Assembly and Service Robotic Space Module. Mathematical Model of the Reduced System

Pavel P. Belonozhko

Abstract Despite the significant achievements of the last decades in the field of space robotics, the task of automated Assembly and maintenance of large space objects continues to be relevant. At the same time, it is advisable to consider the set of serviced facilities and maintenance facilities of robotics in the future as a single cyber-physical system. Its key element is the assembly and service robotic space module (ASRSM). An important feature of the ASRSM as an element of the cyber-physical system is the potential variety of possible modes of controlled motion. The mentioned feature is of fundamental importance in the development of a complex of Autonomous robotic means interacting with a complex technical object in extreme conditions. The study of the characteristics of dynamic regimes ASRSM is advantageously carried out with the use of model problems involving the study of simplified models with the subsequent generalization of the results. It provides both theoretical and practical interest to mechanical design scheme ASRSM of the "movable base—massless single-stage handling mechanism payload". It is shown that in the absence of external forces, a nonlinear oscillatory system with one degree of freedom can be put in correspondence with this system. This system is described by an independent Routh equation, and, in accordance with the terminology adopted in analytical mechanics, is called reduced. The methodical features of the mathematical description of the reduced system for the model problem are considered. It is shown that the Routh function considered as the Lagrange function of the reduced system can be excluded from the term corresponding to zero gyroscopic force and being a full derivative in time from some function of positional velocity and coordinate. In the absence of a control moment, an integral of energy can be written in the hinge, which has the form of the sum of the kinetic and potential energy of the reduced system, and determines the family of phase trajectories of the system's own motions. The considered problem is of both applied and methodological interest. Qualitative generalization of the obtained results in the case of spatial reduced systems with several degrees of freedom is relevant from the point of view of using their own inertial motions in the construction of control.

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1 Introduction

Robotic assembly and maintenance of large space objects is one of the promising areas of development of both space technology and space robotics [1–19]. For Fig. 1 as an example, the use of an autonomous grouping of assembly and service robotic space modules for the assembly of a large-size space object is presented [3].

Management of such assembly and service group of robots assumes a significant amount of sensor data processed in real-time mode; intensive interaction between physical and computational processes; use of current information about the state of the system to optimize control processes.

Thus, the combination of mounted and operated by advanced space infrastructure and set of supporting tools for space robotics (Fig. 1) naturally regarded as a single cyber-physical system.

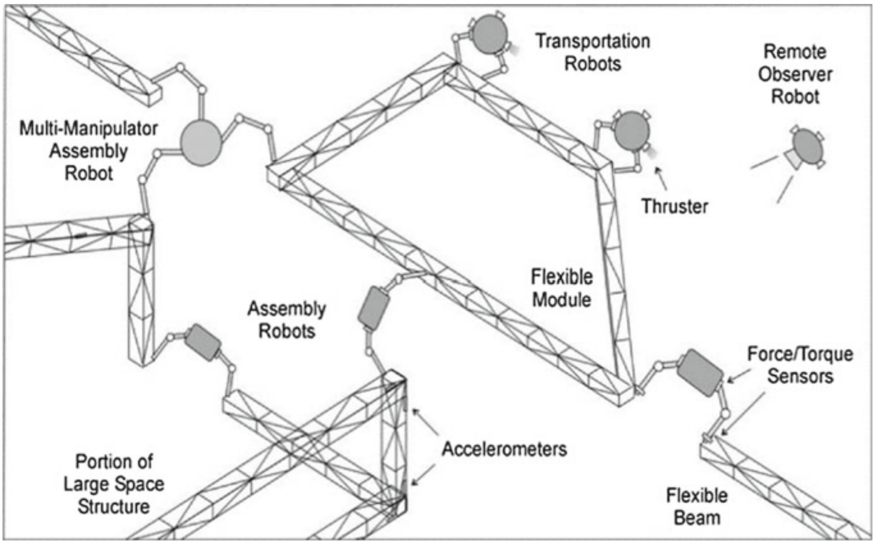

Fig. 1 1—large-size space object, assembled with the help of autonomous grouping of assembly and service robotic space modules [3]

2 Assembly and Service Robotic Space Module as an Element of Cyber-Physical System

As noted in the introduction, the concept of assembly and service autonomic robotic space modules (ASRSM), carrying out the capture of fragments of the assembled structure, delivering them to the Assembly site and installing them in the normal position with the help of the manipulator Fig. 1. Important design features of ASRSM [1]:

– the presence of a movable base;
– the presence of one or more manipulators.

Today there is an experience of experimental orbital testings of such devices (ETS-VII, Orbital Express).

