Optical incoherent direction finder as a part of a fault-tolerant complex for landing onto small bodies of the Solar System

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Abstract. The subject of the study is the on-board guidance and navigation system for an autonomous landing of a space probe. The list of on-board equipment for safe landing of the spacecraft on the small bodies of the solar system (SBSS) is offered. The algorithm is proposed to combine all the on-board equipment into a single fault tolerance system. All the equipment is selected under the condition of the ability to identify failures at an early stage. The novelty of the method is in diversifying methods that are used in each stage of failure analysis. Such general method allows rejecting the results of some failure measurements from the further process thus preventing possible accident. The algorithm suggests two-stage control of the on-board systems that allows improving the fault tolerance. The first stage is based on the method of analysis of a number of double unequal measurements, but unlike the classical approach, it is assumed not to improve accuracy, but to search for errors. The second stage is based on the analysis of the parameters to control the internal equipment in order to predict failures.

1. Introduction
The study of the small bodies of the Solar system (SBSS) is generally accepted as an important cosmological problem. The soil samples and detailed study of the other SBSS parameters could help to understand the process of the Solar system formation and reveal the mystery of the origin of life on the Earth. Further research requires landing a spacecraft on the surface of the SBSS. Another problem is an asteroid impact avoidance. Most of the methods for diverting threatening near-Earth objects are based on precise guidance or a landing a spacecraft on the asteroid [1-5]. The precise and reliable landing procedure on the asteroids surface in the autonomous mode is an essential stage of the mission. It is important to develop a precise and reliable space probe autonomous landing procedure.

As it is already mentioned an autonomous landing is an essential since the distance between the flight control centre and the landing site is about 3AU (astronomical unit). The control signal propagates in both directions for about 40 minutes and manual control is not possible. A precise and reliable autonomous spacecraft landing is a complex procedure because of the limited on-board computing facilities. The analyse of the space missions with the landing on the other bodies of the Solar system showed that it is necessary to develop modern approach for the future missions [7]. For example, the progressive on-board equipment of the Schiaparelli mission did not prevent the collision with the surface because of the processing in a sequential mode [8, 9]. A new approach must process data from all the equipment simultaneously in a single multifunctional complex.
It is necessary to determine the structure of the on-board equipment and the algorithm for processing data from this equipment. The authors earlier [1] determined the structure of the equipment. The present paper proposes an original algorithm for processing data from on-board devices. The algorithm is based on the usage of an optical incoherent direction finder. It is important to note that the introduction of an optical incoherent direction finder (OIDF) can be a quasi-optimal solution. The OIDF provides optical computation without overloading on-board electronics hardware [6]. The operation of the OIDF is based on completely different physical principles than any other on-board computing equipment. This decision allows reducing demanded computational facilities of the on-board hardware and simultaneously it helps to verify another on-board equipment. We assume that it would significantly increase the efficiency and reliability one of the most important procedures of space missions with landing on the SBSS.

2. Autonomous landing of space probe on a small body of the solar system

Small bodies of the Solar system are fundamentally different from the other celestial bodies. Main features of the SBSS as a rule are the tiniest magnetic field and a weak gravitational force. The future on-board system for spacecraft guidance and navigation must be built under the SBSS mentioned features. The on-board navigation and landing system must be precise, reliable and fault-tolerant. This is confirmed with a large number of studies in the field of design and development of on-board systems [10-20].

The authors of the research [21–23] proposed to use a list of the selected subsystems for navigation of the spacecraft. The list of subsystems includes:

• inertial navigation system;
• star sensor;
• altimeter;
• visual navigation system.

