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A Scanning Design Method Suitable for Short-Range Imaging Seekers

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Abstract

Focusing on the problem of improving target capturing probability of the short-range imaging seeker, an effective scanning design method is presented in this paper. The imaging covering width suitable for the field of view (FOV) of the imaging seeker, together with the scanning velocity design is discussed in detail. And the residence time of the targets corresponding to different target positions are solved by using a numerical method. Comparisons are made to test three different scanning strategies. Simulation results have verified the effectiveness of the proposed method.

1 Introduction

Due to the better recognition power of interested regions, imaging seekers have attracted increasing interest [1, 2]. Accurate capturing of the target is of crucial importance to the seeker. Therefore, we would like to guarantee the capturing probability of the target to be 1 (or to be 1 as close as possible). In other words, the target needs to lie in the imaging scope of the seeker when the seeker to target distance is within the effective working range.

However, various errors are inevitable during the flight of the seeker. Non-ideal factors such as measuring errors and control precision exist during the initial flight and midcourse guidance flight, which result in the deviation from the ideal flight trajectory. The trajectory deviation will impose negative influences on the target capturing of the imaging seeker. How to design the appropriate scanning method to improve target capturing probability is the precondition of accurate target recognition and precise attack. And the key point of target capturing is to guarantee the target to lie in the field of view (FOV) of the imaging seeker for enough time. Focusing on the problem, an effective scanning design method is presented in this paper, in which the residence time of the targets for the imaging seeker is calculated in a numerical way.

2 Target Capturing of the Imaging Seeker

Imaging seekers will deliver the ground scene to the monitor screen, on which the shooter needs to recognize the interested target. When the target is determined, tracking instructions will be delivered to the seeker to lock the target. That is to say, the interested target needs to lie in the FOV of the imaging seeker to guarantee target capturing. Besides, the residence time needs to be large enough for the shooter to recognize the target.

The FOV of the seeker and the recognition range of the imaging seeker directly affect the capturing probability of the seeker. Generally, we would like to have a large enough recognition range of the imaging seeker, together with a large enough FOV to guarantee target capturing as early as possible. However, the recognition range of the seeker and the FOV are contradiction elements. Smaller FOV corresponds to further recognition range of the seeker, and larger FOV will result in closer recognition range of the seeker. To balance these two factors, one needs to design appropriate scanning methods to improve coverage scope to achieve a large recognition range, which is more important to required time of target recognition and terminal guidance. Better coverage scope leads to higher capturing probability of the target.

3 Scanning Design of the Imaging Seeker

3.1 Sketch of the Scanning Design of the Seeker

In order to guarantee the interested target to lie in the FOV of the imaging seeker, we need to guide the seeker to point to the interested area by the missile-borne computer first [3, 4]. The intrinsic idea is to adopt the "staring at the target" way (we short it for "staring at" in the following), i.e., we force the optic axis of the seeker to point to the interested target all the time during the flight, as shown in Figure 1.

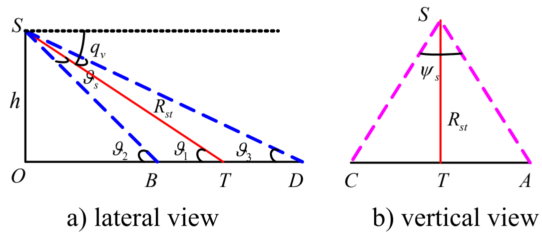

Figure 1. Illustration of the geometry projection of the imaging seeker.

where S represents the seeker, h is the flying height of the seeker, T is the interested target, R_{st} stands for the distance between the seeker and the target, ϑ_s and ψ_s represent the FOV angles in the pitching and yawing direction, respectively, and ST represents the seeker to target line. The angle q_v formed by the optic axis of the seeker and the horizontal line can be expressed as

$$q_v = \arcsin\left(h / R_{st}\right) \tag{1}$$

The depth of the instantaneous FOV of the imaging seeker can be given by

$$\left|BD\right| = \frac{h}{\tan(q_v - \vartheta_s / 2)} - \frac{h}{\tan(q_v + \vartheta_s / 2)} \tag{2}$$

