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Neural network control of automatic height reduction of the transport helicopter when observe focus of landing place

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Abstract: *To choose a trajectory to reduce the helicopter's height, providing the continuous control of a landing place with the onboard television chamber's help is considered. Neuron realization of management by the wobble plate and is offered by the collective pitch of the screw of the helicopter*
In many transport tasks carried out by a helicopter in difficult weather conditions [1], it is advisable to use automatic devices to help the crew, in particular, for the delivery of cargo and its landing, as shown in Fig. 1.
In Figure 1, H_0 and x_0 are the initial coordinates of the descent trajectory, H_k is the specified final height above the landing site for the drop of the cargo, x_1 and x_2 are the coordinates of the landing landmarks, ψ_1 and ψ_2 are the viewing angles of landmarks 1 and 2 on the TV camera screen, formed between the optical axis cameras and directions to each of the landmarks.
The problem of dropping a load suspended on a cable was already considered in [1], where neural network control efficiency is shown. This paper examines the previous stage of automatic descent to the landing site with continuous tracking using an onboard television camera.
This considers the peculiarity of helicopter control in two ways - using the swashplate and changing the total pitch of the propeller.

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I. Statement of the problem

Consider the solution to the problem of the automatic reduction under the following assumptions.

1. It is believed that the helicopter, performing a horizontal flight at a given altitude $H_0 >> H_k$ gradually approaches the landing site. In this case, the initial value of the x0 coordinate is commensurate with H_0 when, with the help of an onboard television camera, a landing site is detected on the screen, and notable landmarks are recognized. The problem of automatic detection and recognition is not considered in this work.

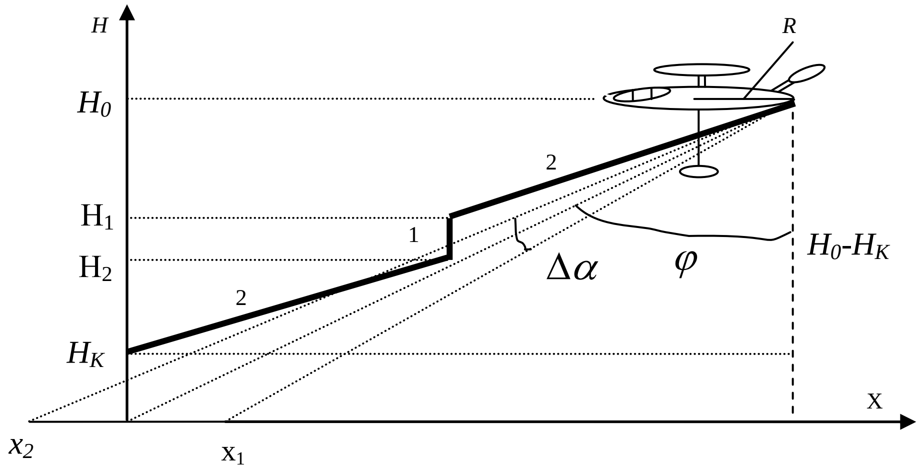


Figure 1. *Trajectory to reduce the helicopter's height*

2. The television camera is rigidly attached to the helicopter body to provide a certain angle during horizontal flight, observation of ground landmarks, and hence the corresponding bearing φ equal to the angle between the direction to the landing site the longitudinal axis of the helicopter. In this work, two landmarks in the longitudinal plane are used, having the given coordinates x_1 and x_2 relative to the landing point. The angular positions ψ_1 and ψ_2 of these landmarks on the camera screen give information about the movement's success to the desired landing point. If the modules of these angles and their angular velocities are equal, then the helicopter velocity vector is directed to the meeting point. Bearing φ with the helicopter's horizontal position

and the field of view of the camera should be chosen so that, taking into account the dynamics of the helicopter's descent, the landing site's image does not leave the field of view of the camera.

