Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 186 (2021) 503–511

Procedia Computer Science

www.elsevier.com/locate/procedia

14th International Symposium "Intelligent Systems"

Development of a vision system for safe and high-precision soft landing on the Moon

Xu Yang, A.V. Bobkov*

Bauman Moscow State Technical Univercity, 2-nd Baumsnskaya st.5-1, Moscow, Russia

Abstract

Modern stage of space exploration is tightly related with the Moon research, with the deployment of long-term research stations on its surface. One of the critical elements here is a system for providing a highly accurate and reliable soft landing. The task of soft landing was solved many years ago, however, its accuracy is insufficient for modern lunar projects.

Modern computer vision systems allow getting high-quality surface images at all stages of landing, and processing them in real time. The use of technical vision is beneficial due to the low weight, dimensions and energy consumption.

The following tasks are assigned to the vision system: self-position determination of the landing unit and selection of a suitable place for a safe landing. Self-position determination by the video is necessary for INS data correction. Two methods are considered: detection and comparison of craters, and GHT. Both methods use the vector map and don't require actual high-precision orthoplan.

The safe site choosing method uses the found position for binding it to the desired and undesirable sites map. After that a precise choice follows, which takes into account the surface angle, smoothness, presence of extensive shadow areas. The algorithm is able to select landing sites close to those manually selected by the operator. The obtained algorithms can work in real time with the influence of interfering factors (noise, changes in the Sun position, changing of camera angle), and can be used to solve the problem.

© 2021 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the 14th International Symposium "Intelligent Systems".

Keywords: Visual navigation; safe landing; landing site selection; hough transform; computer vision

* Corresponding author. Tel.: +7-906-751-6579.
E-mail address: alexander.bobkov@bmstu.ru

1877-0509 © 2021 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the 14th International Symposium "Intelligent Systems".
10.1016/j.procs.2021.04.171

1. Introduction

This work is devoted to the problem of performing a high-precision soft landing of a descent module on the lunar surface using a computer vision system. The system compares the observed image of the surface with an electronic board map, refines its position data and selects the best, safest landing site.

Space exploration is one of the key areas of human development. The conquest of outer space is associated not only with long-cherished dreams. This is a powerful locomotive, capable of accelerating the progress in science, technology, economics and other areas, capable to motivate a man to advance and ascend.

The modern stage of space exploration is associated with the creation and deployment of long-term automatic or inhabited bases on the surface of the nearest celestial bodies, and primary on the moon. These bases serve not only as scientific laboratories and technology research centers, but also act as outposts for the further conquest of outer space.

The problem of soft landing on the moon was successfully solved in the last century, in the programs "Moon" and "Apollo" [1]. Modern tasks of moon exploration are associated with landing in a selected region of the polar regions, deployment and subsequent support of lunar bases. They require very high landing accuracy — tens of meters in position and units of degrees in the slope of the landing site.

The radical improvement of landing accuracy is possible, on the one hand, by improving landing control algorithms, and, on the other, by improving and intellectualizing measuring instruments, their integration.

A typical soft landing scheme can look as follows [2]. Initially, the landing unit is moving on circular lunar orbit, which passes over the desired landing site. The orbit parameters are determined and the transition point to the descent orbit is calculated.

Stage 1 is transition to the descend orbit. To do this, upon reaching the calculated point of the circular orbit, a short braking pulse is performed. The landing unit enters an elliptical descent orbit that passes through the lunar surface at the point of the desired landing. The starting point of braking, which provides conditions for a soft landing, is calculated.

Stage 2 is optimal braking. This is the most energy-consuming stage. Its purpose is to slow down the landing unit, while spending a minimum of fuel and minimum of time (to reduce the error of the inertial system). Optimal braking starts when the calculated braking start point is reached. The brake engine is started, providing complete damping of speed upon reaching a predetermined height (several kilometers). Braking is carried out only according to the INS data, without their correction, in accordance with the constructed control algorithm. The intellectualization of control at this stage is primarily associated with the construction and real-time correction of optimal control, as well as with a more accurate assessment of INS data.