And the width of the instantaneous FOV of the seeker can be given by

$$\left|AC\right| = 2 \times R_{st} \times \tan(\psi_s / 2) \tag{3}$$

In ideal conditions, the interested target should lie in the center of the FOV of the imaging seeker if the “staring at” way is adopted. However, as previously discussed, due to the existence of various non-ideal factors, dispersion of the trajectory is inevitable, which will lead to the deviation of the target pointing. To overcome the problem, scanning design is employed to enlarge the FOV scope. In this paper, the flat shaped scanning method is employed. Besides the “staring at” way, we also conduct the constant angular velocity scanning method and the constant linear velocity scanning method.

3.2 Scanning Covering Width

Supposing that, the event of the target capturing (or more precisely, target that lies in the scope of imaging seeker when it starts to work) of the imaging seeker X obeys a normal distribution $X \sim N(\mu, \sigma^2)$, the target capturing probability can be expressed as [5]

$$\begin{aligned} P_X &= P\left\{\mu - k\sigma \le X \le \mu + k\sigma\right\} \\ &= \varphi\left(k\right) - \varphi\left(-k\right) = 2\varphi\left(k\right) - 1 \end{aligned} \tag{4}$$

where μ is the mean, σ^2 is the variance, k is the multiple, and $\varphi\left(\bullet\right)$ is the normal distribution function. Assuming that, the overall dispersions after midcourse guidance flight are Δ_{pitch} and Δ_{yaw} in the pitching and yawing directions. The target capturing probability of the seeker along the pitching and yawing directions can be given by

$$P_{pitch} = 2\varphi\left(W_{pitch} / \Delta_{pitch}\right) - 1 \quad P_{yaw} = 2\varphi\left(W_{yaw} / \Delta_{yaw}\right) - 1 \tag{5}$$

where P_{pitch} and P_{yaw} represents the target capturing probabilities in the pitching and yawing direction, respectively. W_{pitch} is covering width corresponding to the half of the FOV scope in the pitching direction, and W_{yaw} is the corresponding width in the yawing direction.

$$W_{pitch} = R_s \times \tan\left(\vartheta_s / 2\right) \quad W_{yaw} = R_s \times \tan\left(\psi_s / 2\right) \tag{6}$$

where R_s is the effective recognition range of the imaging seeker. The target capturing probability of the imaging seeker can be given by

$$P_i = P_{pitch} \times P_{yaw} \tag{7}$$

From (5), we can see that enlarging the covering scope of the imaging seeker or reducing the dispersion contributes to improving target capturing probability. However, the dispersion is restricted by various system errors, which is hard to reduce. Fortunately, seeker scanning can enlarge the covering scope effectively.

Taking an imaging seeker as an example, target capturing probability is generally required to be more than 99% to guarantee precise attack. The associated parameters are $\Delta_{pitch} = 45\text{m}$, $\Delta_{yaw} = 88\text{m}$, ϑ_s=5°, and ψ_s=7°. The seeker’s effective working range is $R_s = 3000\text{m}$. In this case, according to (5) and (6), we have $W_{pitch} = 131\text{m}$, P_{pitch}=99.64% [5]. Based on (7), we can get the required target capturing probability $P_{yaw} = P_i / P_{pitch} = 0.9936$, and according to (5), we have $\varphi(W_{yaw} / \Delta_{yaw}) = (P_i / P_{pitch} + 1)/2 = 0.9968$. Hereto, we can get the desired W_{yaw} to be 240m based on the probability theory [5]. In other words, the scanning scope needs to touch the lateral dispersion of ±240m to guarantee target capturing.

According to plenty of application practice, the interested target needs to lie in the scope of the seeker for more than 1s for the shooter to recognize. Therefore, the scanning covering width needs to more than 240m for the mentioned example. The determination of the edge of the scanning covering width is realized via a numerical method in this paper.

