739. Design of adaptive sliding mode control for spherical robot based on MR fluid actuator

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Abstract. Inner suspension platform of a spherical robot undergoes dynamic oscillation process when the robot is rolling ahead, which significantly reduces stability and precision of the motion. To suppress these vibrations, this study considers an adaptive sliding mode control method for a spherical robot based on application of magnetorheological (MR) fluid actuator. After analyzing the mechanical structure of the spherical robot, a dynamic model describing its rolling motion is derived. Considering the uncertainty of the disturbances introduced by modeling error and outside perturbation, an adaptive scheme is proposed to estimate the dynamic disturbances. Sliding mode technology is applied to construct system controller characterized by robustness and parameter insensibility. Simulations are performed in order to verify the effectiveness of the proposed control methods.

Keywords: spherical robot, MR fluid actuator, sliding mode control, adaptive.

Introduction

Spherical robots recently attracted a lot of research attention owing to its special configuration and movement performances [1-3]. Most spherical robots adopt inner suspension platform to install sensors and other devices. In this case the suspension is in an under-actuated state by the driving motor's reaction torque [4-6]. This under-actuated state causes violent vibration of inner suspension. Such vibration may cause great damages to the robotic imaging system and may even lead the failure of detection mission, especially, when the spherical robot is operating within unstructured environment.

A lot of research work has been performed to solve the aforementioned problems. In [4], a mechanical structure was designed in spherical robot to form a stabilized platform that can always keep a stable attitude automatically. In [5], spherical robot was equipped with two cameras which can hold a state attitude when the robot moves. However, because spherical robot internal space is very narrow, the additional mechanical structure will increases the complexity of the robotic system. In [7], a state feedback controller was designed based on sigmoidal function, which ensures globally asymptotic convergence of the system state to a desired small neighborhood. In [8], based on the linear dynamic model, a state feedback controller was designed, and this controller can realize arbitrarily pole assignment. Such treatments for holding the balance of the inner suspension platform are complex and are difficult to realize in practice.

Motivated by [9, 10], we chose to apply a MR fluid actuator to suppress the vibration of inner suspension platform of a spherical robot. MR fluid, as a type of smart material, has a property that the rheological properties can be continuously and reversibly changed within several milliseconds by applying or removing external magnetic fields. Owing to this superior characteristic, MR fluid has been widely investigated and applied in practice recently [9-11]. Therefore, we attempted to implement the MR effect into a spherical robot because it can achieve active vibration suppression within a much smaller space. Targeted at a typical spherical robot, a mechanical structure is developed to realize the MR fluid actuator, followed by the development of the dynamic model describing the rolling motion.

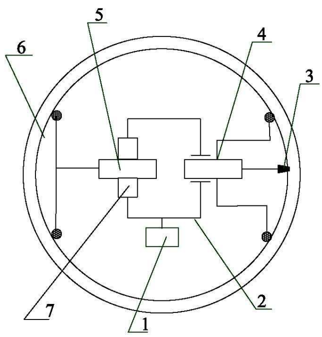
Another difficulty to implement MR fluid actuator is the control problem. Enhancement of system adaptability and robustness is a challenging task, especially, in the complex and dynamic unstructured environment. Therefore, a design method for control system of the spherical robot with MR fluid actuator is also discussed in this study. Furthermore, the sliding mode control technology is applied to derive the controller owing to their better robustness and parameter insensibility [12-14].

In addition, the disturbances are unavoidable and it is unrealistic to achieve their practical value ahead in unstructured exploration environment. Considered these facts, we developed a disturbance adaptive control scheme to estimate the disturbance on line. The adaptive control schemes are derived via Lyapunov stability theorem, and it can significantly enhance the adaptability and robustness of the robot system. Moreover, the inherent chattering behavior on sliding mode surface is suppressed because continuously differentiable hyperbolic tangent function is applied in sliding mode controller.

This paper is organized as follows: in section 2, a MR fluid actuator applied in spherical robot system is presented. Dynamic model of the spherical robot is derived in section 3. Section 4 addresses the sliding mode control design process via Lyapunov stability theorem. In section 5, the simulation study is conducted to demonstrate the effectiveness and feasibility of control method. Finally, some conclusions are provided.

