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Control Systems II

Hierarchical Principle of Construction of Spatial Dynamic Positioning Systems of Sea Mobil Objects (SMO)

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Abstract

The hierarchical principle of synthesis of dynamic positioning systems for sea mobile objects is offered at the given arrangement of the thrusters. The method consists in synthesis of vectors of controlling forces and moments ensuring dynamic positioning of object with given quality (management of the top level) and the subsequent distribution of these forces and the moments on the thrusters (formation of management of the bottom level). The offered approach for management of the top level is based on a method of functions Lyapunov and allows to synthesize nonlinear control laws ensuring exponentially stable positioning SMO.

It is supposed, that the number of the thrusters, their arrangement and directions of vectors of action of their forces (is usual in body-fixed reference frame) satisfy to the offered criterion controllability and provide sole or infinite number of the decisions of a task of distribution of managements. In the latter case is possible optimum somewhat distribution of a vector of controlling force and moment of the top level on the thrusters. It is necessary to note, that the spatial task of management of the bottom level has features, connected that skew-symmetrical a matrixes in the equations of distribution of the managing moments, are special. In this connection many such tasks were reduced to frame (for which these features are absent), if the behavior of movement allowed such division (for example, at a small roll). In the given work an arrangement of thrusters is offered which allows and in a spatial case to reduce a task of distribution of resources of management to frame case without restrictions on a behavior of movement.

The managing forces of the bottom level are realized as inputs on the executive drives, which have own dynamics and, accordingly, delays. In additional, the tractions of executive drives usually are rather limited, that can result in unstable behaviors. Are considered ways of formation of the top-level management for the established behaviors (small initial deviations and at presence of various external influences limited on size) and the for transfer processes (large initial deviations).

The report is illustrated by an example of synthesis of system of dynamic positioning for some SMO.

Key words: dynamic positioning systems, control systems, task of distribution of managements.

1. Introduction

In works [1-6,8] the statement and method of the decision of a task of distribution on the executive drives of the generalized vector of control forces and moments acting on SMO in space is resulted. The vector of managing forces and moments was formed proportionally to deviations of the centre of weights SMO from a point of positioning in earth-fixed (geographical) system of coordinates, and then was recalculated in body-fixed and was distributed on the executive drives, the direction of which tractions was set in body-fixed (SMO) system of coordinates. It was supposed, that number of the executive drives, their arrangement and the directions of vectors of action of their forces provide the decision of a task of spatial positioning SMO, that was defined by controllability criterion, given in Appendix, [5,6].

In the given work the method of synthesis both algorithms of nonlinear control laws and observers based on a Lyapunov method and ensuring exponentially steady positioning SMO in space (or in some area concerning a point of positioning is offered where nonlinearities of dynamics of object satisfy to Lipschitz conditions) and presence of noise of position and angles measurements, and also scheme of an arrangement thrusters, which allows and in a spatial case to reduce a task of distribution of resources of management to frame variants without restrictions on a behaviors of movement.

The considered approach can be used, both for projected systems of dynamic positioning, and for existing, provided that last have drives, which arrangement satisfies to criterion controllability. The approach is illustrated by an example of synthesis of system of dynamic positioning SMO.

2. The equations of movement SMO

It is supposed, that at the decision of a top-level DP-task the position deviations SMO in earth-fixed system of coordinates ξ, η, ζ (ξ- a deviation of the centre of weights SMO from a point of positioning on altitude, η- on depth, ζ- on a longitude) and angular θ, φ, ψ (roll, yaw and pitch accordingly) are considered.

Dynamics SMO is generally described by the equations in the body-fixed system of coordinates and by the kinematical equations of connections similar [11,12], but for a spatial case and arrangement of axes appropriate fig. 1:

$$M\dot{v} + C(v)v + D(v)v + g(\Lambda) = L_{con} + L_w, \qquad (1)$$
$$\dot{\Lambda} = H(\Lambda)v,$$

where $v^T = (v_x, v_y, v_z, \omega_x, \omega_y, \omega_z)$ - the vector of linear and angular speeds SMO in the body-fixed system of coordinates;
$\Lambda^T = (\xi, \eta, \zeta, \theta, \varphi, \psi)$ - the vector of linear and angular motions SMO in earth-fixed system of coordinates;
$M = diag(m_x, m_y, m_z, J_x, J_y, J_z)$ -the positive matrix (or positively defined) of masses + added masses matrix of the SMO;
$C(v)$ - the Coriolis and centripetal matrix, which for ellipsoid SMO looks like [14]:

$$C(v) = \begin{bmatrix} A \\ B \end{bmatrix}, \text{ where } A = \begin{bmatrix} 0 & -m_y\omega_z & m_z\omega_y & 0 & 0 & 0 \\ m_x\omega_z & 0 & -m_z\omega_x & 0 & 0 & 0 \\ -m_x\omega_y & m_y\omega_x & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (2)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ (m_x - m_z)v_z & 0 & 0 & (J_x - J_z)\omega_z & 0 & 0 \\ 0 & (m_y - m_x)v_x & 0 & 0 & (J_y - J_x)\omega_x & 0 \end{bmatrix}$$

$D(v)$ - the damping matrix of hydrodynamic forces and moments; simplified which form for low speed given in [13], looks like

$$D(v) = diag\left\{ \begin{matrix} d_{10} + \sum_{i\ge1} d_{1i}|v_x|^i, d_{20} + \sum_{i\ge1} d_{2i}|v_y|^i, d_{30} + \sum_{i\ge1} d_{3i}|v_x|^i, d_{40} + \sum_{i\ge1} d_{4i}|v_x|^i, \\ d_{50} + \sum_{i\ge1} d_{5i}|v_x|^i, d_{60} + \sum_{i\ge1} d_{6i}|v_x|^i \end{matrix} \right\}; \quad (3)$$

L_w - the vector of wind-wave and other revolting forces and moments acting on SMO; $L_{con} = (F_{conx}, F_{cony}, F_{conz}, M_{conx}, M_{cony}, M_{conz})^T$ - vector of control forces and moments limited, generally, on absolute meaning;
$g(\Lambda)$ -vector of forces and moments caused by forces of weight and displacement

$$g(\Lambda)^T = [(Q-G)\sin\psi, (Q-G)\cos\psi\cos\theta, -(Q-G)\cos\psi\sin\theta, -Q(z_Q\cos\psi\cos\theta + y_Q\cos\psi\sin\theta),$$
$$Q(x_Q\cos\psi\cos\theta - y_Q\sin\psi), Q(x_Q\cos\psi\sin\theta + z_Q\sin\psi)], \quad (4)$$

where x_Q, y_Q, z_Q -coordinates of a point of the appendix of displacement force, G - force of the weight enclosed in the beginning of connected system of coordinates.
The matrix of the kinematical connections (in Euler corners) $H(\Lambda)$ looks like:

$$H(\Lambda) = \begin{bmatrix} R & 0 \\ 0 & S \end{bmatrix}, \quad (5)$$

where $$R = \begin{bmatrix} \cos\varphi\cos\psi & \sin\theta\sin\varphi - \cos\theta\cos\varphi\sin\psi & \cos\theta\sin\varphi + \sin\theta\cos\varphi\sin\psi \\ \sin\psi & \cos\theta\cos\psi & -\sin\theta\cos\psi \\ -\sin\varphi\cos\psi & \sin\theta\cos\varphi + \cos\theta\sin\varphi\sin\psi & \cos\theta\cos\varphi - \sin\theta\sin\varphi\sin\psi \end{bmatrix},$$

$$S = \begin{bmatrix} 1 & -\cos\theta tg\psi & \sin\theta tg\psi \\ 0 & \dfrac{\cos\theta}{\cos\psi} & -\dfrac{\sin\theta}{\cos\psi} \\ 0 & \sin\theta & \cos\theta \end{bmatrix}.$$

The task of dynamic positioning consists in synthesis and realization of a vector of managing forces and moments L_{con} ensuring exponentially stable positioning SMO concerning a given vector of a position of SMO in space Λ_d $(\xi_d, \eta_d, \zeta_d, \varphi_d, \psi_d, \theta_d)$ and realization of these forces and the moments with the help of the executive drives SMO. The matrix $H(\Lambda)$ has features at $\psi = \pm 90^\circ$. If to choose as parameters of orientation other parameters, for example, Rodrigo-Hamilton, the specified features can be avoided [15].