Stage 3 is redirecting. At the beginning of the stage, the landing unit hangs above the surface, determines its own position according to the observed landmarks, corrects the INS error, and then selects a safe landing site and develops a control algorithm for reaching this place. There are a large number of known terminal control synthesis algorithms for performing such redirection [3], each with its own advantages and disadvantages.

Redirecting can be performed repeatedly, as more accurate information is obtained about position or about a more accurate choice of location when approaching the surface. The stage is completed by reaching a predetermined height, after which the landing unit proceeds to the vertical descent stage. The achievement of this height is measured by the rangefinder and confirmed by the INS. Management at this stage is built in such a way that the speed is reduced to zero.

Stage 4 is vertical descent. At this stage, the landing unit is stabilized vertically, and the height is monitored by the readings of the range finder. The control is constructed in such a way as to ensure near-zero speed at the moment the device touches the surface.

2. Tasks for computer vision system for soft landing

Thus, to perform a high-precision soft landing, it is necessary to solve two important problems - determine your own location and choose a safe landing site. Both of these tasks can be solved using a computer vision system.

Computer vision systems are rarely used in automatic space missions. This is due both to the lack of sufficiently productive and reliable image recognition algorithms, and to the relatively low productivity of on-board computers, which is insufficient to implement existing methods in real time. However, at present, a significant breakthrough has been outlined in algorithms and methods of computer vision. At the same time, high-performance radiation-resistant on-board computers suitable for the implementation of modern methods appear. In this case, the main problem on the way of widespread use of computer vision systems remains the complexity of the problem. It is this complexity that must be overcome: automatic stations should not sit blindly. The device must correlate the observed surface with the results of other measurements - long-range, inertial, radio navigation, draw reasonable and reasonable conclusions based on them, plan and implement control for accurate and soft landing in a given area.

The vision system can solve a whole range of problems at different stages of landing. These tasks may include:

- Initial orientation (determination of the presence on the image of the surface or edges of the Moon, Earth, stars) - as a backup orientation system in case of failures or malfunctions of the corresponding sensors;
- Determining the position of the device - as an accurate position sensor for correcting errors in the integration of inertial sensors;
- An alternative sensor for approach speed and distance to the surface;
- The final choice of the best landing site;
- Detection and tracking of the layout of the landing site for maintenance tasks and supply of deployed bases;
- Assessment of the adequacy of the state vector assessment of the observed set of measurements, identification and exclusion of faulty sensors.

It is the recognition system that allows to form around itself an intelligent system, that contains all the blocks, from the state vector estimation to the decision-making and control synthesis. Such a system can play the role of a relatively slow "self-awareness" of the landing unit, which controls and corrects faster and less intelligent processes in control loops.

3. Determining the exact location of landing unit

Determining the exact self-location is necessary to bind the position of the landing unit to the surface of the moon and descend in a given area. In the case of its absence, the error can reach hundreds and thousands of meters, which is unacceptable for modern missions.

It is possible to increase the accuracy of determining self-position by detecting landmarks – artificial markers, the position of which is easy to detect, or – by natural features of the landing site. Artificial markers can be systems of radio beacons, satellites of global positioning in the moon orbit or pseudo-satellites on its surface. However, their deployment, maintenance and topological binding is a separate complex technical problem, which is currently not solved. Therefore, it is necessary to consider an alternative visual orientation system, that uses observable landmarks (craters, mountains, faults) to determine the position and comparing their position with the on-board map of the area.

Since the computing time to compare the frame with the map is large, it is a good solution to perform it in the delayed correction mode. The INS data are recorded for the time the frame is received, then the frame position is located on the map, and the mismatch between the found position and the recorded INS data is computed. This mismatch will now act as a correction signal and will be added to the INS data. If it is impossible to detect the frame position on the map, the correction value remains zero, and the landing is performed only by uncorrected INS data.

Position determination by video does not require a complete stop of the landing unit and can be performed repeatedly to achieve a required positioning accuracy. However, it is necessary to perform at least one successful correction in order to proceed to the next step – the choice of a safe landing place.