3. The task is to lower the helicopter to a given height H_k while reducing the height H and the x coordinate. Only the longitudinal motion of the helicopter is considered; at the same time, two methods of descent are different and can be used - vertical with the help of a common pitch of the propeller (section 1 is shown in Fig. 1 with a continuous line) and the so-called gentle with the help of the swashplate, when the deviation in pitch does not exceed (section 2 is also shown as a solid line in Fig. 1). Therefore, it is necessary to find a combination of different descent sections so that at the end of the flight with $H_k << H_0$, hovering" over the landing site for airborne cargo.

4. The dynamics of the longitudinal motion of the helicopter is described using the following differential equations:

$$\dot{x} = A * x + B * u \qquad (1)$$

with $x=[V_x \ V_y \ \omega_z \ \vartheta]^T$ $A=\begin{bmatrix} X^{V_x} & X^{V_Y} & X^{\omega_Z} & X^{\upsilon} \\ Y^{V_Y} & Y^{V_Y} & Y^{\omega_Z} & Y^{\upsilon} \\ M_z^{V_Z} & M_Z^{V_Y} & M_Z^{\omega_Z} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$ $B=\begin{bmatrix} X^{\delta} & X^{\varphi} \\ Y^{\delta} & Y^{\varphi} \\ M_Z^{\delta} & M_Z^{\varphi} \\ 0 & 0 \end{bmatrix}$ $U=[\delta \ \varphi]^T$

δ, φ - the angles of deflection of the swashplate in the longitudinal plane and the total pitch, respectively.
5. It is necessary to take into account the complicating observation of the effect of the angular rotation of the helicopter both with a gentle and vertical descent and hence the angular rotation of the line of sight of the camera, in the field of view of which the seat is located with a changing bearing.
6. Under these conditions, it is necessary:
- find the programmed descent trajectory.
- form the laws of flight control and get examples for training neural networks.
- to determine the structure and parameters of neural networks and evaluate their effectiveness.
- to give recommendations on installing a television camera for continuous monitoring of the implementation of transport tasks.

II. Choice of descent trajectory

Taking into account the fact that, $\frac{H_0}{H_k} << 1$, and $\frac{X_0}{H_0} \approx 1$, it becomes clear that the helicopter descent cannot be carried out in one way - neither flat nor vertical. Therefore, there should be several such sections, as shown in Fig. 1.
This means that the camera's bearing φ and the mean tilt angle of the selected trajectory must be close to each other.
Therefore, given the specific values of H_0 and H_k of the initial and final heights, as well as the size R (see Figure 1), determined by the length of the helicopter body and equal to the distance from the center of gravity of the helicopter to the place where the camera is attached, the following simple calculations can be carried out.
Let the height H_k = 20m, H_0 = 100m, required for the landing of the cargo; size R = 10m. The bearing of a rigidly fixed camera can be taken φ = 0.5 rad, the angle of inclination of the trajectory can be taken when considering the field of view of the camera Δα = 0.6 rad. In this case, the initial coordinate x_0 will be equal to:

$$X_0=(H_0-H_\kappa)*tg(\frac{\Pi}{2}-\frac{1}{2}\Delta\alpha-\varphi)=75m \qquad (2)$$

To gradually reduce to zero the values of x_0 and H_0-H_k, it is necessary to "dock" the programmed trajectory from many gentle and vertical descent sections, since the helicopter's capabilities in pitch deflection are limited. In this case, the landing site should not leave the field of view, for example, its initial value $\Delta\alpha = 20^0$, refining it later, taking into account the camera's angular vibrations.
Calculations have shown that the programmed trajectory consists of the following sections:
- a gentle decline to a height of H_1 = 77.5 m.
- vertical descent to the height H_2 = 42.5 m.
- a gentle descent to the final height H_k = 20m, sufficient for the landing operation.

The programmed path requires two control algorithms - a swashplate for shallow sections and a common pitch for vertical sections.

III. Neural network algorithm for controlling the total pitch of the propeller with vertical descent

Consider three steps in finding this algorithm:

- considering the measurements of the angles ψ_1 and ψ_2 of the observation of landmarks as known, a control signal is calculated proportionally to the angular velocity of the line of sight directed to the landing site (q is the angle between the horizon lines and the direction to the given landing point, for example, the hold of the ship).
- the law of control of the total pitch of the screw is formed, and with its help, examples are formed for training the neural network;
- a two-layer neural network is trained, the structure of which was chosen in [1], and as a result of computer simulation, an assessment of its performance is given.

