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Analysis of a Hybrid Guided Bomb Control System while Self-guided to a Ground Target

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Abstract. This article presents a mathematical model and an algorithm for controlling a guided bomb to a moving and a stationary ground target. The target path was determined from the kinematic relationships of the reciprocal movement of the bomb and the ground target, based on the proportional approximation method. The analysed control system used sliding control, with the PID algorithm to determine the sliding plane. Three types of sliding planes were considered. In addition, a comparative analysis was carried out for three types of controllers: classic PID, sliding and hybrid. Selected results of the computer simulation are listed.
Keywords: guidance, guided bomb, hybrid control system, sliding control, proportional navigation

1. INTRODUCTION

Many control methods for non-linear systems are described and studied in the literature. The guided bomb (GB) belongs to one such system and is still a major challenge for contemporary research into autonomous objects. The GB flight control systems use a variety of controls, ranging from classical PID through optimal and fuzzy logic. PID controllers are the most common and simplest controllers, often used to guide flying objects [1 - 3]. A new approach in control system design is to combine different types of controllers to achieve the objectives of the designed system [4]. They combine the advantages of selected types of controllers, and in the literature, we can find the following structures: PID and fuzzy [5], sliding and fuzzy controller [6], sliding and adaptive controller [7, 8] and sliding and PID controller [9]. It should be noted that the combination of a classical controller with a sliding one is becoming increasingly common, starting with the simplest form of proportional controller with a sliding controller, through the inclusion of integral [10] or differential [11] terms, up to the PID-SMC structure [12]. The main objective of hybrid combinations in UAVs is to increase the control efficiency of such a system, as well as to improve selected flight parameters, including resistance to in-flight disturbances. This article proposes a hybrid combination of a PID controller and a sliding controller. It should be noted that there is no research in the available literature on the use of a PID in combination with an SMC in guided bomb control with the aim of stable guidance (elimination of the harmful chatter phenomenon) and achieving greater accuracy in hitting a ground target. The sliding plane in this case is the PID algorithm used to self-guide the GB onto a ground target.

2. MATHEMATICAL MODEL OF GUIDING A BOMB AIMED AT A GROUND TARGET

2.1. Equations of the vertical movement of the bombs

The vertical-guided bomb motion equations were derived from Newton's laws, according to which the sum of the external forces acting on the object in the selected direction is equal to the change in the amount of motion in that direction per unit time. Figure 1 shows the system of forces acting on a guided bomb along with the adopted coordinate systems.

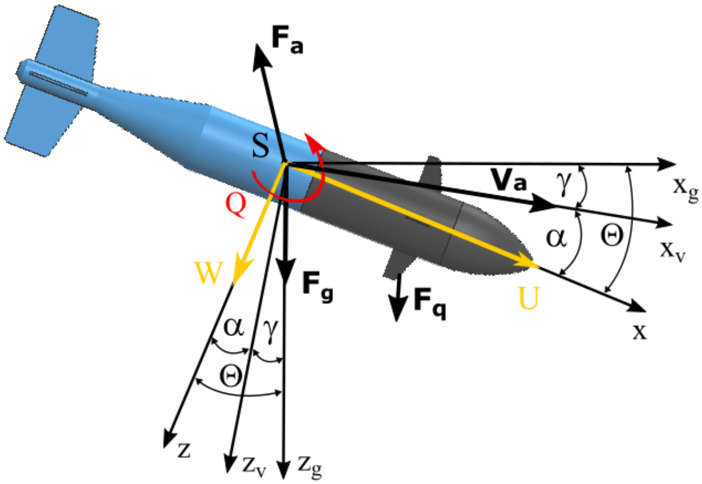

Fig. 1. Systems of forces acting on a guided bomb, linear velocity and angular velocity

Figure 1 introduces the following quantities and designations:

$\boldsymbol{F}_a$ – resultant aerodynamic force vector,

$\boldsymbol{F}_g$ – gravity force vector,

$\boldsymbol{F}_q$ – control force vector,

P, R – angular velocity components in the system associated with the guided bomb,

U, W – linear velocity components in the system associated with the guided bomb,

Θ – quasi-Eulerian inclination angle,

α – angle of attack,

γ – inclination angle of the velocity vector of the guided bomb.

