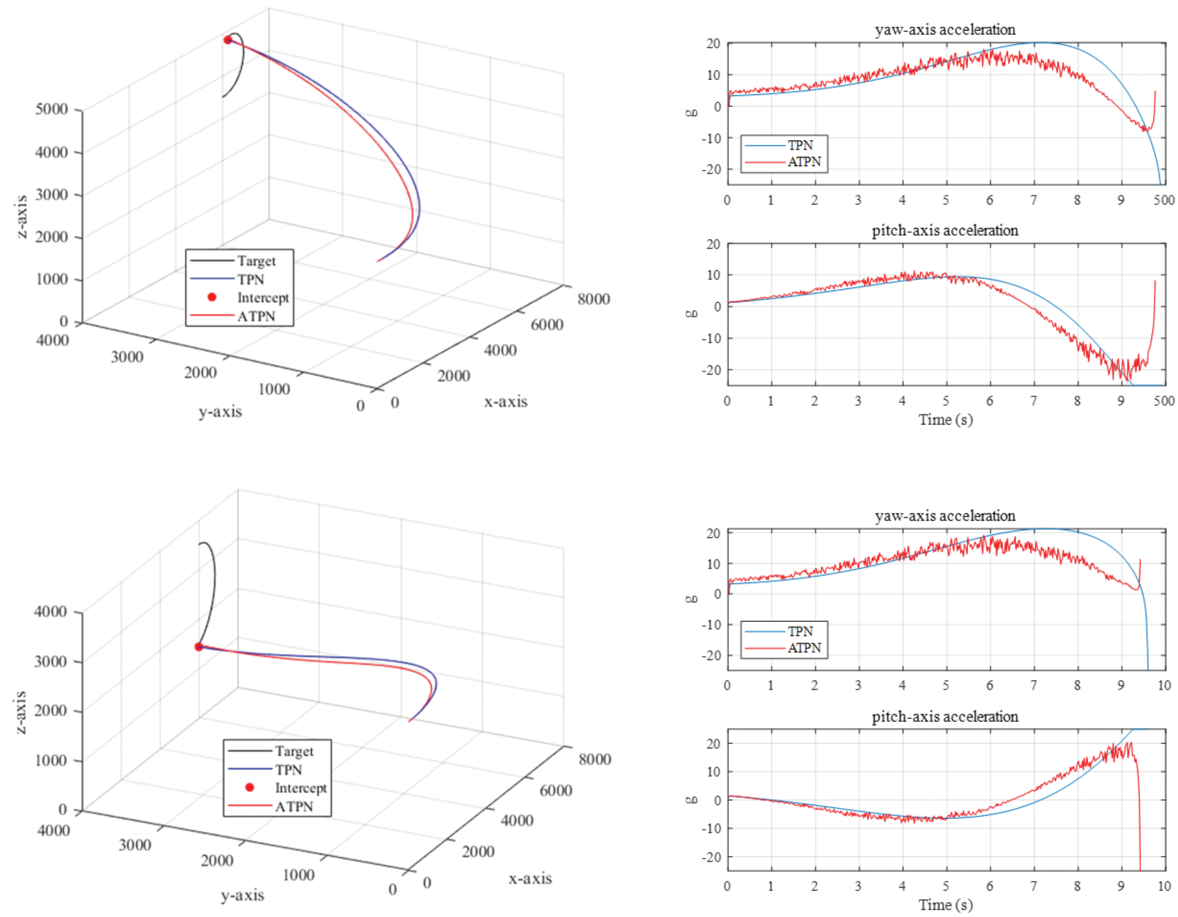

Figure 7. The curves regarding manoeuvre-6 (upper) and 7 (below).

Table 4. The simulation results regarding standard maneuvers

Maneuvers		Miss-distance [m]	t_{go} [sec]	Lateral acceleration [g]							
				y-axis (pitch)				z-axis (yaw)			
				Mean	Min.	Max.	Gap	Mean	Min.	Max.	Gap
1	TPN	8.818	8.600	1.018	-25.000	1.735	26.735	11.304	0.000	25.000	25.000
	ATPN	0.406	8.540	1.152	-1.969	6.049	8.018	9.771	0.000	22.079	22.079
2	TPN	13.238	14.820	-0.673	-25.000	1.338	26.338	2.155	-25.000	3.615	28.615
	ATPN	12.778	14.700	-0.416	-2.112	1.545	3.657	1.815	-1.934	5.428	7.362
3	TPN	5.656	11.660	0.365	-0.779	1.339	2.118	5.875	-4.713	7.841	12.554
	ATPN	11.446	11.540	0.444	-0.458	1.547	2.005	4.851	0.000	7.935	7.935
4	TPN	5.236	10.260	2.087	1.000	11.578	10.578	8.748	-10.513	12.882	23.395
	ATPN	4.939	10.140	1.918	1.000	10.441	9.441	7.334	0.000	11.976	11.976
5	TPN	7.534	10.860	0.843	0.147	6.483	6.336	12.277	-25.000	24.535	49.535
	ATPN	6.444	10.560	0.896	-2.726	1.674	4.400	9.821	-19.352	24.988	44.352
6	TPN	8.045	9.920	0.638	-25.000	9.446	34.446	9.977	-25.000	20.254	45.254
	ATPN	13.669	9.760	0.722	-23.625	11.380	35.005	8.739	-8.079	18.154	26.233
7	TPN	5.677	9.600	0.830	-6.399	25.000	31.399	12.213	-25.000	21.298	46.298
	ATPN	5.525	9.420	0.675	-25.000	20.342	45.342	10.466	0.000	19.178	19.178
Average	TPN	7,743	10,817	0,730	-	-	19,707	8,936	-	-	32,950
	ATPN	7,887	10,666	0,770	-	-	15,410	7,542	-	-	19,874