Can be allocated to different modes of functioning of Autonomous ro-botirovna space module [1]: the controlled movement of a module without a load; the module docking to the base station or the mounting structure without the use of a manipulator, docking module to the base station or Monti-financed project design by using the manipulator; a grip manipulator mounted relative to the base station unit; the capture of the manipulator in inertial free space of the block; the controlled movement of a module with a load held by the manipulator; controlled the movement of goods by means of a manipulator; controlled movement of the module with the load fixed on the base; connection of the unit to the mounted structure.

Taking into account the variety of possible modes of movement, an important principle of the organization of the movement of robots—ensuring compliance with the free and forced movements of the manipulator-is relevant in relation to the ASRSM.

3 Model Problem

Consider the flat motion of a system of two solids: the space module 1 (base) and the movable load 2, connected by an ideal single-stage massless manipulator (Fig. 2).

Masses of bodies 1 and 2—m_1 and m_2 respectively, J_1 and J_2—moments of body inertia 1 and 2 in respect to the centers of mass C_1 and C_2, l_1 and l_2—distance between centers of mass and a joint. The motion is viewed in respect to the nonrotating coordinate system XCY originating in the system's center of mass C, which will be inertial should there be no external forces and moments applied to the system. Position relative to XCY is defined by angle φ_1, which describes absolute motion of the platform, and joint angle q, which describes motion of the load in respect to the platform (Fig. 1). Control moment is applied to the joint bounding platform and load M.

Kinetic energy of the system

$$T = T(\dot{\varphi}_1, \dot{q}, q) = \frac{1}{2} a_{\dot{\varphi}_1} \dot{\varphi}_1^2 + a_{\dot{\varphi}_1 \dot{q}} \dot{\varphi}_1 \dot{q} + \frac{1}{2} a_{\dot{q}} \dot{q}^2, \tag{1}$$

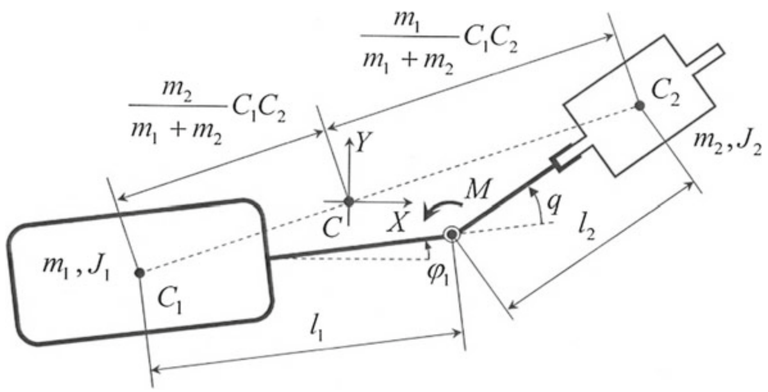

Fig. 2 2—the system: space module—the manipulator moves the load

where

$$
\begin{aligned}
a_{\dot\varphi_1} &= a_{\dot\varphi_1}(q) = J_1 + J_2 + \tilde m l_1^2 + \tilde m l_2^2 + 2\tilde m l_1 l_1 \cos q,\\
a_{\dot\varphi_1\dot q} &= a_{\dot\varphi_1\dot q}(q) = J_2 + \tilde m l_2^2 + \tilde m l_1 l_1 \cos q,\\
a_{\dot q} &= a_{\dot q}(q) = J_2 + \tilde m l_2^2,\\
\tilde m &= \frac{m_1 m_2}{m_1 + m_2}.
\end{aligned}
\tag{2}
$$

The point is the derivative of time *t*.

Let the forces and moments external to the system be absent. Then the coordinate q is positional, and the coordinate φ_1 is cyclic, and the cyclic integral takes place

$$
\frac{\partial T}{\partial \dot\varphi_1} = a_{\dot\varphi_1}\dot\varphi_1 + a_{\dot\varphi_1\dot q}\dot q = K = const,
\tag{3}
$$

reflecting the fact of constancy of the kinetic moment of the system K in the absence of external moments.

