ISSN 0038-0946, Solar System Research, 2021, Vol. 55, No. 7, pp. 642–652. © Pleiades Publishing, Inc., 2021.
Russian Text © The Author(s), 2020, published in Vestnik NPO imeni S.A. Lavochkina, 2020, No. 3, pp. 10–20.

Active Braking for Soft Landing on the Surface of Mars: Part 2: Braking Control

A. E. Shirshakov[a, *], **I. A. Grudev**[a, **], **V. N. Likhachev**[a, ***], **and P. E. Rozin**[a, ****]
[a] Lavochkin Association, Khimki, Moscow oblast, Russia
*e-mail: Shirshakov@laspace
**e-mail: grudevia@laspace.ru
***e-mail: likhachev@laspace.ru
****e-mail: rozinpe@rambler.ru

Received July 10, 2020; revised July 10, 2020; accepted July 10, 2020

Abstract—The execution of a soft landing of an unmanned spacecraft on Mars' surface requires implementation of several technically challenging flight phases. The final one is an active braking using a steerable thrust jet engine. In this article we present an analysis of the flight environment before and during active braking, specify the composition of technical means for motion control, present one of the possible braking profiles, a sequence of the active braking modes, algorithms for guidance and control, and mathematical simulation results.

Keywords: gravitational acceleration, inertial navigation aids, attitude, guidance, control, thrust, braking engine

DOI: 10.1134/S0038094621070182

3. LANDER MOTION CONTROL DURING BRAKING ENIGINE OPERATION

The main task of steerable braking is to reduce the descent speed after separation of the parachute system and transfer the landing platform to the surface of Mars with the final motion parameters not exceeding the capabilities of the landing supports. The landing gear of the lander usually consists of three or four landing legs, supported by struts. To absorb the impact energy and maintain the stability of the lander on the ground after contact of the landing supports with the surface, the following requirements are necessary (Artem'ev et al., 2019):

— The vertical contact speed should not exceed 2–3 m/s.

— The horizontal speed should be no more than 1–2 m/s.

— The deviation of the longitudinal axis from the gravitational vertical should not exceed 7°. In this case, the possibility of landing and further maintaining a stable position of the spacecraft on the surface with a slope of up to 15° is being considered.

3.1. Descent Profile of the Lander

Summarizing the features of the lander descent under a parachute and taking into account the tasks of steerable braking, the following operations should be performed:

— Detachment of the aerodynamic screen, and liberation of the hemisphere for operation of the stabilization engines and DVDM, as a result.

— Opening of landing supports to fix them before future contact with the surface.

— Triggering the "damping" algorithms and operation for control of the stabilization engines to reduce the angular velocity of rotation of the lander to values not exceeding 0.5–2°/s, which will greatly facilitate the work of the DVDM during descent by parachute.

— Receiving information from the DVDM after jettisoning the aerodynamic screen to a sufficient distance.

— Correction and calculation of navigation parameters when using the DVDM information.

— Forecasting the moment of braking engine start and separating the protective casing with the parachute.

— Calculation of movement control and guidance algorithms.

— Control command generation for the propulsion system.

The moment of braking engine start is predicted as a function of the current values of altitude and vertical speed. The criterion for start to be satisfied is the suf-

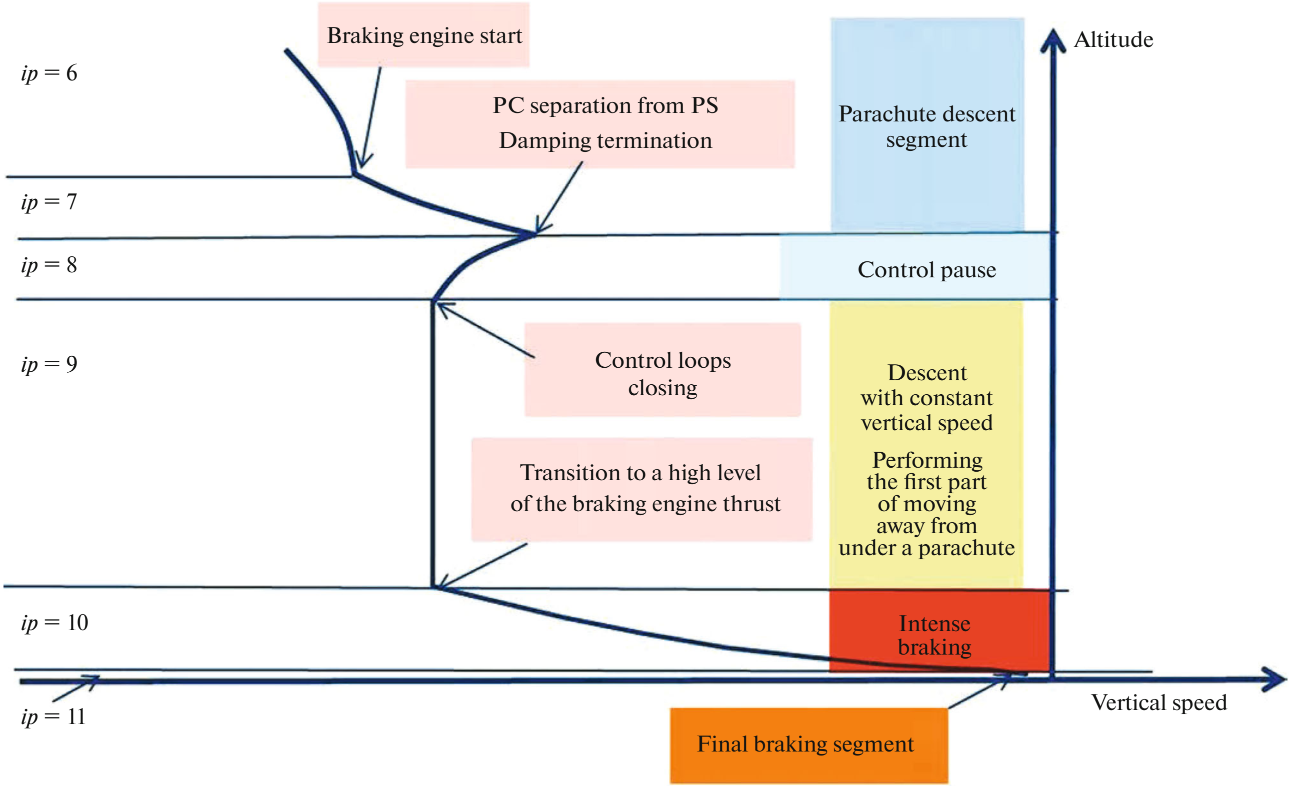


Fig. 7. "Landing" profile of the lander.

ficiency of the remaining height difference. This involves the following operations:

— Descent by parachute during the braking engine "warming-up" mode.

