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A Hybrid Guidance Law for a Strapdown Seeker to Maintain Lock-on Conditions against High Speed Targets

Chae Heun Lee*, Chul Hyun†, Jang Gyu Lee,
Jin Yung Choi** and Sangkyung Sung*****

Abstract – This paper proposes a new guidance law, which considers the Field of View (FOV) of the seeker when a missile has a strapdown seeker mounted instead of a gimbal seeker. When a strapdown seeker, which has a narrow FOV, is used for tracking a target, the FOV of the seeker is an important consideration for guidance performance metrics such as miss distance. We propose a new guidance law called hybrid guidance (HG) to address the shortcomings of conventional guidance laws such as proportional navigation guidance (PNG), which cannot maintain lock-on conditions against high speed targets due to the narrow FOV of the strapdown seeker. The aim of the HG law is to null miss distance and to maintain the look angle within the FOV of the strapdown seeker. In order to achieve this goal, we combine two guidance laws in the HG law. One is a PNG law to null the LOS rate, and the other is a sliding mode guidance (SMG) law derived to keep the look angle within the FOV by employing a Lyapunov-like function with a sliding mode control methodology. We also propose a method to switch these two guidance laws at certain look angles for better guidance performance.

Keywords: Field of view, Sliding mode control, Strapdown seeker, Switching boundary

1. Introduction

In recent years, numerous studies have attempted to replace the gimbaled seeker with a strapdown seeker for homing missiles. The gimbaled seeker is installed on a platform which is stabilized by the gimbal system. The gimbaled seeker has a stabilization loop to isolate body rotation, and a track loop to maintain the seeker axis along the missile-target LOS (Line-Of-Sight). On the other hand, the strapdown seeker is rigidly mounted on the missile body. The strapdown seeker has an advantage in that it can be more simply and economically implemented with sensor electronics in comparison to a gimbaled seeker. But the strapdown seeker has a relatively narrow FOV (Field-Of-View) compared to the gimbaled seeker [1, 2]. This weak point of the strapdown seeker leads to target misses air-to-air engagements. In view of this problem, our research in this paper focuses to derive a guidance law so that missiles with narrow FOV strapdown seekers maintain lock-on conditions until intercepting the target.

Most modern homing missiles make use of PNG (Proportional Navigation Guidance) law based on LOS rate [3-7]. The PNG law seeks to null the LOS rate by making the missile flight angle rate be directly proportional to the LOS rate. The PNG law can be easily implemented with the LOS rate. The simplicity of the PNG law has been widely recognized [8, 9]. But targets can frequently move out of the seeker FOV when a missile with a strapdown seeker is guided by the PNG law against high speed targets. This leads the missile to lose the lock-on condition, which results in the failure of intercepting the target.

Xin, balakrishnan and Ohlmeyer [10] used the seeker FOV as a constraint of the nonlinear optimal control problem to create a missile guidance law. Daekyu Sang [11] proposed a guidance law switching logic between an original law such as PNG and a guidance law which makes the look angle constant during the homing phase at a predefined FOV limit. The above two instances are limited to a target that stands still. Meanwhile, to overcome the limitation of FOV for a high speed target, this paper proposes a hybrid guidance (HG) law. To maintain lock-on conditions, this law combines two guidance laws. One is a conventional PNG law to null the LOS rate, the other is a Sliding Mode Guidance (SMG) law derived in this paper to decrease the look angle of the strapdown seeker. Because the PNG has robustness for model parameters and good homing guidance performance compared with the proposed SMG, the PNG is mainly used in HG. And the SMG contributes only to decrease the look angle. The PNG law is used when the look angle is under a certain angle that is used as a switching boundary, and represents an alert for the possibility that the look angle may become larger than the FOV limit. The SMG law is used over the switching

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† Corresponding Author: M&S R&D Lab, LIG Nex1(chul.hyun@lignex1.com)

* Department of Electrical and Computer Engineering Seoul National University/ASRI (dlcogms1@snu.ac.kr)

** Department of Electrical and Computer Engineering Seoul National University ({jgl, jychoi} @snu.ac.kr)

*** Department of Aerospace Information Engineering, Konkuk University (sksung@konkuk.ac.kr)

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boundary. The switching boundaries are derived by considering guidance system characteristics such as time constant, the missile velocity and the look angle rate. This method increases the confidence in intercept success because the missile maintains the lock-on conditions on a nearby target.