We assume that the movement of the bomb takes place in the vertical plane, therefore the non-linear system of equations describing its movement can be written using the form:

$$m\left[\dot{U} + QW\right] = F_x \tag{1}$$

$$m\left[\dot{W} - QU\right] = F_z \tag{2}$$

$$\dot{Q} = \frac{1}{I_y}\left[M_y + (I_z - I_x)PR\right] \tag{3}$$

$$\dot{\Theta} = Q \tag{4}$$

The forces F_x and F_z, and moment M_y acting on the guided bomb in the relationship (1)-(3) can be presented using the form:

$$F_x = -mg\sin\Theta - C_{aX}\frac{\rho|\boldsymbol{V}_a|^2}{2}S_b \tag{5}$$

$$F_z = mg\cos\Theta + \frac{\rho|\boldsymbol{V_a}|^2}{2}S_b\left(-C_{aN}\left(\frac{W}{|\boldsymbol{V_a}|}\right) - C_{aNr}\left(\frac{Qd}{2|\boldsymbol{V_a}|}\right) - C_{Nd}\delta_w\right) \quad (6)$$

$$M_y = \frac{\rho|\boldsymbol{V_a}|^2}{2}S_b\left(dC_m\left(\frac{W}{|\boldsymbol{V_a}|}\right) + dC_q\left(\frac{Qd}{2|\boldsymbol{V_a}|}\right) - l_d C_{Nd}\delta_w\right) \quad (7)$$

where: m – guided bomb mass, g – acceleration of gravity, U, W – components of the velocity vector of the guided bomb in relation to the air in the boundary system $Sxyz$, Q – component of the angular velocity vector of the guided bomb in the boundary system, ρ – air density, d – diameter of the guided bomb body, S_b – characteristic surface (cross-sectional area of the guided bomb), l_d – distance between the centre of pressure of the rudder and the centre of mass of the guided bomb, $\boldsymbol{V}_a$ – velocity vector of the guided bomb centre of mass in relation to the air, δ_w – deflection angle of the height rudder, C_{aX} – coefficient of the aerodynamic axial force, C_{aN} – coefficient of the aerodynamic normal force, C_{aNr} – coefficient of the aerodynamic damping force, C_m – coefficient of the aerodynamic tiling moment, C_q – coefficient of the damping tiling moment, C_{Nd} – coefficient of the aerodynamic control force.

The aerodynamic coefficients appearing in formulas (5) - (7) were taken from a doctoral dissertation [13].

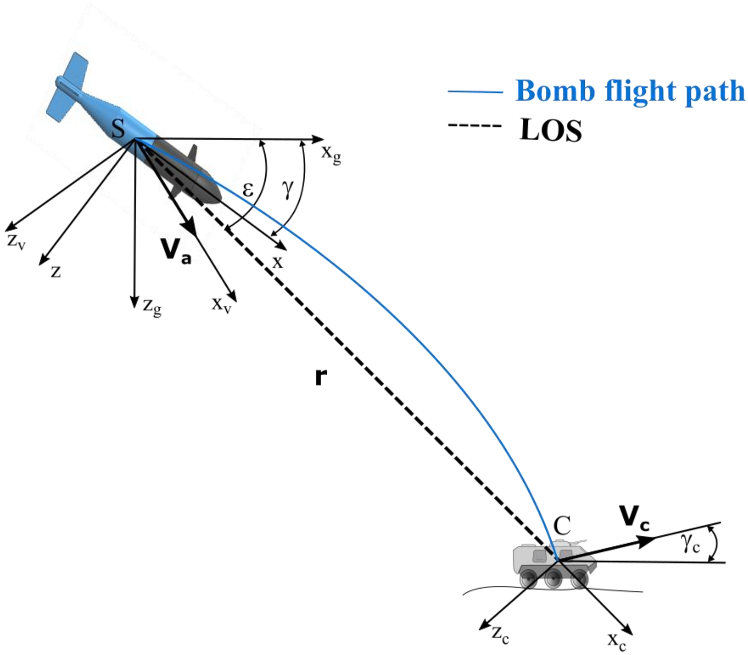

Fig. 2. General view of a self-guided bomb on a ground target

In considering Fig. 2, the equations of the kinematics of the reciprocal motion of the target and the guided bomb in the case of a vertical plane can be written in the form:

$$\frac{dr}{dt} = V_c(\cos\gamma_c \cos\varepsilon + \sin\varepsilon \sin\gamma_c) - V_a(\cos\gamma \cos\varepsilon + \sin\varepsilon \sin\gamma) \qquad (8)$$

$$-\frac{d\varepsilon}{dt} r = V_c(\cos\gamma_c \sin\varepsilon - \cos\varepsilon \sin\gamma_c) - V_a(\cos\gamma \sin\varepsilon - \cos\varepsilon \sin\gamma) \qquad (9)$$

where: r – distance of the guided bomb from the ground target, V_c – target velocity, γ_c – inclination angle of the target velocity vector, γ – inclination angle of the guided bomb velocity vector, ε – inclination angle of the target line of sight (LOS).