Spherical robot with MR fluid actuator

Though mechanical structures of various spherical robots are different from each other, the robots with inner suspension platform are much more similar. In this case, we discuss a typical spherical robot with suspension platform, which is described in more detail in [2]. Generally, the movement of the spherical robot can be separated as rolling ahead and turning motions, among which the rolling ahead movement is a more important motion mode (a mode where the oscillations occur). Therefore, we mainly address this motion mode to improve the accuracy and performance of the robot. The mechanical structure of the MR fluid actuator in spherical robot proposed in this study is illustrated in Fig. 1.



1. Storage battery 2. Support frame 3. Bevel gear 4. Steering motor
5. Drive motor 6. Gear ring 7. MR fluid actuator

Fig. 1. Structural diagram of the spherical robot

The motor housing is designed as an input component of the MR fluid actuator, which consists of the MR fluid, the electromagnetic coil and the yoke. When the external magnetic field is applied to the electromagnetic coil, the corresponding magneto-motive force is generated. Then, the shear force is generated in the opposite direction of the rotary motor housing motion, i.e., in the presence of the magnetic field, additional shear force occurs due to the MR effect. As a result, the torque is transmitted from the input component to output one. Since the yield stress of the MR fluid changes according to the strength of the magnetic field, the output torque can be continuously and reversibly controlled by adjusting external magnetic field.

Therefore, in Fig. 1, the torque generated by the motor can be transmitted from the motor to the inner suspension continually. Then, the inner suspension could be driven by the output torque, so the under-actuated characteristics are changed to the active ones.

Dynamic model of the spherical robot

A typical spherical robot in rolling ahead motion can be described in Fig. 2, which has one motor to drive the shell and a MR fluid actuator to drive the inner suspension. In Fig. 2, the inner suspension is connected with the MR fluid actuator housing rigidly. The clearance between motor housing and MR actuator housing is full of MR fluid, which is represented by shaded parts shown in Fig. 2.

The equation of dynamic behavior of the robot based on MR actuator is governed by:

$$\mathrm{M}(q)\ddot{q} + \mathrm{C}(q,\dot{q})\dot{q} + \mathrm{G}(q) + \mathrm{W}(t) + = \tau \qquad (1)$$

where $\mathbf{M}(\mathbf{q}) \in R^{2\times2}$ is a symmetric and positive definite inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) \in R^{2\times2}$ is a damping matrix, $\mathbf{G}(\mathbf{q}) \in R^{2\times1}$ is a stiffness matrix, and $\mathbf{W}(t) \in R^{2\times1}$ is a disturbance matrix. $\boldsymbol{\tau} \in R^{2\times1}$ is a control input matrix and state vector is $\mathbf{q} = [\varphi \quad \theta]^{\mathrm{T}}$. Specific parameters are as follows.

$$\mathbf{M} = \begin{bmatrix} a & b\cos\theta \\ b\cos\theta & c \end{bmatrix}, \mathbf{C} = \begin{bmatrix} 0 & -b\dot{\theta}\sin\theta \\ 0 & 0 \end{bmatrix},\ \mathbf{G} = [0 \quad d\sin\theta]^{\mathrm{T}},\ \mathbf{W} = [w_1 \quad w_2]^{\mathrm{T}}, \boldsymbol{\tau} = [\tau_1 \quad \tau_2]^{\mathrm{T}},$$

where $a = \frac{1}{3}(5m_1 + 3m_2)r^2$, $b = m_2 r l^2$, $c = m_2 l^2$, and $d = m_2 g l$. φ represent the angle that the shell rolls from the start point, and θ is the angle that the inner suspension sways away from the vertical direction; m_1 is the mass of shell and m_2 is the mass of inner suspension; r represents the shell radius and l describes the distance between shell center and inner suspension centroid; g is acceleration of gravity. τ_1 and τ_2 are the control input of motor and the output of the MR fluid actuator respectively, and τ_2, which can be controlled by external magnetic fields, is restricted by τ_1.