This paper is organized as follows. Section 2 clarifies the characteristics of the strapdown seeker and deals with equations related to the engagement geometry of the missile and target. Section 3 presents the derivation of the proposed guidance law and the switching boundary. Section 4 gives the simulated evidence in support of the performance. In the final section, we will conclude by summarizing this paper.

2. Strapdown Seeker Characteristics and Pursuit Kinematics and Dynamics

2.1 Strapdown seeker characteristic

A general seeker angular configuration is depicted in Fig. 1. In gimbaled seeker, the antenna centerline and missile centerline move independently from each other by a seeker stabilization loop. That is, a seeker head angle $\theta_h(t)$ can be varied with time. In the strapdown seeker, on the other hand, the antenna centerline and missile centerline are fixed because the strapdown seeker is rigidly mounted on the missile body. Therefore their measurements are relative to the body frame of the missile. In this paper, we assume the following for simplicity of analysis:

A1) The antenna centerline is aligned with the missile centerline ($\theta_h = 0$).
A2) The seeker dynamics are fast enough to be neglected.

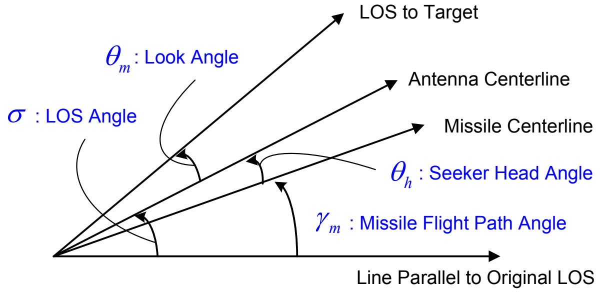


Fig. 1. Seeker angular configuration

2.2 Pursuit kinematics and dynamics

The general three-dimensional guidance can be dealt with by resolving the LOS rate vector into two lateral planes of the missile by neglecting cross-coupling between the two orthogonal components such as pitch and yaw plane. We consider only two-dimensional planar guidance in this paper. To facilitate the performance analysis of the proposed guidance law, we assume the following.

A3) The missile and the target are considered as geometric points moving in the pitch plane.
A4) The missile angle-of-attack is ignored.
A5) The missile velocity V_m and target velocity V_t are constant.
A6) The autopilot and airframe have first order dynamics.

Under the above assumptions, the engagement geometry of the missile and the target is depicted in Fig. 2.

The target moves with the velocity V_t and the normal acceleration a_t. The missile chases the target with the velocity V_m and the normal acceleration a_m. The normal acceleration a_m is obtained by an acceleration command a_{mc} through first order dynamics with time constant τ. The strapdown seeker measures the look angle θ_m, which depends on the attitude of the missile and the LOS angle σ. The LOS angle σ, which is used in PNG law, is obtained by combining the look angle and the attitude of the missile. From A3), A5), the missile flight path angle γ_m replaces the attitude of the missile.

Based on the above engagement geometry, the kinematics and the dynamics are obtained as follows:

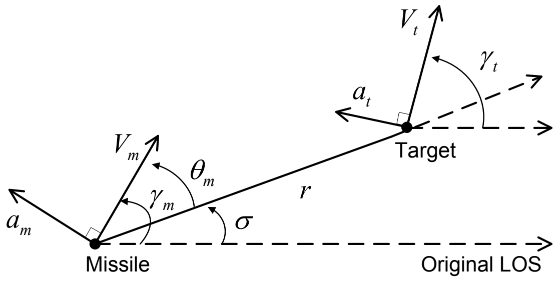


Fig. 2. Engagement geometry

$$\dot{\gamma}_t = \frac{a_t}{V_t} \tag{1}$$

$$\dot{\gamma}_m = \frac{a_m}{V_m} \tag{2}$$

$$\dot{r} = V_t \cos\theta_t - V_m \cos\theta_m \tag{3}$$

$$r\dot{\sigma} = V_t \sin\theta_t - V_m \sin\theta_m \tag{4}$$

where θ_t, θ_m and a_{mc} are defined by:

$$\theta_t = \gamma_t - \sigma \tag{5}$$

$$\theta_m = \gamma_m - \sigma \tag{6}$$

$$a_m = \frac{1}{\tau s + 1} a_{mc} \tag{7}$$

where τ and γ_t are a time constant and a target flight angle, respectively.