The trajectory of the bomb's centre of mass in the ground-related coordinate system is obtained using appropriate transformations provided in the paper [14]. Finally, for the vertical movement of the bombs, we have:

$$\begin{aligned} \frac{dx_g}{dt} &= U \cos\Theta + W \sin\Theta \\ \frac{dz_g}{dt} &= -U \sin\Theta + W \cos\Theta \end{aligned} \qquad (10)$$

The equations of movement of the target's centre of mass in the system related to its flight path for the vertical plane may be presented using the form:

$$\begin{aligned} \frac{dx_c}{dt} &= V_{cx} \\ \frac{dz_c}{dt} &= -V_{cz} \end{aligned} \qquad (11)$$

In this article, we consider the case for which V_{cx} = const and $V_{cz} = 0$, where the target moves in a uniform, rectilinear motion.

3. GUIDED BOMB CONTROL ALGORITHM

The control algorithm is intended to ensure that the GB control actuator operates in such a way as to ensure that the ground target is hit with the stated accuracy. Selecting an algorithm to determine the relationship for the slide plane is the most important step in designing the slide control. This allows the system to be more efficient and thus reach the ground target in the case of GB.

In the case of conventional sliding control, the sliding surface is determined as follows [15]:

$$S(e_w, t) = \frac{de_w}{dt} + c_\Theta e_w \qquad (12)$$

where: c_Θ - constant, a controller parameter.

The control deviation necessary to generate the control signals for the control actuator may be described by the following relationship:

$$e_w = \Theta_z - \Theta \qquad (13)$$

where: Θ, Θ_z – current and set value of the inclination angle.

Determination of the set value of the inclination angle Θ_z results from the adopted guidance method used in the article as a method of proportional navigation. It is assumed that during the GB self-guiding process to a ground target, the inclination angle Θ_z coincides with the LOS inclination angle ($\Theta_z = \varepsilon$). The self-guidance of a bomb directed at a ground target follows the proportional navigation algorithm, which can be expressed as [16]:

$$\frac{d\gamma}{dt} = a_\varepsilon \frac{d\varepsilon}{dt} \tag{14}$$

where: a_ε - constant proportional navigation coefficient.

In this paper, an integrating action was added to the slide plane described by equation (11) to obtain the structure of the PID controller. As a result of this modification, the algorithm determining the slide plane can be expressed as:

$$S(e_w, t) = k_{p\Theta} e_w + k_{i\Theta} \int_0^{t_s} e_w dt + k_{d\Theta} \frac{de_w}{dt} \tag{15}$$

where: $k_{p\Theta}$, $k_{i\Theta}$, $k_{d\Theta}$ – constant gain coefficients of the PID controller.

The slide plane determined according to the relation (14) has been used by many researchers and for various dynamic systems [17]. The next step in the design of the GB control system is to determine a control algorithm that will ensure the stability of the sliding motion on that sliding plane. In this paper, three control laws for the sliding controller are investigated, namely:

1. **classical sliding control**, which includes a signum switching function. In this case, the control signal for the GB control actuator can be written as:

$$\delta_w = \lambda_w \, sgn(S) \tag{16}$$

2. **quasi-sliding control**, which uses a hyperbolic tangent approximating function [18] to eliminate chatter [19]. The control signal for this case can be presented in the form:

$$\delta_w = \lambda_w \, tanh\left(\frac{S}{k_{\varepsilon\Theta}}\right) \tag{17}$$

3. **super-hanging type control** for which the sliding controller is a second-row type and the control signal algorithm is specified in the form:

$$\delta_w = k_{c\Theta} \sqrt{|S|} \, sgn(S) + w \tag{18}$$

$$\dot{w} = k_{b\Theta} \, sgn(S) \tag{19}$$

The fixed parameter λ_w is defined as the maximum height rudder angle δ_{max}, which for the GB under consideration, is $\delta_{max}=\pm 20^o$. The constant gain coefficients $k_{\varepsilon\Theta}$, $k_{c\Theta}$, $k_{b\Theta}$ were selected using the parameter space search method.

Simulation tests will be carried out for each of the three control signals to verify the performance of the GB control system.