3. Method of synthesis of control law and observer

Designing the control law

According to [1-6,8] the method of synthesis of a control system consists of two stages (top level and bottom level).

At the first stage the synthesis of the generalized management (formation of the generalized vector of forces and moments) $L_{con} = (F_{con}, M_{con})^T$, compensating deviation of object on adjustable coordinates is carried out. The method based on use of functions Lyapunov is offered.

Let's enter deviations from a final point:

- on speed (in the body-fixed system)

$s_1 = v - v_d$ at final speed $v_d = 0$, $s_1 = v$ (6)

- on a position (in the earth-fixed system of coordinates)

$s_2 = \Lambda - \Lambda_d$ (7)

Let's generate on the given deviations function Lyapunov of a kind

$$V = \frac{1}{2}\left\{s_1^T M s_1 + s_2^T K_2 s_2\right\}, \tag{8}$$

where K_2 positive diagonal (or positively defined) $K_2 = K_2^T$ matrix.

For a stable of behavior the function $\frac{dV}{dt}$ should be negative function

$$\frac{dV}{dt} = s_1^T M\dot{s}_1 + s_2^T K_2 \dot{s}_2 = v^T M\dot{v} + (\Lambda - \Lambda_d)^T K_2 \dot{\Lambda},$$

with the account (1) it is possible to write

$$\begin{aligned}\frac{dV}{dt} &= v^T\left\{L_{con} - C(v)v - D(v)v - g(\Lambda)\right\} + (\Lambda - \Lambda_d)^T K_2 H(\Lambda)v = \\ &v^T\left\{L_{con} - C(v)v - D(v)v - g(\Lambda) + H^T(\Lambda)K_2^T(\Lambda - \Lambda_d)\right\}.\end{aligned} \tag{9}$$

If to generate control law as

$$L_{con} = C(v)v + D(v)v + g(\Lambda) - K_1 v - H^T(\Lambda)K_2(\Lambda - \Lambda_d), \tag{10}$$

where K_1 - positively defined matrix, the function (9) will accept a kind

$$\frac{dV}{dt} = -v^T K_1 v, \qquad (11)$$

i.e. will be negatively defined. Thus, for stability of system the performance of conditions is necessary

$$K_1 > 0, K_2 > 0. \qquad (12)$$

From (10) it is visible, that the control law should compensate Coriolis and centripetal of force, forces of weight and displacement and of a deviation on the generalized vector of speed (damping of force of management), thus damping a component $D(v)v$ it is possible in (10) to not include; to generate forces and moments compensating deviations $\Lambda - \Lambda_d$ and to count them in the body-fixed system of coordinates. For compensation of constant components external forces in (10) the additional integrated component from the coordinates deviations $\Lambda - \Lambda_d$, counted in body-fixed system

$$L_{con} = C(v)v + D(v)v + g(\Lambda) - K_1 v - H^T(\Lambda)K_2(\Lambda - \Lambda_d) - K_3\int_0^t H^T(\Lambda)(\Lambda(\tau) - \Lambda_d)d\tau. \qquad (13)$$

The meanings of factors of matrixes K_1, K_2, K_3 are generally determined by the given quality of transients, their duration t_{tp}, accuracy of stabilization, restrictions of $L_{con}(\mathbf{F}_{con}(t), \mathbf{M}_{con}(t))$. In case of weak executive drives the vector of management is limited $|L_{con}| \le \overline{L}_{con}$ also equality in (10) is broken. For maintenance of steady management in this case it is recommended to increase factors of a matrix K_1 (is increased damping) and to reduce L_{con}, that results in reduction of a vector v, accordingly, $C(v)v, K_1 v$ and provides steady management, but thus the time of transients is increased.

Designing the observing device.

For realization of the laws of management (10,13) it is necessary to measure vectors Λ, v.

It is considered, that the vector $y = \Lambda$ is usually measured, and the vector v is restored with the help of some nonlinear observer [7,9,11,12].

If to designate estimations of vectors v, Λ, as $\hat{v}, \hat{\Lambda}$, the law of management (10) will accept a kind

$$L_{con} = C(\hat{v})\hat{v} + D(\hat{v})\hat{v} + g(\Lambda) - K_1\hat{v} - H^T(\Lambda)K_2(\hat{\Lambda} - \Lambda_d). \qquad (14)$$

Use of direct measurements $g(\Lambda), H(\Lambda)$ for calculation is allowed, as the elements of these matrixes represent functions from Euler corners, which, in turn, are measured rather precisely (up to 0.1 ° [12]).

Then the equations (1) can be copied

$$\begin{aligned} M\dot{v} &= -C(v)v - D(v)v - g(y) + C(\hat{v})\hat{v} + D(\hat{v})\hat{v} + g(y) - K_1\hat{v} - H^T(y)K_2(\hat{\Lambda} - \Lambda_d), \\ \dot{\Lambda} &= H(y)v, \end{aligned} \qquad (15)$$

Equation of the observer is offered to search as

$$\begin{aligned} M\dot{\hat{v}} &= -K_1\hat{v} - H^T(y)K_2(\hat{\Lambda} - \Lambda_d) + \overline{K}_2(\Lambda - \hat{\Lambda}), \\ \dot{\hat{\Lambda}} &= H(y)\hat{v} + \overline{K}_1(\Lambda - \overline{\Lambda}), \end{aligned} \qquad (16)$$

Subtracting (16) of (15), we shall receive

$$M(\dot{v}-\dot{\hat{v}}) = -C(v)v - D(v)v + C(\hat{v})\hat{v} + D(\hat{v})\hat{v} - \overline{K}_2(\Lambda - \hat{\Lambda}), \qquad (17)$$
$$\dot{\Lambda} - \dot{\hat{\Lambda}} = H(y)(v-\hat{v},) - \overline{K}_1(\Lambda - \hat{\Lambda}).$$

In a process of positioning, the vector of speeds is small, therefore matrix $D(v)$ can be presented as a constant diagonal positive matrix dissipative of forces $D(v) = D(\hat{v}) = D = diag(d_{i0})$ [12].
Then (17) it is possible to copy

$$M(\dot{v}-\dot{\hat{v}}) = -(C(v)v - C(\hat{v})\hat{v}) - D(v-\hat{v}) - \overline{K}_2(\Lambda - \hat{\Lambda}),$$
$$\dot{\Lambda} - \dot{\hat{\Lambda}} = H(y)(v-\hat{v},) - \overline{K}_1(\Lambda - \hat{\Lambda}). \qquad (18)$$

We shall designate estimation errors $v - \hat{v} = \tilde{v}$, $\Lambda - \hat{\Lambda} = \tilde{\Lambda}$, then (18) will accept a kind

$$M\dot{\tilde{v}} = -(C(v)v - C(\hat{v})\hat{v}) - D\tilde{v} - \overline{K}_2\tilde{\Lambda},$$
$$\dot{\tilde{\Lambda}} = H(y)\tilde{v} - \overline{K}_1\tilde{\Lambda}. \qquad (19)$$

The conditions of stability also are defined by a method Lyapunov, for what the Lyapunov function of a kind is entered

$$W = \frac{1}{2}(\tilde{v}^T M\tilde{v} + \tilde{\Lambda}^T Q_2 \tilde{\Lambda}),$$

