Điều khiển tay máy Robot phỏng sinh học được truyền động bởi các cơ bắp nhân tạo

Control of a biologically inspired manipulator actuated by pneumatic artificial muscles

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Tóm tắt

Bài báo đề xuất thuật toán điều khiển cho Robot 2DOF được truyền động bởi động cơ khí nén dạng cơ bắp nhân tạo. Robot đối tượng được xây dựng từ cấu hình của cánh tay con người, các khớp được truyền động bởi hai cặp đơn cơ và một cặp liên cơ được sắp xếp đối ngẫu. Mô hình động lực học của hệ thống được xây dựng theo phương pháp Euler-Lagrange kết hợp với phương trình đặc tính của các cơ bắp nhân tạo. Dựa trên thuật toán Li-Slotine đề xuất cho các Robot thanh nối cứng và bỏ qua động lực học của cơ cấu chấp hành, thuật toán mới được bài báo phát triển để điều chỉnh mô men từ ba cặp cơ bắp dẫn đến chuyển động mong muốn của các khớp nối. Phân tích ổn định của thuật toán đề xuất dựa trên tiêu chuẩn ổn định Lyapunov. Để khẳng định lại tính hiệu quả của thuật toán đề xuất, các mô phỏng động lực học kín của hệ thống được thực hiện trên MabLab/Simulink.

Từ khóa: cơ bắp nhân tạo truyền động bằng khí nén, tay máy robot, truyền động liên cơ, sắp xếp đối ngẫu, mô hình cơ xương khớp của con người.

Abstract

This paper investigates a control algorithm for 2 DOF robot manipulator actuated by pneumatic artificial actuators. The robot configuration is developed from the muscle model of human arm, joints are driven by two pairs of mono-articular and one pair of bi-articular muscles, and then three pairs are in antagonistic arrangement. Dynamics of the system are formulated based on Euler-Lagrange approach in combination with natural force-length-velocity relation of the contracting muscle. Based on Li-Slotine algorithm for rigid-link manipulators as moment response of actuators is ideal, a novel algorithm is developed to regulate joint torques from muscle contractile forces to ensure a desired motion ij joint space. Stability analysis of the proposed control algorithm is based on Lyapunov principle. Finally, the effectiveness of the proposed control inputs has been reconfirmed by simulation results in MatLab/Simulink .

Keywords: pneumatic artificial actuator, robot manipulator, bi-articular driving, antagonistic arrangement, human musculoskeletal model.

1. Introduction

Industrial robots are designed according to the principal design rules to have strong and heavy construction, for these reasons, industrial robots are dangerous to human when they worked in a domestic environment that requires human-robot interaction. To ensure for robots to be safe in domestic environment, they must be compliant to provide a soft contact with human. An option to make robots compliant is using compliant actuators, for example McKibben pneumatic artificial muscles (PAMs). PAMs are extremely lightweight, compliant and capable of higher specific work than comparable-sized hydraulic actuators and electrical motors [1,2]. Furthermore they possess all advantages of traditional pneumatic actuators (i.e. cheapness, quickness of response, high power/weight and power/volum ratios). PAMs are typically composed of a helically braided sleeve surrounding an elastomeric bladder and are held together by end fittings. PAMs generate axial tension from air pressure. Our research focuses on a 2DOF robot arm driven by pairs of PAMs. The robot imitates the structure of the human arm, which has antagonistic muscle pairs for each joint. The objective of our research is to develop a control algorithm that can smoothly and accurately track the desired motions of such a robot arm.

Previous studies suggested joint angle control methods for robot manipulators actuated by PAMs. Based on model estimation, Caldwell et al. [3] proposed an adaptive algorithm for payloads over 9 deg of arm rotation. Kumamoto [4] introduced modeling of human arms using two antagonistic pairs of mono-articular muscles and one antagonistic pair of bi-articular muscles. More important, Kumamoto revealed control properties induced by the existence of antagonistic pairs of bi-articular muscles in paradigm of mechanical engineering model analyses. Tsujiuchi [5] developed PID control system with highly accurate performance, but it actives only one PAM while bending a joint, resulting in the invariable joint stiffness. Wereley [6] developed control system for manipulator in heavy-lifting, but also used ony a pair of PAMs. Kawai [7] proposed passivity-based control for 2DOF PAM-actuated manipulators, the bi-articular dynamics for three muscle torques (two pairs of mono- and one pair of bi-articular muscles) have been formulated in order to find out control algorithm. However, stability analysis of their proposed control law has been not satisfied. In this paper, we solved the same robotic system proposed by Kawai [7] and proposed a novel control algorithm and proved the asymptotical stability of the closed dynamics based on Lyapunov function.