4. RESULTS OF THE SIMULATION TESTS

In order to verify the correct operation of the proposed hybrid control algorithm, tests were carried out for three sliding planes. For each of the cases under consideration, a numerical simulation was performed in Matlab for identical initial conditions, namely:

- initial position of the guided bomb: $x_{g0} = 0$ m, $z_{g0} = 3000$ m,
- initial components of the drop velocity: $U_0 = 120$ m/s, $W_0 = 20$ m/s,
- initial position of the ground target: $x_{c0} = 1000$ m, $z_{co} = 0$ m,
- initial ground target velocity: for a stationary target we assume $V_{c0} = 0$ m/s, while the moving target moves in uniform rectilinear motion with a constant velocity of $V_{c0} = 5$ m/s,
- initial inclination angle of the bomb: $\Theta_0 = - 71.56^o$,
- initial inclination angle of the flight path: $\gamma_0 = - 81.06^o$,
- the other parameters have zero values.

Guidance for the guided bomb was performed using the proportional navigation algorithm with the $a_\varepsilon = 3.5$ coefficient.

The results of the numerical simulation of GB self-guidance on a stationary ground target for a sliding plane defined according to equation (16) are shown in Figures 3 – 6.

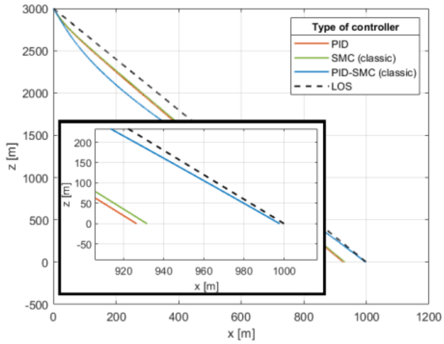

Fig. 3. Bomb flight tracks to a stationary target with classical sliding control

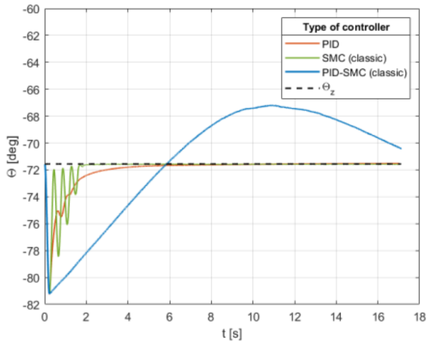

Fig. 4. Angles of bomb inclination as a function of time with classical sliding control

The results of the numerical simulation of GB self-guidance on a stationary ground target for a sliding plane defined according to equation (17) are shown in Figures 7 – 10.

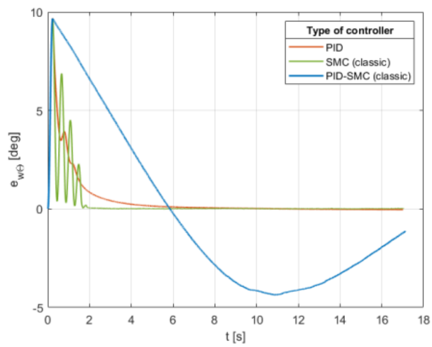

Fig. 5. Angle deviations of bomb flight as a function of time with classical sliding control

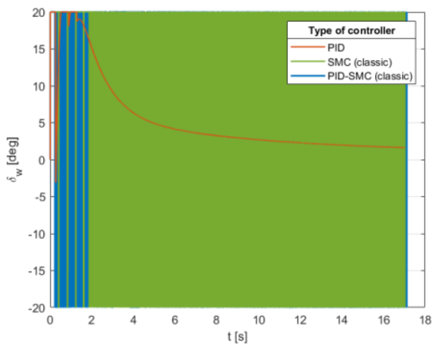

Fig. 6. Deflection angle of the height rudder as a function of time with classical sliding control

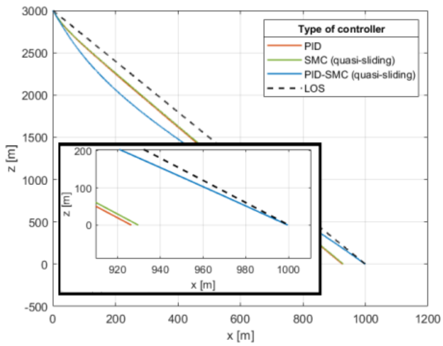

Fig. 7. Bomb flight tracks to a stationary target with quasi-sliding control

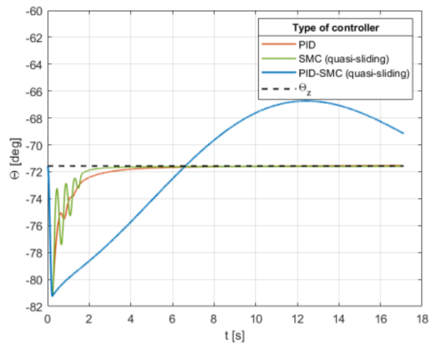

Fig. 8. Angles of bomb inclination as a function of time with quasi-sliding control