Express $\dot\varphi_1$ from (3)

$$
\dot\varphi_1 = f_{\dot\varphi_1} = f_{\dot\varphi_1}(\dot q, q, K) = -\frac{a_{\dot\varphi_1\dot q}}{a_{\dot\varphi_1}}\dot q + \frac{1}{a_{\dot\varphi_1}}K.
\tag{4}
$$

Substitute (4) into (1)

$$
\begin{aligned}
T^* &= T^*(\dot q, q, K) = T(\dot\varphi_1, \dot q, q)|_{\dot\varphi_1 = f_{\dot\varphi_1}}\\
&= \frac{1}{2}a_{\dot\varphi_1} f_{\dot\varphi_1}^2 + a_{\dot\varphi_1\dot q} f_{\dot\varphi_1}\dot q + \frac{1}{2}a_{\dot q}\dot q^2.
\end{aligned}
\tag{5}
$$

4 The Routh Function of the Original System and the Lagrange Function of the Reduced System

Let's write down the Routh function

$$R = R(\dot{q}, q, K) = T^{*}(\dot{q}, q, K) - f_{\dot{\varphi}_1}(\dot{q}, q, K) \cdot K, \tag{6}$$

$$R = \frac{1}{2}\left(a_{\dot{q}} - \frac{a_{\dot{\varphi}_1\dot{q}}^2}{a_{\dot{\varphi}_1}}\right)\dot{q}^2 + \frac{a_{\dot{\varphi}_1\dot{q}}}{a_{\dot{\varphi}_1}}K\dot{q} - \frac{1}{2}\frac{1}{a_{\dot{\varphi}_1}}K^2. \tag{7}$$

We assume that the Routh function (7) is a Lagrange function of some reduced mechanical system with one degree of freedom. The positional coordinate q of the original system is the generalized coordinate of the reduced system. The independent equation of dynamics of the controlled relative motion of the initial system is the Routh equation for the reduced system

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial R}{\partial \dot{q}}\right) - \frac{\partial R}{\partial q} = M. \tag{8}$$

Thus, in the task of controlling the movement of cargo relative to the base, the above system can be considered as an object of control. For a qualitative analysis of the eigen dynamics of the reduced system, we analyze the structure of the Routh function.

Let's write (7) taking into account designations (2)

$$\begin{aligned} R = R(\dot{q}, q, K) = \frac{1}{2}\dot{q}^2 &\frac{\left(J_1 + \tilde{m}l_1^2\right)\left(J_2 + \tilde{m}l_2^2\right) - \tilde{m}^2 l_1^2 l_2^2 \cos^2 q}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)} \\ &+ \dot{q}K\frac{\left(J_2 + \tilde{m}l_2^2 + \tilde{m}l_1 l_2 \cos q\right)}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)} \\ &- \frac{1}{2}K^2\frac{1}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)}. \end{aligned} \tag{9}$$

We introduce notations for the terms of the right part (7)

$$R_2 = \frac{1}{2}\left(a_{\dot{q}} - \frac{a_{\dot{\varphi}_1\dot{q}}^2}{a_{\dot{\varphi}_1}}\right)\dot{q}^2, \qquad R_1 = \frac{a_{\dot{\varphi}_1\dot{q}}}{a_{\dot{\varphi}_1}}K\dot{q}, \qquad R_0 = -\frac{1}{2}\frac{1}{a_{\dot{\varphi}_1}}K^2. \tag{10}$$

We introduce also an auxiliary designation

$$\begin{aligned} \alpha_1 &= J_1 + \tilde{m}l_1^2, \\ \alpha_2 &= J_2 + \tilde{m}l_2^2 \end{aligned}$$

$$\beta = \tilde{m} l_1 l_2. \tag{11}$$

Then the term R_1 included in the Routh function can be represented as

$$R_1 = \dot{q} K \frac{\alpha_2 + \beta \cos q}{\alpha_1 + \alpha_2 + 2\beta \cos q}. \tag{12}$$

Integrate the right side (12)

$$\begin{aligned} F_{R_1}(t) &= \int \dot{q} K \frac{\alpha_2 + \beta \cos q}{\alpha_1 + \alpha_2 + 2\beta \cos q} \mathrm{d}t = \frac{1}{2} K \int \frac{\alpha_2 - \alpha_1 + \alpha_1 + \alpha_2 + 2\beta \cos q}{\alpha_1 + \alpha_2 + 2\beta \cos q} \mathrm{d}q \\ &= \frac{1}{2} q K + \frac{1}{2} K \int \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 + 2\beta \cos q} \mathrm{d}q. \end{aligned} \tag{13}$$

The integration constant in (13) is omitted. Use the substitution

$$tg \frac{q}{2} = z. \tag{14}$$

Then

$$\cos q = \frac{1 - z^2}{1 + z^2}, \quad \mathrm{d}q = \frac{2}{1 + z^2} \mathrm{d}z. \tag{15}$$

