Systematic approach of guidance information reconstruction of laser strapdown guidance air-to-ground missile

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Abstract. The decoupling algorithm of laser strapdown guidance which can effectively suppress the disturbance rejection rate problem and a method of extracting line of sight angle rate are studied. Firstly, the decoupling mathematical model of strapdown seeker is established, the cause of the disturbance rejection rate problem of strapdown guidance is analyzed, and the time synchronization algorithm is designed to reduce the coupling of the attitude motion of the missile to the guidance information. Secondly, an extraction algorithm of line of sight angle rate is established, an extraction algorithm of filter parameters changing with the remaining flight time is designed to suppress the attitude oscillation of the initial phase of terminal guidance and improve the tracking speed of the last phase, and the extracted line of sight angle rate is compared with the output characteristics of the platform seeker. Finally, the effectiveness of the proposed line of sight angle rate extraction algorithm is verified by six degrees of freedom trajectory simulation, and the influence of disturbance rejection rate parasitic loop on strapdown terminal guidance accuracy is analyzed by simulation.

1. Introduction
Since the 1960s, as a new guidance technology that can effectively improve the system reliability and reduce the cost, self-homing strapdown guidance technology has been paid more and more attention by various countries and developed rapidly. It has become one of the development trends of tactical missile guidance technology. The strapdown seeker has two advantages over the platform seeker. Firstly, the elimination of mechanical devices increases the reliability of the system. Secondly, the removal of the universal framework reduces the cost. However, due to the practical aspects of optics and electronics, strapdown seeker may produce a large measurement error and has strong nonlinear, so it is necessary to use modern filtering technology to filter out the noise and estimate the effective guidance information. The strapdown seeker cannot provide the measurement information that is relative to the inertial space and is required by the proportional guidance law, it can only provide the measurement information relative to the projectile body. Therefore, it is necessary to establish a decoupling model to extract the line of sight angle under the inertial coordinate system, and then extract the line of sight angular velocity information through the differential filtering technology.

At present, researches on strapdown guidance mainly focus on the estimation of rate of LOS angle and the influence analysis of disturbance rejection rate. As the angle measurement information of strapdown seeker contains noise, the direct differential method will amplify the noise and drown the angle rate information, so the commonly used method is the nonlinear filter estimation method. In literature [1], a strapdown seeker rate of LOS angle estimation method based on particle filter is proposed. In literature [2], an H square root filter is designed to estimate the relative motion of the missile and target, which can effectively deal with maneuvering targets. In reference [3], for the
terminal guidance of a certain type of guided ammunition, the relative motion information is extracted by means of strong tracking kalman filter, which is used for the realization of the optimal guidance law. When the nonlinear filtering method is used to estimate the rate of LOS angle information, the key problem lies in the selection of the nonlinear filtering algorithm, which must take into account both the estimation accuracy and the calculation amount. In the study of the influence analysis of disturbance rejection rate, many scholars have analyzed the causes of the strapdown guidance disturbance rejection rate problem and the influence of the disturbance rejection rate parasitic loop on guidance. TIAN Yuan[4] derived the expression describing the disturbance rejection rate of the strapdown seeker. The influence of disturbance rejection rate on the guidance loop is discussed. The parasitic loop filter is designed to make the time-frequency characteristics of the seeker measurement information transmission channel and attitude measurement information transmission channel consistent, and to suppress noise interference during signal measurement and transmission.

In this paper, a laser strapdown guidance decoupling algorithm and rate of LOS angle extraction systematic approach that can effectively suppress the influence of the disturbance rejection rate are established. Considering the design of non-linear filtering algorithm filtering parameters from the perspective of proportional guidance terminal guidance characteristics, the strapdown terminal guidance accuracy is improved. Finally, the effectiveness of the designed rate of LOS angle extraction algorithm was verified by a six-degree-of-freedom ballistic simulation.