3.1. Choosing a safe landing place

For successful operation of the landing unit equipment, it is required to land on a relatively flat surface, with an inclination angle of no more than 10...15 degrees. To search for suitable sites, it is possible to use either the active method (scanning laser rangefinder) or the passive method (visual observation). Using a rangefinder (Lidar) is easier in the algorithmic point of view, since it allows direct measurement of the height map and determine the relief of individual areas from it. Lidar is used, for example, to land on a Chang'e-4 mission [4]. However, from a technical point of view, the use of Lidar is more complicated, since it is a rather complicated and heavy device itself, and for its operation, complete immobility of the landing unit and absence of vibrations are required. Therefore, from the point of view of technical implementation, the visual method looks preferable. It can be used repeatedly without completely stopping the device, and share the same equipment (camera and computer) as the visual navigation system. Algorithms for finding a safe site in an image are more complex, because the surface slope has to be estimated using indirect brightness values. In this paper, one of such algorithms is proposed.

The choice of landing site requires prior clarification of their own position. This is necessary so that the landing site is not chosen in an arbitrary place, but in a predetermined desired area.

3.2. Possible approaches to determine own location

By the type of feature used, the matching methods can be divided into the following groups:

- Methods using the brightness of all points [5, 6]. These are all classical spectral-correlation methods [5-7], which are widely used in real-time systems. They have high reliability and performance. Unfortunately, they cannot be used in this task because of the excessively large size of the map, which, moreover, must be updated at the time of landing. Therefore, we will seek a solution among of other approaches;
- Key point matching methods [7-10]. The key points in this task can be the centers of impact craters. Crater formations found are easy to locate in the list of known craters, and a large raster map is not required in this case. Today this is the fastest growing and most promising direction, and a rather large number of various algorithms are known both for detecting craters and for comparing them with a map. The disadvantage of this group of methods is that they are highly dependent on the quality of crater detection. In case of crater detector failures due to interference, lighting characteristics or poor visibility of crater elements, further work of the method will be impossible. Particularly big problems arise with the detection of the largest and oldest craters, with a degraded edges and irregular shape – because they are precisely the most important landmarks;
- Neural networks and machine learning [11]. Another fast-growing and promising group of methods. It is possible to detect craters with high reliability, but there are problems with the detection of craters of different sizes. As a result, it takes a lot of passes for each of the desired sizes, which greatly increases the search time;
- Contour methods. This is an intermediate group of methods that allows you to combine the advantages of the methods of the other groups. Contour points do not change when visibility conditions change. They can be used with both vector and raster maps. The algorithms for their detection are quite reliable and efficient. In addition to brightness, the contour points provide an additional characteristic – the direction of the contour, which increases the selectivity of the methods. At the same time, contour methods are used relatively rarely: there are still too many contour points for applying key point matching methods, and spectral methods are not suitable for them because of the impossibility of comparing with a vector map.

The paper considers this particular group. As a strategy for comparing a frame with a map, we will use the variant of the Generalized Hough Transform [12] adapted for comparing the contours of impact craters. This transformation is widely used to search for complex objects on their own, or as part of other methods (structural search, the method of implicit models, etc.). Using the Generalized Hough Transform allows to obtain the necessary processing speed for a sufficiently large number of contour points, while ensuring a sufficiently high reliability of the algorithm.

3.3. Proposed approach to determine own location

As reference points for comparing the frame with the map, we choose the boundary points lying on the crest of the crater shaft. These points will have a maximum brightness difference, since they are on the border of the inclined surface of the crater wall and the full shadow. However, other elements of the lunar surface, such as steep slopes, the boundaries of shadow and glare, can also have sharp brightness transitions. It is apparently impossible to completely filter them at the level of individual points, so we will consider their presence as interference.

Each point of the crater crest A_i can coincide with the corresponding point B_j of one of the craters on the map (Fig. 1). It is impossible to determine, which of the craters the point belongs to, so we must consider all the hypotheses A_iB_j about the belonging of each point of the frame contour to each map crater.