3. Hybrid Guidance Law Logic Design

3.1 Hybrid guidance law scheme

The PNG law is the most widely used in guidance because it is easily implemented and has good homing guidance performance. But it can frequently occur that the missile fails to chase high speed targets when a strapdown seeker is used. Alternatively, this paper proposes the HG law, which combines two guidance laws: the PNG law and the SMG law. The two guidance laws are switched between each other at a certain value of the look angle θ_m called the switching boundary, $\theta_{m,boundary}$. In the first phase, where the look angle is within the switching boundary, the PNG law controls the missile. In the second phase, when the look angle is over the switching boundary, the SMG law is adopted to keep the look angle within the FOV. If a guidance system is ideal, there exists a chattering problem when two guidance laws are switched for one switching boundary. But the continuity of the delayed acceleration through the autopilot removes the chattering phenomenon.

As can be seen in Fig. 3, while the missile is guided by the PNG law in the first phase, a maximum look angle is predicted on-line under the adoption of the SMG law based on the current look angle. When the predictive maximum look angle is equal to the FOV, the second phase is started and the current look angle is regarded as the switching boundary. In the second phase, the SMG law controls the missile while the look angle is larger than the switching boundary. When the look angle is less than the switching boundary, the first phase is adopted again. This logic is iterated until the missile intercepts the target.

3.2 Proportional Navigation Guidance

Recently, proportional navigation guidance (PNG) law has been widely used for tactical applications. The PNG law can be derived to null the LOS rate. Among various PNG laws, we use the pure PNG (PPNG) law, which generates the acceleration command perpendicular to the velocity vector of the missile:

$$a_{mc} = N_1 V_m \dot{\sigma} \tag{8}$$

where N_1 is a unitless designer-chosen gain that is usually in the rage of $3 \sim 5$. In this paper, we use N_1 of 3.

3.3 Sliding mode guidance law

The sliding mode control methodology is used in the second phase guidance law derivation [12, 13]. In order to apply the sliding mode control, we set a switching surface. The guidance goal in this phase is to reduce the look angle against the high speed target. Hence, the switching surface should be chosen such that:

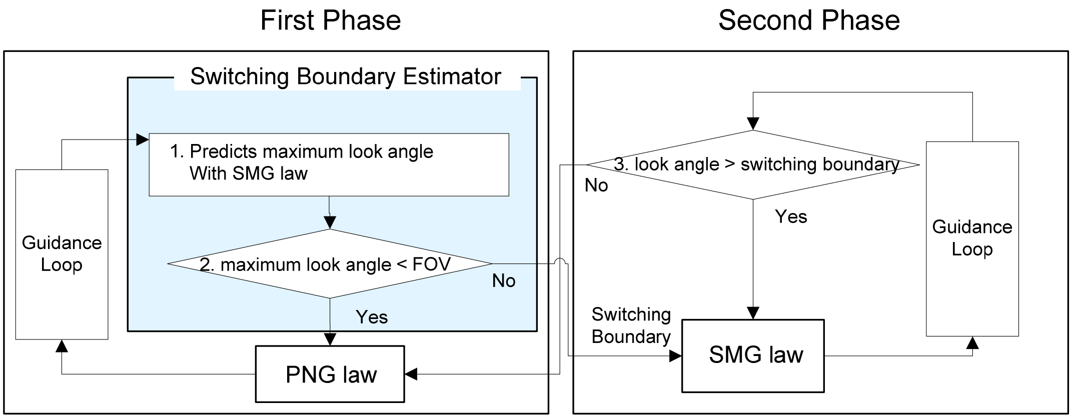
$$s(t) = \theta_m(t) \tag{9}$$

The basic idea for the selection of the above switching surface is to decrease the look angle. The next step is to design a control law that satisfies the sliding condition. To achieve this, we consider the time derivative of a Lyapunov function $V = s^2(t)/2$.