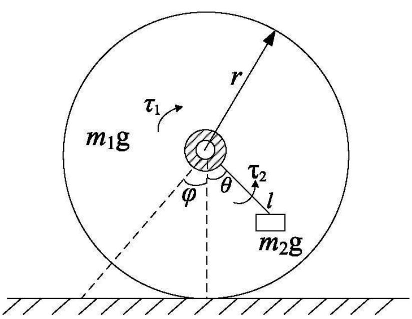


Fig. 2. Rolling ahead movement of a spherical robot with the MR fluid actuator

Design of controller for the spherical robot

Sliding mode controller. The goal of the spherical robot control system is to track the desired speed and restrain the irregular vibration of the inner suspension. Meanwhile, sliding mode control is applied to derive the system dynamic controller owing to its better robustness and parameter insensibility characteristics. Then, we apply sliding mode control technology to derive the control algorithm of the spherical robot [15-17]. Suppose that $\mathbf{e}=[e_1 \quad e_2]^{\mathrm{T}}=\mathbf{q_d}-\mathbf{q}$, where $\mathbf{q_d}$ and $\mathbf{q}$ represent the desired state value and the actual state value respectively.

To achieve the performance mentioned above, the sliding surface can be defined by

$$\mathbf{s}=\dot{\mathbf{e}}+\Gamma\mathbf{e} \tag{2}$$

where $\Gamma=\begin{bmatrix}\lambda_1 & \\ & \lambda_2\end{bmatrix}$ is a diagonal positive matrix. It is obvious that the tracking error $\mathbf{e}\to 0$ if the positive matrix is selected properly.

Suppose that the disturbance is known and it can be directly applied in the controller design. The control input can be defined as:

$$\boldsymbol{\tau}=\mathbf{M}(\ddot{\mathbf{q}}_{\mathbf{d}}+\boldsymbol{\Gamma}\dot{\mathbf{e}})+\mathbf{C}(\dot{\mathbf{q}}_{\mathbf{d}}+\boldsymbol{\Gamma}\mathbf{e})+\mathbf{G}+\mathbf{W}+\delta_1\tanh(\kappa\mathbf{s})+\delta_2\mathbf{s} \tag{3}$$

where δ_1, δ_2 and κ are positive constants. Note that the continuously differentiable hyperbolic tangent function tanh(κs) is used to replace the sign function here, which could largely suppress the chattering behavior of the control system on sliding mode surface.

According to the above analysis, we can give a theorem as follows:

Theorem 1. The errors $\mathbf{q_e}$ will asymptotically converge to zero, if the controller (3) is applied to the system (1).

Proof: A Lyapunov function is defined as

$$V=\frac{1}{2}\mathbf{s}^{\mathrm{T}}\mathbf{M}\mathbf{s} \tag{4}$$

Clearly, $V>0$. Differentiating V with respect to time yields

$$\dot{V}=\frac{1}{2}\mathbf{s}^{\mathrm{T}}\dot{\mathbf{M}}\mathbf{s}+\mathbf{s}^{\mathrm{T}}\mathbf{M}\dot{\mathbf{s}}=\frac{1}{2}\mathbf{s}^{\mathrm{T}}(\dot{\mathbf{M}}-\mathbf{2C})\mathbf{s}+\mathbf{s}^{\mathrm{T}}\mathbf{C}\mathbf{s}+\mathbf{s}^{\mathrm{T}}\mathbf{M}\dot{\mathbf{s}} \tag{5}$$

Let matrix $\mathbf{A}=\dot{\mathbf{M}}-2\mathbf{C}$, then the matrix $\dot{\mathbf{M}}$ and $\mathbf{A}$ can be derived as follows: $\dot{\mathbf{M}}=\begin{bmatrix}0 & -b\dot{\theta}\sin\theta \\ -b\dot{\theta}\sin\theta & 0\end{bmatrix}$, $\mathbf{A}=\begin{bmatrix}0 & b\dot{\theta}\sin\theta \\ -b\dot{\theta}\sin\theta & 0\end{bmatrix}$