2. Dynamics of PAM-Actuated Robotic Manipulator

a. Analyzing protocol

As pointed out in a lot of research on human anatomy that the characteristics of human arm are bi-articular driving, antagonistic arrangement and variable viscoelasticity. These characteristics recently have been realized by means of PAM-actuated robotic manipulators. Mechanical link models utilized in the paper consist of three segments and two joints as shown in Fig. 1. Two couples of the antagonistic mono-articular muscles of f_1 and e_1, and of f_2 and e_2 were attached to the joints of J_1 and J_2, respectively. A couple of the antagonistic bi-articular muscles f_3 and e_3 were attached to the both joints J_1 and J_2. The visco-elastic muscle model in the research was demonstrated by Ito and Tsuji [2].

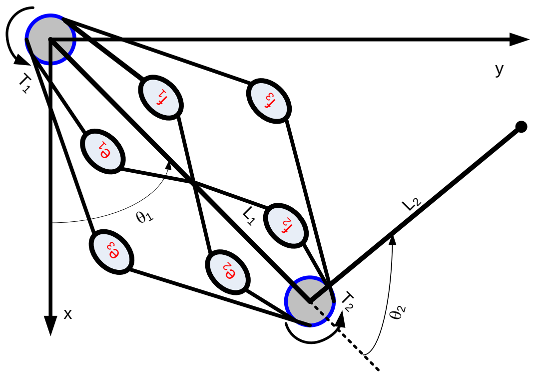

Fig.1. 2DOF robot manipulator actuated by two pairs of mono-articular muscles and one pair of bi-articular muscles.

Fig. 2 illustrates model of a muscle, the muscular output force F is a function of contractile force u

$$F = u - kux - bu\dot{x} \quad (1)$$

where x is contracting length of the muscle and $\dot{x}$ is shortening velocity, k is elastic coefficient and b is viscous coefficient. Contractile force u is only settled actively element and other are passive, then u is considered as an active level of muscle. In order to produce dual-directional force, pair of muscles should be constructed in antagonistic arrangement. Pairs of mono-articular muscles f_1-e_1 and f_2-e_2 produce torques about joints 1 and 2, respectively. Pair of bi-articular muscles f_3-e_3 produces torques about joints 1 and 2 contemporaneously.

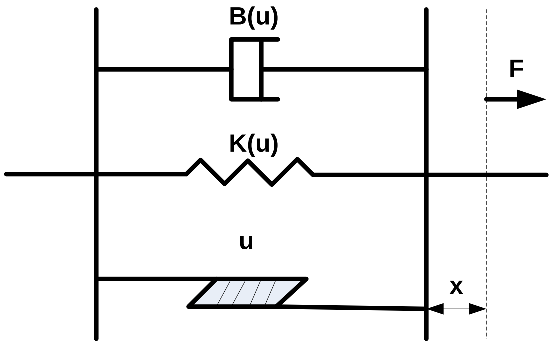

Fig.2. Visco-elastic-contractile muscle model

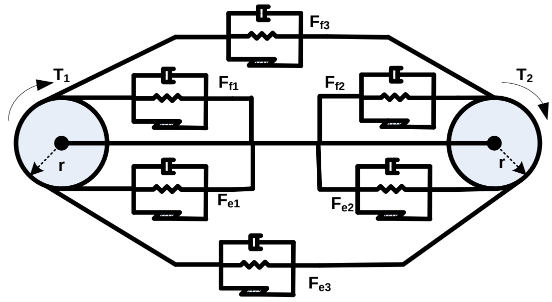

Fig. 3. Visco-elastic model of the first link L1

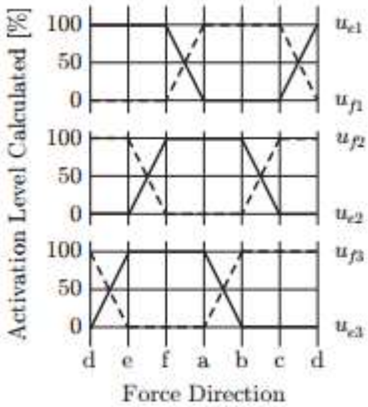

Fig. 4. Each muscle respond depending on the direction of the force at the tip point