The point of the map B_j of the *j*-th crater corresponding to the boundary point A_i can be found using information on the brightness gradient G_A at the point: the gradient vector is perpendicular to the contour at the point A_i and passes near the center of the crater (Fig. 1). Therefore, the point B_j will be shifted from the center of the $_j$-th crater C_j at a distance of the radius R_j of this crater in the direction opposite to the brightness gradient G_A with direction γ:

$$x_B = x_C - R\,Cos\,\gamma\,,\;\; y_B = y_C - R\,Sin\,\gamma$$

Each pair of points (*A, B*) will generate a hypothesis (Δx, Δy) about the coincidence of the point of frame A and the point of map *B*. We introduce the hypotheses space (HS), represented by accumulator array $H\,[\Delta x, \Delta y]$, and mark each hypothesis in it, increasing the counter $H\,[\Delta x, \Delta y]$ for it by one (Fig. 2). In this case, the correct hypotheses will coincide, give the same values ($\Delta x^*, \Delta y^*$) and will repeatedly increase the same counter $H\,[\Delta x^*, \Delta y^*]$, as a result of which it will accumulate significant value equal to the number of coincident points of the frame and map boundaries. Incorrect hypotheses, generated by an incorrect determination of the point belonging to the crater or by taking into account noise points not belonging to the crest of the crater, will generate random values (Δx, Δy) distributed randomly and unordered, for the most part not coinciding with each other. These hypotheses will not give rise to any significant values in any of the counters. Now the position of the frame on the map can be defined as the position of the maximum $h_{max} = H\,[\Delta x^*, \Delta y^*]$ in the HS.

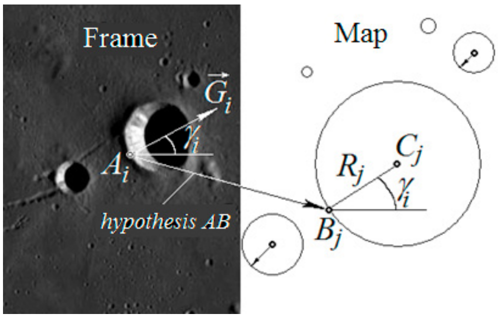

Fig. 1. The scheme for calculating hypotheses about the coincidence of the crater ridge point on the frame and map

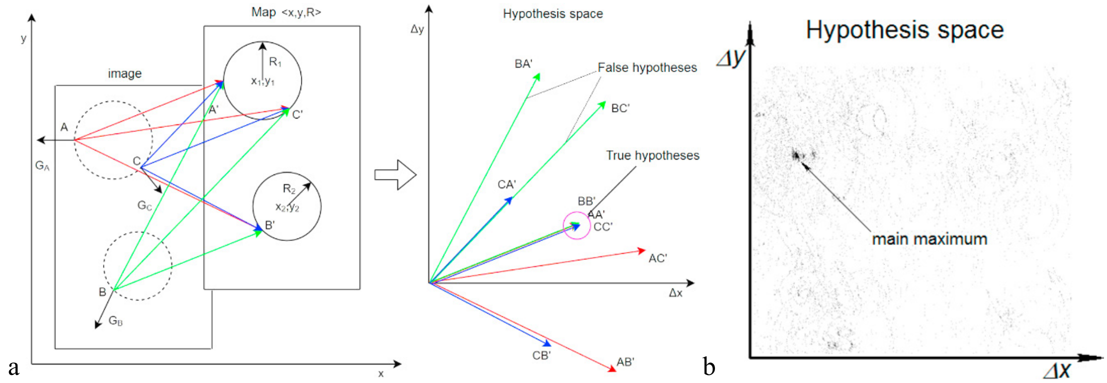

Fig. 2. Modified GHT algorithm: (a) calculation scheme for responses in the space of hypotheses; (b) fragment of hypothesis space near global maximum

True hypotheses in the HS will exactly match in the hypothesis space only if the crater in the frame is an ideal circle and its radius exactly matches the radius of the map crater. However, these assumptions in practice are not fulfilled. As a result, true hypotheses don’t fall at one point, but form the cluster of true hypotheses. The size of the area depends on the distortion size. The maximum in the HS is blurred over the region in a rather complicated way (Fig. 3(a)), and decreases significantly. Therefore, additional measures will be required to find a cluster of correct hypotheses and estimate the number of correct hypotheses in it.