2. Decoupling model and disturbance rejection rate

Suppose that $q_{\alpha}$ and $q_{\beta}$ are respectively pitch line of sight angle and yaw line of sight angle under inertial launch coordinate system, $q_{\alpha}$ and $q_{\beta}$ are respectively pitch line of sight angle and yaw line of sight angle under projectile coordinate system, $\theta, \psi, \gamma$ are respectively pitch attitude angle, yaw angle and roll angle of missile. The decoupling algorithm of strapdown seeker can be obtained by coordinate transformation:

$$q_{\alpha} = \arcsin(\sin \theta \cos \psi \cos q_{\beta} +$$

$$cos \theta \cos \gamma \sin q_{\alpha} + \cos \theta \sin \gamma \cos q_{\alpha} \sin q_{\beta})$$

$$q_{\beta} = \arctan(-\frac{M}{N})$$

$$M = -\cos \theta \sin \psi \cos q_{\beta} +$$

$$\tan q_{\alpha}(\sin \theta \sin \psi \cos \gamma + \cos \psi \sin \gamma) -$$

$$\sin q_{\beta}(\cos \theta \cos \gamma - \sin \theta \sin \psi \sin \gamma)$$

$$N = \cos \theta \cos \psi \cos q_{\beta} +$$

$$\tan q_{\alpha}(\sin \gamma \sin \psi - \sin \theta \cos \psi \cos \gamma) -$$

$$\sin q_{\beta}(\sin \psi \cos \gamma + \sin \theta \sin \psi \cos \gamma)$$

It can be seen from the decoupling algorithm that strapdown guidance system uses the information of seeker and inertial navigation system to construct a mathematical platform to realize the isolation of projectile motion. Therefore, the disturbance rejection rate of the full strapdown seeker is the ability of the rate of LOS angle extraction algorithm or the decoupling algorithm of the mathematical platform to suppress the effects of the angle measurement error of the seeker, the scale error of the seeker and the inertial navigation system, the dynamic error and the delay of the guidance signal on the calculation of rate of LOS angle. In this paper, the principle of the disturbance rejection rate problem caused by the delay of guidance signal is considered and a method to suppress the influence of this kind of disturbance rejection rate is proposed.

Considering the angle measurement relationship in the longitudinal plane of the strapdown seeker and ignoring the scale error of seeker and inertial navigation system, the measured line of sight angle under projectile coordinate system of the strapdown seeker can be expressed as
\[ q_{\text{lo}}^h = q_{\text{lo}}^h - \dot{\theta}_M \]  \hspace{1cm} (5)

Where, \( q_{\text{lo}}^h \) is the line of sight angle under inertial launch coordinate system at the moment \( t_k \); \( \dot{\theta}_M \) is the attitude angle of the projectile body at time \( t_k \); \( q_{\text{lo}}^h \) is the line of sight angle under projectile coordinate system measured by the seeker at time \( t_k \).

If the seeker signal lags \( \Delta \tau \) behind the signal of inertial navigation system due to the delay of the guidance system, and the output attitude angle of inertial navigation system during the decoupling calculation of the mathematical platform is \( \dot{\theta}_M^{k+\Delta \tau} \), then the reconstructed line of sight angle is

\[ \hat{q}_{\text{lo}}^h = q_{\text{lo}}^h + \dot{\theta}_M^{k+\Delta \tau} \]  \hspace{1cm} (6)

Where, \( \hat{q}_{\text{lo}}^h \) is the estimated line of sight angle under inertial launch coordinate system at time \( t_k \).

Substituting equation (5) into equation (6) can get

\[ \hat{q}_{\text{lo}}^h = q_{\text{lo}}^h + (\dot{\theta}_M^{k+\Delta \tau} - \dot{\theta}_M^k) \]  \hspace{1cm} (7)

It can be seen from equation (7) that due to the delay of guidance signal makes \( \dot{\theta}_M^{k+\Delta \tau} \neq \dot{\theta}_M^k \), the missile attitude information is coupled into the guidance information, resulting in the disturbance rejection rate of the seeker.

The laser strapdown guidance system is mainly composed of laser strapdown seeker, inertial navigation system and flight control computer. The seeker measures the angle between the line of sight and the missile body, that is, the line of sight angle under projectile coordinate system. The inertial navigation system measures the attitude angle of the missile body. The flight control computer reconstructs the line of sight angle and calculates the rate of LOS angle by using the line of sight angle under projectile coordinate system measured by the seeker and the attitude angle of the missile body measured by the inertial navigation system.

The laser strapdown seeker and INS send data to the flight control computer at their respective data update frequency. When calculating the rate of LOS angle, because the data update rate of the seeker is far less than the data update rate of the INS, the flight control computer judges the rising edge of the photoelectric signal of the laser strapdown seeker as the effective data of the seeker at the time of arrival to extract the seeker data and extract the latest INS data for decoupling calculation. In this case, from the point of view of data generation, the information delay of INS used in decoupling is less than or equal to one update cycle of INS data. Such delay will not be compensated.

