Improving the accuracy of homing mobile objects with semi-passive method by reducing the time of forming the control force

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Abstract. The options of relative motion of a homing object with a semi-passive method and a mobile end waypoint are considered. For the given options, estimates for the required transverse acceleration of the homing object and the miss distance are given. It is shown that to reduce the miss in homing by method of proportional guidance it is advisable to reduce the time for the control force formation, and the decrease of distance of switching off the control system, when in the object control system only angular information about the current position of the end way points and motion parameters of their own mass center is used.

1. Introduction
To deliver payloads to the desired point depending on its location, land, sea, air or space-controlled mobile objects, including unmanned ones, can be used. To implement the desired trajectory of unmanned mobile objects, a variety of control systems, from autonomous to homing, can be used. Existing methods and homing systems for mobile objects, respectively, are usually classified into active, semi-active and passive according to the location of sources and receivers for applied radiation [1]. In addition to the existing classical methods, new methods of homing mobile objects are being developed [2], including the so-called semi-passive one [3]. Among the indicators characterizing various aspects of the mobile object control process, one of the most important is the accuracy of reaching the desired waypoint. Mobile object control systems, depending on their purpose and complexity, can have a sufficient set of measuring tools to determine their own coordinates and movement parameters, as well as coordinates and movement parameters for the end waypoint [4]. To improve the accuracy of way movement (trajectory), control systems can be integrated with various navigation systems, communication systems for transmitting corrective signals, etc. At the same time, for homing systems, due to a number of features of the mobile objects use, there may be a significant restriction of information resources [5]. For example, if the end waypoint is mobile, the semi-passive homing system does not directly measure parameters such as the range and relative approach rate. The article considers the possibility of improving the accuracy of reaching the required mobile end waypoint (MEP) in relation to a homing mobile object with semi-passive method, the control
system of which uses only angular information and information on the movement parameters of the mass center.

2. Problem statement
There is a mobile homing object, own speed and lateral overload of which are 3-5 times higher than similar parameters of the MEP object. The relative position of the mobile object and the MEP currently in the vertical plane in the earth reference system with the beginning at the mass center of the object is shown in Figure 1 [6].

Figure 1. Relative position of the homing object and the mobile end way point in the vertical plane in the earth reference system

The homing system includes a semi-passive tracking coordinator that measures the angular misalignment and angular velocity of the MEP line relative to the longitudinal axis of the moving object, as well as a block of accelerometers that measure the longitudinal and transverse overloads of the moving object. Control of a moving object, namely the direction of the velocity vector, is carried out in accordance with the method of proportional guidance [6], in which the equations of the ideal connection and the required transverse acceleration have the form:

\[ \dot{\theta} - N \dot{\varepsilon} = 0 \]  
\[ a_{nm} = NV_{sb} \dot{\varepsilon} \]

where \( \dot{\theta}, a_{nm}, \) - respectively the angular rate of the velocity vector and the required transverse acceleration of the moving object; \( V_{sb} \) - the speed of approaching objects; \( \dot{\varepsilon} \) is the angular rate of the sightline; \( N \) is the coefficient called the navigation constant. Kinematic equations of motion for a homing mobile object in accordance with Figure 1 have the form:
\[ \dot{D} = V_c \cos(\varepsilon - \vartheta_c) - V \cos(\varepsilon - \vartheta) \] (3)

\[ D \dot{\varepsilon} = V \sin(\varepsilon - \vartheta) - V_c \sin(\varepsilon - \vartheta_c) \] (4)

where \( D, \dot{D} \) is, respectively, the range and approaching rate of the movable object and the MEP; \( \varepsilon, \dot{\varepsilon} \) is, respectively, the inclination angle of the range and velocity vectors for the movable object; \( \vartheta, V_c \) are, respectively, the speed and the angle of the MEP velocity vector.

It is required to estimate the required transverse acceleration (normal overload) \( a_{nm} \) and the homing accuracy (the value of the segment \( h \) in Figure 1) for the movable object.

### 3. Variant of solution

Even with accurate measurement of the kinematic parameters for relative motion and dynamic parameters for the mass centers motion of the mobile object and an MEP object, it is very difficult to obtain exact dependences of \( a_{nm} \) and \( h \) on the size and duration of the control force formation. This is due to the fact that these values are influenced by a large number of factors, which, in turn, are in mutually overlapping, time-varying dependencies [7]. Such factors include: the change of mass and, as a consequence, the change of dynamic motion characteristics against the mass center of the mobile object because of the fuel consumption; change of speed and normal acceleration of the MEP object; the amendment of the mobile object speed, range and range rate with the MEP; changing parameters of the environment where objects move, etc.