— Descent during 1 s after separation of the casing and parachute for their safe detachment with the lander (at the end of this time interval the control loop in the channel "height-vertical speed" and in "orientation-horizontal velocity component" channels is closed).

— Descending at a constant rate, fixed at the moment of closing control loops (fixed duration of the horizontal deflection speed interval).

— Descent with intense braking of the vertical and horizontal speed (the transition to intense braking is determined by reaching a certain ratio between height and vertical speed).

— Descent in the final segment until the lander contact with the surface.

Figure 7 shows the landing profile in the coordinates height and vertical speed.

The motion parameters at the moment when the braking engine is switched on into the warming-up mode are determined by:

— The spread of the angle of entry of the capsule into the atmosphere.

— The distribution of atmospheric density as a function of altitude.

— The aerodynamic characteristics of the capsule and their deviations from rated values.

— Algorithms for execution and parachute system characteristics.

— According to statistical calculations of trajectories of descent and landing at the time of separation of the casing with the parachute, the maximum horizontal speed is 25 m/s, the maximum vertical speed should be 45–65 m/s, and the minimum vertical speed is about 30 m/s. Accordingly, at this moment, for $n = 2$, the maximum height is 1000–1500 m, and the minimum, 600 m.

3.2. Algorithms for Navigation, Guidance and Control

At the "Landing" stage, the motion control task is implemented by the onboard computer in three software functional blocks:

— Navigation task unit.

— Guidance units.

— Control units.

The interaction of these units, as well as those for generating the commands and the means for their proper execution is shown in Fig. 8.

The algorithms for the navigation problem are not described in detail in this article. To control the movement, the blocks of the navigation task should perform the following basic functions:

— At each cycle in the interval of 5–10 ms, to receive information from the CLIU about changes in the angles of rotation of the spacecraft around the sensitivity axes of fiber-optic gyroscopes, evaluate the reliability of this information, process this information and perform a computational procedure for determining the orientation of the base axes of the lander in the landing coordinate system.

— To obtain information about the apparent velocity increment along the axes of sensitivity of the accelerometers (during the same intervals of 5–10 ms), to evaluate the reliability of this information, to perform calculations of the current parameters of the trajectory using the information on the orientation, and to assess the direction of the gravitational acceleration vector.

— To obtain information on the distance to the surface and the projection of the speed on each of the beams of the DVDM antenna system at each 50–200 ms cycle.

— Calculate the change in distance and speed for the two previous beams in the pause interval in their operation, taking into account changes in orientation and apparent speed.

— Calculate the height and projections of speed in the landing coordinate system using the recovered information in the polling pause for the two previous beams and the polling information of the current beam.

— Use this information to correct the results of calculating the trajectory parameters obtained using inertial information during the interval between polls of the DVDM beams.

— To form an array of navigation information in the landing coordinate system for the tasks of guidance and steering of the lander deceleration, where h is the navigation estimate of the height of the lander above the surface of Mars; Vr_{nav} is the navigation estimate of the vertical speed; Vx_{nav}, Vy_{nav} are the navigation estimates of the horizontal speed projections in the landing coordinate system; Q_{nav} is the quaternion of the lander orientation, and W_{nav} is an assessment of projections of its angular velocity.

The use of DVDM information at altitudes below 5–15 m is terminated when performing the navigation task, which should calculate further changes in the movement parameters only according to the CLIU information. This event only affects the change in navigation measurement errors, but not the deceleration software.

Table 1. Flags for stabilization engines starts

Flag of the moment			Stabilization engine number							
ix	*iy*	*iz*	1	2	3	4	5	6	7	8
−1	−1	−1	0	1	0	1	0	0	0	0
−1	−1	0	0	1	0	0	0	0	0	0
−1	−1	1	0	1	0	0	0	0	0	1
−1	0	−1	0	0	0	1	0	0	0	0
−1	0	0	0	1	0	0	0	1	0	0
−1	0	1	0	0	0	0	0	0	0	1
−1	1	−1	0	0	0	1	0	1	0	0
−1	1	0	0	0	0	0	0	1	0	0
−1	1	1	0	0	0	0	0	1	0	1
0	−1	−1	0	1	1	0	0	0	0	0
0	−1	0	1	1	0	0	0	0	0	0
0	−1	1	1	0	0	0	0	0	0	1
0	0	−1	0	0	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	1	1
0	1	−1	0	0	0	1	1	0	0	0
0	1	0	0	0	0	0	1	1	0	0
0	1	1	0	0	0	0	0	1	1	0
1	−1	−1	1	0	1	0	0	0	0	0
1	−1	0	1	0	0	0	0	0	0	0
1	−1	1	1	0	0	0	0	0	1	0
1	0	−1	0	0	1	0	0	0	0	0
1	0	0	1	0	0	0	1	0	0	0
1	0	1	0	0	0	0	0	0	1	0
1	1	−1	0	0	1	0	1	0	0	0
1	1	0	0	0	0	0	1	0	0	0
1	1	1	0	0	0	0	1	0	1	0

The navigation block forms the landing coordinate system (LCS), where information about the movement of the lander relative to the surface is accumulated. The LCS origin is placed on the surface of Mars, the Z_ℓ axis is also directed from the center of mass of Mars to its surface, the plane of the axes OX_ℓ and OY_ℓ is perpendicular to OZ_ℓ, while the direction of these axes is taken as the closest to the directions of the axes OY_b and OZ_b of a comoving coordinate system of the lander at this moment. In this case, the calculation of the trajectory is carried out based on the information of the CLIU, corrected by information from the DVDM so that the calculation of the trajectory continues in the absence of information from the DVDM.