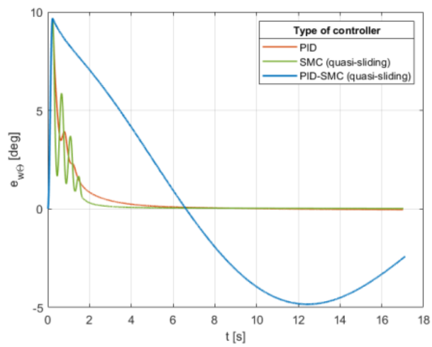

Fig. 9. Angle deviations of bomb flight as a function of time with quasi-sliding control

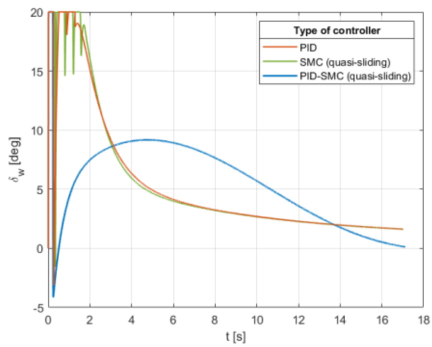

Fig. 10. Deflection angle of the height rudder as a function of time with quasi-sliding control

The results of the numerical simulation of GB self-guidance on a stationary ground target for a sliding plane defined according to equation (18) and (19) are shown in Figures 11 – 14.

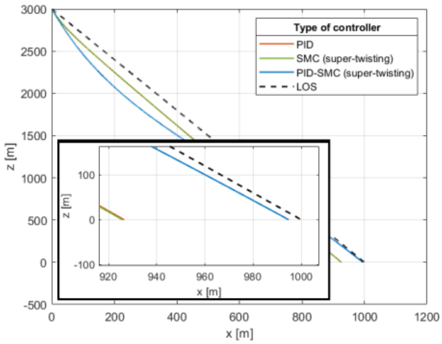

Fig. 11. Bomb flight tracks to a stationary target with super-twisting sliding control

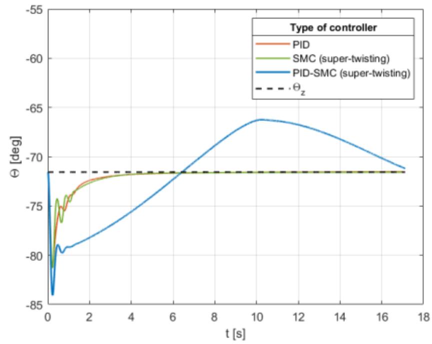

Fig. 12. Angles of bomb inclination as a function of time with super-twisting sliding control

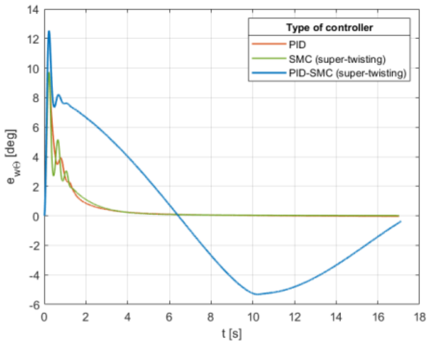

Fig. 13. Angle deviations of bomb flight as a function of time with super-twisting sliding control

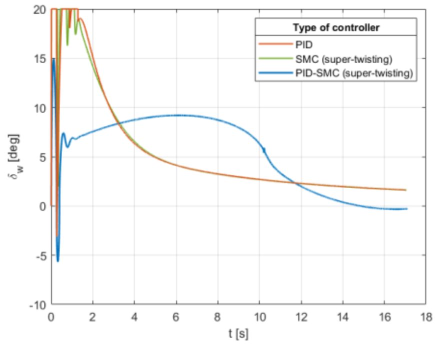

Fig. 14. Deflection angle of the height rudder as a function of time with super-twisting sliding control

Table 1 shows the selected values of the gain coefficients for all tested controller types. As part of the conducted simulation tests, the values of three self-guidance parameters were determined: guidance time, accuracy of hitting the ground target and quality indicator. The values of the obtained parameters are listed in Table 2.

