Control method of high-precision soft docking of moving objects using low-accurate values of relative speed and distance

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Abstract. An analytical expression is constructed for the main vector of control forces, providing the pursuit of an unpredictably moving object with the purpose of shockless high-precision docking with it or its shockless capture in a finite period of time using low-accurate values of the measured relative velocity and distance. The constructed control ensures the pursuit of the goal on the principle of proportional navigation, brings the pursuing point in a finite time to the “initial position”, which provides the possibility of reducing the distance to the target, and then ensures the subsequent sliding movement of a point from the “initial position” along the line of discontinuity to the origin of the phase coordinate system. To solve the problem with large relative measurement errors, it was proposed to construct a continuous part of the control force, which provides the process of sliding movement of the representative point along the line of discontinuity, as a function, depending on the current values of the relative velocity and distance. The article also analyzes the issue related to the expansion of the class of control forces by introducing some positive parameter in the expression for the continuous component of the control force. The choice of this parameter affects the duration of the rapprochement of the pursued and pursuing points.

Keywords: control forces, shockless, high-precision docking, finite time, quasi-speed.

1. Introduction
At this stage of development of modern civilization, the total automation of all management processes takes place in technology and other areas of human activity. A major obstacle here is the presence of unpredictable random disturbances. In particular, in technology, this leads to the appearance of shock loads at the moment of contact, dangerous for both controlled and pursued objects. Therefore, an extremely important task is the selection of such a control algorithm that allows you to perform the task of docking the objects or capturing the targets, avoiding an impact, in a finite period of time. Every year, a large number of works devoted to the problem of automatic control in conditions of uncertainty appear. We list only a small part of them as an example. In [1], a control scheme for a hybrid robot to capture a non-cooperative target in space is proposed. The study [2] sets up a class of absolutely continuous robust controllers which seem to be effective in counteracting both uncertain dynamics and unbounded disturbances. In [3], an adaptive control scheme is constructed which guarantees the asymptotic satisfaction of the control objective in the presence of bounded parametric uncertainties. In [4], a robust adaptive tracking controller is proposed to control the nonholonomic mobile manipulator. In [5], robust task-space motion control of a mobile manipulator using a nonlinear control with an uncertainty estimator is constructed. The work [6] deals with orbit and attitude control of a chaser spacecraft when approaching in the vicinity of the target spacecraft; then the impact of the robot manipulator dynamics on the attitude motion and the associated control effort to keep the
attitude stable during the manipulator's operation is analyzed. In [7], the control of flexible-joint robotic manipulators while avoiding actuator saturation is investigated. The paper [8] proposes a finite time synergetic control scheme which is synthesized with synergetic theory and a terminal attractor technique for controlling robot manipulators; this control scheme has the characteristics of finite time convergence and chattering free phenomena. In [9], a voltage-based sliding mode control is presented to control the position of rigid-link flexible-joint serial robot manipulator in the presence of structured and unstructured uncertainties. The study [10] investigates a novel optimal adaptive radial basis function neural network control for a class of multiple-input-multiple-output nonlinear robot manipulators with uncertain dynamics. In [11] a control algorithm of the movement of robotic manipulator by the method of Lyapunov function with a significant influence of the disturbing moments in operating conditions is obtained. The work [12] presents a robust interaction control approach for underwater vehicle manipulator systems. The paper [13] investigates the task-space prescribed performance tracking control problem of free-floating space manipulators with kinematic and dynamic uncertainty. In [14], a model reference adaptive state-dependent Riccati equation control of nonlinear uncertain systems is proposed and applied for regulation and tracking of free-floating space manipulator. The work [15] demonstrates the capability of the model free controller to be able to command a highly nonlinear and uncertain system. Neither of the above studies (the list of which can be continued) does not aim to avoid an impact at the moment of contact with the target. In [1], it was noted that the problem of shock loads exists and they are caused by errors in measuring. In [16], an attempt was made to construct the control of a collision-free contact of two bodies, but none of applicable in practice algorithm was constructed. Thus, in none of the well-known studies the problem is solved in the most general formulation in which it is posed and solved in this work.

The aim of the research is to build the most autonomous (“self-tuning”) control that allows to avoid the appearance of the impact contact forces and to achieve the target in finite time in conditions of uncertainty. In this formulation, all the problems arising in the control process are completely solved.