$$\begin{aligned}\dot{V} &= s(t)\dot{s}(t)\\ &= \theta_m(t)\dot{\theta}_m(t)\\ &= \theta_m(t)\big(\dot{\gamma}_m(t) - \dot{\sigma}(t)\big)\\ &= \theta_m(t)\left(\frac{a_m(t)}{V_m} - \dot{\sigma}(t)\right).\end{aligned} \tag{10}$$

It is regarded that a delay between the normal acceleration a_m and the acceleration command a_{mc} is neglected herein. That is,

$$a_m = a_{mc} \tag{11}$$


First Phase

Second Phase

Fig. 3. Hybrid guidance law scheme

The control a_{mc} that will ensure that the above equation is less than zero is:

$$a_{mc}(t) = V_m \dot{\sigma}(t) - N_2 \operatorname{sgn}(\theta_m) \tag{12}$$

where $N_2 > 0$ is constant, and $\operatorname{sgn}(\theta_m)$ is a sign function as follows:

$$\operatorname{sgn}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \tag{13}$$

The first term of the SMG law of (12) is an acceleration value to keep the look angle steady. The second term influences the degree to lead the look angle to zero.

3.4 Switching boundary estimation

If the missile is guided by only the SMG law, it is steered so that the velocity vector of the missile points at the target at every instant in time. Then, the closer the missile approaches the target, the more it needs the normal acceleration command to turn towards the target. Finally, the normal acceleration command exceeds the missile hardware limit and the missile fails to intercept the high speed target. On the other hand, because the PNG law orients the missile to an estimated interception point, it does not have this problem. The PNG law has better intercept performance against the high speed target than the SMG law. Therefore it is important that we decide the switching boundary $\theta_{m,boundary}$ to use the PNG law as much as possible during the overall homing phase.

Meanwhile, because there are some delays between a_m and a_{mc} in an actual situation, the look angle is increased gradually during a certain time although the SMG law is adopted. The pattern of the look angle in the second phase is influenced by the characteristics of guidance system, such as system delay, and the engagement, such as missile velocity and look angle rate and so on. In order to keep the pattern of the look angle in second phase as similar as possible in various engagements, the gain N_2 of the SMG law is determined by considering the time constant of the guidance system, the look angle rate and the missile velocity. To consider these factors, let us choose the gain N_2 feasibly such that:

$$N_2 = \rho \tau V_m \dot{\theta}_m(t_b) \tag{14}$$

where τ, V_m, $\rho > 0$ and t_b are the time constant, the missile velocity, a proportional gain and the time to switch from the first phase to the second phase, respectively. $\dot{\theta}_m(t_b)$ is the look angle rate at the time t_b.

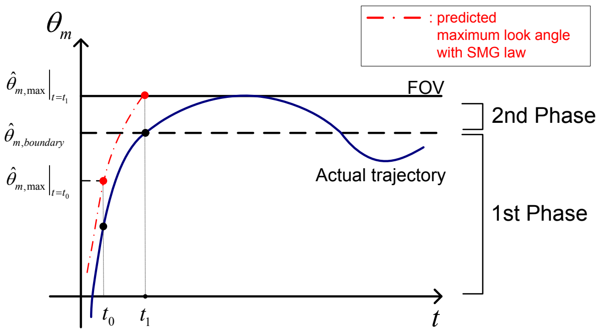


Fig. 4. Estimation of switching boundary

As shown in Fig. 4, we assume that the guidance law is changed from the first phase to the second phase at certain time t_0. The red dash-dot line represents the predicted maximum look angle with SMG law. The look angle reaches its peak at the time $t_0 + \hat{T}_0$, the maximum value of the look angle $\hat{\theta}_{m,\max}\big|_{t=t_0}$ and $\hat{T}_0$ can be predicted by using parameters of the time t_0. To predict these values, we assume as follows:

$$\hat{\dot{\sigma}}(t) = \dot{\sigma}(t_0), \quad t \in [t_0, t_0 + \hat{T}_0] \tag{15}$$