Where Q_2 - positively defined matrix. Derivative on time looks like

$$\frac{dW}{dt} = \tilde{v}^T M\dot{\tilde{v}} + \tilde{\Lambda}^T Q_2 \dot{\tilde{\Lambda}}$$

or

$$\frac{dW}{dt} = \tilde{v}^T(-(C(v)v - C(\hat{v})\hat{v}) - D\tilde{v} - \overline{K}_2\tilde{\Lambda}) + \tilde{\Lambda}^T Q_2(H(y)\tilde{v} - \overline{K}_1\tilde{\Lambda}) =$$
$$= -\tilde{v}^T(C(v)v - C(\tilde{v})\tilde{v}) - \tilde{v}^T D\tilde{v} - \tilde{v}^T\overline{K}_2\tilde{\Lambda} + \tilde{v}^T H^T(y)Q_2^T\tilde{\Lambda} - \tilde{\Lambda}^T Q_2 \overline{K}_1\tilde{\Lambda}. \qquad (20)$$

Let function $C(v)v$ satisfies to Lipschitz conditions in some area concerning a point of positioning. Then in this area the ratio is fair

$$|C(v)v - C(\hat{v})\hat{v}| \le L|v - \hat{v}|,$$

where L a positive matrix.
It is obvious, that derivative of function W is strictly negative, if

$$D - L > 0, \quad \overline{K}_1 > 0, \quad \overline{K}_2 = H^T(y)Q_2^T. \qquad (21)$$

Thus estimation with the help of the observer (16) is steady at performance of conditions (21). In case the condition $D - L > 0$ is carried out (matrix $D - L$ is positively determined), increasing $\overline{K}_1, Q_2$ always it is possible to ensure negative of derivative Lyapunov function. The factors of matrixes $\overline{K}_1, \overline{K}_2$ get out so that to ensure the given accuracy of estimation and stability of system as a whole.

Estimation of stability of controlled movement SMO at use of the observer.
The law of management (10) is used. In this case controlled movement of object in the made earlier assumptions is described by the equations

$$M\dot{v} = -(C(v)v - C(\hat{v})\hat{v}) - D\tilde{v} - K_1\hat{v} - H^T(y)K_2(\hat{\Lambda} - \Lambda_d),$$
$$\dot{\Lambda} = H(y)v, \qquad (22)$$

where $v = \hat{v} + \tilde{v}$, $y = \Lambda = \hat{\Lambda} + \tilde{\Lambda}$.

After substitution v, Λ in (22) and with the account (19), we have the following equations of movement of object in estimations

$$M\dot{\hat{v}} = -K_1\hat{v} - H^T(y)K_2(\hat{\Lambda} - \Lambda_d) + \overline{K}_2\tilde{\Lambda},$$
$$\dot{\hat{\Lambda}} = H(y)\hat{v} + \overline{K}_1\tilde{\Lambda}. \qquad (23)$$

The equations (23) together with (19) form the closed system of the equations.

Not breaking a generality of results, let's assume $\Lambda_d = 0$. besides believing, that $\tilde{\Lambda}, \tilde{v}$ aspire to zero for the steady observer, a general estimation of stability of system of positioning we shall carry out for variable $\hat{\Lambda}, \hat{v}$, as it is made, for example, in [12]. In the specified assumptions the possible Lyapunov function is accepted in the following kind

$$S = \frac{1}{2}(\hat{v}^T M\hat{v} + \hat{\Lambda}^T Q_1\hat{\Lambda} + \tilde{v}^T M\tilde{v} + \tilde{\Lambda}^T Q_2\tilde{\Lambda}), \qquad (24)$$

where - Q_1, Q_2 positively defined matrixes.

Its derivative on time looks like

$$\dot{S} = \hat{v}^T M\dot{\hat{v}} + \hat{\Lambda}^T Q_1\dot{\hat{\Lambda}} + \tilde{v}^T M\dot{\tilde{v}} + \tilde{\Lambda}^T Q_2\dot{\tilde{\Lambda}} =$$
$$\hat{v}^T[-K_1\hat{v} - H^T(y)K_2\hat{\Lambda} + \overline{K}_2\tilde{\Lambda}] + \hat{\Lambda}^T Q_1[H(y)\hat{v} + \overline{K}_1\tilde{\Lambda}] +$$
$$\tilde{v}^T[-(C(v)v - C(\hat{v})\hat{v}) - D\tilde{v} - \overline{K}_2\tilde{\Lambda}] + \tilde{\Lambda}^T Q_2[H(y)\tilde{v} - \overline{K}_1\tilde{\Lambda}] = -\hat{v}^T K_1\hat{v} - \hat{v}^T H^T(y)K_2\hat{\Lambda} + \hat{v}^T\overline{K}_2\tilde{\Lambda} + \qquad (25)$$
$$\hat{v}^T H^T(y)Q_1^T\hat{\Lambda} + \hat{\Lambda}^T Q_1\overline{K}_1\tilde{\Lambda} - \tilde{v}^T(C(v)v - C(\hat{v})\hat{v}) - \tilde{v}^T D\tilde{v} - \tilde{v}^T\overline{K}_2\tilde{\Lambda} + \tilde{v}^T H^T(y)Q_2^T\tilde{\Lambda} - \tilde{\Lambda}^T Q_2\overline{K}_1\tilde{\Lambda}.$$

Negative of derivative Lyapunov function is provided with equality:

$$K_2 = Q_1^T, \overline{K}_2 = H^T(y)Q_2^T \qquad (26)$$

and inequalities: K_1>0, D-L>0, $Q_2\overline{K}_1 > 0$, (27)

which were received earlier

The choice $\overline{K}_1$ is carried out from equality (additional condition)

$$(\hat{v}^T\overline{K}_2 + \hat{\Lambda}^T Q_1\overline{K}_1)\tilde{\Lambda} = 0, \qquad (28)$$

which with the account (25) can be copied

$$(\hat{v}^T H^T(y)Q_2^T + \hat{\Lambda}^T Q_1\overline{K}_1)\tilde{\Lambda} = 0 \text{ or } [(H(y)\hat{v})^T Q_2^T + \hat{\Lambda}^T Q_1\overline{K}_1]\tilde{\Lambda} = 0. \qquad (29)$$

As, $H(y)\hat{v} = \dot{\hat{\Lambda}} - \overline{K}_1\tilde{\Lambda}$ after substitution in (29), we shall receive

$$[\dot{\hat{\Lambda}}^T Q_2^T + \hat{\Lambda}^T Q_1\overline{K}_1]\tilde{\Lambda} - \tilde{\Lambda}^T\overline{K}_1^T Q_2^T\tilde{\Lambda} \quad , \qquad (30)$$

whence also follows that $\overline{K}_1$>0 and equation for definition $\overline{K}_1$

$$\dot{\hat{\Lambda}}^T Q_2^T + \hat{\Lambda}^T Q_1\overline{K}_1 = 0. \qquad (31)$$

The matrixes $Q_2^T = Q_2, Q_1, \overline{K}_1$ are usually diagonal positive matrixes

$$Q_2 = diag\{q_{2i}\}, \quad Q_1 = diag\{q_{1i}\}, \quad \overline{K}_1 = diag\{\overline{k}_{1i}\},$$

Then the sums of the appropriate elements of lines in (31) represent the differential equations of a kind

$$\dot{\hat{\Lambda}}_i q_{2i} + \hat{\Lambda}_i q_{1i} \bar{k}_{1i} = 0 \text{ or } \dot{\hat{\Lambda}}_i + \hat{\Lambda}_i q_{1i} \bar{k}_{1i} / q_{2i} = 0 \ , \quad i = 1..6 \ ,$$

which decisions $\hat{\Lambda}_i(t) = Ce^{-\frac{q_{1i}\bar{k}_{1i}}{q_{2i}}t}$ are exponentially steady, and constant time $T = \frac{q_{2i}}{q_{1i}\bar{k}_{1i}} = \frac{t_{tp}}{3}$. Then

$$\bar{k}_{1i} = \frac{3q_{2i}}{q_{1i}t_{tp}} . \tag{32}$$

Thus general algorithm of construction exponentially of steady DP systems with the observer will be the following:

1. Investigating the closed system (without the observer) the elements of matrixes $K_1, K_2 = Q_1$ ensuring required quality and duration of transients of system of positioning are determined t_{tp}.
2. The noise of measurements is imposed on real variable Λ and the mixed signal is considered as an input signal of the observer. Proceeding from the requirements of estimation accuracy there are factors of a matrixes Q_2 determining a matrix $\bar{K}_2$.
3. From a condition (32) the elements of a matrix $\bar{K}_1$ are defined and the estimations are entered in the law of management.