Table 1. Summary of PID controller gain coefficients for a stationary target

PID	SMC (classic)	PID - SMC (classic)
$k_{\mathrm{p}\Theta} = 20.64$ $k_{i\Theta} = 0.2998$ $k_{\mathrm{d}\Theta} = 6.05$	$c_\Theta = 34.5$	$k_{\mathrm{p}\Theta} = 0.11$, $k_{\mathrm{i}\Theta} = 0.069$ $k_{\mathrm{d}\Theta} = 0.76$
	SMC (quasi-sliding)	**PID - SMC (quasi-sliding)**
	$c_\Theta = 13.36$ $k_{\varepsilon\Theta} = 0.0581$	$k_{\mathrm{p}\Theta} = 0.18$, $k_{\mathrm{i}\Theta} = 0.105$ $k_{\mathrm{d}\Theta} = 1.12$, $k_{\varepsilon\Theta} = 0.065$
	SMC (super-twisting)	**PID - SMC (super-twisting)**
	$c_\Theta = 9.95$ $k_{\mathrm{c}\Theta} = 0.5908$ $k_{\mathrm{b}\Theta} = 0.0001$	$k_{\mathrm{p}\Theta} = 0.21$, $k_{\mathrm{i}\Theta} = 0.058$ $k_{\mathrm{d}\Theta} = 0.11$, $k_{\mathrm{c}\Theta} = 0.5908$ $k_{\mathrm{b}\Theta} = 0.01$

Table 2. Summary of self-guidance parameters for a bomb directed at a stationary target

Type of controller	Hit accuracy [m]	Guidance time [s]	Quality indicator I_{IAE}
PID	73.61	17.03	0.1377
SMC (classic)	68.40	17.05	0.1072
SMC (quasi-sliding)	70.30	17.04	0.108
SMC (super-twisting)	70.44	17.02	0.1372
PID - SMC (classic)	2.19	17.13	1.105
PID - SMC (quasisliding)	0.51	17.13	1.241
PID - SMC (super twisting)	1.18	17.14	1.148

The results of the numerical simulation of GB self-guidance on a moving ground target for a sliding plane defined according to equation (16) are shown in Figures 15 – 18.

The results of the numerical simulation of GB self-guidance on a moving ground target for a sliding plane defined according to equation (17) are shown in Figures 19 – 22.

The results of the numerical simulation of GB self-guidance on a moving ground target for a sliding plane defined according to equation (18) and (19) are shown in Figures 23 – 26.

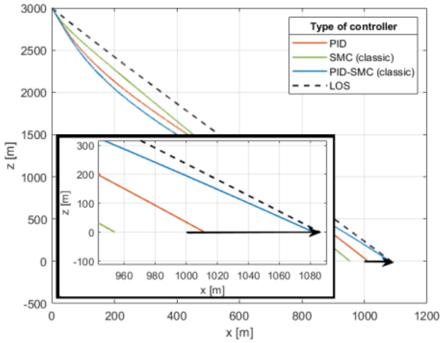

Fig. 15. Bomb flight tracks to a moving target with classical sliding control

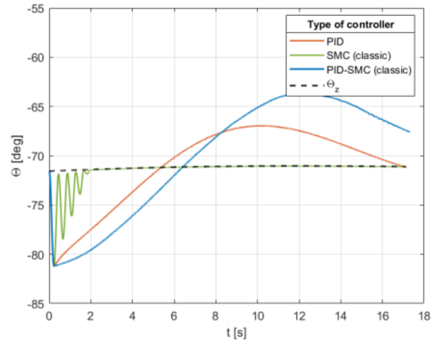

Fig. 16. Angles of bomb inclination as a function of time with classical sliding control

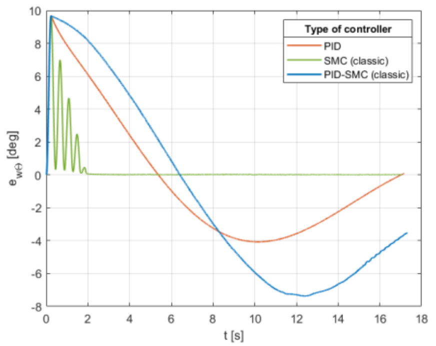

Fig. 17. Angle deviations of bomb flight as a function of time with classical sliding control

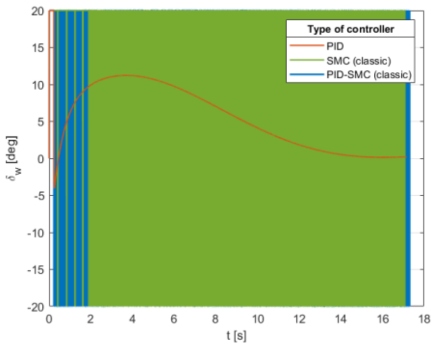

Fig. 18. Deflection angle of the height rudder as a function of time with classical sliding control

