Adaptation of frame frequency to observation stages at control of spacecraft convergence

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Abstract. The method of the frame frequency adaptation is proposed. It is used for space objects observing when they are detected and tracked. This method is used under conditions of large variations in range and apparent brightness on a stellar background due to the difference in the speed of blurring the images of dominant and background objects. The equation for controlling the state of the system with a discrete change in the frame frequency is formulated. The prospects of using the adaptation method in spacecraft proximity control systems due to the expansion of the sensitivity horizon of the equipment are shown.

1. Introduction

During creation of systems for observing space objects in the interests of orbital services, the systems approach is used. This approach consists of the joint application of synthesis of information processing in the photodetector array and image processing software, hardware responsible for the high reliability of detecting and tracking moving objects on a star background. The development of software and hardware associated with the use of cluster analysis methods [1, 2], parallel computing methods and learning algorithms [3, 4], including neural network [5] methods [6, 7].

An important part of the parametric synthesis of the observation system of dynamic scenes is the determination of the optimal frame frequency and the determination of the method of its restructuring during observation in the face of changes in the signal intensity of the observed space object (SO), for example, due to distance changes between them and a spacecraft observations (SCO).

2. Selection the type of stabilization of SCO

At observation a remote SO on a star background the main feature of distinguishing of signals of an object and background is different high-speed blurring [8] which depends on the visible motion speed of objects. In this case, two types of stabilization of a SC-observer (SCO) are possible [1, 2]:

1. Three-axis (star sensors) used with prior guidance from ground-based surveillance. In this variant, the observed stars have a constant position in the frame, and the image of SO has the form of tracks, the length of which depends on the apparent speed of SO and the accumulation time (duration of the frame).
2. Three-axis (including infra-red (IR) vertical with course and roll stabilization by star sensors). In this variant, the sighting axis of SCO is perpendicular to the normal to the surface of the Earth, i.e., is tangent to a circular orbit. In this version images of an artificial space object (ASO) in the instrument plane at identical orbits of SCO and SO are not mobile, and images of stars have an appearance of tracks which length depends on accumulation time (frame duration). At various orbits (an altitude, an inclination) the stars images and the SO images have various blurring.

The principal difference between these observation options is that the sensitivity of the SO detection system is reduced in proportion to the value of blurring compared to stationary objects. This means that for expanding the horizon of sensitivity (increasing the ASO detection range) the IR vertical stabilization mode looks preferable.

The quantitative value of blurring in both modes depends on the parameters of the SCO and SO orbits. For fairly typical orbits, fields of view and significant ranges image blur distances can be a few pixels per second. In this case, building a system with a constant frame frequency leads to the need to use a sufficiently high frame frequency (at frame time of tens of milliseconds), which is necessary to reduce measurement errors of the space-time coordinates SO at close proximity control distances. This means that blurring, as the main feature of selection of SO against the star background, may turn out to be below the sensitivity threshold of the algorithm for distinguishing between object signals and background [6].

3. Method of adaptation of frame frequency
The analysis of the model of signals accumulation in a matrix photodetector and direct experiment shows that at too small time of accumulation there is a deficit both sensitivity and blurring as a distinguishing feature. Thus, both noise and background information prevent the reliable selection of the dominant information about SO. If the accumulation time is too long, delays in obtaining information on space-time coordinates of SO become unacceptable. Object selection errors are also increasing due to the increasing likelihood of overlap and merge stars tracks. Therefore, long range frame rate should decrease and increase at small distances. There should be an optimal accumulation time, i.e. an optimal frame rate. This method of adjustment of system parameters is a development of the principle of the iterative convergence control SC, proposed by S. P. Korolev. Adaptation of the frame frequency due to an increasing in the accumulation time at low visible speeds SO increases the detection range. At high visible speeds of SO frame rate adaptation reduces time delay.

Consider the frame time optimization using the example of the stabilization method of the sighting axis tangentially to the common orbit SCO and SO, which determine the observation model as a stationary object and a moving background. A reasonable criterion of optimality is the minimum of the weighted sum of the decision-making delay \( \tau \) proportional to a frame time \( T_k \), and a risk \( R \) [1] (with corresponding weights \( c_r \) and \( c_\tau \)), which here we consider in a form that includes two components: \( R_b \) due to background effect (background suppression qualities) and \( R_n \) due to noise effect (dominant object to noise ratio):

\[
T_{k_{opt}} = \arg \min \left\{ c_\tau T_k + c_R (R_b + R_n) \right\}.
\]

Criterion (1) in practice means that in order to minimize the decision \( \tau \) delay, it is necessary to choose the frame time \( T_k \) by the smallest of those for which the risk \( R \) of an erroneous decision about each object to a different class is close to zero. For risk components \( R_b \) and \( R_n \) there is a threshold beyond which a decision errors can be ignored. The signal detection threshold for Gaussian noise corresponds to a signal-to-noise ratio of about 10. Blur detection threshold is also related to the signal-to-noise ratio, but even with its sufficient value, due to instrumental errors of sampling and quantization, it usually has a value close to 2 pixels [6].