In case the condition $D - L > 0$ in considered area of deviations is not carried out, increasing $\bar{K}_1, Q_2$ it is possible to ensure stability of the observer. Also increasing K_1 it is possible to ensure stability of controlled movement SMO at the limited drafts of the executive devices.

The total motion SMO in waves is given by the sum of a low-frequence component and a wave-frequence motion. These components are separated by a wave filtering system. For control is used low-frequence component.

The given laws of control (10) and observer (16) (with the account (26), (27), (32)) substantially depend on the available information on matrixes and can be more exact in process of accumulation of the information about the matrixes $M, C(v), D(v), g(\Lambda)$. The methods of synthesis of the adaptive laws of management are in detail enough stated, for example, in [7,11] here again are not considered.

At the second stage - the task of optimum distribution of the received generalized management on the executive drives (task of distribution of required management is decided in view of all of its features). Accepted in the further designation are similar accepted in [1-6].

As the task of distribution of managing forces was specified in [1-6] and moments consists in definition of vectors of separate thruster tractions $\mathbf{f}_i(t)$ on the known generalized managing vectors of force both moment, $\mathbf{F}_{con}(t), \mathbf{M}_{con}(t)$ and coordinates of points of the appendix of vectors of traction of the executive drives $\mathbf{f}_i(t)$, which are defined skew-symmetric by matrixes, $\mathbf{x}_i$,(3×3) in the connected system of coordinates.

Then at known $\mathbf{F}_{con}(t), \mathbf{M}_{con}(t)$ the conditions of balance of forces and moments should be carried out:

$$\begin{aligned} \mathbf{F}_{con}(t) &= \sum_{\mathbf{i=1}}^{\mathbf{N}} \mathbf{f}_i(t); \\ \mathbf{M}_{con}(t) &= \sum_{\mathbf{i=1}}^{\mathbf{N}} \mathbf{x}_i \cdot \mathbf{f}_i(t). \end{aligned} \tag{33}$$

The existence of the decision of system (34) (for three-dimensional space as against plane case) essentially depends on coordinates of points of the appendix of forces determining skew-symmetric a matrixes $\mathbf{x}_i$, and directions of vectors of tractions.

So the moment $\mathbf{M}_{con}$=($M_{conx}, M_{cony}, M_{conz}$), created by one vector of traction $\mathbf{f} = (f_X, f_Y, f_Z)^{\mathrm{T}}$, enclosed in a point with coordinates x_1, y_1, z_1, is defined by a ratio

$$\begin{bmatrix} 0 & -z_1 & y_1 \\ z_1 & 0 & -x_1 \\ -y_1 & x_1 & 0 \end{bmatrix} \begin{bmatrix} f_X \\ f_Y \\ f_Z \end{bmatrix} = \begin{bmatrix} M_{conx} \\ M_{cony} \\ M_{conz} \end{bmatrix}. \qquad (34)$$

The equation (34) generally has no the decision concerning unknown f_X, f_Y, f_Z, as skew-symmetric the matrix is special. However in the case that some coordinates of skew-symmetric matrix or components of a vector of tractions (the drive traction is fixed along one of axes, for example) are equal to zero, the equation (35) has the decision and at use several drives always it is possible to find tractions ensuring the required moment. Such approach is equivalent to splitting of a vector of force on components enclosed in different points or allocation by one component.

In case of superfluous number of thrusters for the decision of a task of distribution of managing forces and moments is used usually Method of the least squares.

That is from equations (34) and condition

$$\min_{f_i} J = \min_{f_i} \frac{1}{2} \sum_{i=1}^{N} \lambda_i(t) \mathbf{f}_\mathbf{i}^{\mathrm{T}}(t) \mathbf{f}_\mathbf{i}(t), \qquad (35)$$

where $\lambda_i(t)$ - weights of tractions.

In Appendix the criterion of SMO controllability for the various schemes of an arrangement of the executive drives and their vectors of draft was formulated, also [6]. The decision of a task of distribution general of forces and moments of management on the executive drives is illustrated by the given below example for the concrete scheme of an arrangement drives.

4.Example of synthesis of system of dynamic positioning SMO

The block diagram of a control system

Further the case, fig. 1 is considered, when SMO has four thrusters (5,6,7,8), fixed in a vertical direction (in the body-fixed system of coordinates) and located symmetrically concerning axes 0x, 0y and four thrusters (1,2,3,4), representing rotary thrusters, located in a horizontal plane. The scheme of an arrangement of thrusters and directions of vectors of tractions are submitted in a fig. 1.

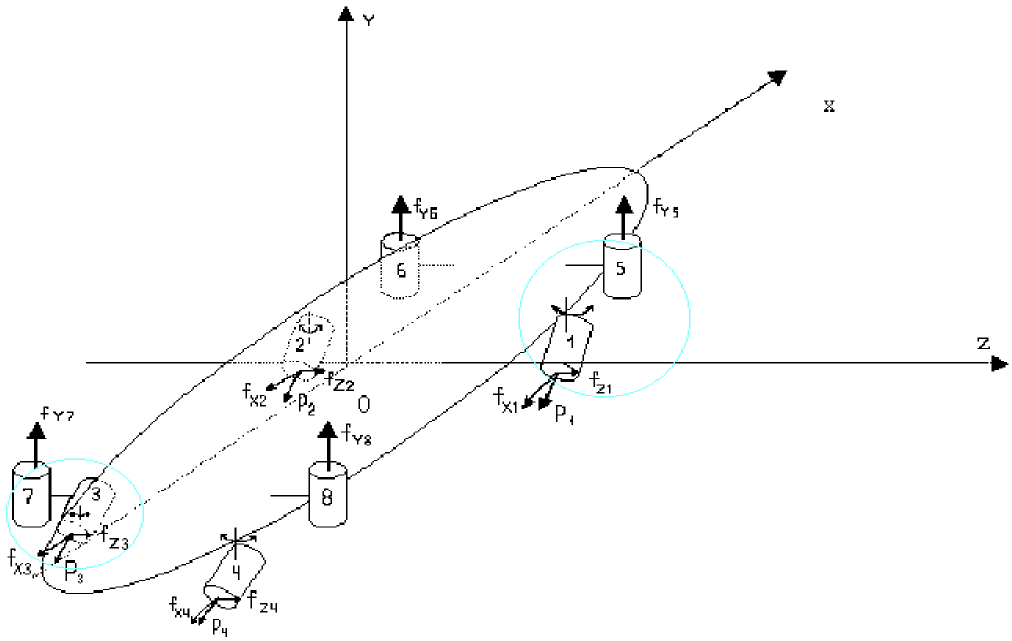


Fig. 1

Coordinates of points of the appendix of a tractions the following:
1 (x1, y1, z1), 2 (x1, y1, -z1), 3 (-x1, y1, -z1), 4 (-x1, y1, z1), 5 (x2, y2, z2), 6 (x2, y2, -z2), 7 (-x2, y2, -z2),8 (-x2, y2, z2).
Further is accepted $x_1 = 6м,\ y_1 = -2м,\ z_1 = 2м,\ x_2 = 8м,\ y_2 = 0м,\ z_2 = 2м.$
It is easy to check up, that at the given scheme of a thruster arrangement the system is controlled; two groups of a thrusters satisfy to criterion (A8)(i.e. probably distribution of force and moment of management on the executive drives) [6].
Generally during the decision of a task of distribution of force and moment of management on executive drives, the drafts f_{Xi}, f_{Yi}, f_{Zi} are defined. For the considered scheme for thrusters 1,2,3,4 are defined tractions P_i and corners of turn γ_i (first group thrusters). For thrusters 5,6,7,8 (second group) were defined only tractions f_{Yi}.
The tractions P_i are adjusted by a corners of thruster blades turn δ_i, which are determined from the adjusting thruster characteristics on tractions f_{Yi} or P_i. For thrusters 5,6,7,8 the tractions are determined only $f_{Yi} = P_i$.
Then the structure of a control system looks like, given on a fig. 2.
In a Fig. 2 $\delta_i(f_{zi})$ - dependence of a corner of turn of thrusters blades from required traction f_{zi}; $\delta_i(P_i)$ - dependence of a corner of turn of rotary thrusters blades from required traction P_i, γ_i - corner of turn of a rotary thrusters; $\bar{f}_i$ - real tractions created thrusters.