This list of the equipment is essential for a precise and reliable landing on the SBSS. It also allows controlling the failures of specific (single) component of the list. It is important to note that all the devices operate according to different physical principles. The components are selected under a special condition. If one component is out of order, the other components could substitute the failure one. The measurements (data) from the components could be then processed as series of unequal measurements. The last allows using the well-known Lagrange equation for processing unequal measurements. However, the classical theory of measurement indicates that at least 8 (eight) or more measurements of the same value are necessary for effective use of the Lagrange equation [24]. However, even measurement data set produced by 4 (four) components could significantly improve the accuracy, fault tolerance and reliability of the on-board system. The proposed components interaction schematically presented on a figure 1.

![Figure 1. The scheme of control of inertial navigation system according to indications of other on-board devices.](image-url)
In the comparison and verification block, statistical processing of measurement results of different on-board devices is performed. Indices $p_1$, $p_2$, $p_3$, $p_4$ in fact represent the weight of the measurement and can be calculated or assigned based on the design features of the devices.

3. Optical incoherent direction finder as a main part of the on-board system for guidance of a space probe in the process of landing on small bodies of the solar system

The direction finding is a process based on image recognition with the definition of the angular coordinates of the object. Nowadays, optical direction finding is widely used to control unmanned vehicles. It is important that optical direction finding demands relatively small number of control points of the object for the recognition and direction finding. Most of the modern optical direction-finding devices based on an extreme electronic correlation. The computing speed of such devices depends on the on-board computational facilities performance.

The suggested original optical incoherent direction finder is an optical computing device based on the principles of the Fourier transform. Optical computing devices have several advantages over optoelectronic devices performing similar functions [9, 10]. Optical direction finders process the two-dimensional spatial information (X and Y coordinates) simultaneously. The processing speed does not depend on the complexity of functions. It is only emitted by the speed of light. Devices with correlation in the optical path have a sufficiently high reserve of reliability due to the simplicity and compactness of the structure.

The OIDF guides a space probe during the decent and landing on the SBSS by comparing a current view and an image of the landing point in optical spectrum.

The operation of mutual correlation of two functions $g$ and $h$, depending on the coordinates $x$, $y$ and on the shift $u$, $v$ is described by the following expression [25, 26]:

$$R(u,v) = \int \int g(x,y) \cdot h^*(x+u,y+v) dx dy$$

where $h^*$ – is a function complex conjugate to the function $h$.

It can be shown that the modulus of the autocorrelation function (real or complex) has an absolute maximum at $u = 0$, $v = 0$:

$$|R(u,v)| < R(0,0)$$

The expression (2) allows determining the coordinates of the shift ($u$, $v$) from the position of the maximum of the correlation function, which can be used to construct the direction-finding characteristic.

The operating principle of the direction finder is based on optical processing of spatial two-dimensional (visual) information. The finder based on the optical processing is quite applicable for the targeting the spacecraft to the landing site. The angular coordinates of the target can be steadily calculated and processed [27-28].

The main part of the direction finder is an optical system (see figure 2). The optical system is designed to create an image of a remote object in the focal plane of the lens. The finder optical system will form and transmit a radiation flux to the radiation receiver proportional to the area correlation of the object image and the transmission of the standard.
Figure 2. Schematic diagram of an incoherent optical direction finder, where 1 – field stop, 2 – lens, 3 – an optical transparency standard, 4 – condenser (lens Fabry-Perot) and 5 – four-sector radiation receiver.

The optical incoherent direction finder operates based on a different physical principle. This property is extremely important when building a space probe navigation system. This solution increases the system’s fault tolerance and verifiability of data derived from various equipment. Let us consider the proposed algorithm for verification and data processing.

4. The algorithm for verification and data processing
Measurements that have an unknown variance are unequal measurements. In this case, it is assumed that:

$$\sigma_i^2 = \frac{\sigma_0^2}{p_i}$$

(3)

where $\sigma_0^2$ – arbitrary constant, and $p_i$ – the weight of the measurement and could be determined by the following expression:

$$p_i = \frac{\sigma_0^2}{\sigma_i^2}$$

(4)

If the variances are unknown, the weight is calculated using the approximate formula:

$$p_i = \frac{\mu^2}{m_i^2}$$

(5)

where $\mu$ – the RMS error of a measurement with weight is equal 1, and $m_i$ – RMSE of the measurement with index I [24].