The diagram of the observation of landmarks with a vertical descent presented in Fig. 2 allows, following the theorem of sines, to obtain the following approximate dependence of the angle q on the measured angles ψ_1 and ψ_2

$$q=-\frac{R(\psi_1-\psi_2)-x_1(\varphi-\psi_2)-x_2(\varphi-\psi_1)}{r(\psi_1-\psi_2)(1+(\varphi-\psi_1)(\varphi-\psi_2))} \tag{3}$$

R is the current distance between the helicopter and the drop point; The formula is obtained under the simplifying assumption that x0 << H0.

Differentiating expression (3), the researcher can obtain the desired estimate for the angular velocity

$$\begin{aligned}
\dot{q}=&-\Big(\frac{1+(\varphi-\psi_1)(\varphi-\psi_2)(\varphi-\psi_2)(x_1+x_2)}{r_i(\psi_1-\psi_2)^2[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}+\\
&+\frac{(\psi_1-\psi_2)[\psi_1(R+x_2)+\psi_2(x_1-R)-(x_1+x_2)\varphi]}{r_i(\psi_1-\psi_2)^2[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}\Big)\dot{\psi}_1+\\
&-\Big(\frac{1+(\varphi-\psi_1)(\varphi-\psi_2)(x_1+x_2)(-\varphi+\psi_1)}{r_i(\psi_1-\psi_2)^2[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}+\\
&+\frac{(\psi_1-\psi_2)[\psi_1(-R+x_2)+\psi_2(x_1-R)-(x_1+x_2)\varphi]}{r_i(\psi_1-\psi_2)^2[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}\Big)\dot{\psi}_2+\\
&+\Big(\frac{(X_1+X_2)(\psi_1-\psi_2)[1+(\varphi-\psi_1)(\varphi-\psi_2)]}{r_i(\psi_1-\psi_2)[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}+\\
&+\frac{[\psi_1(R+X_2)+\psi_2(X_1-R)-(x_1+x_2)\varphi][2\varphi-\psi_1-\psi_2]}{r_i(\psi_1-\psi_2)[1+(\varphi-\psi_1)(\varphi-\psi_2)]^2}\Big)\dot{\varphi}+\\
&+\frac{\dot{r}}{r^2}*\frac{R(\psi_1-\psi_2)-x_1(\varphi-\psi_2)-x_2(\varphi-\psi_1)}{r(\psi_1-\psi_2)(1+(\varphi-\psi_1)(\varphi-\psi_2))}
\end{aligned} \tag{4}$$

Formula (4) is not easy, and therefore it makes sense to go to neural network control. For this purpose, when forming the control law for the total pitch of the propeller at the second stage of synthesis, the research will use a relay element with a dead zone shown in Fig. 3

This is necessary to obtain control U_1 in the form of alternative solutions $U_1 = \delta 1; -\delta 1; 0$, bearing in mind that the trained neural network NS_1 replacing this algorithm has an alternative output. The well-known law of proportional navigation [3] requires the control of the module to consider the helicopter's speed of approach with the landing site so that the researcher can get the formula.

$$U_1=\begin{cases}-\delta_1 & \text{if } k_1|\dot{r}|\dot{q}>\Delta_1;\ j=1\\ +\delta_1 & \text{if } k_1|\dot{r}|\dot{q}<-\Delta_1;\ j=2\\ 0 & \text{if } -\Delta_1<k_1|\dot{r}|\dot{q}<\Delta_1;\ j=3\end{cases} \tag{5}$$