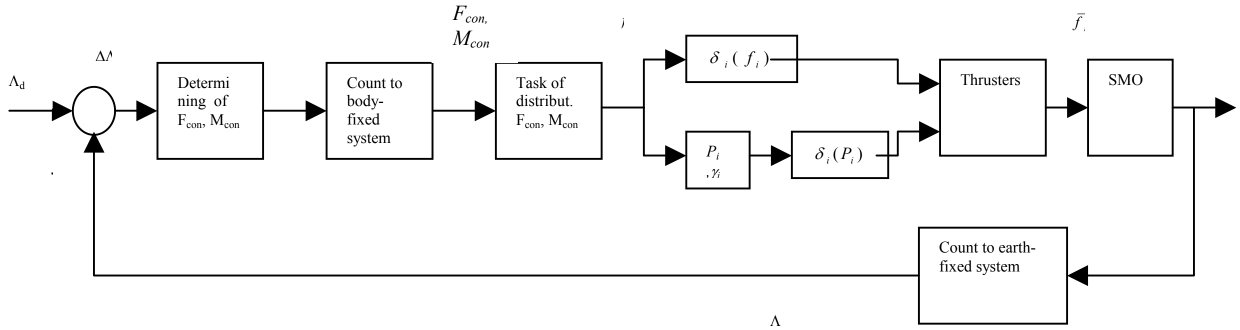


Fig.2

At research model thruster was represented as

$$T_i \frac{d\bar{f}}{dt} + \bar{f}_i = k_i(\delta_i), \qquad (36)$$

where T_i - constant time of thruster, $k_i(\delta_i)$ - working characteristic thruster (dependence of the established draft on a corner of turn of blades of the screw)

$$k_i(\delta_i) = \bar{k}_i(\delta_i)\rho n^2 D^4 (1-\bar{t}), \qquad (37)$$

where n - frequency of rotation of the screw, D - his diameter, $\bar{t}$ - factor of engulfing $(\bar{t} = 0{,}07 \div 0{,}1)$.

The decision of a task of distribution of the generalized management on the executive bodies

The system of the equations (34) for the considered scheme, fig. 1, looks like

$$\begin{aligned}
&f_{x1} + f_{x2} + f_{x3} + f_{x4} = F_{conx} \\
&f_{y5} + f_{y6} + f_{y7} + f_{y8} = F_{cony} \\
&f_{z1} + f_{z2} + f_{z3} + f_{z4} = F_{conz} \qquad (38) \\
&y_1(-f_{z1} - f_{z2} - f_{z3} - f_{z4}) + z_2(f_{y5} - f_{y6} - f_{y7} + f_{y8}) = M_{conx} \\
&z_1(-f_{x1} + f_{x2} + f_{x3} - f_{x4}) + x_1(f_{z1} + f_{z2} - f_{z3} - f_{z4}) = M_{cony} \\
&y_1(f_{x1} + f_{x2} + f_{x3} + f_{x4}) + x_2(-f_{y5} - f_{y6} + f_{y7} + f_{y8}) = M_{conz} \quad ,
\end{aligned}$$

Let's enter designations

$$F_1 = f_{x2} + f_{x3}, \quad F_2 = f_{x1} + f_{x4}, \quad F_3 = f_{z1} + f_{z2}, \quad F_4 = f_{z3} + f_{z4},$$
$$F_5 = f_{y5}, \quad F_6 = f_{y6}, \quad F_7 = f_{y7}, \quad F_8 = f_{y8}.$$

Then (38) is possible to copy as

$$\begin{aligned}
&F_1 + F_2 = F_{conx} \\
&F_3 + F_4 = F_{conz} \qquad (39) \\
&z_1(F_1 - F_2) + x_1(F_3 - F_4) = M_{cony}
\end{aligned}$$

and

$$\begin{aligned}
&F_5 + F_6 + F_7 + F_8 = F_{cony} \\
&F_5 - F_6 - F_7 + F_8 = \frac{1}{z_2}(M_{conx} + y_1 F_{conz}) \qquad (40)
\end{aligned}$$

$$-F_5 - F_6 + F_7 + F_8 = \frac{1}{x_2}(M_{conz} - z_1 F_{conx}).$$

As the system of the equations is visible has broken up to two independent groups of the equations:

- first three equations concerning unknown F_1, F_2, F_3, F_4 ; from the decision of these equations then the tractions are defined f_{xi}, f_{zi} . Is usually accepted

$$f_{x2} = f_{x3} = \frac{F_1}{2}, \quad f_{x1} = f_{x4} = \frac{F_2}{2}, \quad f_{z1} = f_{z2} = \frac{F_3}{2}, \quad f_{z3} = f_{z4} = \frac{F_4}{2}. \quad (41)$$

- The second group of the equations concerning unknown F_5, F_6, F_7, F_8 determines tractions f_{zi} .

Using a method given in [1-6], we shall receive

$$F_1 = \frac{1}{2z_1}(M_{cony} + 2x_1F_4 - x_1F_{conz} + z_1F_{conx}),$$

$$F_2 = F_{conx} - \frac{1}{2z_1}(M_{cony} + 2x_1F_4 - x_1F_{conz} + z_1F_{conx}), \quad (42)$$

$$F_3 = F_y - F_4,$$

and

$$F_5 = \frac{1}{2}[F_{cony} + \frac{1}{z_2}(M_{conx} + y_1F_{conz})] - F_8,$$

$$F_6 = -\frac{1}{2}[\frac{1}{x_2}(M_{conz} - y_1F_{conx}) + \frac{1}{z_2}(M_{conx} + y_1F_{conz})] + F_8, \quad (43)$$

$$F_7 = \frac{1}{2}[F_{cony} + \frac{1}{x_2}(M_{conz} - y_1F_{conx})] - F_8 .$$

From condition (35)

$$\min_{F_4,F_8} J = \min_{F_4,F_8} \frac{1}{2}\sum_{i=1}^{8} \lambda_i F_i^2 \text{, follows}$$

$$F_4 = \frac{\lambda_3 F_{conz} + \lambda_2 \frac{x_1}{z_1}[F_{conx} - \frac{1}{2z_1}(M_{cony} - x_1F_{conz} + y_1F_{conx})] - \lambda_1 \frac{x_1}{2z_1^2}(M_{cony} - x_1F_{conz} + z_1F_{conx})}{(\lambda_1 + \lambda_2)\frac{x_1^2}{z_1^2} + \lambda_3 + \lambda_4}. \quad (44)$$

At $\lambda_i = 1$, (uniform loading of the executive drives at identical power) we have

$$F_4 = \frac{F_{conz} + \frac{x_1}{z_1}[F_{conx} - \frac{1}{2z_1}(M_{cony} - x_1F_{conz} + z_1F_{conx})] - \frac{x_1}{2z_1^2}(M_{cony} - x_1F_{conz} + z_1F_{conx})}{2\frac{x_1^2}{z_1^2} + 2}. \quad (45)$$

Similarly for the second group of the equations we find

$$F_8 = \frac{\lambda_5[F_{cony} + \frac{1}{y_2}(M_{conx} + y_1F_{conz})] + \frac{\lambda_6}{2}[\frac{1}{x_2}(M_{conz} - y_1F_{conx}) + \frac{1}{z_2}(M_{conx} + y_1F_{conz})] + \frac{\lambda_7}{2}[F_{cony} + \frac{1}{x_2}(M_{conz} - y_1F_{conx})]}{\lambda_5 + \lambda_6 + \lambda_7 + \lambda_8}. \quad (46)$$

At $\lambda_i = 1$, we have

$$F_8 = \frac{1}{4}[F_{cony} + \frac{1}{z_2}(M_{conx} + y_1 F_{conz}) + \frac{1}{x_2}(M_{conz} - y_1 F_{conx})]. \qquad (47)$$

Below are resulted results of research of system DP of SMO with the above mentioned laws of management and observer for SMO by displacement 800 т., thrusters, which traction did not exceed 4E4 H., and constant time $T_i = 0.2c$.