The delay of the seeker and INS from the angle change to be measured to the angle change of the component output is the inherent algorithm, which can be compensated by the following algorithm.

\[ \dot{\theta}(k) = \dot{\theta}(k) + \tau \times \omega_{\text{ INS}}(k) \]
\[ \psi(k) = \psi(k) + \tau \times \omega_{\text{INS}}(k) \]
\[ \gamma(k) = \gamma(k) + \tau \times \omega_{\text{INS}}(k) \]  \hspace{1cm} (8)

\[ \tau = \tau_1 - \tau_2 \]  \hspace{1cm} (9)

Where, \( \dot{\theta}(k) \), \( \psi(k) \), \( \gamma(k) \) are the latest INS attitude angle data extracted by the flight control computer while sampling the seeker signal, and \( \omega_{\text{INS}}(k) \), \( \omega_{\text{INS}}(k) \), \( \omega_{\text{INS}}(k) \) are the attitude angle rate data. \( \tau_1 \) is the inherent delay of INS, \( \tau_2 \) is the inherent delay of seeker. \( \dot{\theta}(k) \), \( \psi(k) \), \( \gamma(k) \) are the delayed compensated attitude angles of the mathematical platform decoupling algorithm participating in the decoupling calculation.

3. Design of differential filtering

Because the angle information measured by strapdown seeker contains noise, the decoupled line of sight angle under inertial launch coordinate system must also contain noise information. The direct differential method will amplify the noise and submerge the rate of LOS angle, so the current common method is nonlinear filter estimation. In this paper, a common tracking differential algorithm is used to
extract the rate of LOS angle. By designing the change rule of filter parameters to match the characteristics of proportional guidance, the precision of strapdown terminal guidance is improved.

The nonlinear tracking differentiator (TD) is mostly used in auto disturbance rejection control. It generates two output signals \( v_1 \) and \( v_2 \) for the input signal \( v(t) \). \( v_1 \) tracks \( v(t) \) according to a reasonable transition process, \( v_2 \) tracks \( \dot{v}(t) \). Thus, it can track the input signals and their derivatives reasonably. Usually, the discrete fastest tracking differentiator shown in equation (10) is used:

\[
\begin{align*}
  e(k) &= v_1(k) - v(k) \\
  fh(k) &= \text{fhan}(e(k), v_2(k), r_0, h_0) \\
  v_1(k + 1) &= v_1(k) + hv_2(k) \\
  v_2(k + 1) &= v_2(k) + h \cdot fh(k)
\end{align*}
\]

In equation (10), \( h \) is the sampling step, \( r_0 \) and \( h_0 \) are the adjustable parameters, \( r_0 \) determines the tracking speed, \( h_0 \) determines the filtering effect of the tracking differentiator on the noise, and its expansion plays a good filtering role. It is called the filtering factor of the tracking differentiator. The algorithm of the function \( \text{fhan}(e, v_2, r_0, h_0) \) is shown in equation (11):

\[
\begin{align*}
  d &= r_0h_0 \\
  d_0 &= h_0d \\
  y &= e + h_0v_2 \\
  a_0 &= \sqrt{d^2 + 8r_0|y|} \\
  a &= \left\{ \begin{array}{ll}
    v_2 + \frac{a_0 - d}{2} \text{sgn}(y) & |y| > d_0 \\
    v_2 + \frac{y}{h_0} & |y| \leq d_0
  \end{array} \right.
  \text{fhan} = \left\{ \begin{array}{ll}
    r_0 \text{sgn}(a) & |a| > d \\
    \frac{a_0}{a} & |a| \leq d
  \end{array} \right.
\end{align*}
\]

During the extraction of rate of LOS angle of strapdown seeker, if \( v(t) \) gets the value of the LOS angle of pitch \( q_{i\alpha} \) and yaw \( q_{i\beta} \) under the inertial launch coordinate system respectively, then the output of TD \( v_2 \) is the extracted rate of LOS angle of pitch \( \dot{q}_\alpha \) or rate of LOS angle of yaw \( \dot{q}_\beta \).