The results can be used to build control systems for the berthing of ships; landing of aircraft; landing, docking or berthing of spacecraft. Also, this control can be adapted for robotic manipulators with the purpose of shockless capture of various objects, including space debris.

2. Materials and methods

2.1 Formulation of the problem
Consider a controlled body with the center of mass at point \( C \). The task is to construct an analytical expression for the main vector of control forces, providing the pursuit of an unpredictably moving object with the purpose of shockless high-precision docking with it or its shockless capture in a finite period of time using low-accurate values of the measured relative velocity and distance.

The terms “high-precision” and “low-accurate” are estimated by the value of the relative error of meters.

2.2 The vector of control force, providing movement on the principle of proportional navigation
We construct the force \( \vec{F} \), providing the movement of point \( C \) after point \( O \) according to the principle of proportional navigation in the form

\[
\vec{F} = m\vec{\dot{b}} (\vec{\omega} \times \vec{V}),
\]

where \( m \) and \( \vec{V} \) – the mass and absolute velocity of point \( C \), \( \vec{\omega} \) – absolute angular velocity of the line of sight \( \vec{CO} \), \( \vec{b} \) is a positive coefficient of proportionality.

It is assumed that the following conditions are to be met:

\[
(\vec{s} \cdot \vec{s}) < 0, \quad |\vec{V}| > |\vec{V}_0|,
\]

where \( \vec{V}_0 \) – the absolute speed of the point \( O \), \( \vec{s} = \vec{CO} \).

Note that \( \vec{s} \) is a law of the relative motion of the point \( C \) in the moving coordinate system with the origin at the point \( O \), one axis of which is directed along the vector \( \vec{CO} \), the other axis \( \vec{s} \) is orthogonal to the vector \( \vec{CO} \).
2.3 Bringing the haunting point to the “initial position”

We define the component \( R \) of the main vector of control forces, which ensures the shockless bringing of the point \( C \) to the point \( O \) in a finite period of time.

Note that to solve this problem, it is necessary to ensure that the conditions (2) are met. This is due to the fact that at the initial moment of time \( t = 0 \) the first of the conditions (2) may be unfulfilled. In this case, the point \( C \) must be brought to its initial position in a finite period of time, where this condition is met.

We show that as an initial point we can use any point of the line

\[
\frac{\dot{s}}{\dot{s}} + \mu s = 0 \quad (3)
\]

in the phase plane \((\ddot{s} \cdot \dot{s})\), where \( s \) and \( \dot{s} \) are projections of the vectors \( \ddot{s} \) and \( \dot{s} \) onto \( CO \), \( \mu = \text{const} > 0 \).

From (3) it follows that the first condition (2) is guaranteed by the choice of \( \mu \) in the form

\[
\mu = -\frac{\ddot{s}(0)}{s(0)} > 0.
\]

Therefore, the first condition from (2) in the case of

\[
\dot{s}(0) + \mu s(0) \neq 0
\]

can be achieved by vanishing the value

\[
\ddot{V} = \dot{s}(t) + \mu s(t) \quad (4)
\]

in a finite period of time.

This problem can be solved as follows. We use the basic law of dynamics to describe relative motion of the point \( C \) in the projection on the \( CO \) axis:

\[
m\ddot{s}(t) = R + U,
\]

where \( R \) is the projection of a part of the main vector of control forces, \( U \) is the projection of the main vector of non-control forces, including inertial forces, on the same axis \( CO \).

Choose \( R \) in the form

\[
R = -R^0 \text{sign} \ddot{V},
\]

where \( R^0 \) is a positive constant or piece-wise constant function satisfying the condition

\[
R^0 \geq |U + m\mu s| + \delta, \quad \delta = \text{const} > 0.
\]

the choice of the magnitude of which in each specific case is carried out according to the principle of feedback on quasi-accelerations (see, for example, [17,18]).

Now, substituting (6) into (5) and taking into account the time-differentiated equality (4), we get

\[
m\frac{d\ddot{V}}{dt} = -R^0 \ddot{V} + \dot{U} + m\mu \dot{s},
\]

where \( R^0 \) satisfies the condition (7).