In the presence of distortion of the angle, each pair of points will generate not just one hypothesis, but a whole region. The shape of the area will depend on many factors: the type and amount of distortion, the position of the points, etc., therefore, it is not possible to specify the exact position of the area of hypotheses. Moreover, voting for a whole region instead of a single point will reduce the computational speed strongly.

The possible solution may be the construction of areas after the voting procedure. In this case, the detuning of the region occurs for all hypotheses in one cell of the counter space at the same time.

As a model of the region, we take a square whose side is equal to two maximum deviations of the extreme points of the frame due to the expected distortions. Of course, you can refine the model by taking an area in the form of a circle, preferably with a Gaussian distribution of votes, but this will require significant computational costs. The construction of the area-square will be reduced to counting the total number of votes that fall into this square for a given position in its middle. For such a summation, high-performance algorithms are known that are similar to calculating an integral image, and four operations per point of the hypothesis space are sufficient to calculate.

Figure 3(b) shows the results of summing the responses over a square area. It can be seen that the responses corresponding to the coincidence of individual craters are again combined into one, with a large value. The position of the main maximum now again corresponds to the position of the frame on the map.

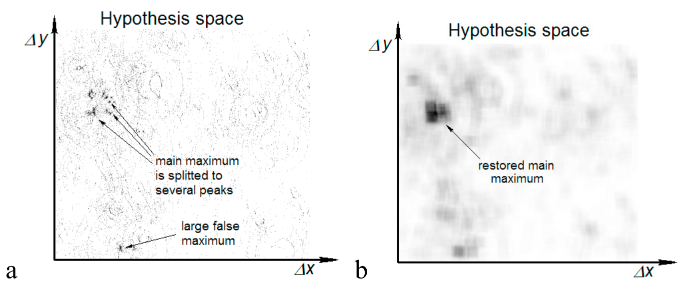

Fig. 3. Results of correction of unaccounted for geometric distortions: (a) hypothesis space without correction; (b) with correction

For the experiments, a 400x400 image was used. For it, a one-degree rotation relative to the center results in a displacement of the borders of not more than 5 pixels. For an image with different rotation angles, windows ranging in size from 3x3 to 11x11 were sorted out, the magnitude of the main response, the minor maximum outside the cluster of valid hypotheses were measured, and their ratio was calculated.

Experiments have shown that the presence of anti-aliasing almost always leads to increased reliability of the search, therefore, its use is advisable. At the same time, the optimal window size increases with increasing angle of rotation. For small angles within five degrees, a smoothing window of 3x3 or 5x5 size is enough. A similar situation is observed when scaling an image.

The increase in the signal-to-noise ratio when using the summation of responses is quite significant (from 20% and higher), therefore, summing the responses over the window seems necessary.

4. Selection of areas suitable for safe landing

There are several fundamental types of relief for the lunar surface for landing:

- Plains. This is the most suitable type of terrain for landing. The main requirement here is the absence of large pits, boulders and other irregularities that could interfere with the landing;
- Mountains, hills, ridges, clefts, crater slopes. Landing in these areas is highly undesirable;
- Shadow areas. Landing is undesirable because it is impossible to assess the quality of the surface.

In addition, the on-board map may contain markings specified by the operator in advance:

- Areas of interest. The selected landing site must necessarily lie inside this area. These may be, for example, areas of occurrence of water and minerals, areas near objects of interest to be investigated. Failure to enter this area leads to a complete or partial failure of the mission;
- Areas of avoidance. These may be areas that are visually difficult to recognize and should be avoided. These may be, for example, regions of radio shadow in the polar regions that do not allow maintaining stable communication.