Then the predicted acceleration command is:

$$\begin{aligned} \hat{a}_{mc}(t) &= V_m \hat{\dot{\sigma}}(t) - \rho \tau V_m \dot{\theta}_m(t_0) \\ &= V_m \hat{\dot{\sigma}}(t_0) - \rho \tau V_m \dot{\theta}_m(t_0), \quad t \in [t_0, t_0 + \hat{T}_0] \\ &= \hat{a}_{mc}(const). \end{aligned} \tag{16}$$

If the predicted acceleration command is a constant, the estimate of the normal acceleration is related to the predicted acceleration command.

$$\hat{a}_m(t) = e^{-(t-t_0)/\tau} a_m(t_0) + \left(1 - e^{-(t-t_0)/\tau}\right) \hat{a}_{mc} \tag{17}$$

Differentiating (6) and using (2), (9) and (14), we can derive the following equation for the estimation of the look angle rate.

$$\begin{aligned} \hat{\dot{\theta}}_m(t) &= \hat{\dot{\gamma}}(t) - \hat{\dot{\sigma}}(t) \\ &= \frac{\hat{a}_m(t)}{V_m} - \dot{\sigma}(t_0) \\ &= \frac{1}{V_m} \left\{ e^{-(t-t_0)/\tau} a_m(t_0) + \left(1 - e^{-(t-t_0)/\tau}\right) \hat{a}_{mc}(t) \right\} - \dot{\sigma}(t_0) \\ &= \frac{1}{V_m} \{ e^{-(t-t_0)/\tau} a_m(t_0) + \left(1 - e^{-(t-t_0)/\tau}\right) \\ &\qquad \times \left(V_m \hat{\dot{\sigma}}(t_0) - \rho \tau V_m \dot{\theta}_m(t_0) \right) \} - \dot{\sigma}(t_0) \\ &= e^{-(t-t_0)/\tau} \left(\frac{a_m(t_0)}{V_m} - \dot{\sigma}(t_0) \right) - \left(1 - e^{-(t-t_0)/\tau}\right) \rho \tau \dot{\theta}_m(t_0) \end{aligned}$$

$$\begin{aligned} &= e^{-(t-t_0)/\tau}\dot{\theta}_m(t_0) - \left(1-e^{-(t-t_0)/\tau}\right)\rho\tau\dot{\theta}_m(t_0) \\ &= \left\{e^{-(t-t_0)/\tau}\left(1+\rho\tau\right)-\rho\tau\right\}\dot{\theta}_m(t_0). \end{aligned} \tag{18}$$

In Fig. 4, when the estimated look angle rate is zero, the estimated look angle reaches its peak.

$$\hat{\dot{\theta}}_m(t_0+\hat{T}_0) = \left\{e^{-\hat{T}_0/\tau}\left(1+\rho\tau\right)-\rho\tau\right\}\dot{\theta}_m(t_0) = 0 \tag{19}$$

Thus, $\hat{T}_0$ satisfying (17) is the estimated time that elapses from the start time of the second phase up to the time when the estimated look angle is maximum.

$$\hat{T}_0 = -\tau\ln\left(\frac{\rho\tau}{1+\rho\tau}\right) \tag{20}$$

Therefore the varied quantity of the estimated look angle during t_0 and $t_0+\hat{T}_0$ is:

$$\begin{aligned} \int_{t_0}^{t_0+T}\hat{\dot{\theta}}_m(t)dt &= \int_{t_0}^{t_0+T}\left\{e^{-(t-t_0)/\tau}\left(1+\rho\tau\right)-\rho\tau\right\}\dot{\theta}_m(t_0)dt \\ &= \left\{\tau\left(1+\rho\tau\right)\left(1-e^{-T/\tau}\right)-\rho\tau T\right\}\dot{\theta}_m(t_0). \end{aligned} \tag{21}$$