The change rules of the filter parameters \( r_0 \) and \( h_0 \) are designed. \( r_0 \) increases with the remaining flight time and \( h_0 \) decreases with the remaining flight time to reduce the dynamic delay of the rate of LOS angle tracking, increase the tracking speed, and help to match the characteristics of the proportional guidance and improve the guidance accuracy. However, this design inevitably causes the reduction of the end noise filtering effect and the missile body’s attitude oscillations intensify. As long as the disturbance rejection rate is not reached the disturbance rejection rate threshold of the parasitic loop instability, the final guidance accuracy can be guaranteed.

4. The simulation results

In this paper, a simulation study is carried out on the six-degree-of-freedom motion model of an air-to-ground missile. The launch conditions and wind speed are set as disturbance factors. The model of laser strapdown seeker is built by using the attitude angle of the missile body and the relative relation of the missile and target. White noise is injected to simulate the output of line of sight angle in projectile coordinate system of the actual seeker. The guidance information reconstruction is used for the terminal homing guidance. Therefore, the terminal guidance section is mainly analyzed.
The control scheme of terminal guidance is overload autopilot and the guidance law is proportional guidance law. When the distance between the missile and the target reaches 4km, the strapdown seeker captures the target. The height of missile relative target is about 200m. The missile flight speed is about 200 m/s. The pitch attitude angle is about 3 degrees. Strapdown seeker optical axis relative to the vertical axis of missile body under 4 degrees installation in order to improve the contact probability, and makes the space missile capture target, light spot is located in the center of the seeker view as far as possible to minimize noise detection, provide good initial conditions for the terminal guidance.

Simulation results show that the guided miss distance is less than 0.5m under different perturbation and aerodynamic deflection conditions. The simulation curve under the nominal condition is shown in figure 1, figure 2 and figure 3.

![Figure 1](image1.png)

**Figure 1.** The pitch angle and line of sight angle curves.

Figure 1 shows the pitch angle and line of sight angle curves of the terminal guidance segment. It can be seen from the figure that the line-of-sight angle of the pitching body changes in the range of -4 ° to +6 °, which meets the constraints of the linear region of the terminal guidance strapdown seeker, creating favorable working conditions for the seeker. Working within this range, angle measurement error of seeker is small. It can be seen from the elevation angle curve that the missile body's attitude oscillation gradually increases during the terminal guidance process. This is due to the change of the filtering parameters during the terminal guidance process. The speed of the terminal rate of LOS angle extraction is improved, but the noise is relatively large. The guidance and control system caused obvious attitude oscillations on the missile body, but the guidance information lag is small, and the comprehensive miss distance is optimal.
Figure 2. Pitch line of sight angle curve.

Figure 2 shows the pitch line of sight angle in the inertial coordinate system. The output value of strapdown decoupling is the pitch line of sight angle of the inertial coordinate system which is the same as the update rate of the line of sight signal of the strapdown seeker. The optical axis of strapdown seeker is installed 4° below the vertical axis of the projectile body without compensation, which does not affect rate of LOS angle solution. Filtering process 1 is the output of strapdown decoupling output value after passing through butterworth filter. Filtering process 2 refers to the tracking signal of the signal in step 1 of filtering after passing through TD. Compared with the strafing decoupling output value and the high frequency hopping in filtering process 1, the signal is significantly weakened, which filters out part of the noise signal and effectively extracts the guidance information.

Figure 3. The rate of LOS angle of pitch curve.

Figure 3 shows the rate of LOS angle extracted by the strapdown guidance algorithm and the rate of LOS angle curve output by the platform seeker model. Visible, the designed rate of LOS angle extraction algorithm can effectively extract the rate of LOS angle information, compared with platform seeker output, in the guided end zone disturbance rejection rat features is a bit poor but did not reach disturbance rejection rat parasitic loop instability threshold, and the rate of LOS angle tracking characteristics is good. The extracted rate of LOS angle can be used for proportional guidance terminal guidance, the guidance precision is very ideal.
5. Conclusions
In this paper, the decoupling algorithm of laser strapdown guidance which can effectively suppress the disturbance rejection rate problem and a method of extracting line of sight angle rate are studied. The method reduces the influence of disturbance rejection rate by compensating the delay of the guidance components and improves the strapdown guidance precision by designing the filter parameters to match the characteristics of the proportional guidance. The algorithm has the advantages of low complexity, good extraction effect of rate of LOS angle and improved strapdown terminal guidance precision.

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