The control is based on the principle of vertical landing, when the deviation of the longitudinal axis of the lander (thrust vector) from the gravitational vertical is limited to an angle of 25°–30° for the possibility of DVDM operation. The control is based on the navigation assessment of the flight altitude, vertical and horizontal speed and deviation of the longitudinal axis

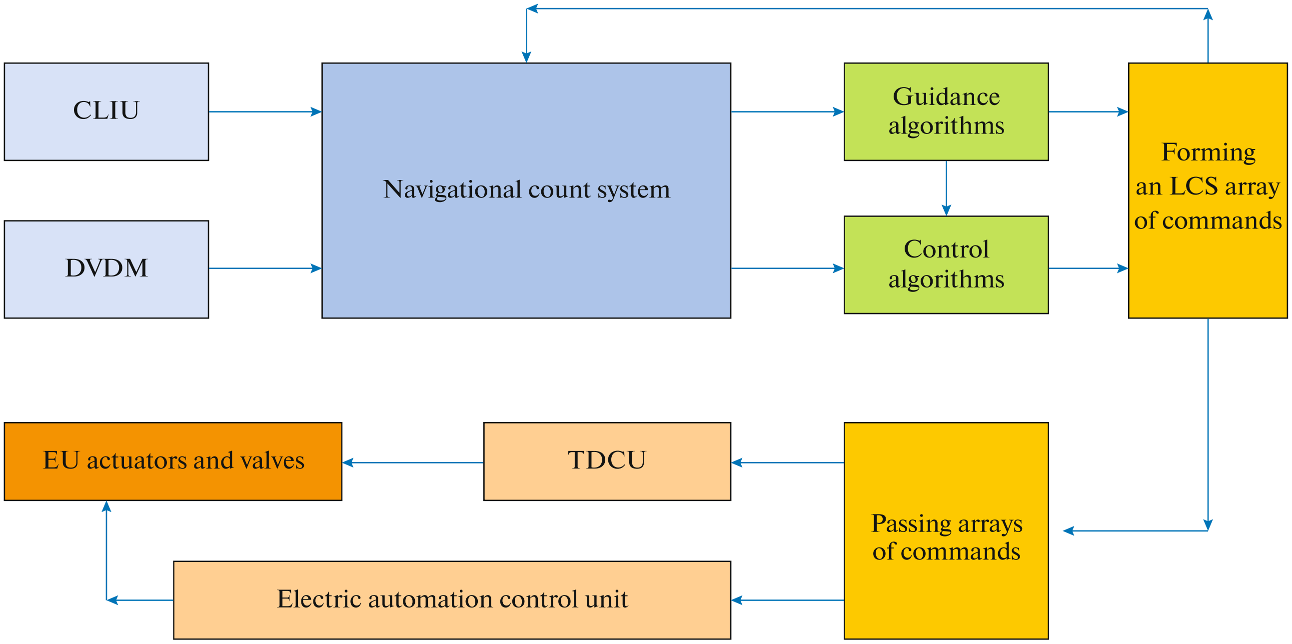


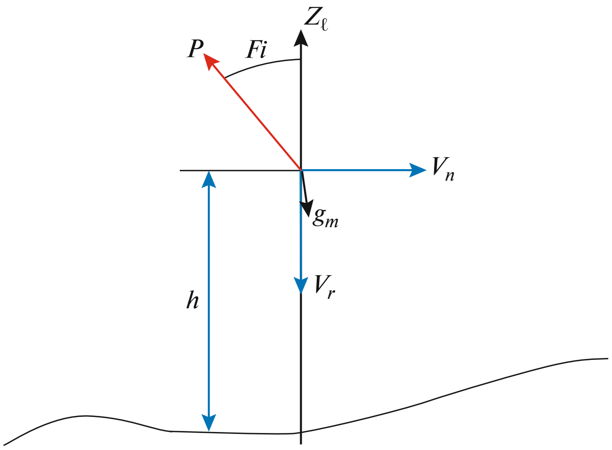
Fig. 8. Interaction layout of navigation, guidance and control units.

from gravitational vertical, formed by the navigation task of the control system.

Given the weak dependence of control by altitude and vertical speed from orientation of the thrust vector relative to the vertical, the guidance and control of altitude and vertical speed are performed regardless of the lander orientation and its horizontal speed. In accordance with this, control is formed in two channels:

— A control channel for height and vertical speed.

— A control channel for orientation and horizontal speed.



g_m—Free fall acceleration on the surface of Mars
Z_ℓ—Vertical axis of the landing coordinate system

Fig. 9. Scheme of movement of the gravitational vertical.

3.2.1. Control channel for orientation and horizontal speed. The braking engine is switched on at an altitude of about 1 km, while the lander movement along the surface does not exceed 1 km. Therefore, control can be performed under the assumption of a plane-parallel gravitational field, assuming the gravitational acceleration vector in the LCS to be constant. Fuel consumption during braking does not exceed 5–7% of the initial mass of the lander, therefore, when making decisions on control and guidance, the mass of the lander can be considered unchanged, leaving the effect of the true change in mass as a perturbing effect in the control loop.

Taking these assumptions into account, consider the scheme of the speed projections and braking engine thrust in the LCS shown in Fig. 9.

Here h is the SC height above the surface of Mars; Vn is the horizontal component of the SC speed; Vr is the vertical component of the velocity; P is the braking engine thrust; $Fi \equiv \varphi$ is the thrust vector angle of deviation from the vertical.

The equations of motion of the SC in the landing coordinate system in the plane of motion can be written in the form

$$\begin{gathered} dVr/dt = A\cos\varphi - g_m, \quad dVn/dt = A\sin\varphi, \\ dh/dt = Vr, \quad dm/dt = -P/Pud, \\ dVxar/dt = A, \end{gathered} \tag{2}$$

where $A = P/m$ is the acceleration created by the braking engine, $Vxar$ is the characteristic braking velocity, m is the lander mass, and Pud is the specific impulse of the braking engine.

Under the assumptions made and for zero value of the horizontal velocity, the system of equations of motion (2) has the form of differential equations with constant coefficients, which are integrated in the final form $ho - h = \dfrac{Vro^2 - Vr^2}{2(A - g_m)}$, where ho and Vro are the height and vertical speed at the moment of the braking engine start.

If at the termination of braking the conditions of an ideal contact of the lander with the surface are met, when the height and vertical speed simultaneously take zero values, then at a constant value of the acceleration created by the braking engines, the following relationship should be satisfied: $h = \dfrac{Vr^2}{2(A - g_m)}$. This ratio is transformed so that the required vertical speed is chosen as the programmed value as a function of the measured height

$$V_{\mathrm{pr}} = \sqrt{h_{\mathrm{nav}} A_{\mathrm{pr}} - g_m}, \tag{3}$$

where h_{nav} is the navigation assessment of altitude, A_{pr} is the constant programmed value of the apparent acceleration. To achieve ideal contact conditions, it is necessary that at each moment of time the navigation assessment of the vertical speed is equal to the programmed value in accordance with relation (3). However, during braking, there are errors in assessing the navigation parameters of vertical speed and altitude. A change in height can also be caused by the horizontal movement of the lander along a surface with variable relief height. To level such disturbances during braking in accordance with the deviation from the programmed value of the vertical speed $\Delta V_{\mathrm{pr}} = V_{\mathrm{nav}} - V_{\mathrm{pr}}$, it is necessary to regulate the apparent acceleration generated by the braking engine in accordance with relationship $A = A_{\mathrm{pr}} + S_{\mathrm{vr}} \Delta V_{\mathrm{pr}}$, where S_{vr} is the tuning factor of the vertical speed control algorithm. Apparent programmed acceleration A_{pr} should be chosen from the conditions of minimizing fuel consumption for braking and from the conditions of sufficient range of the braking engine thrust control.