Plain regions have a fairly high reflectivity and occupy a significant part of the surface of the moon. In the image, the flat areas will have a large number of points of approximately the same average brightness, with a relatively low gradient amplitude. The brightness of the flat points mainly depends on the position of the sun.

The range of brightness of the points of the plains can be found without knowing the position of the Sun, using a histogram of brightness. A typical histogram of the brightness of the points on the lunar surface, as a rule, contains two modes (shadows and a flat surface), and a long right “tail” (highlights of the illuminated side of mountains and slopes of craters). The nature of this distribution is preserved for a fairly wide range of types of the lunar surface. The boundaries of the modes can be found, for example, using clustering algorithms, or can be bound to the percentage of points that will be considered shadows and highlights.

Points assigned to planar areas are then filtered and areas of avoidance are removed from them. The remaining points are considered as potential candidates for landing, and they pass to the next stage – selection of optimal site.

There are two criteria that will be considered as a measure of the quality of the selected place:

- Smoothness of the surface (the smoother the better). Smoothness implies the absence of small stones and pits. As a numerical criterion, the total amplitude of the brightness gradient over some neighborhood of the selected point can be used;
- Large area sizes (the larger the better). The large-sized area reduces the requirements for soft-landing control algorithms, and ensures the constancy of the characteristics of the area on a substantial part of it. The size of the region can be described as the maximum diameter of the circle inscribed in this region.

Simultaneous calculation of these criteria is difficult, therefore, they will be applied sequentially.

To solve this problem, we calculate the amplitude of the brightness gradient at each selected point of the plain, and sum them over a sliding window. Based on the obtained values, we construct a histogram of the total amplitudes of the gradient. Choose a threshold on the histogram corresponding to approximately 1/32 of its total area. Points whose total gradient does not exceed a given threshold will form regions with the smoothest surface (Fig. 4).

As an algorithm for calculating the gradient, the Sobel filter was used, and algorithm of integral image calculation was used to summarize it. This allows to find flat areas in a very small number of operations.

To search for the largest area, the well-known distance map construction algorithm was used: for each marked point, the distance to the nearest border point in the 8-neighborhood was found. A point, the distance to which is maximum, and is the desired point – the center of the largest region. Doubled distance sets the size of this area.

The algorithm for calculating the distance map requires only two passes and is able to work in real time. The results are shown in Fig. 4(c).

Experiments have shown that the method allows you to select landing sites close to places manually selected by the operator. The results of the method turned out to be resistant to changing lighting conditions. For this, images of the same area were taken, obtained by various missions at different times. The method gives close positions for different sessions.

The method worked unstable in the case of presence of large shadow areas in the field of view (40% or more). In this case, not all shadow points were eliminated, and the method could select a shadow point because of the uniformity of the surrounding space. This is dangerous because of the positive feedback: once mistakenly choosing the landing area in the shadow, the device will begin to approach it, thereby increasing the number of shadow points in the field of view and more and more confident in its choice. For bright areas, a similar problem does not arise because of their strong texturing. Thus, to solve this problem, a more accurate shadow detection algorithm is required.

The operation of the method is also unstable in the case of the presence of structured interference. Such interference is often arising, for example, in linear cameras. Interference makes the image of the plains uneven, with a fairly substantial gradient. As a result, large flat areas are divided into parts, and the choice is between these parts. Such a mistake is not critical, but it degrades the quality of work, not allowing you to make the best choice. Because of this, there is a need for both identifying potential interference and filtering it, and adjusting the gradient averaging window.