The following procedures are performing in the ‘Verification and data processing’ function block (figure 1):

Step 1: it is calculating the most reliable value using the equation of the weighted arithmetic mean:

$$\bar{X} = \sum_{i=1}^{n} \frac{p_i \cdot x_i}{p_i}$$

(6)
**Step 2:** it is calculating a RMS error of the weight unit using the Bessel:

$$
\mu^2 = \frac{\sum_{i=1}^{n} P_i \delta_i^2}{n-1}
$$

(7)

where $\delta_i = x_i - x$ – deviation from the simple average of the measured value.

**Step 3:** it is getting error of the most reliable value (common arithmetic mean) by the equation:

$$
m_x = M = \frac{\mu}{\sqrt{\sum_{i=1}^{n} P_i}}
$$

(8)

**Step 4:** it is finding a confidence intervals for the true value of the measured value X according to the known formula:

$$
\bar{x} - K \cdot m_z < X < \bar{x} - K \cdot m_z
$$

(9)

where $K$ – accuracy factor, which is selected based on the degree of responsibility of the measurement results.

**Step 5:** it is finding a measurement out of the confidence interval.

At step 5 is necessary to compare the measurement from each component with the most reliable value $X$. The difference must not exceed the limits of the confidence interval (9), otherwise the measurement results of this device must be excluded from processing, and the procedures (3)–(7) are repeated.

The algorithm described above (equations (3)–(7)) allows finding gross errors of measurements. It helps to exclude from processing data of on-board navigation components that are out of order. When all the measurements are within the confidence interval (9), then the algorithm proceeds to the second stage. Schematically a first stage of the algorithm could be presented on the figure 3.

5. The second stage for assessing the state of the internal hardware elements of the on-board navigation system

The first stage enables us to monitor and give a general assessment both for hardware and for software of the on-board navigation system. This procedure allows finding the gross failures in subsystems operation. However, the problem occurs, as we could not separate hardware and software failures. The second stage is designed to monitor the state of the hardware components of the on-board navigation system. It is important to note that the proposed technique enable us to find and separate failures of hardware and software origin. Before the description of the algorithm of the second stage let us solve a mathematical problem in general.

There is an equation of the form:

$$
y = \sum_{i=1}^{n} a_i \varphi_i(t)
$$

(10)

where $y$ – are measured functions $\varphi_i(t)$

The problem is to find the unknown parameters $a_i$ that are constants. Since the parameters are unknown, it is possible to replace them with the estimates of $\hat{a}_i$, then the measured value $y$ – could be replaced by its estimate

$$
\hat{y} = \sum_{i=1}^{\ell} \hat{a}_i \varphi_i(t),
$$

(11)

then:

$$
\bar{y} = \hat{y} - y,
$$

(12)

where $\bar{y}$ presents the difference between the estimate and the true value of the measured value.
However, \( \bar{y} \) could be expressed as follows:

\[
\bar{y} = \sum_{i=1}^{k} \bar{a}_i \varphi_i (t),
\]

where, \( \bar{a}_i = \bar{d}_i - a_i \) is the difference between the true value of the variable and its estimation. Expression (13) could be written as follows:

\[
\bar{y} = \bar{a}^T \varphi .
\]

It is chosen a positive definite Lyapunov function \( V \):

\[
V = \frac{1}{2} (\bar{a}^T \bar{a}).
\]