Since the assessment of the real acceleration contains a high noise component caused by the vibrations from the engine, the engine thrust steering algorithm is based on changing the angle of rotation of the TCD depending on the deviation of the assessment of the vertical speed from the programmed value

$$Del(1) = S_{\mathrm{vr}} \Delta V_{\mathrm{pr}} + S_{\mathrm{int}} \int \Delta V_{\mathrm{pr}} dt + Del_{ip}, \tag{4}$$

where $Del(1)$ is the required TCD rotation angle; S_{int} is the tuning factor for the integral of vertical velocity deviation; Del_{ip} is the TCD rotation angle, corresponding to the nominal braking engine thrust on the corresponding control section.

3.2.2. Horizontal speed control. The main task of the control loop of altitude and horizontal speed after the braking engine start is to create the horizontal speed for the lander to move away from under the parachute, and in the region of intense deceleration, to zero the horizontal velocity by the time the lander contacts the surface. Controlling horizontal components of the velocity is possible only due to the deviation of the braking engine thrust vector from gravitational vertical by the angle φ. With ideal tracking of the braking program, the vertical component of the total acceleration from the braking engine in the first part of the maneuver is $A_r = g_m$. Then the horizontal component of acceleration in this part of the maneuver will be $A_{\mathrm{hor}} = g_m \tan\varphi$ and $A_r = A_{\mathrm{pr}}$ in the region of intense braking, and, accordingly, $A_{\mathrm{hor}} = A_{\mathrm{pr}} \tan\varphi$.

When performing a deviation maneuver, the optimal in terms of speed is the process with a fast transition to the maximum permissible angle of deviation from the vertical of a certain sign, and in the segment of intensive braking, with a fast transition to the limiting angle of the opposite sign. Assuming that the transitions to the limitation are performed with the maximum angular velocity W_{max}, then the equations of motion in the horizontal plane take the form

$$dV_n/dt = A_{\mathrm{pr}} \tan\varphi, \quad d\varphi/dt = W_{\mathrm{max}}.$$

Integration of this system with zero initial values of variables at the moment of reaching the value $\varphi = \varphi_{\mathrm{max}}$ gives the relation $V_n = A_{\mathrm{pr}} \ln(\cos\varphi_{\mathrm{max}})/W_{\mathrm{max}}$. In the first part of the maneuver at $\varphi_{\mathrm{max}} = 20°$ and $W_{\mathrm{max}} = 10°/\mathrm{s}$, the change in the horizontal speed at the moment of reaching the orientation angle limitation is V_n = 1.33 m/s, while for $A_{\mathrm{pr}} = 2g_m$ one obtains $V_n = 2.65$ m/s. If the duration of the first part of the maneuver is $t_{\mathrm{man}} = 12$ s, then the process of changing the angle of orientation of the lander relative to the gravitational vertical after closing the control contours will have the form shown in Fig. 10. The change in the horizontal speed is also shown in this figure.

The integral of the horizontal speed will correspond to the distance of the lander deviation maneuver from the point of the separation of the casing with the parachute. For the given process, the deflection distance is $L = 127$ m, which creates a margin of more than 50% of the required value. Thus, the duration of the first part of the deflection maneuver should be at least $t_{\mathrm{man}} = 12$ s, while the maximum horizontal velocity component should have the value about 15 m/s.

To obtain a process close to that shown in the figure, it is possible to use a proportional control law with the formation at each control cycle of the required value of the orientation angle, $Fi_{\mathrm{pr}} = k\nu n(Vn_{\mathrm{nav}} - Vn_{\mathrm{pr}})$, where the value $Vn_{\mathrm{pr}} = 15$ m/s should be accepted as the required value of the design horizontal speed, if $t < t_{\mathrm{max}}$, or $Vn_{\mathrm{pr}} = 0$ otherwise. To compensate for the perturbing torque from the thrust eccentricity of the braking engine, the integral of the deviation should be

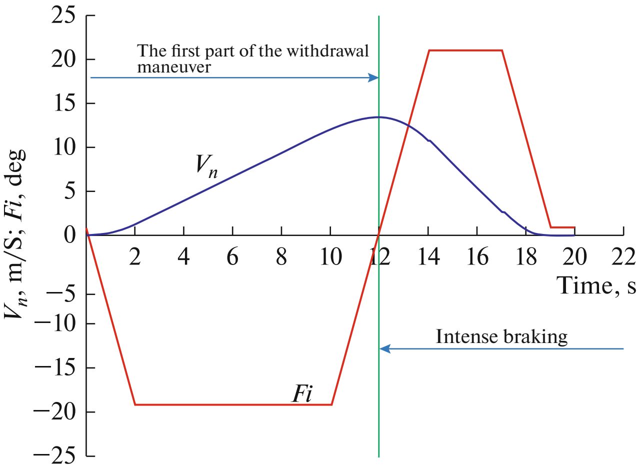


Fig. 10. Typical change of orientation and horizontal speed during the deflection maneuver.

introduced into the control algorithm of the navigation horizontal speed value from the programmed value.

The implementation of the deflection maneuver, on the one hand, depends on the vertical component of the acceleration required for operation of the “height—vertical speed” channel. At the same time, it affects this channel operation, increasing the acceleration modulus due to deflection of the braking engine thrust vector from the gravitational vertical by an angle of the order of 20° without a change in the vertical acceleration component.

3.2.3. Final braking segment. Since the navigation estimates of the height and vertical speed always contain errors, then the completion of intensive braking at zero altitude at zero vertical speed is almost impossible. The lander will either collide with the surface or start moving away from the surface at a positive vertical speed. In addition, due to the short duration of intense deceleration and the high angular rate of change in the angular motion, the transient processes in the orientation—horizontal velocity channel do not have time to complete by this moment. Therefore, to complete them and to reach a well-defined vertical contact speed, the final segment of the lander descent is introduced with a constant or little changing vertical descent speed. In this case, the achievement of contact and the stability of the vertical speed at this moment are guaranteed.