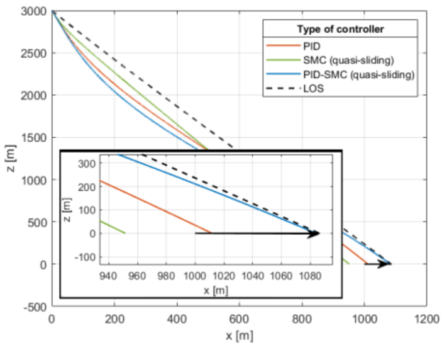

Fig. 19. Bomb flight tracks to a moving target with quasi-sliding control

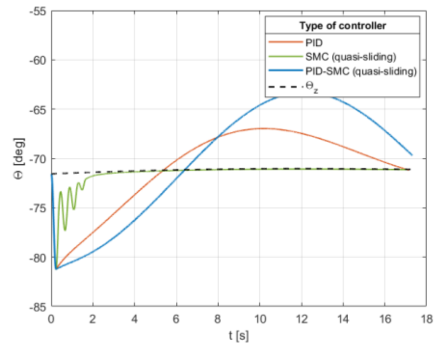

Fig. 20. Angles of bomb inclination as a function of time with quasi-sliding control

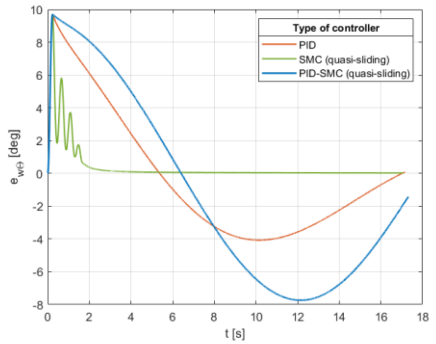

Fig. 21. Angle deviations of bomb flight as a function of time with quasi-sliding control

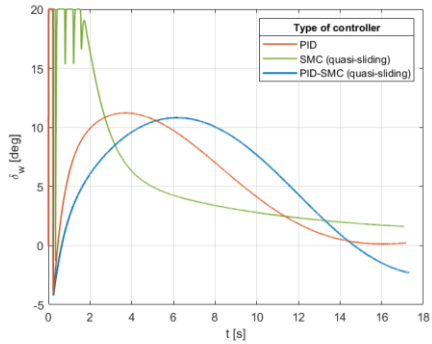

Fig. 22. Deflection angle of the height rudder as a function of time with quasi-sliding control

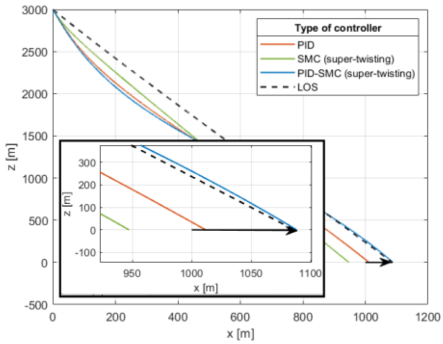

Fig. 23. Bomb flight tracks to a moving target with super-twisting sliding control

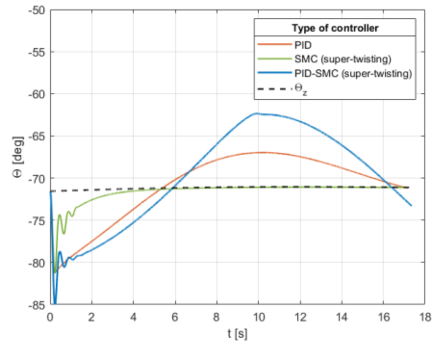

Fig. 24. Angles of bomb inclination as a function of time with super-twisting sliding control

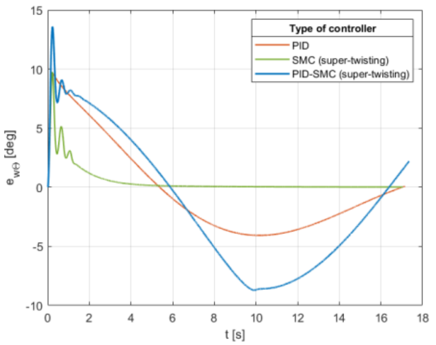

Fig. 25. Angle deviations of bomb flight as a function of time with super-twisting sliding control

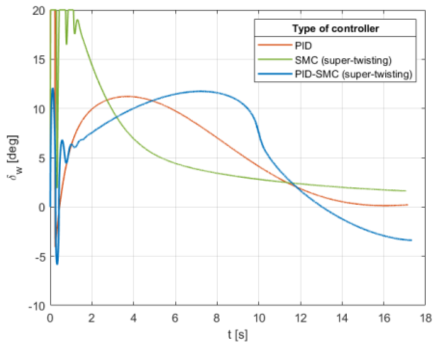

Fig. 26. Deflection angle of the height rudder as a function of time with super-twisting sliding control

Table 3 summarises the gain coefficients for all controller types tested for the moving target. In addition, Table 2 summarizes the three GB self-guidance parameters: guidance time, accuracy of hitting the ground target and quality indicator. The values of the obtained parameters are listed in Table 4.