b. Dynamics of 2 DOF robotic manipulator actuated by 3 pairs of PAMs

The dynamics of n-DOF rigid-link robot can be written as

$$T = H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) \quad (2)$$

where $\ddot{q}, \dot{q}, q \in \Re^n$ are vectors of joint angle, velocity, acceleration, respectively. $H(q) \in \Re^{n\times n}$ are inertia matrix, $C(q,\dot{q}) \in \Re^{n\times n}$ Coriolis and centrifugal matrix, $G(q) \in \Re^n$ is gravity vector. The manipulator dynamics (2) has following important properties:

Property 1. The inertia matrix $H(q)$ is symmetric and positive definite with all *q*.
Property 2. $\dot{H}(q) - C(q,\dot{q})$ is skew-symmetric

For a 2DOF Elbow Robot, the dynamics can be written as

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} p_1 + p_2 c_2 & p_3 + p_4 c_2 \\ p_3 + p_4 c_2 & p_5 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} p_6 s_2 \dot{q}_2 & -p_6 s_2 (\dot{q}_1 + \dot{q}_2) \\ p_6 s_2 \dot{q}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} p_7 c_1 + p_8 c_{12} \\ p_8 c_{12} \end{bmatrix} \quad (3)$$

where $p_1 = m_1 l_{c1}^2 + m_2 l_1^2 + I_{zz1} + I_{zz2}$, $p_2 = 2m_2 l_1 l_{c2}$, $p_3 = m_2 l_{c2}^2 + I_{zz2}$, $p_4 = m_2 l_1 l_{c2}$.
m_i, l_i,l_{ci} and I_{zzi} are weight, length, distance from joint *i* to mass center of link *i* (C*i*) and inertia moment at C_i, for *i*=1,2. sinq_i, cosq_i, sin(q_i+q_j), cos(q_i+q_j) are defined as s_i, c_i, s_{ij}, c_{ij}.

As shown in Fig. 1, when the antagonistic pair of bi-articular muscles was incorporated in the two-joint robot in addition to the mono-articular muscles, joint torques would be presented as

$$\begin{aligned} T_1 &= (F_{f1} - F_{e1})r + (F_{f3} - F_{e3})r \\ T_2 &= (F_{f2} - F_{e2})r + (F_{f3} - F_{e3})r \end{aligned} \quad (4)$$

where *r* is joint radius, F_{fi} and F_{ei} (for *i*=1-3) define the forces by the flexor and extensor muscles, respectively and can be calculated as

$$\begin{aligned} F_{fi} &= u_{fi} - ku_{fi}x - bu_{fi}\dot{x} \\ F_{ei} &= u_{ei} + ku_{ei}x + bu_{ei}\dot{x} \end{aligned} \quad (5)$$

where u_{fi}, u_{ei} are contractile forces or activation levels generated by flexor and extensor muscles, for *i*=1-3.

Note that joint angle *q* may create two different contacting lengths *x* due to the directions of *x* are different in two muscle. Then $x = -rq$ for the flexor muscle and $x = rq$ for the extensor muscle.