The desired estimates \( a_{nm} \) and \( h \) with acceptable accuracy for practice can be obtained by making some assumptions and simplifications due to the peculiarities of a mobile object motion in close proximity to the MEP.

Assume that the mobile object and the MEP move at constant speeds, i.e. \( V = \text{const}, \ V_C = \text{const}, \ V_c \) and therefore \( \dot{D} \approx \text{const} \). The force controlling the mobile object is formed with a certain delay \( \tau \), depending on the mechanism of its formation and the parameters of the object motion environment, in accordance with the approximate equations

\[ \tau \dot{\alpha} + \alpha = kN \dot{\varepsilon} \] (5)

\[ \dot{\varepsilon} = A \alpha \] (6)

where \( \alpha \) is the attack angle of the mobile object (the angle between the longitudinal axis and the velocity vector); \( k, A \) are the proportionality coefficients.

By differentiating equation (4) with its further converting, taking account of the equations (3), (5), (6), the equation with respect to \( \varepsilon \) is obtained in [8]

\[ \tau \ddot{\varepsilon} + (D - 3\tau V_{sb}) \dot{\varepsilon} + (B - 2) V_{sb} \dot{\varepsilon} = V_{c1} \dot{\vartheta}_c \] (7)

where \( B = ANV_1/V_{sb} \) is the generalized gain; \( V_{sb} = -\dot{D}; \ V_1 = \cos(\varepsilon - \vartheta); \ V_{c1} = V_c \cos(\varepsilon - \vartheta_c) \) .

Assuming that the ideal connection is exactly fulfilled, which corresponds to the inertia-free formation of the control force, i.e., for \( \tau = 0 \) and \( k = A = 1 \), equation (7) is transformed to [5]

\[ D \ddot{\varepsilon} + \left[ NV \cos(\varepsilon - \vartheta) + 2\dot{D} \right] \dot{\varepsilon} = V_c \dot{\vartheta}_c \cos(\varepsilon - \vartheta_c) + \dot{V} \sin(\varepsilon - \vartheta) - \dot{V}_c \sin(\varepsilon - \vartheta_c) \]

and has a solution
$$\dot{\varepsilon} = \varepsilon_0 \left[ \frac{D}{D_0} \right]^{B-2} + \frac{V_c \dot{\vartheta}_c}{V_{sb}(B-2)} \left[ 1 - \left( \frac{D}{D_0} \right)^{B-2} \right]$$

(8)

where $D = D_0 - V_{sb} t$, $D_0$, $\varepsilon_0$ is the range to the MEP and the angular velocity of its sight at the initial time, $t$ is the current time.

The equation (8) is used as the limiting case for instantaneous formation of the required control force when analyzing the dependencies of the values $a_{nm}$ and $h$ on $D$ for different values $B$ and $\dot{\vartheta}_c$ are analyzed. The equation for the required transverse acceleration $a_{pt}$ is obtained by substituting from (8) to (2) and has the form

$$a_{nm} = NV_{sb}\varepsilon_0 \left( \frac{D}{D_0} \right)^{B-2} + \frac{N V_c \dot{\vartheta}_c}{V_{sb}(B-2)} \left[ 1 - \left( \frac{D}{D_0} \right)^{B-2} \right]$$

(9)

The expression for $h$ at the moment $k$ of the end of the control system operation [9], when substituting the second term for $\varepsilon$ from (8), associated with the MEP maneuvering, will have the form

$$h = \left( \frac{D}{V_{sb}} \right)^2 \frac{V_c \dot{\vartheta}_c}{B-2}$$

(10)

In this case, the equation (10) does not take into account the ratio $D/D_0$ because of its vanishingly small effect on the value $h$ (Figure 1). The values of all parameters in the equation (10) correspond to the moment of time $k$.