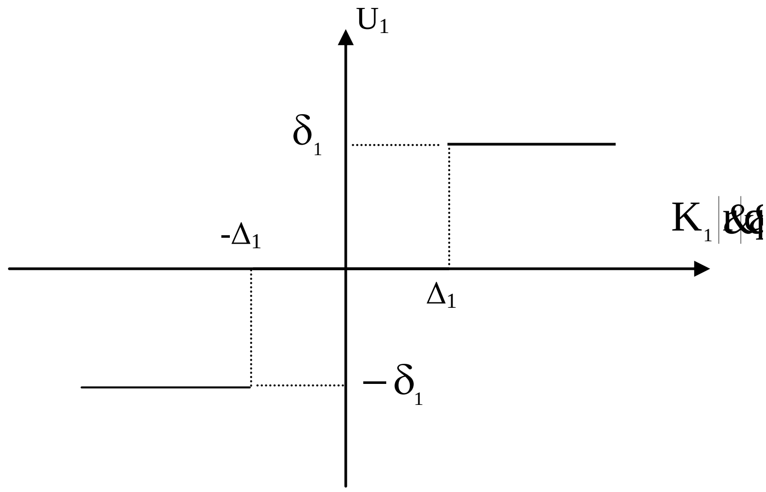


Figure 2. *Restrict control signals*

Where δ is the specified maximum control limit; Δ and k_1 are the experimentally selected dead zone size and proportional navigation coefficient.
Computer simulation of the vertical descent process was carried out using equations (2) with the following numerical data H_0 = 77.5m; H_k = 20m; x_1 = 5m; x_2 = -5m; $|\dot{r}|$= 5m / s; R = 10m. Acceptable flight control results are provided at δ_1 = 0.005 [m / s]; Δ = 0.05 [rad / s]; k_1 = 8. This allows to form a connection between the input signals, the parameters ψ_1, ψ_2, φ, r, and the output number of the alternative used. (Table 1)

Table 1. Examples for training the neural network N1.

i	*Ψ1* [rad]	*Ψ2* [rad]	*φ* [rad]	$|\dot{r}|$ [m/s]	*j*
1	0.03599	-0,0899	0,1	5	1
2	0,0352	-0,0920	0,099	5	1
3	0,03188	-0,10024	0,0991	5	1
4	0,02665	-0,11131	0,096988	5	1
5	0,015916	-0,13182	0,091462	5	1
6	0,0027	-0,1555	0,084	5	1
7	-0,020874	-0,2308	0,072	5	1
8	-0,0305	-0,2308	0,0739	5	1
9	-0,028886	-0,2364	0,79771	5	2
10	-0,0105	-0,236	0,18856	5	3

At the third stage of the synthesis, a two-layer feedforward network N1 was trained, which has already shown successful results for other transport problems [1]. The following parameters were obtained: N1 of forwarding propagation contains ten tangy-hyperbolic neurons in the first layer and one linear neuron in the output layer.

```
      Net.IW{1,1}=[ 4.6463    3.1083  -13.6905   -0.5968
  -4.5570   12.8902   -7.4763    0.6135
   1.6461   16.9671   14.4568   -0.1629
  -0.1831    7.4075  -17.5667    0.5933
   5.2136  -11.1307  -14.4461   -0.1009
   5.2115   -4.9148  -17.8526   -0.3557
  -0.5632   14.8500  -11.8091    0.7868
  -6.1837   13.9745    4.0073    0.0074
   5.3060   -3.8713  -11.3224   -0.9788
  -0.8750   16.1588  -14.2232   -0.2462]
net1.b{1}=    [ -0.1906    3.8465   -0.9689    1.9198   -1.0418
                   0.9011    0.8658    0.9582    2.9562    0.0366]^T ;
net1.IW{2,1}=[0.3816 -0.6451 0.2359-0.2456 0.1224-0.4784 0.0846 –
  0.0310 -0.5435 -0.8376]
net.b{2}=[ -0.3176]
```

The results of computer simulation of vertical descent are shown in Fig. 4 in the form of graphs of changes in height H, pitch angle φ and, accordingly, angle 0.5 ($\psi_1 + \psi_2$) of the deviation of the image of the seat from the middle of the camera screen

It can be seen that fluctuations in the seat position on the screen are not dangerous, and the risk of disruption of observation is minimal even with a field of view $\Delta\alpha = 10^0$.

