Application of Kalman Filter in Satellite Propellant Remaining Prediction Technology

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Abstract. The prediction of the propellant remaining is related to the use efficiency of the propellant, it is of great significance for the estimation of the remaining life of the spacecraft. The gauging uncertainty of the commonly used propellant remaining prediction method is high, and the single gauging method can not meet the higher requirements of long life satellites on-orbit management. In order to further improve the accuracy of the spacecraft propellant remaining prediction, combined with the characteristics of the existing propellant remaining estimation method, a real-time estimation method of propellant remaining is proposed. The algorithm combines two gauging methods to further improve the reliability of propellant consumption estimation. The practical application shows that the algorithm can effectively reduce the disadvantages of the BK method and the PVT method, and provide a more reasonable estimation of the real-time propellant remaining.

1. Introduction

With the development of spacecraft technology, especially the application of long-life satellites, higher and higher requirements are put forward for the on-orbit management level during the life of spacecraft. The prediction of the propellant remaining is closely related to the working life of the spacecraft, and the exhaustion of the propellant means the end of the life of the spacecraft. The accurate estimation of the propellant remaining can improve the use efficiency of the propellant and prolong the life of the spacecraft, thereby obtaining huge economic benefits.

The PVT method and the BK method are the earliest applied satellite liquid propellant remaining prediction technologies, and their applications are very common [1~5]. The gauging techniques of these two methods are simple, and there is no special requirement for the hardware of the satellite propulsion system. However, the short-time accuracy of the BK method is high, but there is a cumulative error, and the PVT method is suitable for long-term estimation, but the accuracy is low. Obviously, no matter which calculation method is used, there is a lack of long-term high measurement accuracy.

Based on the analysis of the measurement characteristics of PVT method and BK method, a real-time estimation algorithm based on Kalman filter is proposed. The method is based on the existing gauging method and does not require redundant measurement data, and has strong practicability. The on-orbit data is used to verify the method, and the calculation results show that the method effectively reduces the disadvantages of PVT and BK methods, and improves the estimation accuracy and stability of propellant consumption.
2. Propellant remaining gauging method

2.1. Bookkeeping method
The BK method is based on the telemetry data including temperature, pressure and orbital velocity of the spacecraft propulsion system, combined with the ground test data of the engine and the thrusters, and calculates the propellant consumption of the engine and each thruster at each specific working sequence. The consumption is cumulatively added to obtain the total propellant consumption for a period of time.

2.2. PVT method
Based on the pressure and temperature telemetry data of the pressurizing gas in the propellant tanks and helium tanks, the PVT method calculates the gas volume in the propellant tanks using the gas equation of state, and then calculates the liquid volume in the tanks from the total volume of the tanks and the propellant density. The PVT method relies on the initial propellant mass in the tanks and cannot obtain the propellant remaining in each tank of the parallel tanks. If an accurate initial propellant mass can be obtained, the PVT method can achieve relatively high accuracy combined with high precision pressure sensor.

3. Calculation model

3.1. Kalman filter
Kalman filter is an algorithm that uses the linear system state equation to estimate the state of the system through the input and output observation data of the system [6]. The Kalman filter algorithm takes the minimum mean square error as the optimal estimation principle and uses the recursive method to solve the linear filter problem of discrete systems. The core content is three recursive formulas, which mainly describe two processes, namely prediction and correction, which are calculated by continuous “predictive-correction” recursive method, based on the previous time estimate and the most recent observation data. Estimate the current value of the signal to achieve the purpose of filter.

Consider a discrete-time linear dynamic system as follows:

\[
\begin{align*}
X_k &= AX_{k-1} + BU_{k-1} + W_{k-1} \\
Z_k &= HX_k + V_k
\end{align*}
\] (1)

The Kalman filter equations are respectively state update equations and observation correction equations.