The managing forces and moments (10) are defined by diagonal matrixes $K_1 = diag(k_{1i})M, K_2 = diag(k_{2i})M, K_3 = diag(k_{3i})M$, where $k_{1i} = 20, k_{2i} = 1, k_{3i} = 0.1$. In this case time of transient processes $t_{tp} = 60\,c.$, i.e. T=20c. The restrictions on tractions at the first stage were not taken into account.

The presence of the uniformly distributed noise on an interval was supposed [-1м, +1м] for linear and [-0.1 °, + 0.1 °] for angular of coordinates. Allowable errors in 0.5м on linear and 0.05 ° on to angular coordinates is provided at $\overline{K}_2 = diag\{1,1,1,1E4,10,1E4\}$.

Then from (33)follows $\overline{K}_1 = diag\{0.05;0.05;0.05;500;0.5;500\}$. In a fig. 3,4 the diagrams acting on an input(entrance) of the observer of signals with noise of a deviation SMO on coordinate ξ (KsiN) and on pitch (PsiN), and also signals on an output of the observer - KsiF, PsiF are given at steady positioning of object with use of output signals of the observer and without restrictions on thruster traction. The initial deviation on linear coordinates - 5м., and on angular- 0.1rad. (or 1rad).

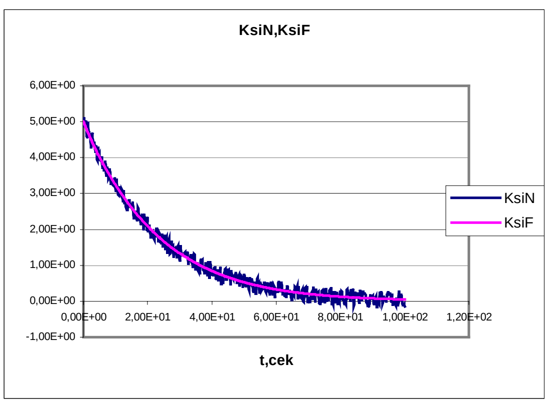


Fig.3

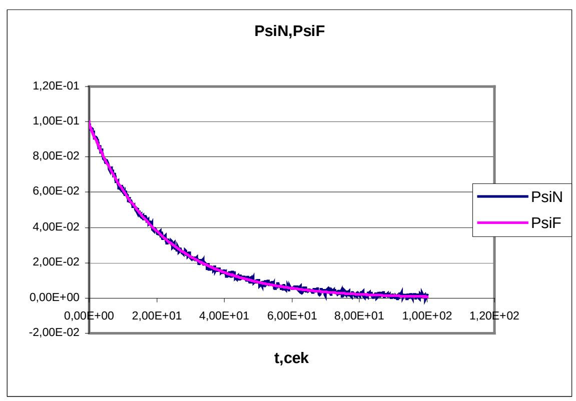


Fig.4

The linear and angular deviations SMO during positioning are given in a fig. 5.6 accordingly.

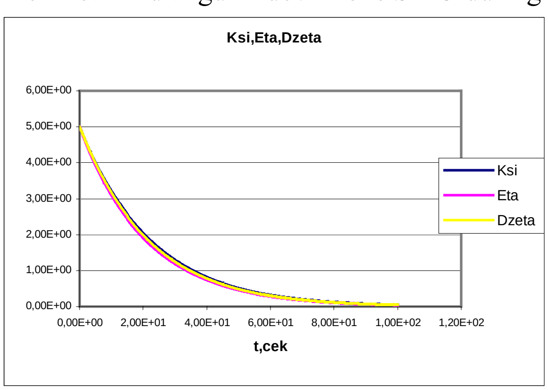


Fig.5

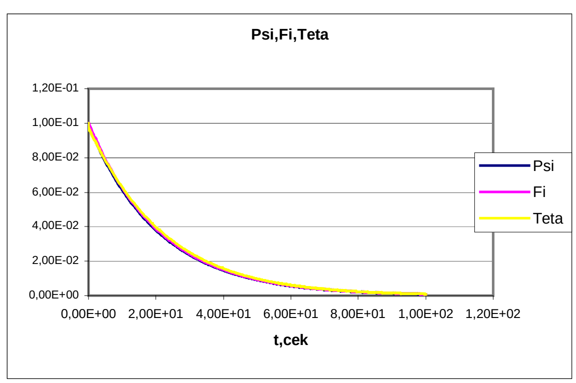


Fig.6

Further the restrictions 4E4 H. were imposed on tractions of the executive engines, and constant time of drives was accepted equal 0.2c. In this case for maintenance of steady movement the factors k_{1i} were accepted equal 100 (vector L_{con} decreased in 10 times). The diagrams of linear and angular deviations SMO during positioning are submitted in a fig.7.8.

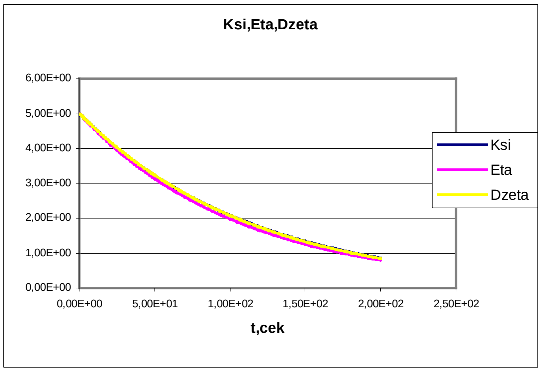


Fig.7

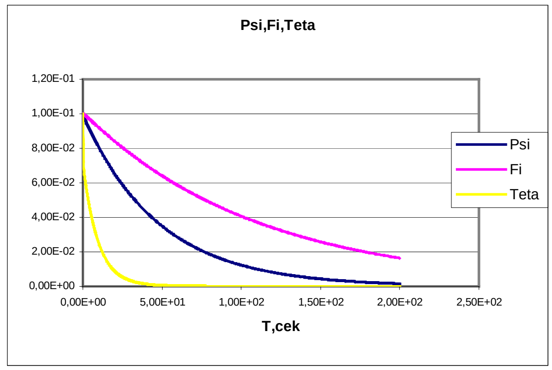


Fig.8

From the given figures it is visible, that exponential character of changing of deviations is kept, though the time of transients has increased up to 250 c.

The diagrams of tractions of the executive drives of the first and second groups are given in a Fig. 9,10,11.

The first group: tractions and corners of turn.