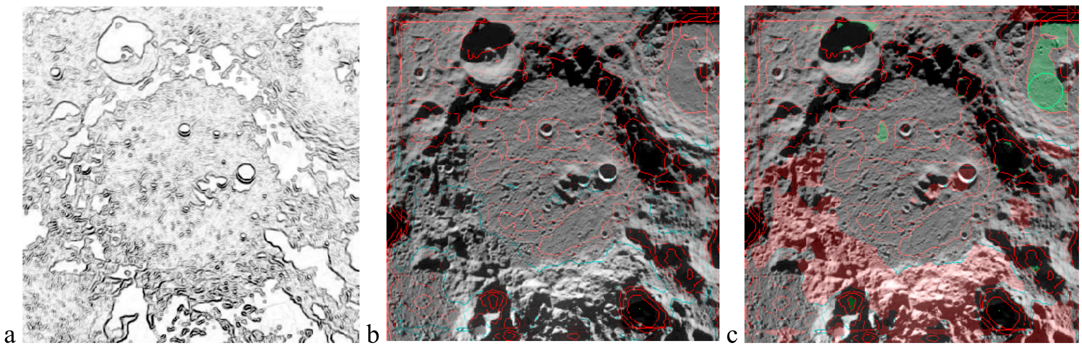

Fig. 4. Selection of points with the smoothest surface: (a) brightness gradient; (b) isolines of equal smoothness; (c) results of largest smooth area selection (green circle)

5. Conclusion

Two important elements of the computer vision system designed to ensure a safe soft landing on the moon were examined: a visual navigation system and a system for selecting the best landing site.

Possible approaches to the development of these systems were analyzed, algorithms for their operation were presented, and experiments were conducted to evaluate the reliability of their operation. The experiments showed that both algorithms can be successfully used to solve the problem under consideration and can function on modern on-board computers under the influence of various interfering factors.

Using a computer vision system is another step towards creating intelligent control systems that can deliver goods and equipment to the surface of the moon and planets in the desired areas and in areas with complex terrain, previously inaccessible for landing.

References

[1] Klumpp, A.R. (1974). Apollo Lunar Descent Guidance. *Automatica*, 10(2), pp.133-146.

[2] Razygraev, A.P. (1990). The method of terminal control of spatial motion during soft landing at a given point on the surface of the planet. In: *Fundamentals of flight control of spacecraft: a manual for technical colleges*. M: Machinostroenie, pp.378-386.

[3] Filimonov, A.B. and Filimonov, N.B. (2015). Methods of "flexible" trajectories in the tasks of terminal control of aircraft vertical maneuvers. In: *Problems of managing complex dynamic objects of aviation and space technology*. M: Machinostroenie, pp.51-110.

[4] Wang, Q. and Liu, J. (2016). A Chang'e-4 mission concept and vision of future Chinese lunar exploration activities. *Acta* Astronautica, 127, pp.678-683.

[5] Brown, L.G. (1992). A survey of image registration techniques. *ACM Computing Surveys*, 24, pp.326-376.

[6] Pupkov, K.A. and Neusypin, K.A. (1997). *Questions of the theory and implementation of control and navigation systems*. M.: Bioinform.

[7] Salamunićcara, G. and Lončarić, S. (2008). Open framework for objective evaluation of crater detection algorithms with first test-field subsystem based on MOLA data. *Advances in Space Research*, 42(1), pp.6-19.

[8] Jahn, H. (1994). Crater detection by linear filters representing the Hough Transform. In: *ISPRS Commission III symposium: Spatial information from digital photogrammetry and computer vision*. pp.427-431.

[9] Wei, Z. (2019). Shadow–highlight feature matching automatic small crater recognition using high-resolution digital orthophoto map from Chang'E Missions. *Acta Geochimica*, 38, pp.541-554.

[10] Rad, A.A., Faez, K. and Qaragozlou, N. (2003). Improvement of Fast Circle Detection Algorithm Using Certainty Factors. In: *VIIIth Australian and New Zealand Intelligent Information Systems Conference*. pp.101-108.

[11] Wang, H., Jiang, J. and Zhang, G. (2018). CraterIDNet: An End-to-End Fully Convolutional Neural Network for Crater Detection and Identification in Remotely Sensed Planetary Images. *Remote Sens.*

[12] Bobkov, A.V. and Yang, X. (2019). Methods of Visual Navigation in the Task of Moon Landing. In: *Procedia Computer Science*. vol.150, pp.201-207.