Considering that matrix $\mathbf{A}$ has the characteristic of $\mathbf{A}^{\mathrm{T}}=-\mathbf{A}$, then we can draw the conclusion that matrix $\mathbf{A}$ is a skew symmetric matrix. Therefore, we can obtain $\mathbf{s}^{\mathrm{T}}\mathbf{A}\mathbf{s}=0$, i. e.,

$$\mathbf{s}^{\mathrm{T}}(\dot{\mathbf{M}}-\mathbf{2C})\mathbf{s}=0 \tag{6}$$

Substituting (6) into (5) yields

$$\begin{aligned}\dot{V}&=\mathbf{s}^{\mathrm{T}}(\mathbf{C}\mathbf{s}+\mathbf{M}\dot{\mathbf{s}})=\mathbf{s}^{\mathrm{T}}[\mathbf{C}\mathbf{s}+\mathbf{M}(\ddot{\mathbf{e}}+\boldsymbol{\Gamma}\dot{\mathbf{e}})]=\mathbf{s}^{\mathrm{T}}[\mathbf{C}\mathbf{s}+\mathbf{M}(\ddot{\mathbf{q}}_{\mathbf{d}}-\ddot{\mathbf{q}})+\mathbf{M}\boldsymbol{\Gamma}\dot{\mathbf{e}})]\\&=\mathbf{s}^{\mathrm{T}}(\mathbf{C}\dot{\mathbf{e}}+C\boldsymbol{\Gamma}\mathbf{e}+\mathbf{M}\ddot{\mathbf{q}}_{\mathbf{d}}+\mathbf{C}\dot{\mathbf{q}}+\mathbf{G}+\mathbf{W}-\boldsymbol{\tau}+M\boldsymbol{\Gamma}\dot{\mathbf{e}})\\&=\mathbf{s}^{\mathrm{T}}[\mathbf{C}(\dot{\mathbf{e}}+\boldsymbol{\Gamma}\mathbf{e})+\mathbf{M}(\ddot{\mathbf{q}}_{\mathbf{d}}+\boldsymbol{\Gamma}\dot{\mathbf{e}})+\mathbf{C}\dot{\mathbf{q}}+\mathbf{G}+\mathbf{W}-\boldsymbol{\tau}]\\&=\mathbf{s}^{\mathrm{T}}[\mathbf{C}(\dot{\mathbf{q}}_{\mathbf{d}}+\boldsymbol{\Gamma}\mathbf{e})+\mathbf{M}(\ddot{\mathbf{q}}_{\mathbf{d}}+\boldsymbol{\Gamma}\dot{\mathbf{e}})+\mathbf{G}+\mathbf{W}-\boldsymbol{\tau}]\end{aligned} \tag{7}$$

Substituting (3) into (7) achieves that

$$\dot{V} = -\delta_1 \mathbf{s}^{\mathrm{T}} \tanh(\kappa \mathbf{s}) - \delta_2 \mathbf{s}^{\mathrm{T}} \mathbf{s} \tag{8}$$

Clearly, $\dot{V} \le 0$. By LaSalle's theorem [18], the errors $\mathbf{q_e}$ converge to zero globally, and then the theorem 1 is proved.

A disturbance adaptive scheme. Although the theorem 4.1 is certified correct above, the disturbance is impossible to measure correctly because of its uncertainty due to the complex unstructured environment. Considering the above limitations, the controller (3) is impractical for control of the spherical robot system (1).

Though the disturbance is uncertain, the change rate of disturbance is much slower in practical exploration. Then, we attempt to use an adaptive control scheme to estimate the disturbance value considering this case. Let $\hat{\mathbf{W}}$ represents the estimated vector of disturbance $\mathbf{W}$, the estimated error could be defined by $\tilde{\mathbf{W}} = \mathbf{W} - \hat{\mathbf{W}}$. Then, the disturbance and the estimated error can be governed by $\dot{\tilde{\mathbf{W}}} = -\dot{\hat{\mathbf{W}}}$. Therefore, the control law can be rewritten as

$$\boldsymbol{\tau} = \mathbf{M}(\ddot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\dot{\mathbf{e}}) + \mathbf{C}(\dot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\mathbf{e}) + \mathbf{G} + \hat{\mathbf{W}} + \delta_1 \tanh(\kappa \mathbf{s}) + \delta_2 \mathbf{s} \tag{9}$$

Adaptive law can be given as

$$\dot{\hat{\mathbf{W}}} = \lambda \mathbf{s} \tag{10}$$

where $\delta_1, \delta_2 > 0$ and $\kappa, \lambda > 0$. The parameter λ determines the convergence time, and the bigger value of the parameter is set, the shorter time of converging to the disturbance is obtained, but the bigger overshoot of estimation of disturbances is generated.