When descending at a constant speed, the thrust of the braking engine in the nominal case should balance the Martian weight of the lander. But at the same time, before moving to this segment of the trajectory, the thrust of the braking engine should correspond to the intense braking program, that is, exceed the Martian weight by $n = 2$–2.5 times. There is, obviously, a need to introduce a transient mode of engine thrust control. This can be accomplished by introducing a new vertical speed change program. For example, instead of relation (3) for a programmed speed, a new ratio $V_{\text{pr1}} = V_k + \Delta V$ is introduced, where V_k is the average vertical speed of the landing device from the allowable range. ΔV should vary smoothly with time, reaching zero by the time the speed V_k is reached. In this case, its initial value can be equal to the calculated change in the vertical speed during transition from the thrust of intense braking to the thrust that balances the Martian weight of the lander. It is quite natural that the introduction of such a segment of the trajectory will lead to additional fuel consumption, but guarantees a successful landing of the SC with the parameters of movement admissible for the landing device. The transition to this segment should be performed at the moment when the programmed value of the vertical speed, calculated by relation (3), becomes equal to or less than V_{pr1}.

3.2.4. The structure of the guidance and control algorithms. Algorithms for guidance and control should form the flags (requirements) for the execution of commands to control the TCD and TCC drives and start the stabilization engines. The dispatcher for issuing commands of the onboard computer transmits these commands, and their execution is carried out by the electrical automation units of the lander and the drive control unit (DRU) for regulating the thrust of the braking engine and its chambers.

Guidance and control algorithms are implemented in four software blocks: UPR, C_1, C_2, C_3. The TMI subroutine forms an array of telemetric information about the operation of these algorithms.

The UPR program block contains algorithms for guidance and control of the “height-vertical speed” channel. It forms the flags of a change of events (*ip* = 1–11) that implement the braking profile of the lander, a sequence diagram of the change of operations and changes in the numerical parameters of the altitude and vertical speed control algorithms, as well as the parameters of algorithms for controlling the orientation and horizontal speed. At *ip* = 1, the segment of the PS descent is implemented until the formation of the flag for issuing the command “Separation of the aerodynamic screen” (AS); at *ip* = 2, the descent segment is implemented from the moment of issuing the command “AS separation” to the moment of generating the flag for issuing the command to deploy the landing gear; at *ip* = 3, the descent segment of the PS from the moment the command is issued to deploy the landing gear to the formation of a flag for the start of damping; in the same segment, the drive TCD (TCD(1)) is transferred to the position Del_PRT(1) = Del1 specified for warming-up. At *ip* = 4, the descent segment of the PS is implemented from the moment of the formation of the flag “Damping” to the moment of the formation of the flag for issuing the command to switch the DVDM into measurement mode; at *ip* = 5, the descent segment is implemented from the moment of issuing the command to switch the DVDM to measurement mode until the flag for the navigation task transition to relative navigation mode (using reliable information from the DVDM).

Flags of the events presented above are formed according to a rigid time cyclogram, the onset of which corresponds to the moment the parachute is deployed. The following flags and changes of events are formed on the basis of certain functionals.

At *ip* = 6, the descent segment on PS is implemented from the moment of receiving from the navigation task the flag of reliable information from the DVDM until the formation of the flag for issuing the "Start" command to turn on the braking engine in the thrust mode, ensuring its warming-up. Flag *ip* = 6 is formed in accordance with the following procedure:

— The projected height is calculated, which is required for turning on the braking engine

$$h_{\mathrm{tr}} = h_k + (t_{\max} + dt_{\mathrm{tr}})|Vr_{\mathrm{nav}}| + 0.5V^2\, r_{\mathrm{nav}}/(A_{\mathrm{pr}} - g_m).$$

— The time interval before the command is issued to turn on the braking engine is estimated

$$dt_{tr} = (h - h_{tr})/|Vr_{\mathrm{nav}}|,$$

where h_k is the height needed for the intense braking termination, t_{man} is the duration of the first part of the withdrawal maneuver, dt_{tr} is the duration of operations from the command "Start" to closing the control loops. Flag *ip* = 6 is formed if inequality $dt_{\mathrm{tr}} < 0$ is met on three control cycles. At *ip* = 7, the segment of an uncontrolled descent under a parachute (with a given duration) is implemented from the moment of issuing the command "Start" to issuing the command to detach the casing with the parachute. At *ip* = 8, the segment of a given descent duration is implemented from the moment when the command is issued to separate the casing, to the formation of a flag for the control loop closure for the drives TCD, TCC1, TCC2. At *ip* = 9, the descent segment is implemented from the moment of closing the control loop of the drives TCD, TCC1 and TCC2, to the formation of a flag for transition to intense braking; in the same segment, the first stage of the deflection maneuver is performed. At *ip* = 10, the segment of intense braking from the moment of the onset to the formation of a flag for transition to the final braking segment is implemented. Flag *ip* = 10 is formed in accordance with the following procedure:

— The projected height of intense braking is calculated

$$h_{\mathrm{it}} = h_k 0.5 + V^2 r_{\mathrm{nav}}(A_{\mathrm{pr}} - g_m).$$

— The time interval before intense braking is estimated

$$dt_{\mathrm{it}} = (h - h_{\mathrm{it}})/|Vr|, \text{ and if } dt_{\mathrm{it}} < 0 \text{ then } ip = 10.$$

At *ip* = 11, the final braking segment is implemented. Flag *ip* = 11 is formed in accordance with the following procedure:

— The programmed vertical speed of the final braking is estimated

$$V_{\mathrm{pr1}} = V_{cpc} + \Delta V_0, \text{ and if } V_{\mathrm{nav}} \le V_{\mathrm{pr1}} \text{ then } ip = 11. \quad (5)$$

During the execution of the final segment, the value $V_{\mathrm{pr}} = V_{cpc} + \Delta V$ is taken as the programmed vertical speed, where $\Delta V = \Delta V_0 e^{-t/T}$; *t* is the time from the moment of transition to the final segment; the values ΔV_0 = 2–3 m/s, *T* = 0.5–0.7 s should be chosen for a specific lander.

The command "Stop" of the braking engine is generated according to the signals of actuation of the surface touch sensors mounted on each landing support. Each touch sensor must be duplicated. The output information of the sensors is analog, it bypasses the onboard computer and enters directly into electrical automation units. To prevent false triggering of the touch sensors, the activation of information processing from them starts after termination of the DVDM use. At the onset of this processing, the state of all touch sensors is interrogated, and a map of this state is drawn up. The electroautomatic system issues the "Stop" command only when the state of any of the sensors changes.