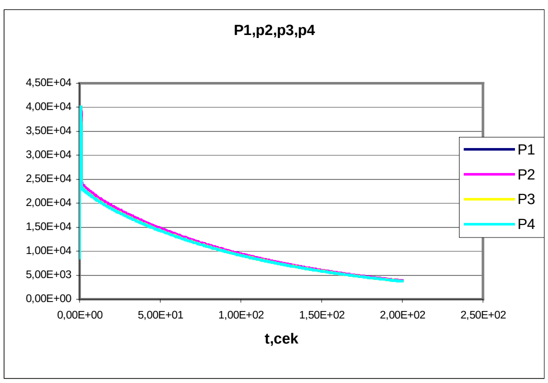


Fig.9

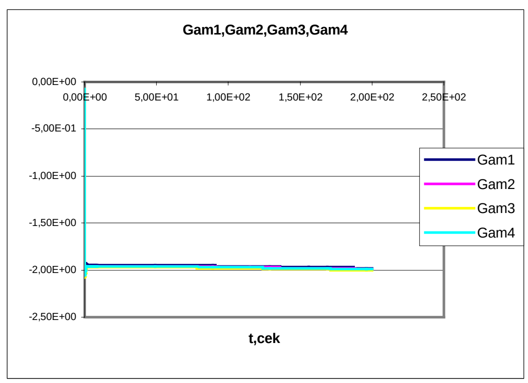


Fig.10

The second group

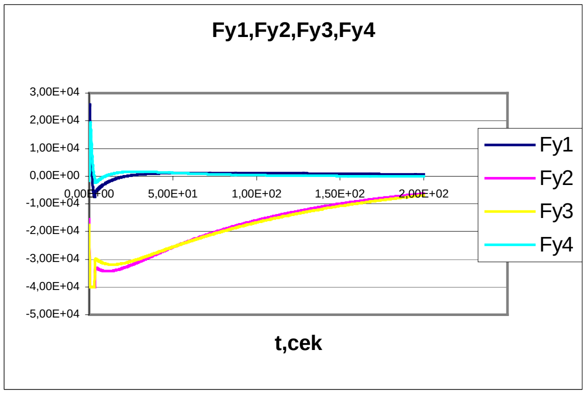
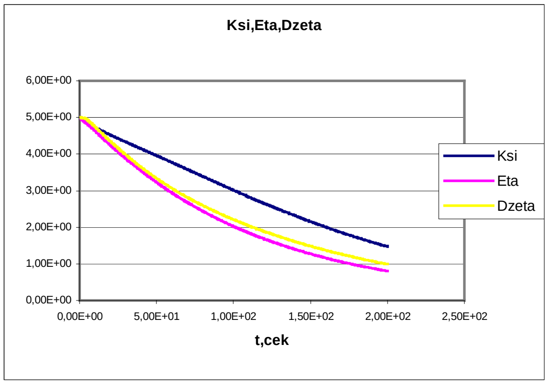


Fig.11

Changing of deviations on linear coordinates in 5м. and angular in 1 rad. shown on. Fig.12.13.



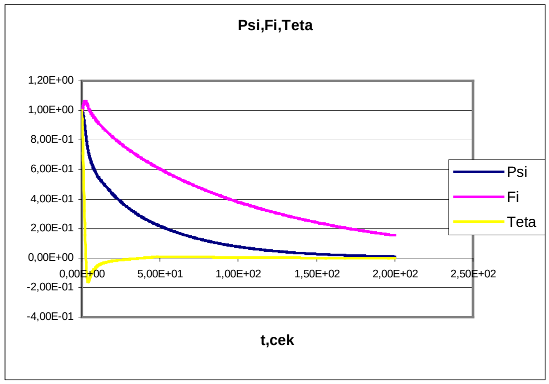


Fig.12 Fig.13

It is visible, that the system keeps stability and at significant initial angular deviations.

Conclusions

In report the method of construction of regulators ensuring exponential stability of dynamic positioning SMO is considered. The method includes procedures of construction of the control laws and observer, which provides exponential stable positioning SMO in the given area of initial deviations. The algorithm of distribution of the received control forces and moments on the executive drives is developed. The modeling has shown efficiency of the offered approach for dynamic positioning SMO.

Appendix

The existence of the decision of system (33) (for three-dimensional space as against frame) essentially depends on coordinates of points of the appendix and directions of vectors of tractions determining skew-symmetric a matrixes $\mathbf{x}_i$,.

Further the following cases are considered, when the system (33) has one or set of the decisions. The sole decision the system (33) has, for example, if vectors of tractions are located, as shown in a fig.A1.

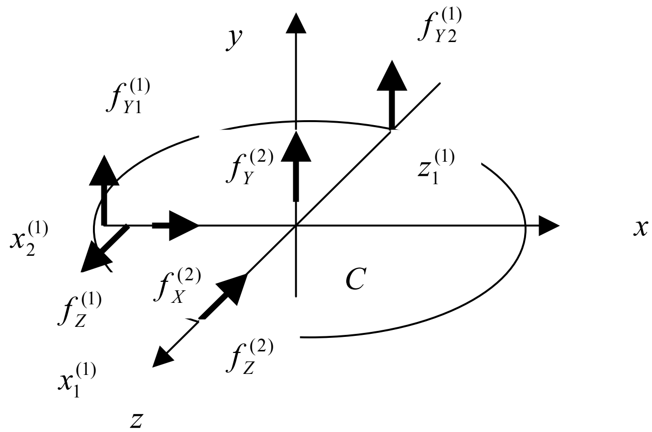


Fig. A1. Possible variant of an arrangement drives with the fixed tractions.
Here $\mathbf{f}_1 = (0, f_{Y2}^{(1)}, 0)^T$, $\mathbf{f}_2 = (0, f_{Y1}^{(1)}, 0)^T$, $\mathbf{f}_3 = (0, 0, f_Z^{(1)})^T$, $\mathbf{f}_4 = (f_X^{(2)}, 0, 0)^T$, $\mathbf{f}_5 = (0, f_Y^{(2)}, 0)^T$, $\mathbf{f}_6 = (0, 0, f_Z^{(2)})^T$
Drives in this case are divided on two groups (top index (1) or (2)). The first group creates the independent moments ($M_{conx} = f_{Y2}^{(1)} z_1^{(1)}, M_{cony} = f_Z^{(1)} x_1^{(1)}, M_{conz} = f_{Y1}^{(1)}$), and second - the forces, which do not create the moments, compensate forces of the first group of drives and provide required forces of control of forward motion $(f_X^{(2)} = F_{conx}, f_Y^{(2)} = F_{cony} - f_{Y1}^{(1)} - f_{Y2}^{(1)}, f_Z^{(2)} = F_{conz} - f_Z^{(1)})$. If to unit points of the appendix of tractions, as it is shown in a fig..A2, we shall receive the scheme with two rotary and one fixed drives, equivalent initial.

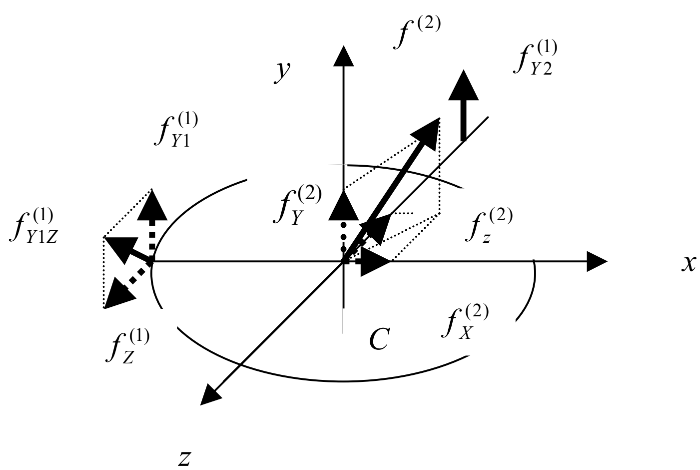


Fig.A2. The scheme with rotary drives.

In this case one drive rotates in a plane, creating traction $f_{Y1Z}^{(1)}$, and second, taking place in the centre of weights rotates in space. Third drive remains fixed and provides stabilization of a roll.
Thus as basic (from which can be received and others more complex) the scheme from two groups drives with the direction of tractions, fixed along the main axes , can be accepted, fig.A3.