The maximum look angle which is estimated at the time t_0 is obtained by:

$$\begin{aligned} \left.\hat{\theta}_{m,\max}\right|_{t=t_0} &= \theta_m(t_0) + \int_{t_0}^{t_0+\hat{T}_0}\hat{\dot{\theta}}_m(t)dt \\ &= \theta_m(t_0) + \left\{\tau\left(1+\rho\tau\right)\left(1-e^{-\hat{T}_0/\tau}\right)-\rho\tau\hat{T}_0\right\}\dot{\theta}_m(t_0). \end{aligned} \tag{22}$$

As depicted in Fig.4, $\left.\hat{\theta}_{m,\max}\right|_{t=t_0}$ is smaller than the FOV of the strapdown seeker. Thus the missile chases the target using the first guidance law. We iterate this process until the updated maximum of the estimated look angle equals the FOV of the strapdown seeker. t_1 is the time satisfying:

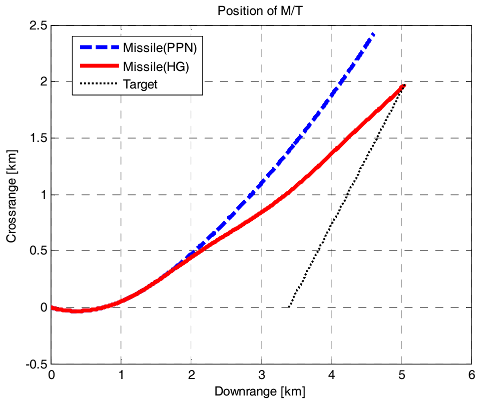
$$\left.\hat{\theta}_{m,\max}\right|_{t=t_1} = FOV \tag{23}$$

where FOV is the FOV of the strapdown seeker. $\theta_m(t_1)$ is determined as the switching boundary. And the missile is guided by the second guidance law from this time t_1 until $\theta_m(t)$ is smaller than the switching boundary.

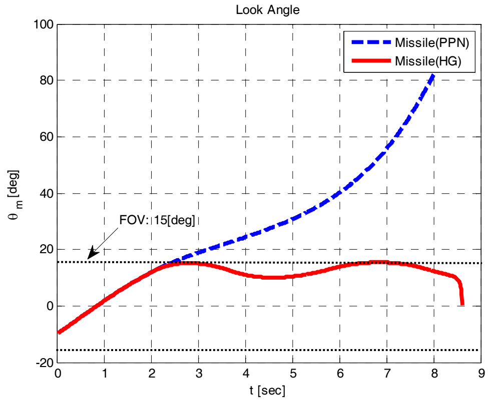
There are some errors between the peaks of actual and estimated look angle, because the estimated LOS angle rate has some errors. The problem occurs when the actual look angle exceeds the FOV of the strapdown seeker. Then the seeker lock-on condition is broken. The missile keeps the acceleration command at the time when it misses the target. The errors between the two peaks of actual and estimated look angle are small and the acceleration command is large enough to decrease the look angle. Thus, even if this situation occurs, the actual look angle eventually enters the FOV of the strapdown seeker quickly.

3. Simulation

In this simulation, the guidance loop is regarded as a first-order system which has a time constant of 1s. The arget initially flies 3.4 km away from the missile. The initial target flight angle, the initial missile flight path angle and the initial LOS angle are 50deg, -10deg and 0deg, respectively. Also, the velocity of the missile and target are 640m/s and 300m/s, respectively. The FOV of the strapdown seeker is 30deg (-15~+15). The simulation results are presented in Fig. 5. For the purpose of comparison, the conventional PNG law is employed in this simulation. The conventional PNG law is a Pure PNG (PPNG) law, as in [14]. In Fig. 5, the dashed line and the solid line represent the trajectories of the missile by the PPNG law and the proposed guidance law, respectively. The dotted line indicates the high speed target trajectory. The missile guided by the PPNG law goes beyond the FOV



(a) Trajectory of missile and target



(b) Look angle of missile by PPN and HG law

Fig. 5. Simulation Results

of the strapdown seeker after 1.4s and fails to intercept the target. On the other hand, the missile guided by the proposed HG law maintains the seeker lock-on condition until it is near the target. Comparing the two guidance laws, the PPNG law and the HG law have miss distances of about 640m and 1.3m, respectively.