Multiplying (8) by \( \ddot{V} \), we get

\[
m\ddot{V} \frac{d\ddot{V}}{dt} = -R^0 \ddot{V} \ddot{V} + (\ddot{U} + m\mu \dot{s})\ddot{V}.
\]

With the condition (7), we have

\[
\frac{1}{2} \frac{d(m\ddot{V}^2)}{dt} \leq -\delta |\dot{V}|,
\]

and

\[
\frac{d\ddot{V}^2}{\ddot{V}} \leq -\frac{2\delta}{m} dt.
\]

Integrating (10) and taking into account \( |\ddot{V}| = \sqrt{\ddot{V}^2} \), we get

\[
2|\ddot{V}|^0 |_{\ddot{V}(0)} \leq -\frac{2\delta}{m} t^\hat{t},
\]

where \( \hat{t} \) is the instant of time when \( \ddot{V} \) vanishes.

Hence,
where \( m|\dot{V}(0)|/\delta \) is the maximum possible value of the time interval for bringing of the representative point \((s, \dot{s})\) on a straight line (3).

\[ t \leq \frac{m|\dot{V}(0)|}{\delta}, \]

2.4 Bringing the representative point to the position \( s = 0, V = 0 \)

Starting from the moment \( t = \hat{t} \) we organize the process of sliding movement of the representative point along the line of discontinuity of the form

\[ V(\tau) - \frac{V(\hat{t})}{\sqrt{|s(\hat{t})|}} \sqrt{|s(\tau)|} = 0, \]

where \( \tau = t - \hat{t} \). To do this, as the quasi-speed, we choose

\[ \dot{V}' = V(\tau) - \frac{V(\hat{t})}{\sqrt{|s(\hat{t})|}} \sqrt{|s(\tau)|}. \]

We represent the control force \( R \) as the sum of the continuous component

\[ R_1 = \frac{mV^2}{2s} \]

and the piece-wise constant component \( R' \) of the form

\[ R' = -\bar{R}^0 \text{sign} \dot{V}', \]

where \( \bar{R}^0 \) satisfies the condition

\[ \bar{R}^0 \geq |\bar{U}| + \delta, \quad \delta = \text{const} > 0. \]

In each specific case the choice of the magnitude of \( \bar{R}^0 \) is carried out according to the principle of feedback on quasi-accelerations (see, for example, [17,18]).

Now we substitute \( R = R_1 + R' \) into (5). Taking into account (12) and (14) we get

\[ m \frac{d\dot{V}'}{dt} = -\bar{R}^0 \text{sign} \dot{V}' + \mathcal{U}. \]

Multiplying (15) by \( \dot{V}' \), we get

\[ m\dot{V}' \frac{d\dot{V}'}{dt} = -\bar{R}^0 \dot{V}' \text{sign} \dot{V}' + \mathcal{U} \dot{V}'. \]

With the condition (14) we have

\[ \frac{1}{\bar{R}^0} \frac{d(\dot{V}')^2}{dt} \leq \frac{m}{2} \dot{V}', \]

and

\[ \frac{d(\dot{V}')^2}{|\dot{V}'|} \leq -\frac{2\delta}{m} dt. \]

Integrating (17) and taking into account \( |\dot{V}'| = \sqrt{(\dot{V}')^2} \), we get

\[ 2|\dot{V}'| \bigg|_{\dot{V}'(\tau_0)}^{0} \leq -\frac{2\delta}{m} \int_{\tau_0}^{\hat{t}} dt, \quad \tau_0 = \hat{t}, \]

where \( \hat{t} \) is the moment in time when \( \dot{V}' \) vanishes.

From here

\[ \hat{t} \leq \frac{m|\dot{V}'(\hat{t})|}{\delta}, \]

Consequently, the maximum possible value of the moment of time at which \( \dot{V}' \) vanishes does not exceed the value

\[ \max \hat{t} = \frac{m|\dot{V}'(\hat{t})|}{\delta}. \]
So, controlling in the time interval \( t \in [0, \bar{t}] \) by the force of the form (6), then in the interval \( t > \bar{t} \) by the force \( R_2 + R' \), we get the desired control force of the point \( C \) directed along line of sight \( CO \). For \( 0 \leq t \leq \bar{t} \), the control has the form

\[
R = -R^0 \text{sign} \bar{\nu},
\]

where

\[
R^0 \geq |\bar{\nu} + m\mu \dot{s}| + \delta, \quad \delta = \text{const} > 0.
\]

When \( \tau = t - \bar{t} \), the control force is \( R = R_1 + R' \), where

\[
R_1 = \frac{mV^2}{2s}, \quad R' = -R^0 \text{sign} \bar{\nu}'.
\]