The braking engine thrust control is provided by turning the output shaft of the TCD. The command value of the TCD angle is determined by the relationship

$$Del(1) = S_{\mathrm{vr}}(Vr_{\mathrm{nav}} + V_{\mathrm{pr}}) + Del_o,$$

where S_{vr} is the tuning parameter for each segment with *ip* = 9, 10, 11; V_{pr} is the vertical speed programmed value. For *ip* = 9, it equals the modulus of Vr_{nav} at the moment of closing the control loops, for *ip* = 10 it is determined from

$$V_{\mathrm{pr}} = \sqrt{0.5(h_{\mathrm{nav}} - h_k)/(A_{\mathrm{pr}} - g_m)},$$

and for *ip* = 11, from (5).

The UPR software block generates a cyclogram of basic operations shown in Fig. 11. Program block C_1 is triggered 5 s after the separation of the aerodynamic screen, when it becomes possible for the stabilization engines to operate. It generates the enable flags $ip_{dmt}(j) = 1$ or $ip_{dmt}(j) = 0$ of each LTE with numbers $j = 1, ..., 8$ and the required duration of their activation. Figure 12 shows the damping algorithm scheme. On each control cycle, the damping algorithm performs the following operations.

First, the values $ip_{dmt}(j) = 0$ are set for $j = 1, ..., 8$. Next, if $Wz > 2°/s$, then $ip_{dmt}(j) = 1$, $dt_{dmt}(j) = dt_{dmt}\_\max$ for $j = 1, 3, 5, 7$ (zone 1);

if $Wz < -2°/s$, then $ip_{dmt}(j) = 1$, $dt_{dmt}(j) = dt_{dmt}\_\max ip_{dmt}(j)$ for $j = 2, 4, 6, 8$ (zone 2);

if $0.58/s < Wz < 2°/s$, then $ip_{dmt}(j) = 1$, $dt_{dmt}(j) = dt_{dmt}\_\min$ for $j = 3, 7$ (zone 3);

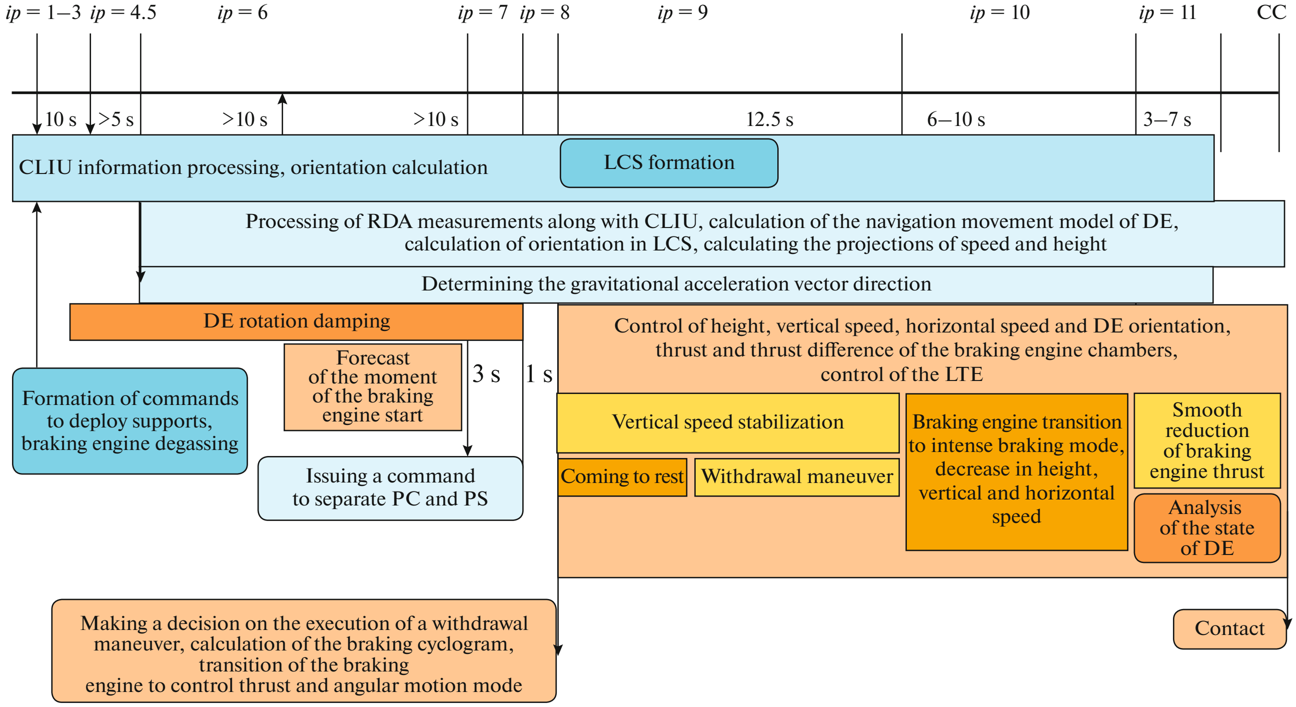


Fig. 11. Cyclogram of basic operations.

if $-0.5°/s > Wz > -2°/s$ then $ip_{dmt}(j) = 1$, $dt_{dmt}(j) = dt_{dmt}\_\min$ (zone 4).

When $ip_{dmt}(j) = 1$, the electroautomatic units of the lander must supply voltage to the electro-pneumatic valve of the corresponding stabilization engine. At the end of the indicated duration, the voltage should be removed by these blocks, unless a new command to turn on was received at this control cycle.

Program block C_3 is intended for the generation of control flags in the orientation–horizontal speed channel. Drives for regulating the difference between the thrust chambers of the braking engine and stabilization engines can be simultaneously used as actuators of pitch and yaw orientation control channels.

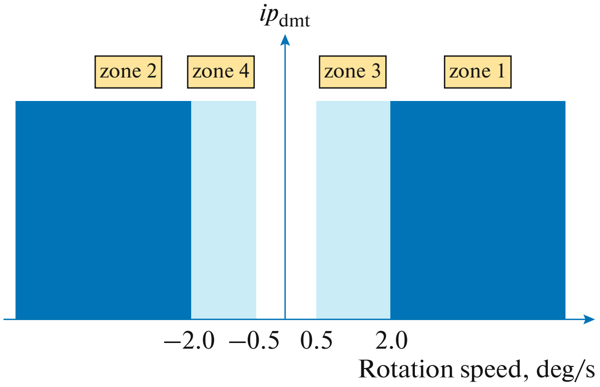


Fig. 12. Damping algorithm diagram.