3.3 Residence Time Determination and Analysis in a Numerical Way

For the imaging seeker, the interested target needs to stay at the monitor screen for enough time for the shooter to detect the target. Supposing that, the seeker position is (x_s, h, z_s) in the ground coordinate, the target position is $(x_t, 0, z_t)$, and the coordinate of any given point on the ground is $(x, 0, z)$. The Euler angles $(\lambda_\vartheta, \lambda_\psi)$ representing the relationships between the line of sight (LOS) and the target in the seeker coordinate can be expressed as

$$\lambda_\vartheta = \arctan\left(\frac{h}{\sqrt{(x-x_s)^2+(z-z_s)^2}}\right) - q_v \qquad (8)$$

$$\lambda_\psi = \arctan\left[(z-z_s)/(x-x_s)\right] - q_h \qquad (9)$$

where q_h represents the angle formed by the optic axis of the seeker and the vertical line.

$$q_h = \arctan\left((z_t-z_s)/(x_t-x_s)\right) \qquad (10)$$

To guarantee the target to lie in the FOV of the imaging seeker, the angles $(\lambda_\vartheta, \lambda_\psi)$ should meet the following constraints.

$$\begin{cases} -\vartheta_s/2 \le \lambda_\vartheta \le \vartheta_s/2 \\ -\psi_s/2 \le \lambda_\psi \le \psi_s/2 \end{cases} \qquad (11)$$

Combining (8) and (11), we have

$$\frac{h^2}{\tan(\vartheta_s/2+q_v)^2} \le (x-x_s)^2+(z-z_s)^2 \le \frac{h^2}{\tan(q_v-\vartheta_s/2)^2} \qquad (12)$$

Combining (9) and (11), we have

$$\tan(q_h-\psi_s/2) \le (z-z_s)/(x-x_s) \le \tan(q_h+\psi_s/2) \qquad (13)$$

Hereto, we can get the target detection regions, as shown in the shadow region of Figure 2.

Geometry relationships between the imaging seeker and the target are displayed in Figure 3. Four points P_1, P_2, P_3, and P_4 projected onto the ground form a trapezoid shape of the imaging scope of the seeker. For any point, it undergoes the scanning covering by the projected trapezoid. Unfortunately, for the constant angular velocity or the constant linear velocity scanning strategy, the trapezoid is time-varying due to multiple factors. The position of the seeker is time-varying, which results in the variance of the shape of the trapezoid projected onto the ground. Besides, the trapezoid itself also changes due to the scanning of the imaging seeker. The analytical solution is hard to deduce. Therefore, a numerical method is employed to calculate the residence time of the imaging seeker in this paper.

To better describe the proposed numerical method, we demonstrate an example for illustration, as shown in Figures 4-5. Figure 4 demonstrates the geometry relationships of the overall scanning process, and the geometry relationships of the scanning process at a given time is displayed in Figure 5. The blue solid line represents the original projected trapezoid when the seeker starts to work. The green dotted and red dash-dotted lines represent the projected shapes of some given time during scanning.

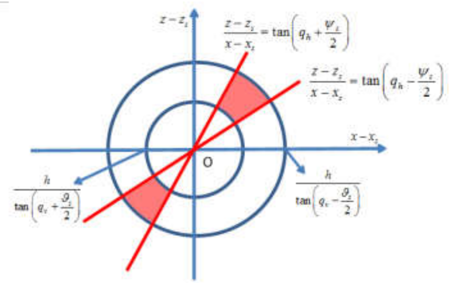

Figure 2. Target distribution to be detected.

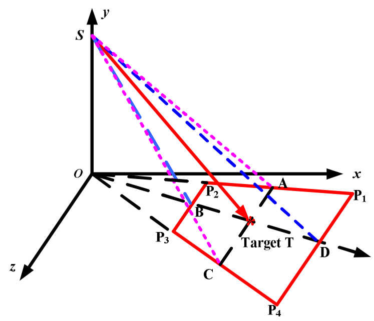

Figure 3. Geometry relationships between the seeker and the target.