Substitute (5) into (4), the joint torques are described as

$$\begin{aligned} T_1 &= (u_{f1} - u_{e1})r - (u_{f1} + u_{e1})kr^2 q_1 \\ &- (u_{f1} + u_{e1})br^2 \dot{q}_1 + (u_{f3} - u_{e3})r \\ &- (u_{f3} + u_{e3})kr^2 (q_1 + q_2) \\ &- (u_{f3} + u_{e3})br^2 (\dot{q}_1 + \dot{q}_2) \\ T_2 &= (u_{f2} - u_{e2})r - (u_{f2} + u_{e2})kr^2 q_2 \\ &- (u_{f2} + u_{e2})br^2 \dot{q}_2 + (u_{f3} - u_{e3})r \\ &- (u_{f3} + u_{e3})kr^2 (q_1 + q_2) \\ &- (u_{f3} + u_{e3})br^2 (\dot{q}_1 + \dot{q}_2) \end{aligned} \quad (6)$$

Activation levels of all the muscles employed were selected by reference to the EMG patterns recorded during the arm extensions under isometric conditions with maximal effort exerted. The antagonistic mono-articular muscles were seen to maintain almost fully active levels during changes in output force direction, and the antagonistic pair of bi-articular muscles showed a criss-cross pattern. Activation levels postulated in order to exert the maximum output force at the end-effector E were as follows [4]:

$$u_{fi} + u_{ei} = 100\% \quad \text{for } i=1\text{-}3 \quad (7)$$

Because the contractile force of flexor muscle u*fi* can be decided by an actuator, muscle torques are defined as $\tau_i = (2u_{fi} - 1)r$ [7]

Substituting (7) in (6) results

$$\begin{aligned} T_1 &= \tau_1 - kr^2 q_1 - br^2 \dot{q}_1 \\ &+ \tau_3 - kr^2 (q_1 + q_2) - br^2 (\dot{q}_1 + \dot{q}_2) \\ T_2 &= \tau_2 - kr^2 q_2 - br^2 \dot{q}_2 \\ &+ \tau_3 - kr^2 (q_1 + q_2) - br^2 (\dot{q}_1 + \dot{q}_2) \end{aligned} \quad (8)$$

The manipulator dynamics (3) driven by antagonistic bi-articular muscles can be specified as bi-articular manipulator dymanics [7] and have a following form

$$\tau = H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + K_r q + B_r \dot{q} \quad (9)$$

where $K_r = \begin{bmatrix} 2k & k \\ k & 2k \end{bmatrix} r^2$, $B_r = \begin{bmatrix} 2b & b \\ b & 2b \end{bmatrix} r^2$

Clearly that K_r and B_r are positive definite matrices.

3. Li-Slotine based controller design

Our purpose is to propose algorithms to control joint angles of the 2DOF Elbow manipulator with antagonistic mono- and bi-articular muscles converge to the desired trajectory. For the first step of the study, we assume that all parameters of dynamics and kinematics are known exactly. Develop from well-known Li-Slotine algorithm for rigid-link manipulator [8], we proposed the control input as follows

$$\tau = H(q)\dot{v} + C(q,\dot{q})v + G(q) + K_r q + K_d r + G(q) \quad (10)$$

and define v according to

$$v = \dot{q}_d + \Lambda(q_d - q) = \dot{q}_d + \Lambda e$$

where Λ is a diagonal matrix of positive gains and the position error is $e = q_d - q$.

Define $r = v - \dot{q} = \dot{e} + \Lambda e$ and substitute (10) into (9) lead to the closed dynamics

$$H(q)\dot{r} + C(q,\dot{q})r + (B_r + K_d)r = 0 \quad (11)$$

Taking inner product (11) with r and noting that $\dot{H}(q) - 2C(q,\dot{q})$ is skew symmetric matrix results to

$$\frac{1}{2}\frac{d}{dt}\left[r^T H(q) r\right] = -r^T (B_r + K_d) r \quad (12)$$

In order to show stability of the system (11), let us select a Lyapunov candidate function V as

$$V(r) = \frac{1}{2}\frac{d}{dt}\left[r^T H(q) r\right] \quad (13)$$

Note that *H(q)* is positive definite, then V is always possitive and is zero only at the desired equilibrium state $r = \dot{e} + \Lambda e = 0$. Along trajectories of closed dynamics (11), the time derivative of V can be computed from (12)

$$\dot{V}(r) = -r^T (B_r + K_d) r \quad (14)$$

Due to both K_d and B_r are positive definite, then $\dot{V}(r)$ is negative definite with all r and is zero only at the desired equilibrium state $r = 0$. Clearly that V is strict Lyapunov function and it is possible to conclude the asymptotical convergence of r to zero as $t \to \infty$, which further implies that $e = q_d - q \to 0$ and $\dot{e} = \dot{q}_d - \dot{q} \to 0$ as $t \to \infty$.