4. Research results

Table 1 shows the values $a_{nm}$ and $h$ for some possible options for the relative motion of the homing controlled object and the MEP with the exact execution of the ideal connection and the accepted assumptions.

| Options regarding the motion of the homing object and the MEP | Parameter estimation |
|---|---|---|---|---|---|---|
| $D$ | $V$ | $V_{sb}$ | $N$ | $D_k$ | $t$ | $a_{nm}$ | $h$ |
| 1 | 10000 | 900 | 600 | 2; 8 | 0.01 | 0.07 | 300 | 2 | 23.4; 38.24 | 5.25; 0.53 |
| 2 | 10000 | 900 | 600 | 2 | 0.01 | 0.07; 0.3 | 300 | 16 | 78.8; 270 | 5.25; 22.5 |
| 3 | 10000 | 900 | 600 | 2 | 0.01 | 0.07; 0.3 | 30 | 16 | 78.8; 270 | 0.05; 4.73 |
| 4 | 10000 | 900 | 1200 | 3; 8 | 0.01 | 0.07 | 300 | 2 | 48.13; 34.24 | 5.3; 0.22 |
| 5 | 10000 | 900 | 1200 | 8 | 0.01 | 0.3 | 30 | 2; 8 | 17.9; 137.4 | 0.11; 0.11 |

The numerical data values shown in the table characterize both the average values of the corresponding parameters, for example, $D$, $V$, $V_{SA}$, $\varepsilon_0$ and possible boundary values, for example, $N$, $\dot{\vartheta}_c$, $D_k$, $t$. The analysis of the numerical values of $a_{nm}$ and $h$, corresponding to the shown in the table options of the relative motion of the homing object and the MEP, allows one to make the following conclusions: the greatest impact on the magnitude of desired lateral acceleration homing object has an intensive MEP maneuvering in the final stage (options 2, 3, 5); significant increase in accuracy (decrease in $h$) is observed with decreasing $D_k$ - distance end of the control system operation (options 3 and 5 compared to option 2); increasing the navigation
constant $N$ leads to a significant increase in the homing accuracy of the mobile object as on pursuit (option 1), and on a collision courses with the relative MEP motion (option 4); the required lateral acceleration for all the motion stages have a finite value, it is technically feasible for designs of modern mobile objects, that allows providing a satisfactory accuracy of homing in intensive MEP maneuvering.

Figure 2. Graphs of changes in the transverse acceleration of a homing object when approaching a maneuvering MEP

The actual motion of the mass center of a mobile object, taking into account the inertia in the formation of the control force ($\tau \neq 0$) when homing by the proportional guidance method, differs from the one studied on the basis of the equation (8) [10]. The delay value depends on both the design features of the control surfaces, the efficiency of their drives, the location on the controlled object, and the conditions of use, for example, the altitude of an aerodynamic object or water turbulence during the movement of an autonomous underwater uninhabited vehicle. The presence of a large number of cross-links between parameters that affect the dynamics of motion, the variability of the value of the control force and delays in its formation cause significant difficulties in analyzing the parameters of $a_{nm}$ and $h$ in the process of the real controlled object movement. Figure 2 shows some results concerning the $a_{nm}$ obtained as a result of numerical integration of equation (7) for various $\dot{\theta}_c$ and $\tau = 0.5 \, \text{s}$ at the final stage of the object’s closure to the MEP. The initial data in the simulation corresponded to the second option regarding the motion of the homing object and the MEP from table 1.

The angle $\theta$ and transverse overload of the mobile object are expressed in terms of angular velocity $\dot{\varepsilon}$ and increase sharply as the distance to the MEP decreases. The nature of the change in $h$ is similar to the change in $a_{pt}$, i.e. in the area of the MEP tends to infinity. Due to technical limitations on tracking the angular velocity of sight $\dot{\varepsilon}$, as well as on the transverse overload of the mobile object, the control system ends at the moment $k$. Figure 3 shows graphs of $h$ values calculated using the equation (10) for the same data as in figure 2.
Figure 3. Graphs of changes in the miss of a homing object when approaching a maneuvering MEP for different ranges when the control system stops operating

Conclusion

When a semi-passive method for homing a mobile object is implemented, it is not possible to measure the relative approach rate $V_{appr}$ with the MEP to ensure an ideal connection in accordance with equation (2). The use of indirect estimates of the $V_{appr}$ or the average value of the navigation constant $N$ leads to a decrease in the accuracy of homing. At the same time, the analysis of the data given in table 1 for the case of instantaneous formation of the control force ($\tau = 0$), as well as the graphs in Figure 2 and Figure 3 for the case of the formation of a control force with a delay ($\tau = 0.5$ s) allow concluding that the accuracy of semi-passive homing at $\tau \leq 0.5$ s is acceptable in practice. In addition, the accuracy increases when the deactivation range $D_k$ of the control system is reduced (Figure 3), which is also proportional to the reduction $\tau$.

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