In Figure 5, similar to Figure 3, S denotes the position of the seeker, T represents the intersection between the original LOS line and the reference line, and L represents the intersection between the instantaneous LOS line and the reference line. For all the positions that lie in the scanning scope of the imaging seeker (Here, we set the target positions to be within the purple rectangular), we will determine their status of whether they lie in the instantaneous projected trapezoid in real time. As can be seen, target positions that lie within the trapezoid with vertexes R1, R2, R3, and R4 can be seen by the seeker at the scanning starting time. And target positions that lie within the trapezoid with vertexes R5, R6, R7, and R8 can be seen by the seeker at time when scanning is implemented with the position corresponds to the green trapezoid. In other words, we will determine whether the target position meets the conditions of (12) and (13) in real time. If the condition is satisfied, we will increase the time accumulator by 1 for the target position. After the whole scanning process, we will count all the accumulators to deduce the residence time of all the target positions.

Furthermore, as can be seen from Figure 5, the projected length onto the ground in the yawing direction corresponds to the lateral distance of the seeker is about 367m (The parameters are used the same as the example in section 3.2), whereas the length in the pitching direction corresponds to the range distance is about 2264m. That is to say, the projection onto the ground in the pitching direction covers large enough area for target capturing. Therefore, we only need to implement scanning along the yawing direction.

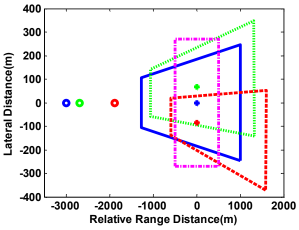

Figure 4. Geometry relationships of the overall scanning process.

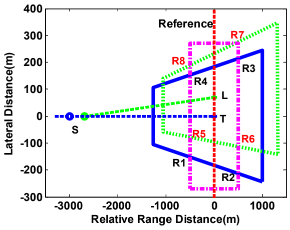

Figure 5. Geometry relationships of the scanning process at a given time.

4 Experimental Results

The following experiments are conducted to verify the effectiveness of the proposed scanning design method for imaging seekers. The velocity of the seeker is set to be 170m/s, the flying height of the seeker is 180m, and the effective working range of the imaging seeker is 3000m. Three different scanning design methods (The "staring at" scanning method, the constant angular velocity scanning method, and the constant velocity scanning method) are conducted respectively. The constant angular velocity is set to be ω_0=1.5°/s, and the constant linear velocity is set to be V_{sm}=60m/s. Results of the residence time of the targets with different lateral and range positions under different scanning methods are given in Figure 6 and Figure 7, respectively.

As can be seen from the experimental results, we have enlarged the lateral imaging scope to reach ±270m by seeker scanning to guarantee the residence time of the targets that lie at the lateral positions of ±240m to be more than 1s. If the "staring at" strategy is adopted, targets at the lateral positions of ±240m will not be seen at all. Taking the target with the position -240m for an illustration, for the constant linear velocity method and the constant angular velocity method, the residence time will be 1.21s and 1.30s, respectively.

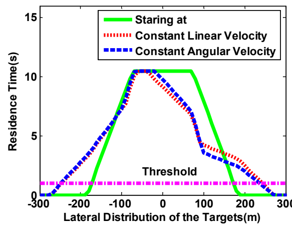

Figure 6. Residence time of the targets with different lateral positions under different methods.

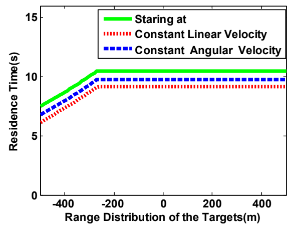

Figure 7. Residence time of the targets with different range positions under different methods.

As for the range distribution of the targets, we can see that from Figure 7, the residence time of all the covering area is much larger than 1s. This further proves that fact that scanning in the pitching direction can be omitted.

Note that, the proposed method is very effective, although numerical computation usually requires computational burden. Since the FOV of the imaging seeker is usually large with respect to the interested regions, the seeker only needs to scan limited angles to satisfy target capturing constrains.

5 Conclusion

Focusing on the problem of improving target capturing probability for short-range imaging seekers, an effective scanning design method is presented in this paper. The scanning scope of the imaging seeker is analyzed according to the restrictions of target capturing probability. The residence time of the targets is calculated in a numerical way. Simulated data have verified the effectiveness of the proposed scanning design method, providing beneficial precondition for accurate target recognition and precise attack.

6 Acknowledgements

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7 References

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