The various engagements are tabulated in Table 1. The other conditions are fixed as above. The miss distances for several cases of engagements are tabulated in Table 2.

In case of the HG law, because the relative range in which a missile needs an acceleration command exceeding its hardware limit is greater as the target flight angle grows larger, the miss distances are longer, as in Table 2. In case of the PNG law, reversely, the miss distances are shorter as the target flight angle grows larger. These results show that the path of the missile which misses the target and the path of the target are close by chance. But these results also demonstrate that the proposed guidance law increases the success probability to intercept the target in various engagements.

Table 1. Various engagements

	a	b	c	d	e	f
Initial Target Flight Angle γ_t [deg]	45	45	90	90	120	120
Initial Missile Flight Angle γ_m [deg]	10	-10	10	-10	10	-10

Table 2. Miss distance for various engagements

	PPN [m]	Proposed GL [m]
a	503.9331	0.88676
b	462.6664	2.3375
c	517.7981	10.7823
d	647.7636	17.0274
e	108.5484	43.2230
f	188.7315	59.3149

4. Conclusion

We have proposed a guidance law suitable for a strapdown seeker with narrow FOV against a high speed target. In this paper, we used the PNG law to null the LOS rate to the target mixed with a second guidance law to lessen the look angle. We used the sliding mode control methodology to derive the second guidance law. In addition, to improve the guidance performance, we determined the switching boundary of the first and second guidance laws in real time. In addition, we obtained the improvement that the strapdown seeker has a bit wider FOV as a result of this modified guidance law. The proposed guidance law excellently accomplishes interception of the target when the conventional PNG law fails to intercept the target because of the narrow seeker FOV.

Acknowledgements

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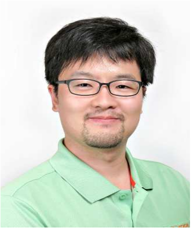
Chae Heun Lee received B.S degree from Seoul National University. He is currently a candidate for the Ph.D. degree in the Department of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea. His main research field is inertial navigation system and guidance.



Chul Hyun received the B.S. and Ph. D. degrees in the School of Electrical Engineering & Computer Science at Seoul National University, Seoul, Korea, in 2001 and 2011, respectively. From 2011, he is Research Engineer in LIG Nex1. His research interests include inertial sensor, control of AUV, and guidance.

Jang Gyu Lee is a Professor in the School of Electrical Engineering & Computer Science at Seoul National University. He received his Ph. D. degree in Electrical Engineering from University of Pittsburgh, USA in 1977. He was the Director of Automation and System Research Institute, Seoul National University, 1996-1998. He worked at the Analytic Sciences Corp. (TASC) & Charles Stark Draper Lab., Technical Staff, 1977-1982. He is currently in charge of the Editorial Advisory Board Member, International Journal of Space Technology and the Associate Editor, International Journal of Parallel and Distributed Systems and Networks. He charged the General Chairman, Editor, 14th IFAC Symposium on Automatic Control in Aerospace, 98.8.24-28. His current research topics include INS, GPS, eLoran, Guidance, Estimation

Jin Young Choi received the B.S., M.S., and Ph.D. degrees in control and instrumentation engineering from Seoul Nation University, Seoul, Korea, in 1982, 1984, and 1993, respectively. From 1984 to 1989, he was with the Electronics and Telecommunication Research Institute (ETRI). From 1992 to 1994, he was with the Basic Research Department of ETRI, where he was a Senior Member of the Technical Staff working on the neural information system. Since 1994, he has been with Seoul National University, where he is currently a Professor in the School of Electrical Engineering and Computer Science, Seoul National University. His research interests include pattern classification, neural computing and control, evolutionary computing, adaptive and learning control, and their applications.

Sankyung Sung received the Ph.D. degrees in Electrical Engineering from Seoul National University, Korea, in 2003. From 2003 to 2007, he was with the TN Research Center in Samsung Electronics Inc. Currently, he is an Associate Professor in the Department of Aerospace Information Engineering, Konkuk University. His research interests include inertial sensors, integrated navigation and system, and autonomous unmanned systems.