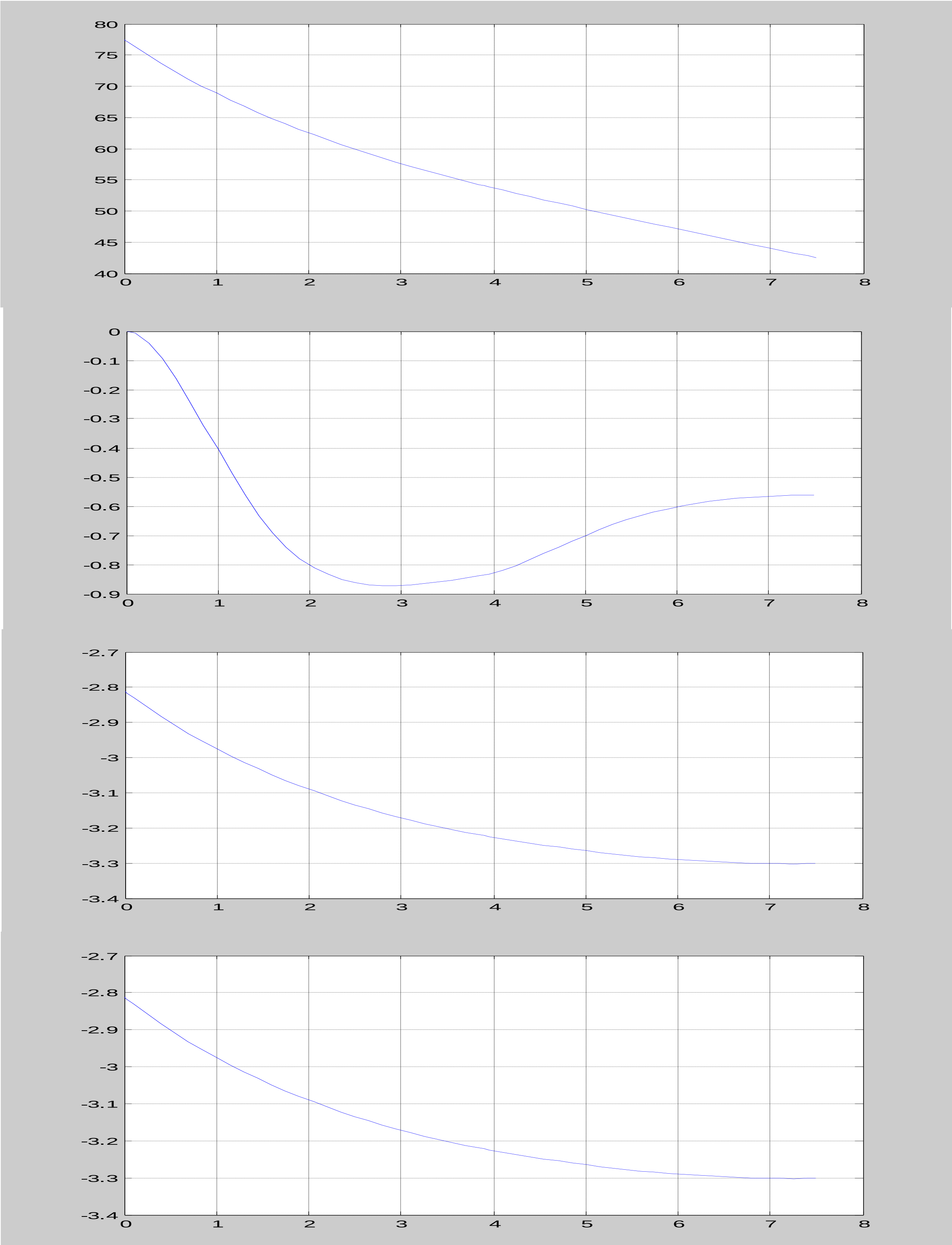


Figure 3. *Graphs of altitude change, horizontal pitch offset and seat position on the screen during vertical descent*

IV. Neural network algorithm for control of the swashplate during a gentle descent of the helicopter.

Due to the impossibility of a direct approach of the helicopter to the landing site with a gentle descent, the image of the landmarks gradually shifts to the edge of the camera, the angular fluctuations of which can lead to leaving the field of view. This means that the camera's field of view should be expanded to the desired size or take other measures.