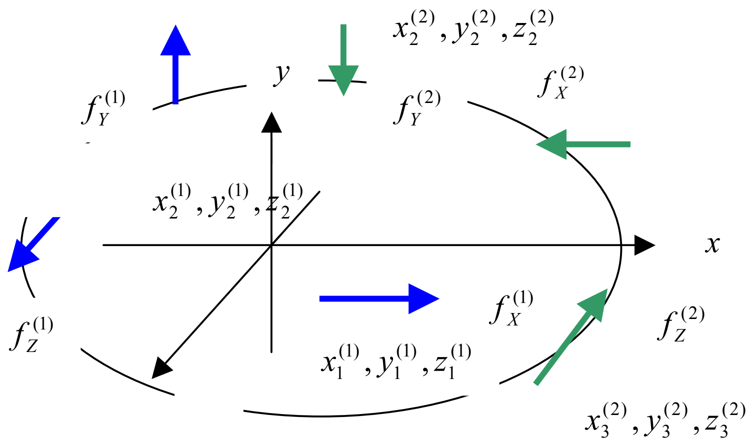


Fig.A3. The general scheme of an arrangement of two groups drives.

Then the system of the equations (33), in a matrix form has the following view:
- for the moments

$$\begin{pmatrix} 0 & z_2^{(1)} & -y_3^{(1)} \\ -z_1^{(1)} & 0 & x_3^{(1)} \\ y_1^{(1)} & -x_2^{(1)} & 0 \end{pmatrix} * \begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} + \begin{pmatrix} 0 & z_2^{(2)} & -y_3^{(2)} \\ -z_1^{(2)} & 0 & x_3^{(2)} \\ y_1^{(2)} & -x_2^{(2)} & 0 \end{pmatrix} * \begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix} = \begin{pmatrix} M_{conx} \\ M_{cony} \\ M_{conz} \end{pmatrix}; \qquad (A1)$$

- for forces

$$\begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} + \begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix} = \begin{pmatrix} F_{conx} \\ F_{cony} \\ F_{conz} \end{pmatrix}. \qquad (A2)$$

The coordinates of points of the appendix of drafts always can be chosen so that even one of two determinants of square matrixes of the equation (A1) did not equals in a zero. Let's assume, that it is the first matrix, then

$$\begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} = \begin{pmatrix} 0 & z_2^{(1)} & -y_3^{(1)} \\ -z_1^{(1)} & 0 & x_3^{(1)} \\ y_1^{(1)} & -x_2^{(1)} & 0 \end{pmatrix}^{-1} * \left[\begin{pmatrix} M_{conx} \\ M_{cony} \\ M_{conz} \end{pmatrix} - \begin{pmatrix} 0 & z_2^{(2)} & -y_3^{(2)} \\ -z_1^{(2)} & 0 & x_3^{(2)} \\ y_1^{(2)} & -x_2^{(2)} & 0 \end{pmatrix} * \begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix} \right] \qquad (A3)$$

Substituting expression (A3) in the equation (A2) and permitting the turned out system rather beforehand of unknown vector - column ($f_X^{(2)}$, $f_Y^{(2)}$, $f_Z^{(2)}$ $)^{\mathrm{T}}$ is received

$$\begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix} = \begin{pmatrix} 0 & (z_2^{(1)} - z_2^{(2)}) & -(y_3^{(1)} - y_3^{(2)}) \\ -(z_1^{(1)} - z_1^{(2)}) & 0 & (x_3^{(1)} - x_3^{(2)}) \\ (y_1^{(1)} - y_1^{(2)}) & -(x_2^{(1)} - x_2^{(2)}) & 0 \end{pmatrix}^{-1} * \\ * \left[\begin{pmatrix} 0 & z_2^{(1)} & -y_3^{(1)} \\ -z_1^{(1)} & 0 & x_3^{(1)} \\ y_1^{(1)} & -x_2^{(1)} & 0 \end{pmatrix} * \begin{pmatrix} F_{conx} \\ F_{cony} \\ F_{conz} \end{pmatrix} - \begin{pmatrix} M_{conx} \\ M_{cony} \\ M_{conz} \end{pmatrix} \right]. \quad \text{(A4)}$$

Further from expression (A4) are defined stayed unknown $(f_X^{(1)}, f_Y^{(1)}, f_Z^{(1)})^T$:

$$\begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} = \begin{pmatrix} F_{conx} \\ F_{cony} \\ F_{conz} \end{pmatrix} - \begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix}. \quad \text{(A5)}$$

If in system of the equations (A1) the determinant of the second matrix does not equals a zero, and the determinant of the first is equal zero, it is possible to search for the decision as follows:

$$\begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} = \begin{pmatrix} 0 & (z_2^{(1)} - z_2^{(2)}) & -(y_3^{(1)} - y_3^{(2)}) \\ -(z_1^{(1)} - z_1^{(2)}) & 0 & (x_3^{(1)} - x_3^{(2)}) \\ (y_1^{(1)} - y_1^{(2)}) & -(x_2^{(1)} - x_2^{(2)}) & 0 \end{pmatrix}^{-1} * \\ * \left[\begin{pmatrix} M_{conx} \\ M_{cony} \\ M_{conz} \end{pmatrix} - \begin{pmatrix} 0 & z_2^{(2)} & -y_3^{(2)} \\ -z_1^{(2)} & 0 & x_3^{(2)} \\ y_1^{(2)} & -x_2^{(2)} & 0 \end{pmatrix} * \begin{pmatrix} F_{conx} \\ F_{cony} \\ F_{conz} \end{pmatrix} \right]. \quad \text{(A6)}$$

And from expression (A2) is determined stayed unknown $(f_X^{(2)}, f_Y^{(2)}, f_Z^{(2)})^T$

$$\begin{pmatrix} f_X^{(2)} \\ f_Y^{(2)} \\ f_Z^{(2)} \end{pmatrix} = \begin{pmatrix} F_{conx} \\ F_{cony} \\ F_{conz} \end{pmatrix} - \begin{pmatrix} f_X^{(1)} \\ f_Y^{(1)} \\ f_Z^{(1)} \end{pmatrix} \quad \text{(A7)}$$

Thus, the put task always has the sole decision, if even one of determinants of matrixes of determining coordinate of an arrangement drives SMO in the ratio (A1) does not equals zero and determinant of a matrix which is included in of expression (A4) or (A6)

$$\begin{pmatrix} 0 & (z_2^{(1)} - z_2^{(2)}) & -(y_3^{(1)} - y_3^{(2)}) \\ -(z_1^{(1)} - z_1^{(2)}) & 0 & (x_3^{(1)} - x_3^{(2)}) \\ (y_1^{(1)} - y_1^{(2)}) & -(x_2^{(1)} - x_2^{(2)}) & 0 \end{pmatrix}$$

is not equal to zero. **SMO is controlled, if the coordinates of an arrangement to any six thrusters directed along orts satisfy to a condition:**

$$\left(x_3^{(1)} - x_3^{(2)}\right) \cdot \left(y_1^{(1)} - y_1^{(2)}\right) \cdot \left(z_2^{(1)} - z_2^{(2)}\right) - \left(x_2^{(1)} - x_2^{(2)}\right) \cdot \left(y_3^{(1)} - y_3^{(2)}\right) \cdot \left(z_1^{(1)} - z_1^{(2)}\right) \neq 0, \quad \text{(A8)}$$

which should be carried out always and

$$x_3^{(1)} y_1^{(1)} z_2^{(1)} - x_2^{(1)} y_3^{(1)} z_1^{(1)} \neq 0, \quad \text{(A9)}$$

or

$$x_3^{(2)} y_1^{(2)} z_2^{(2)} - x_2^{(2)} y_3^{(2)} z_1^{(2)} \neq 0 \ . \qquad \text{(A10)}$$

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