Here

\[
\bar{R} \geq |\bar{\nu}| + \delta, \quad \delta = \text{const} > 0,
\]

\[
\bar{\nu}' = V(\tau) - \frac{V(\bar{\tau})}{\sqrt{|s(\tau)|}} \sqrt{|s(\bar{\tau})|}, \quad \bar{V}(t) = \dot{s}(t) + \mu s(t).
\]

A general view of the control force \( \bar{R}' \) can be represented as

\[
\bar{R}' = R \text{sign} \bar{\nu}^2 + (R_1 + R') (1 - \text{sign} \bar{\nu}^2).
\]

Note that \( \text{sign} \bar{\nu}^2 = 0 \) for \( \bar{\nu} = 0 \); and for \( \bar{\nu} \neq 0 \), the value of this expression is equal to one. The first term \( R \text{sign} \bar{\nu}^2 \) on the right side of (18) is completely excluded from the control for all \( t > \bar{t} \), so for \( t > \bar{t} \) \( \bar{R} = R_1 + R' \).

Thus, the problem is solved by using the force \( \bar{F} \) in the form (1), providing the pursuit mode of the point \( C \) of the controlled body according to the principle of proportional navigation, and the force \( \bar{R}' \) of the form (18), which ensures the shockless capture of the point \( O \) of the pursued body in a finite period of time.

It should be particularly noted that the second term of the control force \( \bar{R}' \) allows for high-precision soft docking of moving objects (pursuing and pursued bodies) at low-accurate values of the relative speed and distance between the points \( C \) and \( O \), used in the construction of the force \( \bar{R}' \). This conclusion is confirmed by the formula (11), since at the time \( \bar{t} \) when \( \bar{V} \) vanishes, takes place

\[
V(\bar{\tau}) - \frac{V(\bar{\tau})}{\sqrt{|s(\bar{\tau})|}} \sqrt{|s(\bar{\tau})|} \equiv 0.
\]

It follows that the origin of the phase coordinate system is the only point where the equalities \( V = 0 \), \( s = 0 \) are satisfied for any initial values of \( V_0 \) and \( s_0 \) (even low-accurate) that satisfy the condition (2). Note that the condition (2) is satisfied in two regions of the phase plane out of four formed by the reference axes \( s \) and \( \dot{s} \). In one of these areas \( s < 0 \), \( \dot{s} > 0 \), and in the second \( s > 0 \), \( \dot{s} < 0 \).

Due to the fact that earlier when a line of discontinuity was chosen in the form (11) this choice was not justified, we consider it appropriate here to look into this question. To do this, we return to the equation (5). When \( R = mV^2/2s \), \( \bar{\nu} = 0 \) we get:

\[
\frac{m}{dt} = \frac{mV^2}{2s}.
\]

From here we have

\[
\frac{dv}{dt} = \frac{v^2}{2s}.
\]

The equation (20) is an equation with separable variables \( s \) and \( v \) and is easily integrated using the expressions

\[
s = |s| \text{sign} s, \quad ds = (\text{sign} s) d|s|.
\]

The general solution of the equation (20) is

\[
|s| = \left[ \frac{V_0}{2\sqrt{|s_0|}} t + \sqrt{|s_0|(\text{sign} s_0)} \right]^2,
\]

where \( V_0 = V(\bar{\tau}), s_0 = s(\bar{\tau}) \). From here we get the following expression for \( s \):

\[
s = |s| = \left[ \frac{V_0}{2\sqrt{|s_0|}} t + \sqrt{|s_0|(\text{sign} s_0)} \right]^2.
\]
\[ s = \left[ \frac{V_0}{2\sqrt{|s_0|}} t + \sqrt{|s_0|}(\text{sign } s_0) \right]^2 \text{sign } s. \]  

(22)

Differentiating \( s \) by \( t \), we have

\[ V = \frac{V_0}{\sqrt{|s_0|}} \left[ \frac{V_0}{2\sqrt{|s_0|}} t + \sqrt{|s_0|}(\text{sign } s_0) \right] \text{sign } s. \]

(23)

Considering

\[ \sqrt{|s|}(\text{sign } s) = \frac{V_0}{2\sqrt{|s_0|}} t + \sqrt{|s_0|}(\text{sign } s_0), \]

from (23) we get

\[ V = \frac{V_0}{\sqrt{|s_0|}} \sqrt{|s|}. \]

(25)

This expression for \( t > \tilde{t} \) is the equation of the discontinuity line (11), and the quasi-velocity \( \bar{R}' \) has the form (12). Therefore, the sum of the forces \( \bar{F} \) of the form (1) and \( \bar{R}' \) of the form (18) completely solves the posed problem.