Table 3. Summary of PID controller gain coefficients for a moving target

<table>
<tr><th>PID</th><th>SMC (classic)</th><th>PID - SMC (classic)</th></tr>
<tr><td rowspan="5">$k_{\mathrm{p}\Theta} = 1.4$
$k_{\mathrm{i}\Theta} = 0.8$
$k_{\mathrm{d}\Theta} = 5.9$</td><td>$c_{\Theta} = 38.5$</td><td>$k_{\mathrm{p}\Theta} = 0.012$, $k_{\mathrm{i}\Theta} = 0.069$
$k_{\mathrm{d}\Theta} = 0.76$</td></tr>
<tr><th>SMC (quasi-sliding)</th><th>PID - SMC (quasi-sliding)</th></tr>
<tr><td>$c_{\Theta} = 12.36$
$k_{\varepsilon\Theta} = 0.06$</td><td>$k_{\mathrm{p}\Theta} = 0.035$, $k_{\mathrm{i}\Theta} = 0.13$
$k_{\mathrm{d}\Theta} = 1.15$, $k_{\varepsilon\Theta} = 0.065$</td></tr>
<tr><th>SMC (super-twisting)</th><th>PID - SMC (super-twisting)</th></tr>
<tr><td>$c_{\Theta} = 9.54$
$k_{\mathrm{c}\Theta} = 0.5908$
$k_{\mathrm{b}\Theta} = 0.0001$</td><td>$k_{\mathrm{p}\Theta} = 0.105$, $k_{\mathrm{i}\Theta} = 0.13$
$k_{\mathrm{d}\Theta} = 0.068$,
$k_{\mathrm{c}\Theta} = 0.5908$; $k_{\mathrm{b}\Theta} = 0.015$</td></tr>
</table>

Table 4. Summary of self-guidance parameters for a bomb directed at a moving target

Type of controller	**Hit accuracy [m]**	**Guidance time [s]**	**Quality indicator I_{IAE}**
PID	74.57	17.17	0.9525
SMC (classic)	132.51	17.07	0.1149
SMC (quasi-sliding)	134.71	17.08	0.1129
SMC (super-twisting)	139.71	17.06	0.1436
PID - SMC (classic)	4.26	17.31	1.654
PID - SMC (quasi-sliding)	2.46	17.32	1.63
PID - SMC (super-twisting)	1.68	17.36	1.564

5. CONCLUSIONS

Theoretical considerations and simulation studies have made it possible to assess the performance of the guided bomb control algorithms proposed in this work. Of the three types of considered algorithms, the most effective is the hybrid algorithm, which is a combination of PID controller with SMC (quasi-sliding for a stationary target and super-twisting for a moving target). The main criterion was the minimum distance of the bomb from the target at the final moment, i.e., the accuracy of the hit. It should be noted that both the PID and the SMC controllers, separately used, have proved to be far from sufficient to hit a stationary ground target with sufficient accuracy (in both cases, the miss was about 70 m for a stationary target and over 130 m for a moving target). The accuracy of the hit improved significantly with the simultaneous use of both controllers with optimally selected parameters due to the quality criterion I_{IAE}. Further studies should examine the resistance of the proposed hybrid control algorithm under the conditions of both kinematic disturbances resulting from GB manoeuvres and external random disturbances due to atmospheric turbulence, including wind turbulence.

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Analiza hybrydowego systemu sterowania bombą kierowaną przy samonaprowadzaniu na cel naziemny

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Streszczenie. W artykule przedstawiony jest model matematyczny oraz algorytm sterowania bombą kierowaną na ruchomy oraz nieruchomy cel naziemny. Tor zadany wyznaczono ze związków kinematycznych ruchu wzajemnego bomby i celu naziemnego z wykorzystaniem metody proporcjonalnego zbliżania. Analizowany system sterowania opiera się o sterowanie ślizgowe z algorytmem PID do określenia płaszczyzny ślizgu. Rozpatrzone zostały trzy rodzaje płaszczyzn ślizgu. Dodatkowo dokonano analizy porównawczej dla trzech typów regulatorów: klasycznego PID, ślizgowego oraz hybrydowego. Przytoczone zostały wybrane wyniki symulacji komputerowej.

Słowa kluczowe: naprowadzanie, bomba kierowana, hybrydowy system sterowania, sterowanie ślizgowe, proporcjonalna nawigacja