This effect causes to increase the initial acceleration and reduces the initial heading error and the terminal-phase acceleration of the missile in ATPN-guidance. Finally, interception probability of the target increases and the time-to-go value decreases. It can be said that the proposed adaptive approach based on heuristic optimisation largely improves the capture performance of TPN-guidance algorithm.

The results of additional maneuver are presented in Fig. 8 and Table 5. This maneuver is designed more aggressive than the maneuvers in Table 3. It can be observed from the Fig. 8 that the missile guided by ATPN-guidance reacts faster than the missile guided by TPN-guidance since its initial acceleration to each change of state of the target is bigger than that of TPN-guidance. First, the missile turns to the target more quickly to catch it in the case of 1 specified in Fig. 8 (below). Second, while the target starts to pass the missile, ATPN guided missile continues to follow by increasing its acceleration more than TPN guided missile as depicted in the case of 2. That is, as stated at the beginning, the proposed method decreases the heading error, provides sufficient initial acceleration to the missile, and reduces the terminal-phase acceleration required for intercepting the target. Finally, all of them are reveal the success of ATPN-guidance based on heuristic optimisation. It can be said that the main reason behind the results is to change the navigation constant optimally by using heuristic optimisation algorithm which has not derivative.

Indeed, it is known that the PN and TPN algorithms are very common methods and have widely usage. But they certainly still need improvement. This novel technique proposed as a new class of adaptation for these algorithms can be applied to air-to-air missiles directly or as a part of the classic methods in order to increase their success toward high maneuvers targets. Because, although there are a lot of adaptation methods for adjusting navigation constants at the related literature, the suggested method is highly simple and fast compared to them. Especially, it is clear that the heuristic optimisation increases the computational cost and runtime, but there is no significant effect observed at the simulation. This increase at the computational cost is not accepted impossibility for hardware implementation. On the other hand, the method is open to develop and the recent and speedier heuristic algorithms can be used for increasing the success of the method.

However, it is clear that the adjustment range of the navigation constant lies in a highly narrow interval. Indeed, this certainly provides a limited control action, but it is sufficient for producing required guidance command. This operation interval of the navigation constant may be increased by using different approach like as fractional order or fuzzy logic for more sensitive control. In addition, speed and accuracy of the chosen heuristic algorithm is quite dominant on the performance of the guidance action. So, more recent and powerful heuristic optimisation algorithms may be applied for increasing efficiency of the method.