We have for the second term of the right part (13)

$$\begin{aligned} &\frac{1}{2} K \int \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 + 2\beta \cos q} \mathrm{d}q = \frac{1}{2} K \int \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 + 2\beta \frac{1 - z^2}{1 + z^2}} \frac{2}{1 + z^2} \mathrm{d}z \\ &= K \int \frac{\alpha_2 - \alpha_1}{(\alpha_1 + \alpha_2)\left(1 + z^2\right) + 2\beta\left(1 - z^2\right)} \mathrm{d}z \\ &= K \int \frac{\alpha_2 - \alpha_1}{(\alpha_1 + \alpha_2 + 2\beta) + (\alpha_1 + \alpha_2 - 2\beta) z^2} \mathrm{d}z \\ &= K \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 - 2\beta} \int \frac{1}{z^2 + \frac{\alpha_1 + \alpha_2 + 2\beta}{\alpha_1 + \alpha_2 - 2\beta}} \mathrm{d}z. \end{aligned} \tag{16}$$

We introduce the notation for the obviously positive expression in the denominator of the integrand

$$a^2 = \frac{\alpha_1 + \alpha_2 + 2\beta}{\alpha_1 + \alpha_2 - 2\beta} = \frac{J_1 + J_2 + \tilde{m}(l_1 + l_2)^2}{J_1 + J_2 + \tilde{m}(l_1 - l_2)^2}. \tag{17}$$

We also denote

$$b = \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 - 2\beta} = \frac{J_2 + \tilde{m} l_2^2 - J_1 - \tilde{m} l_1^2}{J_1 + J_2 + \tilde{m}(l_1 - l_2)^2}. \tag{18}$$

Then the integral (16) is

$$K\frac{\alpha_2-\alpha_1}{\alpha_1+\alpha_2-2\beta}\int\frac{1}{z^2+\frac{\alpha_1+\alpha_2+2\beta}{\alpha_1+\alpha_2-2\beta}}\mathrm{d}z=Kb\int\frac{\mathrm{d}z}{z^2+a^2}=K\frac{b}{a}arctg\frac{z}{a}. \tag{19}$$

Given (19), the function (13) takes the form

$$F_{R_1}=F_{R_1}(q(t))=F_{R_1}(t)=\frac{1}{2}Kq(t)+K\frac{b}{a}arctg\left(\frac{tg\frac{q(t)}{2}}{a}\right)+C_{R_1}, \tag{20}$$

where C_{R_1} is a constant of integration. Thus, the term R_1 functions Routh is the full time derivative of function (20)

$$R_1=\frac{\mathrm{d}}{\mathrm{d}t}F_{R_1}, \tag{21}$$

and can be omitted, since the Lagrange function of the mechanical system is determined to the full time derivative of some function [20].

Then the Lagrange function of the reduced system can be written as

$$\begin{aligned}L_R=&\frac{1}{2}\dot{q}^2\frac{\left(J_1+\tilde{m}l_1^2\right)\left(J_2+\tilde{m}l_2^2\right)-\tilde{m}^2l_1^2l_2^2\cos^2q}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\cos q\right)}\\&-\frac{1}{2}K^2\frac{1}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\cos q\right)}.\end{aligned} \tag{22}$$

We modify the Lagrange function (22) by adding to it a constant T_K defined by the expression

$$T_K=\frac{1}{2}K^2\frac{1}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\right)}. \tag{23}$$

Get

$$\begin{aligned}L_R^*=L_R+T_K=&\frac{1}{2}\dot{q}^2\frac{\left(J_1+\tilde{m}l_1^2\right)\left(J_2+\tilde{m}l_2^2\right)-\tilde{m}^2l_1^2l_2^2\cos^2q}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\cos q\right)}\\&-\frac{1}{2}K^2\frac{1}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\cos q\right)}\\&+\frac{1}{2}K^2\frac{1}{\left(J_1+J_2+\tilde{m}l_1^2+\tilde{m}l_2^2+2\tilde{m}l_1l_2\right)}.\end{aligned} \tag{24}$$

The modified Lagrange function (24) is the difference between the kinetic and potential energy of the reduced system [16, 18, 19]

$$\begin{aligned} L_R^* &= E_k - E_p, \\ E_k &= \frac{1}{2}\dot{q}^2 \frac{\left(J_1 + \tilde{m}l_1^2\right)\left(J_2 + \tilde{m}l_2^2\right) - \tilde{m}^2 l_1^2 l_2^2 \cos^2 q}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)}, \\ E_p &= \frac{1}{2}K^2 \frac{1}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)} \\ &\quad - \frac{1}{2}K^2 \frac{1}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2\right)}. \end{aligned} \tag{25}$$