The state update equation is as follows:

State further prediction: \( \hat{X}_{k|k-1} = A\hat{X}_{k-1|k-1} + BU_{k-1} \) (2)

One-step prediction of the covariance matrix: \( P_{k|k-1} = AP_{k-1|k-1}A^T + Q \) (3)

The measurement correction equation is as follows:

Gain matrix: \( K_k = P_{k|k-1}H^T(HP_{k|k-1}H^T + R)^{-1} \) (4)

Covariance update: \( P_k = (I - K_kH)P_{k|k-1} \) (5)

Status update: \( \hat{X}_k = \hat{X}_{k|k-1} + K_k(Z_k - H\hat{X}_{k|k-1}) = (I - K_kH)\hat{X}_{k|k-1} + K_kZ_k \) (6)

3.2. Calculation model
According to the characteristics of the propellant remaining gauging methods, the BK method is used to construct the measurement equation and the PVT method is used to construct the observation equation. For the BK and PVT methods, it is assumed that the oxidant consumption and the fuel
consumption calculation are completely independent.

Defined at the time $t_k$, the system state $x_k$ is the propellant consumption and the state model can be obtained.

$$x_k = x_{k-1} + u_{k-1} + w_{k-1}$$  \hspace{1cm} (7)

Where, $x = [m_o \ m_f]^T$, $m_o$ is the oxidant consumption and $m_f$ is the fuel consumption.

$u_{k-1}$ is the control signal, which is the propellant consumption mass flow measured by the BK method within the sampling period.

$$u = [u_o \ u_f]^T, \ u_o (k) = \int_{t_{k-1}}^{t_k} \omega_o \times dt, \ u_f (k) = \int_{t_{k-1}}^{t_k} \omega_f \times dt$$  \hspace{1cm} (8)

$w_k = [w_o \ w_f]^T$, $w_o$, $w_f$ are the process noise of the propellant consumption calculation model, which is assumed to be white noise with a mean of zero.

The covariance matrix of $w_k$ is $Q_k$, which is the measurement error variance of BK method within the sampling period.

$$Q_k = \text{diag} \begin{bmatrix} q_o T^2, & q_f T^2 \end{bmatrix}$$  \hspace{1cm} (9)

$T$ is the sampling period, and $q_o$ and $q_f$ the correlation noise intensity of the BK method for the oxidant and the fuel consumption calculation.

The observation equation is:

$$z_k = x_k + v_k$$  \hspace{1cm} (10)

The observed value $z_k$ is obtained by the PVT method, and $z = [z_o \ z_f]^T$, $z_o$ and $z_f$ are the propellant consumption calculated by the PVT method, respectively.

$v_k$ represents propellant consumption error (observation noise), assuming it is also white noise with a mean of zero, and the covariance matrix is $R_k$, which is the measurement error variance of the PVT method.

$$R_k = \text{diag} \begin{bmatrix} r_o, & r_f \end{bmatrix}$$  \hspace{1cm} (11)

$r_o$ and $r_f$ are the error variance of the oxidant and fuel consumption measurements by the PVT method, respectively.

4. Results analysis

Set the propellant consumption measurement interval time $T = 1s$, and the three orbital firing time is 4280s, 4921s, 3976s, respectively. During the ignition period, the calculation error of the BK method within one sampling period is small, and the theoretical error of PVT method is large, and the helium state during the orbital transfer is in an unbalanced state, further increasing its measuring error. During the non-ignition period, since the BK method no longer accumulates propellant consumption, the corresponding calculation noise is zero, and for the PVT method, the helium in the tanks will gradually return to a relatively stable state, the calculation error is close to theoretical error. Therefore, different process noise and measurement noise intensity need to be set separately for different stages.