4. Applying proposed control law into 2DOF elbow manipulator actuated by pneumatic artificial muscles

As mentioned above, sufficient condition for global assymtotically stability of system (9) under the control law (10) are derived. Next simulation tests have been carried out in order to evaluate dynamic performance of the closed dynamic system (11) of 2DOF robot actuated by pneumatic artificial actuators. The relevant parameters of system are reported in Table 1.

Table 1. Parameters of 2DOF PAM-actuated manipulator

Parameters	Sym.	Value	Unit
Length of rigid link 1	l_1	0.26	m
Length of rigid link 2	l_2	0.26	m
Mass of link 1	m_1	6.5225	kg
Mass of link 2	m_2	2.0458	kg
Inertia moment at C_1	I_1	0.1213	kgm^2
Inertia moment at C_2	I_2	0.0116	kgm^2
Elastic coefficient	k	3000	N/m
Viscous coeeficient	b	400	Ns/m
Radius of joint i	r_i	0.05	m

We consider two types of desired trajectory: set-point and periodic function. For the set-point case, the angle joints are required to reach to the desired angles as described in vector $q_d = [1.5, 0.5](Rad)$. The control parameters are reported in the Table 2. The initial angle vector of two joints is $q_0 = [0.7, 1.3](Rad)$. Figs.5 and 6 show the rotation to the desired angles of joints 1 and 2, respectively.

Table 2. Control parameters in set-point case

Parameters	Value
Damping coefficient	$K_D = \begin{bmatrix} 6 & 0 \\ 0 & 4 \end{bmatrix}$
Proportional gains	$\Lambda = \begin{bmatrix} 58 & 0 \\ 0 & 58 \end{bmatrix}$

Table 3. Control parameters in tracking case

Parameters	Value
Damping coefficient	$K_D = \begin{bmatrix} 8 & 0 \\ 0 & 6 \end{bmatrix}$
Proportional gains	$\Lambda = \begin{bmatrix} 35 & 0 \\ 0 & 20 \end{bmatrix}$

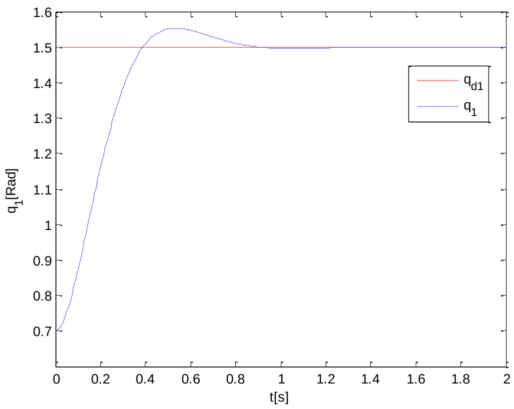

Fig. 5. Response of joint angle 1as the joint reaches to the desired value .

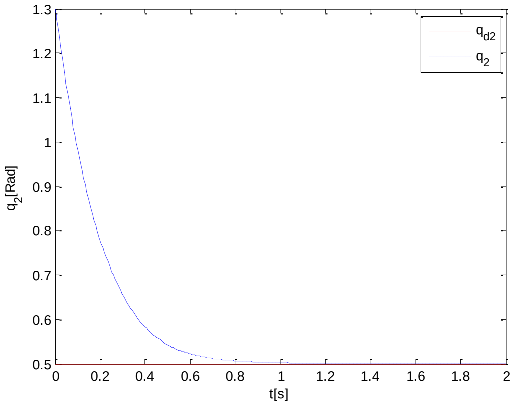

Fig. 6. Response of joint angle 2 as the joint reaches to the desired value $q_{2d} = 0.5[Rad]$.

For the tracking case, the desired angle for two joints are periodic-function trajectories. $q_{1d} = 1 - 0.2\cos\pi t(Rad)$ and $q_{2d} = 1.4 + 0.2\cos\pi t[Rad]$. The control parameters are reported in Table 3.

Figs 6 and 7 illustrate the tracking to the desired periodic trajectories of joint 1 and joint 2, respectively.