The C_3 program block uses the following navigation parameters:

— Orientation quaternion.

— Navigation assessment of the angular speed projections.

— Navigation assessment of the horizontal speed projections.

The required values of the deviation angles *Fx*, *Fy* of the lander from the vertical are determined by expressions

$$Fy = -S_{vy}(Vx - Vnx_{\rm pr}),$$

$$Fx = S_{vx}(Vy - Vny_{\rm pr}),$$

$$Fi = \sqrt{Fx^2 + Fy^2};\quad ex = Fx/Fi;\quad ey = Fy/Fi,$$

where S_{vx}, S_{vy} are the conversion factors of the horizontal velocity projections in the landing coordinate system into the required projection angles of the deviation from the vertical; *ex*, *ey* are the direction cosines of the lander longitudinal axis orientation in the landing coordinate system; $Vnx_{\rm pr}$, $Vny_{\rm pr}$ are the horizontal velocity projections required when performing the deflection maneuver. The indicated parameters are formed by the UPR subroutine for segments *ip* = 9, 10, 11. The projections of the required deflection angle are normalized if the total required angle exceeds the specified limit $F_{\max}$. The value $F_{\max} = 15°$ is accepted taking into account the limitation of the operability range of the DVDM and the expected dynamic control error. The required (programmed) value of the horizontal speed is set to zero if the horizontal speed modulus exceeds $Vn_{\min} = 8$ m/s. At such a horizontal speed, the protective casing with the parachute during the descent will get away from the landed capsule at a distance significantly exceeding a permissible value. In other cases, the programmed value of the horizontal speed $Vn_2 = 15$ m/s is accepted. In most trajectories, this speed is not achieved during the maneuver, but the transients are accelerated. One point five seconds before the forecasted transition to intense braking, the program values are assumed to be zero: $Vnx_{\text{pr}} = Vny_{\text{pr}} = 0$. From this moment, the horizontal speed gained starts to decrease.

Depending on the required orientation angles, a program quaternion (Q_{pr}) is formed: $Q_{\text{pr}}(0) = \cos(Fi/2)$, $Q_{\text{pr}}(1) = \sin(Fi/2)ex$, $Q_{\text{pr}}(2) = \sin(Fi/2)ey$, $Q_{pr}(3) = 0$. The quaternion *Pe* of the lander orientation deviation from the programmed one is defined as the quaternion product of the conjugate quaternion of the current orientation (Q_{nav}) and the quaternion of the desired orientation (Q_{pr}). Given the relative smallness of the lander deviation angles from the required orientation, their values (Er_i) are estimated by the approximate relations:

$$Er_x = 2\times Pe(0)\times Pe(1);\quad Er_y = 2\times Pe(0)\times Pe(2);$$
$$Er_z = 2\times Pe(0)\times Pe(3).$$

The required angle of rotation of the TCC braking engine is formed in accordance with expressions

$$Del\_PRT(2) = -K13$$
$$\times\left(\left(Sn_y(Et_y Rad + Ty(Wy_{\text{nav}} - Wy_{\text{pr}})) + Sy\int Er_y dt\right)\right.$$
$$\left. + \,DelK13\_0\right);$$
$$Del\_PRT(3) = -K24$$
$$\times\left(\left(Sn_x(Et_x Rad + Tx(Wx_{\text{nav}} - Wxy_{\text{pr}})) + Sx\int Er_x dt\right)\right.$$
$$\left. + \,DelK24\_0\right),$$

where $Del\_PRT(2)$ is the required rotation angle of the TCC, regulating the thrust difference of chambers 1 and 3 of the braking engine; $Del\_PRT(3)$ is the required rotation angle of the TCC, regulating the thrust difference of chambers 2 and 4 of the braking engine; Er_x and Er_y are the deviations of the lander orientation angle from the specified values; Wx_{pr} and Wy_{pr} are the programmed (required) angular speeds of the lander; *Snx*, *Sny*, *Tx*, *Ty*, *Sx*, *Sy* are the algorithm settings generated by the UPR subroutine for segments *ip* = 9, 10, 11.

The stabilization engines play an auxiliary role in controlling the orientation of the pitch and yaw channels and they are switched on when the dynamic control error exceeds a certain level, for example, 3°. Maintaining the specified orientation in the rotation channel in all segments of the active braking is provided by the stabilization engines. In the algorithm for engine start, after closing the control loops, the usual proportional-differential control law is used. If the deviation from the given orientation (Er_i) in the corresponding control channel exceeds the dead zone area, then a flag for the control torque issuing (*ix*, *iy*, *iz*) of the corresponding sign is formed.

Each stabilization engine can generate a control torque along each of the lander axes, therefore, to minimize channel disturbances, a certain combination of their start times is formed, presented in the table below.

In accordance with the presented table, the program block C_2 generates the on/off flags of each low-thrust engine (LTE).

3.3. Modeling the Processes of Steerable Braking

In accordance with the guidance and control algorithms, a mathematical program was developed for modeling the processes of the SC landing from the moment of separation of the protective casing with the parachute to the contact of the landing supports with the surface. As a result, we implemented a spatial model of the lander movement in a plane-parallel gravitational field of Mars, software blocks for guidance and motion control have been introduced, the model of the lander itself, including the layout of the braking engine chambers, nozzles of the stabilization engines, mathematical models of the dynamics of the drives and the braking engine thrust.

Based on the results of theoretical developments and mathematical simulation, the selection of the settings of algorithms for each braking segment was carried out. When analyzing the performance of guidance and control algorithms, of particular interest are trajectories with the maximum horizontal speed at the time of separation of the casing with the parachute. In this case, the braking of the lander with a minimum (by modulus) vertical speed is performed for the smallest interval of braking engine operation, and it is necessary to check the fulfillment of the requirement to reduce the horizontal speed to permissible limits at the moment of contact of the landing supports with the surface. For such a trajectory, $Vr_0 = -33$ m/s and $Vn_0 = 20$ m/s. Figures 13–17 show the plots of changes in the parameters of the movement in such a case when a number of perturbing factors prevent the horizontal speed from decreasing.

In this and subsequent figures, the initial time for the casing detachment with the parachute is conventionally assumed to be 100 s.