Since the risk \( R_b \) increases sharply with decreasing blurring background objects (distinguishing feature) to the threshold value and becomes negligible for large blurring (large accumulation time), and the risk \( R_n \) increases dramatically as signal-to-noise ratio decreases to a threshold value and
becomes negligible for large values of the accumulation time, the optimal frame time should be determined by the rule:

$$T_{opt} = \max \left\{ T_{\psi_{\text{min}}}, T_{s_{\text{min}}} \right\}.$$  \tag{2}

4. Information processing in control system frame frequency

Due to criterion (1), it is necessary to use both quality indicators – risks $R_b$ and $R_n$. When the surveillance system is working, both cases are possible: when the required accumulation time $T_{opt}$ must be set on a basis of a required sensitivity, i.e. $T_{\psi_{\text{min}}}$, and when it is set on the basis of necessary blurring of signal of background stars, i.e. $T_{s_{\text{min}}}$.

For stable operation of the algorithm of frame rate adaptation a hysteresis should be introduced, i.e. two thresholds $\gamma_{sh}$ and $\gamma_{sl}$ for each of these indicators. When using a method of a dichotomy adaptation of frame frequency such group of thresholds (upper thresholds for blurring $\gamma_{sh}$ and signal-to-noise ratio $\gamma_{\psi h}$, and lower thresholds for blurring $\gamma_{sl}$, and signal-to-noise ratio $\gamma_{\psi l}$) must satisfy the condition $\gamma_{sh}/\gamma_{sl} = 2 + \delta$, where $\delta$ is a component that has the meaning of „technological” margin of stability of the system. This component is determined by mean square values of blurring estimation and signal-to-noise ratio errors. When using a dichotomy and taking into account a hysteresis the rule (2) takes a form:

$$\max \left\{ T_{\psi_{\text{min}}}, T_{s_{\text{min}}} \right\} < T_{opt} < (2 + \delta) \max \left\{ T_{\psi_{\text{min}}}, T_{s_{\text{min}}} \right\},$$  \tag{3}

and the block diagram of the system with frame rate adaptation [6] is shown in figure 1.

Figure 1. Block diagram of the system with the adaptation of the frame frequency for two indicators of quality and with two feedback loops.

The block diagram in fig. 1 contains two contours of negative feedback stabilizing work of a system according to the criterion (1). These contours contain smoothing filters of the current estimate $\hat{s}$ of blurring $s$ of the images of star background and the current estimation of the signal-to-noise ratio $\psi$ of the selected by SO. The control driver must operate in accordance with the control equation, in which the signs of the difference of values are formed ($\text{sign}(a - b) = 1$, $a > b$; $\text{sign}(a - b) = 0$, $a \leq b$).


\[ Y_{k+1} = \begin{cases} 
Y_{k+1}^+ &= \text{sign}(\hat{s}_k - \gamma_{sh}) \land \text{sign}(\hat{\psi}_k - \gamma_{sh}) \\
Y_{k+1}^- &= \text{sign}(\gamma_d - \hat{s}_k) \lor \text{sign}(\gamma_{wh} - \hat{\psi}_k)
\end{cases} \]

Control signals are passed to the state memory device, which can be an arbitrary number. For the practice of onboard SC approach control systems, the most realistic variant with states determined by the frame time starting from 8 seconds (detection begins with this state) and with 8–10 steps differing twice (4 s, 2 s, 1 s, and etc.). The device memory status of the system can be made in the form of \( \log_2 W \) – bit reversible counter, the inputs of the control addition (+) and subtraction (−) of which are passed to the control signals \( Y_k \), and its counting input is given a signal \( Y_{j,k} \lor Y_{k,k} \) (logical „or”).

A feature of the equation (4) (implementing the rule (3)) is the use of logical „and” and logical „or” corresponding to the fact that to put the system into a state with a large accumulation time it is enough to decrease any of the parameters – blurring or signal to noise ratio below the lower threshold (\( \gamma_{sl} \) or \( \gamma_{sh} \)). To transfer the system to a state with a shorter accumulation time, it is necessary to exceed the upper threshold of both indicators (\( \gamma_{sh} \) or \( \gamma_{wh} \)).

5. Conclusion

Information processing in the system of orbital services (observation of space objects in real time) should be carried out on the basis of criterion (1), the minimum of the weighted sum delay of formation of information and risk due to false (background and noise) information. Reliance on this criterion allows to synthesize the frame frequency control algorithm according to the equation (4). Using the principles of dichotomy, inertia and hysteresis allows to automatically set the frame time when changing the observation conditions, which provides a compromise between the reliability and speed of decision-making.

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