2.5 Expansion of the class of control forces

Now let us choose the force of control \( R \) in (5) in the form

\[ R = \frac{mV^2}{bs}, \]

(26)

where \( b \) is any positive constant.

Then the equation (20) is expressed as

\[ \frac{dV}{dt} = \frac{V^2}{bs}. \]

(27)

This equation, as well as the equation (20), is an equation with separable variables and integrates without much difficulty. The general solution of the equation (27) is

\[ s = \left[ \frac{b - 1}{b} \frac{V_0}{\sqrt{|s_0|}} t + s_0^{(b-1)/b}(\text{sign } s_0) \right]^{b/(b-1)} \text{sign } s. \]

(28)

Differentiating \( s \) by \( t \), we get

\[ V = \frac{V_0}{b\sqrt{|s_0|}} \left[ \frac{b - 1}{b} \frac{V_0}{\sqrt{|s_0|}} t + s_0^{(b-1)/b}(\text{sign } s_0) \right]^{1/(b-1)} \text{sign } s. \]

(29)

Hence, for \( s = 0 \), we have \( t = \tilde{t} \), where

\[ \tilde{t} = \frac{bs_0}{(b - 1)V_0}. \]

(30)

Therefore, under the condition (2), \( \tilde{t} > 0 \) exists for all even positive integers \( b > 1 \). In particular, for \( b = 2, \tilde{t}_2 = 2|s_0|/|V_0| \) holds. Note that for \( b \to \infty \), the value of \( \tilde{t}_\infty = |s_0|/|V_0| \) is two times less than the value of \( \tilde{t}_2 \).

Consequently, with an increase in the value of \( b \), the time of bringing the representative point to the point \( s = 0, V = 0 \) decreases, but not more than twice as compared with the case \( b = 2 \).

3. Results and discussion

3.1 Results

An analytical expression is constructed for the main vector of control forces, providing the pursuit of an unpredictably moving object with the purpose of shockless high-precision docking with it or its shockless capture in a finite period of time using low-accurate values of the measured relative velocity and distance. The terms “high-precision” and “low-accurate” are estimated by the value of the relative error of meters.
The constructed control ensures the pursuit of the target on the principle of proportional navigation, brings the pursuing point in a finite time to the “initial position”, which provides the possibility of reducing the distance to the target, and then ensures the subsequent sliding movement of a point from the “initial position” along the line of discontinuity to the origin of the phase coordinate system. To solve the problem with large relative measurement errors, it was proposed to construct a continuous part of the control force, which provides the process of sliding movement of the representative point along the line of discontinuity, as a function, depending on the current values of the relative velocity and distance. The article also analyzes the issue related to the expansion of the class of control forces by introducing some positive parameter in the expression for the continuous component of the control force. The choice of this parameter affects the duration of the rapprochement of the pursued and pursuing points.

3.2 Discussion
In previously published papers by the authors, when bringing the point C to the point O, the constant control force \( R_1 = \frac{mV_0^2}{2s_0} \) was used. The discontinuity line was an arc of a parabola

\[
V^2(t) = V_0^2 \left( 1 - \frac{s(t)}{s_0} \right).
\]

This shows that the velocity \( V(t) \) (for \( V_0 \neq 0 \)) vanishes at the time point \( \bar{t} \) when the equality \( s(\bar{t}) = s_0 \) is reached. Consequently, the equilibrium point was located on the axis of reference \( s \) at a distance \( s_0 \) from the point from which the rapprochement began.

If this distance were measured with ideal accuracy, then at the moment of time \( \bar{t} \) the representative point would be at the origin of the phase coordinate system. But in practice, this distance could be measured with an error, so the representative point at \( V = 0 \) would not be at the point \( s = 0 \), but at some distance from it (depending on the size of the measurement error).

This article proposes to make part of the control force \( R_1 \) changing as

\[
R_1 = \frac{mV^2(t)}{2s(t)};
\]

where \( V(t) \) and \( s(t) \) are the current values of \( V \) and \( s \). In this case, the angular coefficient \( \mu \) of the straight (3) becomes a variable.