Having considered, as before, the observation scheme of landmarks, but already for the case of a gentle decline, it is possible to obtain its approximate dependence of the angle q on the measured angles ψ1 and ψ2, keeping in mind that $X_0 \approx H_0$.

$$q = -\frac{R(\psi_1-\psi_2) - X_1(\varphi-\psi_2) - X_2(\varphi-\psi_1)}{r(\psi_1-\psi_2)} \tag{6}$$

After differentiating expression (6), the control signal can be calculated by the formula

$$\dot{q} = -\frac{(x_1+x_2)(\varphi-\psi_2)}{r(\psi_1-\psi_2)^2}\dot{\psi}_1 + \frac{(x_1+x_2)(\varphi-\psi_1)}{r(\psi_1-\psi_2)^2}\dot{\psi}_2 - \frac{x_1+x_2}{r(\psi_1-\psi_2)}\dot{\varphi} +$$

$$+- \frac{R(\psi_1-\psi_2) - x_1(\varphi-\psi_2) - x_2(\varphi-\psi_1)}{r^2(\psi_1-\psi_2)}\dot{r} \tag{7}$$

Applying the same idea of using a relay element with a deadband, the selected parameters are $\delta_2 = 0.01$ [m / s]; $\Delta = 0.13$ [rad / s]; $k_1 = 5$; $k_2 = 0.6$ made it possible to obtain the results shown in Fig. 5 for the following numerical data $H_0 = 100$m when simulating on a computer; $H_k = 20$m; $x_0 = 75$m; $x_1 = 5$m; $x_2 = -5$m; $R = 10$m; $|\dot{r}| = 5$m / s;

Illustrates the obvious expansion of the pitch and angular range of the footprint position on the camera screen. This requires a significant increase in the camera's field of view, which will lead to an undesirable decrease in its resolution.

Therefore, an attempt was made to use the combined control, along with the use of the U_2 swashplate, additionally "work out" the deviations of the seat from the middle of the screen with the help of a common screw pitch.

$$U_1 = 0.5(\psi_1+\psi_2)k_2$$

$$U_2 = \begin{cases} \delta_2 & \text{if} \quad k_1|\dot{r}|\dot{q} > \Delta_2; \quad j=1 \\ -\delta_2 & \text{if} \quad k_1|\dot{r}|\dot{q} < -\Delta_2; \quad j=2 \\ 0 & \text{if} \quad \Delta_2 > k_1|\dot{r}|\dot{q} > -\Delta_2; \quad j=3 \end{cases} \tag{8}$$

The coefficients were selected via experiments when simulating on a computer to reduce the risk of failure of observation, and on the other hand, the required quality of reduction. Figure 6 shows the dotted line graph of the change in the position of the seat 0.5 ($\psi_1 + \psi_2$) for combined control, which corresponds to the final belief in the correct choice of the camera's field of view $\Delta\alpha = 20^0$.