From the analysis of the graphs it follows that for a given trajectory under the conditions of an unfavorable combination of angular velocity at the moment of

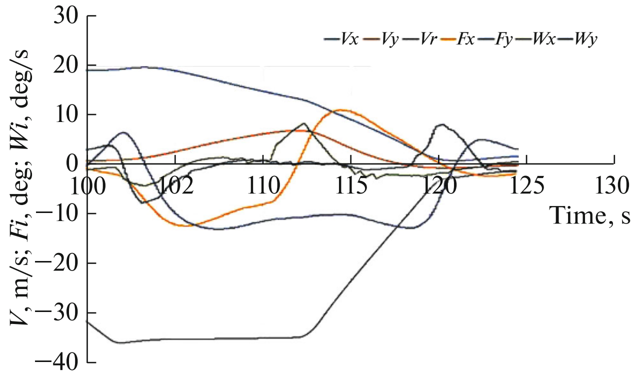


Fig. 13. Variation of the motion parameters.

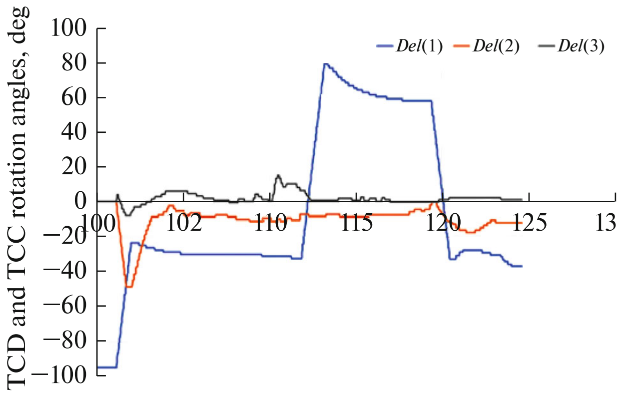


Fig. 14. Variation of the TCD and TCC angles.

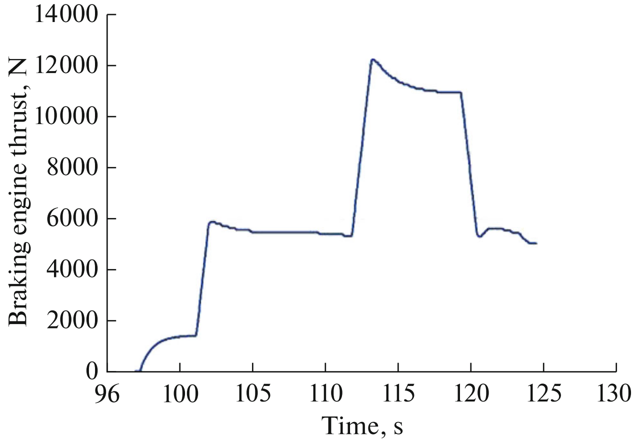


Fig. 15. Thrust variation.

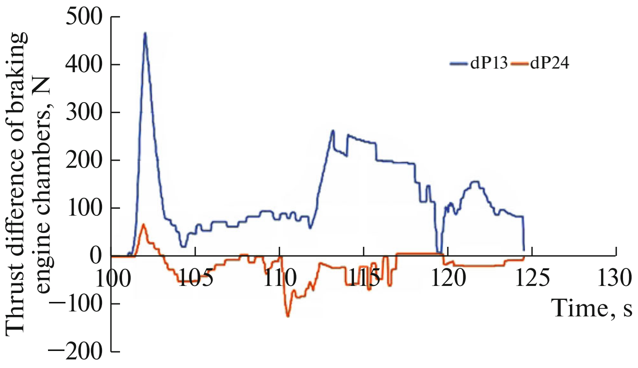


Fig. 16. Thrust difference of braking engine chambers.

separation of the casing with the parachute (7°/s), the deviation of the center of mass by 0.01 m from the thrust vector and the navigation error of orientation of 2°, the developed algorithms ensure the implementation of the horizontal speed requirements ($Vn = 1.65$ m/s) and other motion parameters at the moment the landing supports contact the surface. In this case, the process of decreasing the horizontal speed is performed at angles of deviation from the gravitational vertical of the order of 10°. After separation of the casing, a difference in the thrust of the braking engine chambers up to 500 N may be required, and the static deviation of the TCC angle to exclude thrust eccentricity can be of the order of 10°.

To check the fulfillment of the requirement for the distance of the lander from the separation point with a protective casing (PC) and a parachute system (PS), Fig. 17 shows the simulation results under the same conditions, but at an initial horizontal speed of 1 m/s. On this trajectory, all the requirements for the parameters of motion for the moment of the SC contact with the surface of Mars are fulfilled. The distance of the lander from the point of the separation with PC and PS in unfavorable conditions will be 87 m.

Trajectories with a higher (in absolute value) initial vertical speed are less critical to the dynamic parameters, but they require a higher altitude at the moment

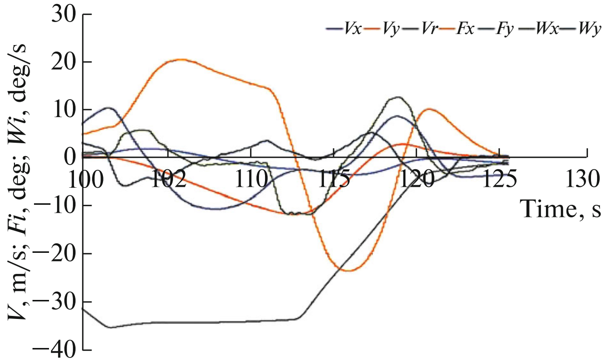


Fig. 17. Performing withdrawal maneuver for $Vn_0 = 1$ m/s.

of the PC separation from the PS (about 1 km) and determine the fuel reserve for braking.

CONCLUSIONS

(1) A landing profile is proposed that takes into account the specifics of the conditions for the descent of the landing module before starting the braking engine and providing the necessary conditions for the operation of the Doppler radar speed-and-distance meter.

(2) The composition and characteristics of the propulsion system for performing the braking tasks for a soft landing on the surface of Mars are substantiated.

(3) Algorithms for guidance and motion control of the lander have been developed, which provide a steerable braking while fulfilling the requirements for the motion parameters at the moment of contact of the landing supports with the surface.

(4) Mathematical simulation of active braking surfaces of the lander after the parachute separation using the proposed guidance and control algorithms showed the feasibility of a soft landing on the surface of Mars with the motion parameters at the moment of contact that are within the acceptable limits of the landing gear.

REFERENCES

Artem’ev, A.V., Bykov, A.I., Rykov, E.V., and Markachev, N.A., Modeling the processes of soft lunar landing of a spacecraft. Development of means and methods of ground testing using the dynamics of a similar spacecraft model, 2019, no. 1, pp. 31–38.

Translated by G. Dedkov