In this case, it is necessary to observe condition of positivity of \( \mu \), then the straight line (3) does not lose the property of the mutually opposition of the signs of \( s \) and \( \dot{s} \) in all its points, only slightly changing the angle of inclination to the axis of reference \( s \).

Thereby the values of \( \bar{t} \) and \( \bar{v} \) will also vary somewhat, remaining finite positive values. Thus, in the case of choosing \( R_1 \) in the form proposed in this article, when using inaccurate (with significant relative errors) values of \( s \) and \( \dot{s} \), the representative point \((s, \dot{s})\) comes to a point equilibrium \( O \) for a finite period of time, as well as in the case of using precisely measured \( s \) and \( \dot{s} \).

In this case, while the representative point approaches the point \( O \), the absolute values of \( s \) and \( \dot{s} \) becomes more and more accurate. At the moment of time \( t = \bar{t} \) they become absolutely accurate if the meters of \( s \) and \( \dot{s} \) have no stagnation zone.

If there is a zone of stagnation, then the distance between the points \( C \) and \( O \) at \( t = \bar{t} \) will be commensurate with its size. Note that the size of the stagnation zone is measured in small relative values, and, therefore, does not have much practical value.

4. Conclusions
This article proposes the most autonomous (“self-tuning”) control, which does not require human intervention and allows to avoid the appearance of the impact contact forces and to achieve the target in finite time in conditions of uncertainty.

The results can be used to build control systems for the berthing of ships; landing of aircraft; landing, docking or berthing of spacecraft; also for shockless capture of various objects (including space debris) by manipulators and robots.
5. References

[1] Jun He, Haichao Zheng, Feng Gao and Haibo Zhang 2019 Mechanism and Machine Theory 140 pp 83–103
[2] Galicki M 2015 Automatica 51 pp 49–54
[3] Bartolini G, Ferrara A and Utkin V I 1995 Automatica 31(5) pp 769–773
[4] Jinzhu Peng, Jie Yu and Jie Wang 2014 ISA Transactions 53(4) pp 1035–1043
[5] Mishra S, Londhe P S, Mohan S, Vishvakarma S K and Patre B M 2018 Computers & Electrical Engineering 67 pp 729–740
[6] Ijar M Da Fonseca, Luiz C S Goes, Narumi Seito, Mayara K. da Silva Duarte and Élcio Jeronimo de Oliveira 2017 Acta Astronautica 137 pp 490–497
[7] Caverly R J, Zlotnik D E, Bridgeman L J and Forbes J R 2014 Robotics and Computer-Integrated Manufacturing 30(6) pp 658–666
[8] Chi-Hua Liu and Ming-Ying Hsiao 2012 Computers & Mathematics with Applications 64(5) pp 1163–1169
[9] Saeed Zaaare, Soltanpour M R and Moattari M 2019 Robotics and Autonomous Systems 118 pp 204–219
[10] Runxian Yang, Chenguang Yang, Mou Chen and Andy SK Annamalai 2017 Neurocomputing 234 pp 107–115
[11] Bragina A A, Shcherbakov V P and Shiryaev V I 2018 IFAC-PapersOnLine 51(32) pp 298–303
[12] Heshmati-Alamddari S, Bechlioulis C P, Karras G C, Nikou A, Dimarogonas D V and Kyriakopoulos K J 2018 Annual Reviews in Control 46 pp 315–325
[13] Zhi-Gang Zhou, Yong-An Zhang and Di Zhou 2017 Aerospace Science and Technology 71 pp 568–579
[14] Saeed Rafee Nekoo 2019 Aerospace Science and Technology 84 pp 348–360
[15] Abouaissa H and Chouraqui S 2019 Journal of Computational Science 31 pp 6–16
[16] Matyukhin V I 2010 Journal of Applied Mathematics and Mechanics 74(5) pp 599–610
[17] Mukhametzyanov I A and Chekmaryova O I 2014 Process control of unstressed docking of plurality of moving objects in an ordered time points Discrete and Continuous Models and Applied Computational Science 4 pp 106–111 URL: http://journals.rudn.ru/miph/article/view/8582
[18] Mukhametzyanov I A 2014 The principle of feedback on the quasi-accelerations for unstressed stabilization in finite time of given manifolds of mechanical and generalized systems Discrete and Continuous Models and Applied Computational Science 3 pp 107–114 URL: http://journals.rudn.ru/miph/article/view/8236