From these simulation results, it is possible to reconfirm the convergence of the joint angles to the desired values.

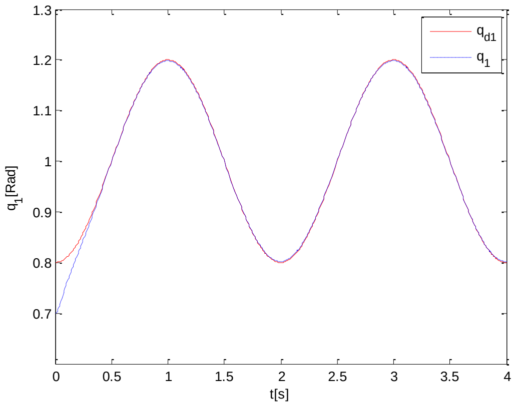

Fig 7. Response of joint angle 1as the joint tracking to the desired periodic trajectory $q_{1d} = 1 - 0.2\cos\pi t(Rad)$

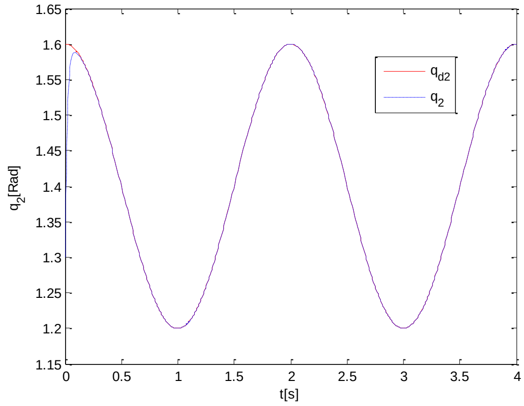

Fig. 8. Response of joint angle 2 as the joint tracking to a desired periodic trajectory $q_{2d} = 1.4 + 0.2\cos\pi t[Rad]$.

5. Conclusions

The paper deals with a novel control for 2DOF robot manipulators actuated by PAMs. The objective robot are actuated by 6 muscle actuators which arranged in three antagonistic pairs, two pairs of mono-articular and one pair of bi-articular muscles. Stability analysis of the robot dynamics governed by our proposed control input is based on Lyapunov principle. The simulation results reconfirm the effectiveness of the proposed control law. In the future work, we will develop intelligent and adaptive control laws for more complicated operations of the robot and cope with uncertainties of dynamic parameters. Similar robotic systems can be developed to assist rehabilitation of elderly and movement disable people.

References

[1] Glute G.K, Czerniecki J.M., Hanaford B. "*Artificial Muscle: Actuators for bioroboticsystems*", Int. J. Robot Res, 2002, 21, pp. 295-309.

[2] Ito K. and T. Tsuji *"The bilinear characteristics of muscle-skeleto motor system and the application to prosthesis control",* Transactions of |Electrical Engineerers of Japan 105-C(10), pp. 201-208, 1995.

[3] Caldwel D., Medrano Cerda, G., *"Control of pneumatic muscle actuators"*, IEEE Control System 15(1), pp. 40-48, 1995.

[4] Kumamoto M., Oshima T., Yamamoto T., *"Control properties induced by the existence of antagonistic pairs of bi-articular muscles-Mechanical engineering model analyses"*, Human Movement Science 13, pp. 611-634, 1994.

[5] Tsujiuchi N., Koizumi T., Shirai S., Nishino S., Kudawara T., Shimizu M., *"Development of a low pressure driven pneumatic actuator and its application to a robot hand"*, The 32nd Annual Conference of the IEEE Industrial Electronics Society , pp. 3040-3045, 2006.

[6] Robinson M.R., Kothera C.S., Wereley N.M., *"Control of a heavy lift robotic manipulator with pneumatic artificial muscles"*, Actuators3, pp. 41-65, 2014.

[7] Kawai, H., Murao T, Fujita M., *"Passivity-based control for 2DOF robot manipulators with antagonistic bi-articular muscles",* Proceedings of IEEE International Conference on Control and Application, pp. 1451-1456, 2011.

[8] Slotine J.J., Li W, *"Applied Nonlinear Control",*Prentice-Hall, Eaglewood Cliffs, New Jersey 07632, 1991.

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