Find the derivative of the function \( V \) in time – \( \dot{V} \):

\[
\dot{V} = \bar{a}^T \dot{\bar{a}},
\]
where \( \hat{a} = \dot{a} \), since \( a \) is a constant, choose \( \hat{a} \) under the condition:

we have to notice that \( \dot{V} \) is negatively defined

\[
\dot{a} = -\lambda \varphi(t) y, \quad \dot{V} = -\lambda \dot{y}^2.
\]  

if \( \lambda > 0 \), and \( \bar{a} \neq 0 \) it is possible to postulate that \( \dot{y} \neq 0 \), and function \( \dot{V} \geq 0 \) and decrease. The process ends when \( \dot{y} = 0 \), and hence, \( \bar{a} = 0 \). In this case:

\[
\dot{a} = a.
\]

6. Algorithm for assessing the state of internal hardware of the onboard equipment

It is very important to monitor parameters from on-board hardware. All the parameters have to be verified under some distinct limits.

Consider a differential equation of the form

\[
\dot{x} = Ax + bu + df(t),
\]

where \( x \in \mathbb{R}, u \in \mathbb{R}, f \in \mathbb{R}, \) and \( u=\text{const}, b, d, x, f \) – known values. In this case, the purpose is to find the matrix of unknown parameters of the system \( A \) and the constant \( u \).

In the beginning let us solve the task for one arbitrary line of the system with an index \( i \):

\[
\dot{x}_i = \sum_{j=1}^{n} a_{ij} x_j + b_j u_j + d_j f(t).
\]

To find the unknown parameters \( a_{ij} \) and \( u_j \), we use the model, replacing these parameters with their estimates \( \hat{a}_{ij} \) and \( \hat{u}_j \), respectively, then:

\[
\dot{x}_i = \sum_{j=1}^{n} \hat{a}_{ij} x_j + b_j \hat{u}_j + d_j f(t) + W_i,
\]

where function \( W_i = -M \cdot \text{sgn}(\bar{x}_i) \), and \( \bar{x}_i = (\hat{x}_i - x_i) \) – is the difference between the estimate and the true value of the variable.

The next equality is correct for a previously defined variable:

\[
\hat{x}_i = \sum_{j=1}^{n} \hat{a}_{ij} x_j + b_j \hat{u}_j - M \cdot \text{sgn}(\bar{x}_i).
\]

The expression (22) turns to 0 in a finite time period if:

\[
M > |\hat{a}_{ij} x_j + b_j \hat{u}_j|.
\]

Inequality (23) holds because \( \hat{x}_i \) and \( x_i \) have opposite signs. In this case if \( x_i = 0 \), then \( \hat{x}_i = 0 \).

If a frequency of switching the function \( W \) is high enough then it is possible to obtain the average value of the function \( W \) using the filter (24).

\[
\int \hat{y}_i = -M \cdot \text{sgn}(\bar{x}_i),
\]

then:

\[
\bar{y}_i = \sum_{j=1}^{n} \hat{a}_{ij} x_j + b_j \hat{u}_j.
\]

Thus the problem has been solved here in the form of (10) – (18). Thus, the true value of the parameters \( a_{ij} \) and \( u \) is found. If the founded parameters \( a_{ij} \) are not equal to the nominal, that is to say that the system is out of order and there was a failure of the hardware components. This decision in combination with the first stage of the algorithm enable us to find and separate both hardware and software failures.

7. Conclusion

The method described above allows excluding from the processing gross measurement errors of on-board navigation devices caused by failures in their operation. If the measured value \( x_i \) from the monitored subsystem is inside the confidence interval (5), it can be considered free from gross error
and can be used for the operation of the on-board navigation system. Otherwise, it is excluded from processing, and the monitored subsystem is being recognized as out of order.

Therefore, the main results are as follows: 1) the list of equipment on-board complex, including coherent optical finder is presented; 2) the precise and fault-tolerance control algorithm of the on-board computational complex is given. The novelty of the results lies in combining parameters of all the devices to protect against failures in the operation of the CLA. The proposed algorithm is based on the method of analyzing a number of double non-exact measurements. It is significant that in contrast to the classical approach, the aim of the proposed algorithm is not to improve the precision of computations but to search for gross errors, such as failures in the device operation.

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