During the ignition period: $Q_k = \text{diag} \begin{bmatrix} 0.00042^2, & 0.000272^2 \end{bmatrix}, R_k = \text{diag} \begin{bmatrix} 8.4^2, & 4.8^2 \end{bmatrix}$

During the non-ignition period: $Q_k = \text{diag} \begin{bmatrix} 0, \ 0 \end{bmatrix}, R_k = \text{diag} \begin{bmatrix} 11.67^2, & 6.67^2 \end{bmatrix}$

System initial state, $x_0 = \begin{bmatrix} 0.23 & 0.137 \end{bmatrix}^T$

Initial state variance: $P_0 = \text{diag} \begin{bmatrix} 0.001, \ 0.0006 \end{bmatrix}$
The kalman filter is used to calculate the propellant consumption during the orbital transfer, and the kalman filter result is compared with the calculation results of the BK method and the PVT method. The propellant consumption calculation results of the three algorithms are shown in Figure 1-Figure 6 and table 1.

It can be seen from Figure 1-Figure 6 that since the accuracy of the BK method within the sampling period is much higher than that of the PVT, the value of kalman filter is closer to the BK method. However, kalman filter can not completely eliminate the cumulative error of BK method. Therefore, with the accumulation of time, the measurement error of BK method becomes larger, and the filtered data gradually approaches the predicted value of PVT method.

Affected by the steady state of helium, the PVT measurement during the ignition period is quite different from that of the non-ignition period. According to the common weighted fusion algorithm, the fusion result variation is consistent with the PVT method. Although the calculation value of the PVT method is relatively stable, the fusion results will be ideal at a moment after the engine ignition, but the error of the real-time fusion result during the ignition period will be too large. For kalman filter, there is no such problem. Since the error of the observation value is much larger than the model error, the change of the prediction value has little effect on the filter result.

**Figure 1.** Comparison of oxidant consumption predictions during 1\textsuperscript{st} orbit transfer.

**Figure 2.** Comparison of fuel consumption predictions during 1\textsuperscript{st} orbit transfer.

**Figure 3.** Comparison of oxidant consumption predictions during 2\textsuperscript{nd} orbit transfer.

**Figure 4.** Comparison of fuel consumption predictions during 2\textsuperscript{nd} orbit transfer.
Figure 5. Comparison of oxidant consumption predictions during 3rd orbit transfer.

Figure 6. Comparison of fuel consumption predictions during 3rd orbit transfer.

Table 1. Comparison of prediction results with theoretical values (units/kg)

|               | O_{Theoretical} | O_{BK}   | O_{PVT}  | O_{Kalman} | F_{Theoretical} | F_{BK}   | F_{PVT}   | F_{Kalman} |
|---------------|-----------------|----------|----------|------------|-----------------|----------|-----------|------------|
| 1             | 439.723         | 434.464  | 456.191  | 437.925    | 262.783         | 260.247  | 262.783   | 263.545    |
| 2             | 951.097         | 940.196  | 960.569  | 947.466    | 567.105         | 562.099  | 567.105   | 568.565    |
| 3             | 1369.558        | 1353.732 | 1374.849 | 1363.951   | 815.362         | 807.228  | 815.362   | 815.655    |

Figure 1 to Figure 6 all show that the PVT value decreases drastically after the end of the orbit change, but the change of the kalman filter value is very small.

Table 1 shows the comparison between the calculated values of three algorithms and the true values of the propellant consumption. It can be noted that the kalman filter value is closer to the true value than the BK method and the PVT method as a whole. Therefore, the kalman filter algorithm can be used as an effective state estimation method for propellant consumption prediction. This method is not limited to the fusion of the BK method and the PVT method, and can also be used for other gauging methods such as the ultrasonic flow meter method and the PVT method.

5. Conclusion

Based on the characteristics of satellite propellant consumption prediction algorithms, this paper proposes a real-time prediction algorithm based on kalman filter. The algorithm combines two gauging methods to further improve the reliability of propellant consumption estimation. The simulation results show that the proposed method reduces the cumulative error effect of the BK method to some extent, and is not affected by the stability fluctuation of the PVT method, which improves the estimation accuracy and stability of the propellant consumption. The method is based on the existing gauging method, does not require redundant measurement data, and is also suitable for fusion of other propellant consumption estimation methods, and has strong practicability.

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