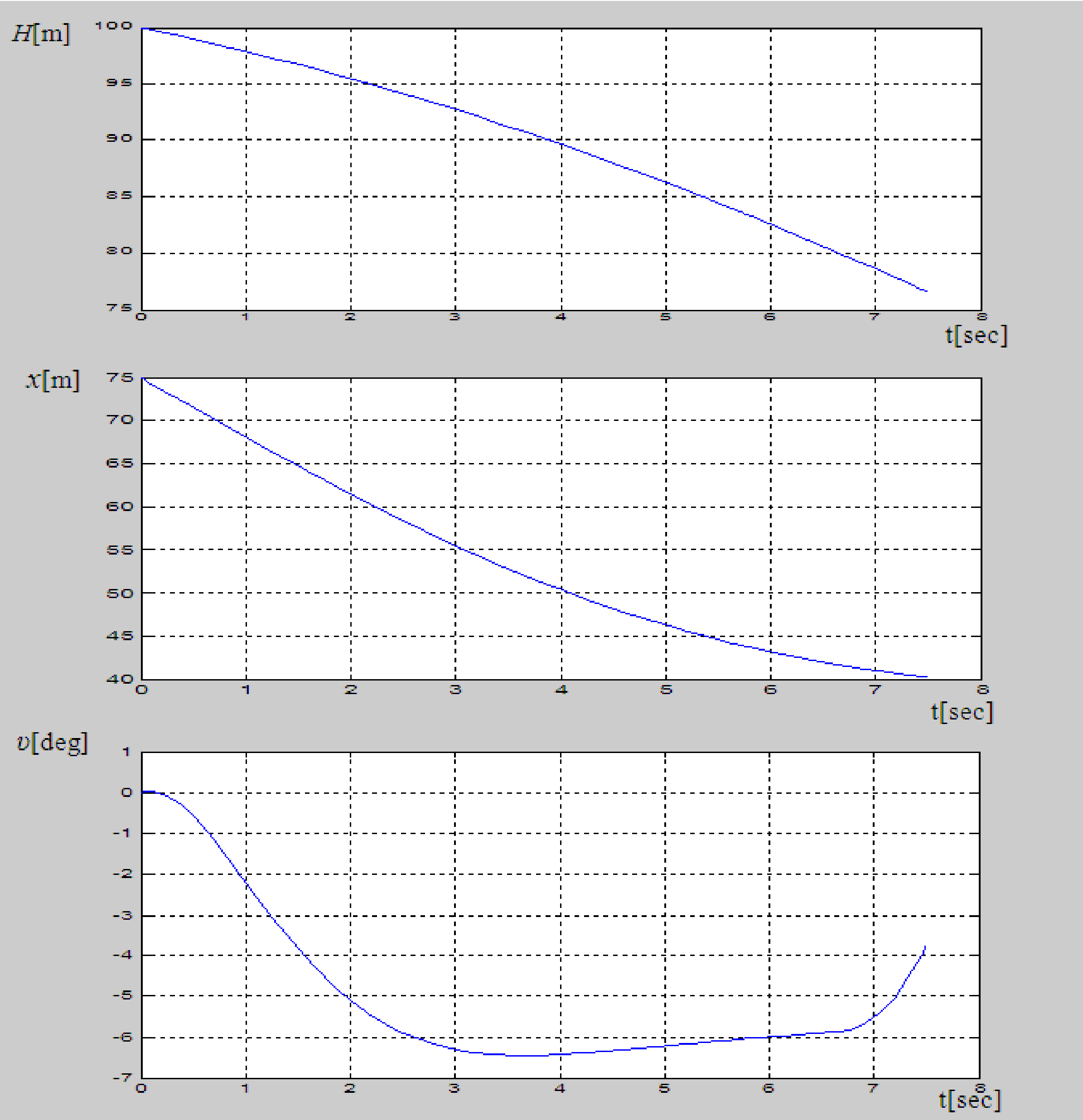
The examples obtained using formula (8) for training the second neural network N2 are presented in Table 2.

i	Ψ_1 [rad]	Ψ_2 [rad]	$\lvert\dot{r}\rvert$ [m/s]	φ [rad]	U_1 [rad]	*J*
1	0.036499	-0.024494	5	-0.68	0.018298	2
2	0.069029	0.0050669	5	-0.69321	0.019189	3
3	0.12014	-0.051018	5	-0.71462	0.020735	1
4	0.16054	-0.084849	5	-0.72043	0.22708	1
5	0.20261	-0.11826	5	-0.71952	0.025304	1
6	0.22757	-0.13784	5	-0.71871	0.027271	1
7	0.25631	-0.1603	5	-0.71805	0.028401	1
8	0.27689	-0.17632	5	-0.71773	0.030169	1