5 Equation of Dynamics of the Reduced System

The equation of dynamics of the reduced system is written in the form

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L_R^*}{\partial \dot{q}}\right) - \frac{\partial L_R^*}{\partial q} = M. \tag{26}$$

Substituting (25) in (26), we obtain

$$\begin{aligned} &\ddot{q}\frac{\left(J_1 + \tilde{m}l_1^2\right)\left(J_2 + \tilde{m}l_2^2\right) - \tilde{m}^2 l_1^2 l_2^2 \cos^2 q}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)} \\ &+ \dot{q}^2 \frac{\tilde{m}l_1 l_2 \sin q\left(J_1 + \tilde{m}l_1^2 + \tilde{m}l_1 l_2 \cos q\right)\left(J_2 + \tilde{m}l_2^2 + \tilde{m}l_1 l_2 \cos q\right)}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)^2} \\ &+ K^2 \frac{\tilde{m}l_1 l_2 \sin q}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1 l_2 \cos q\right)^2} = M. \end{aligned} \tag{27}$$

From (27) it is easy to see that the reduced system is a nonlinear oscillatory system. The minimum potential energy E_p of the reduced system occurs when $q = 0$ (the hinge is located on a straight line passing through the centers of mass of bodies), this position of the system is the “lower” position of stable equilibrium in which the potential energy is zero, the total energy is kinetic E_k. The maximum potential energy E_p of the reduced system takes place at $q = \pi$, this position of the system is the “upper” position of the unstable equilibrium in which the kinetic energy is zero, the total energy is equal to the potential energy.

In the absence of control action in the hinge ($M = 0$) there are own ballistic movements of the reduced system. Setting the values of the coordinate $q^{(0)}$ and velocity $\dot{q}^{(0)}$ at the initial time in accordance with (25) is determined by the value of the total energy $E_k + E_p$ of the reduced system $M = 0$, due to the condition remaining constant. In this case, there is an energy integral, which is an equation of a family of phase trajectories.

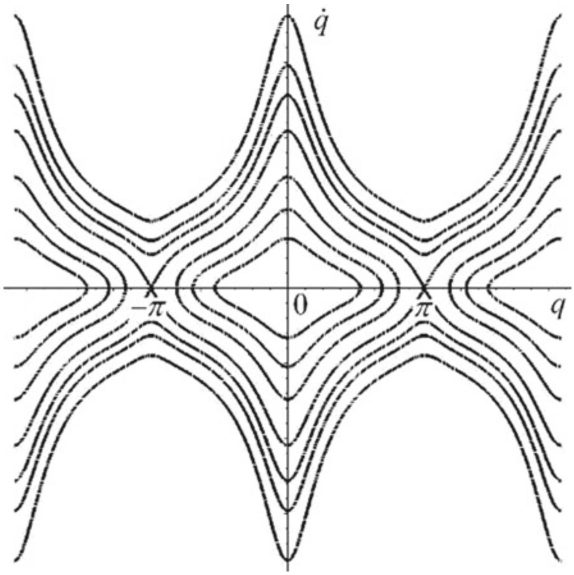

Fig. 3 3—phase portrait of the equation of natural motions of the reduced system

$$E_k + E_p = const. \tag{28}$$

A general view of the phase portrait is shown in Fig. 3.

As shown in Fig. 3, two kinds of own movements can be distinguished: oscillations and circulations. The corresponding groups of phase trajectories are separated by a separatrix. The value of the total energy of the reduced system corresponds to the simulation movement along the separatrix

$$\begin{aligned} E_{p\max} = \frac{1}{2}K^2 \frac{1}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1l_2\right)} \\ - \frac{1}{2}K^2 \frac{1}{\left(J_1 + J_2 + \tilde{m}l_1^2 + \tilde{m}l_2^2 + 2\tilde{m}l_1l_2\right)}, \end{aligned} \tag{29}$$

equal to the maximum possible value of potential energy in the “upper” position of unstable equilibrium.

6 Conclusion

According to the results of the analysis of trends in the development of space robotics, the actual problem of automated assembly of large-size space objects with the help of assembly and service robotic space modules is highlighted. It is shown that the set of serviced space objects and serving ASRSM is a cyber-physical system.

By the example of the plane motion of the system of two hinged bodies it is shown that when controlling the movement of the payload relative to the space module, the nonlinear oscillatory system can be considered as the control object.

The use of proper motions of the reduced system in the synthesis of control in some cases may be appropriate [18, 19, 21]. In particular, the case of impulse control with subsequent free movement along the "ballistic" trajectory is possible.

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