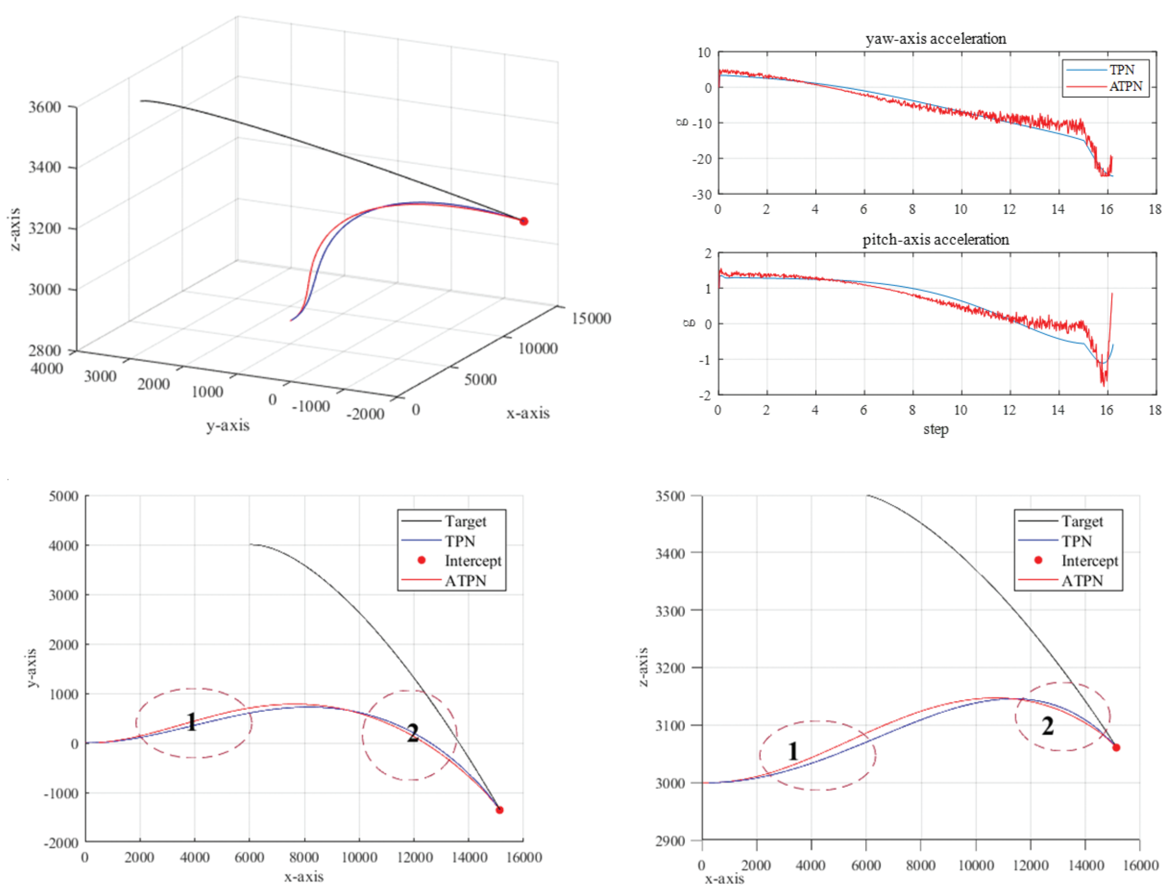

Figure 8. The curves regarding additional maneuver (upper) and two dimensional lateral views of the trajectories (below).

Table 5. The simulation results regarding the additional maneuver

	MD [m]	t_{go} [sec]	Lateral acceleration [g]							
			y-axis (pitch)				z-axis (yaw)			
			Mean	Min.	Max.	Gap	Mean	Min.	Max.	Gap
TPN	13.594	16.220	0.625	-1.110	1.345	2.455	-5.266	-25.000	3.314	28.314
ATPN	12.437	16.180	0.659	-1.771	1.557	3.328	-4.921	-25.000	4.992	29.992

6. CONCLUSIONS

The adaptation of PN algorithm is still an open research area nowadays. Although, there are many various methods for this purpose in the literature, heuristic optimisation is a new and excited approach in order to obtain optimal adaptation. So, the novel heuristic-based method is suggested as a new class of PN-guidance adaptation. In this study, the optimal ATPN-guidance against changing maneuvers is performed. The novel method is very promising. Although, range of the navigation constant lies in a highly narrow adjustment interval, the main striking result obtained is the significant reduction in the acceleration gaps. While the gap of the pitch axis decreases 21.8%, the gap of yaw axis reduces 39.68%. These reductions mean that while the missile guided by ATPN is maneuvering at the standard maneuvers, it is exposed to less acceleration and less strain. In addition, at the more aggressive maneuver, the interception can be provided more quickly. Also miss-distance and the time-to-go values reduce 8.52% and 0.24%, respectively. Conclusively, the proposed ATPN-guidance is more successful than the TPN-guidance in terms of capturing ability and energy consumption. The main reason behind this success is to change the navigation constant optimally in accordance with changing target maneuvers by using heuristic optimisation algorithm.

At the future studies, first of all, the operation interval of the navigation constant will be increased by using different approach like as fractional order or fuzzy logic in order to obtain more sensitive control. Second, more powerful heuristic algorithms than PSO will be applied to the method in order to increase more the success of proposed ATPN-guidance.

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APPENDIX

Parameters	Values	Units	Definitions
ω_n	10	rad/s.	Natural frequency
ξ	0.7		Damping ratio
τ_T	0.1	s.	Time constant of target
τ_M	0.1	s.	Time constant of missile
k_1	0.001		Drag coefficient
k_2	1		Drag coefficient
T_M	5900	N.	Thrust of missile
m_M	160	kg.	Mass of missile
g	9.81	m/s^2	Gravity force
N_p	3		Navigation constant of pitch axis
N_y	3		Navigation constant of yaw axis
RM	15	m.	Kill radius of missile
t	0.02	s.	Time step
T	40	s.	Simulation time
N	2		Number of optimised parameters
M	40		Number of particles
I	50		Number of iterations
x_{min}	3		Minimum value of optimised parameters
x_{max}	5		Maximum value of optimised parameters