As a result of training, the following main parameters of N2 were obtained: the number of layers - 2, the number of neurons in the first layer - 10, in the second - 2. neuron activation function - tangy-hyperbolic and linear:

Net2.IW{1,1}=[3.4521   1.4224   0.5022   41.1787
-3.9431   -2.5584   0.3715 -37.1137
7.1293   -2.3124   -0.1860 -25.2486
6.1559   -1.3631   0.2496   32.6081
3.2128   0.5424   0.3207   41.5462
-0.0588   2.1786   0.4317 -34.7711
4.9635   -1.1840   0.5687 -30.3110
5.2397   2.7522   -0.0569   32.0781
2.8265   0.6639   0.7424 -29.3421
6.1349   -1.2608   -0.4870 -19.4757]

Net2.b{1}=[24.3029 -23.4886 -15.7040   21.0334   26.4548
-24.3439 -19.0490   23.4367 -18.2828   -7.0097]^{T}
Net2.IW{2,1}=[0.1158 -0.06771 -0.0048 0.07608 -0.16301 -0.5692
0.50305 -0.0114-0.2576 0.3134; -0.50701 -0.9576
0.0037 -0.2337 0.3307 -0.1503 -0.05142 0.01111 0.45715 -0.1689]
Net2.b{2}=[0.1185; 0.4791]



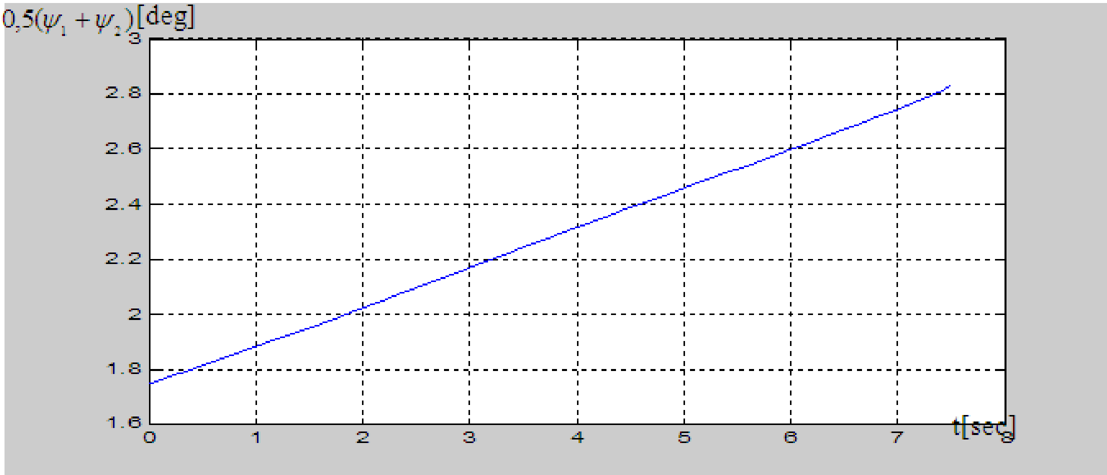


Figure 4. *Graphs of the change in altitude, horizontal offset of the pitch angle and the position of the footprint on the screen of a gentle descent using the swashplate and the total propeller pitch*

V. Conclusion

Based on the studies carried out, the following conclusions can be drawn:

The proposed programmed flight path of a transport helicopter to the landing site, consisting of alternating vertical and gentle descent sections, provides continuous observation of the landing landmarks by an onboard television camera.

Recommendations are given on the choice of the field of view and the method of fixing a television camera to the helicopter body, which can be used both at the stage of helicopter descent and cargo landing.

Algorithms for controlling the propeller's total pitch and the swashplate have been formed, and structures for trained neural networks that implement a gentle and vertical descent have been obtained. A combined control is proposed to reduce the footprint image's risk, leaving the camera's field of view.

The fact of alternate use of the formed neural networks in-flight allows them to be connected in a conveyor mode to the solution of other transport problems, such as recognition of landing landmarks, damping of cargo oscillations, their landing, and soft mooring. This reduces the weight, size, and cost parameters of onboard automatic flight control devices.

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