According to the above analyses, we can formulate a theorem as follows：

Theorem 2. The errors $\mathbf{q_e}$ will asymptotically converge to zero, if the control law (9) and adaptive law (10) are applied to the system (1).

Proof: A new Lyapunov function could be defined as follows:

$$V = \frac{1}{2}\mathbf{s}^{\mathrm{T}}\mathbf{M}\mathbf{s} + \frac{1}{2\lambda}\tilde{\mathbf{W}}^{\mathrm{T}}\tilde{\mathbf{W}} \tag{11}$$

Clearly, $V > 0$. Similarly, differentiating V with respect to time yields

$$\begin{aligned}
\dot{V} &= \mathbf{s}^{\mathrm{T}}[\mathbf{C}(\dot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\mathbf{e}) + \mathbf{M}(\ddot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\dot{\mathbf{e}}) + \mathbf{G} + \hat{\mathbf{W}} + \tilde{\mathbf{W}} - \boldsymbol{\tau}] - \frac{1}{\lambda}\tilde{\mathbf{W}}^{\mathrm{T}}\dot{\hat{\mathbf{W}}} \\
&= \mathbf{s}^{\mathrm{T}}[\mathbf{C}(\dot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\mathbf{e}) + \mathbf{M}(\ddot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\dot{\mathbf{e}}) + \mathbf{G} + \hat{\mathbf{W}} - \boldsymbol{\tau}] + \mathbf{s}^{\mathrm{T}}\tilde{\mathbf{W}} - \frac{1}{\lambda}\tilde{\mathbf{W}}^{\mathrm{T}}\dot{\hat{\mathbf{W}}} \\
&= \mathbf{s}^{\mathrm{T}}[\mathbf{C}(\dot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\mathbf{e}) + \mathbf{M}(\ddot{\mathbf{q}}_\mathbf{d} + \boldsymbol{\Gamma}\dot{\mathbf{e}}) + \mathbf{G} + \hat{\mathbf{W}} - \boldsymbol{\tau}] + \tilde{\mathbf{W}}^{\mathrm{T}}\mathbf{s} - \frac{1}{\lambda}\tilde{\mathbf{W}}^{\mathrm{T}}\dot{\hat{\mathbf{W}}}
\end{aligned} \tag{12}$$

Substituting (9) and (10) into (12) provides:

$$\dot{V} = -\delta_1 \mathbf{s}^{\mathrm{T}} \tanh(\kappa \mathbf{s}) - \delta_2 \mathbf{s}^{\mathrm{T}} \mathbf{s}$$

Clearly, $\dot{V} \le 0$. By LaSalle's theorem [18], the errors $\mathbf{q_e}$ converge to zero globally, and then the theorem 2 is proved.

Simulation study

The parameters of the spherical robot and the control coefficients are listed in Table 1. Suppose that initial state vector of spherical robot is $[\varphi_0 \quad \dot{\varphi}_0 \quad \theta_0 \quad \dot{\theta}_0]^T = [0 \quad 0 \quad 0.15 \quad 0]^T$ and, considering that the rolling resistance is existent in unstructured environment, θ_d is set to 0.2 rad to deal with the rolling resistance. Therefore, the desired value of spherical robot is set as $[\varphi_d \quad \dot{\varphi}_d \quad \theta_d \quad \dot{\theta}_d] = [5t \quad 5 \quad 0.2 \quad 0]^T$. Meanwhile, the disturbances to the system are hypothesized as a step change form, which represents a worst situation to verify the effectiveness of the control algorithms. Furthermore, white noise is introduced to the system to simulate the real application environment as much as possible.

Fig. 3 shows curves of states of spherical robot with adaptive sliding mode control. The simulation results demonstrate that the derived controller with disturbances estimation can control states to their desired states. The control effect is closely related to the control parameters matrix Γ which determine overshoot and response time of the control system. The overshoot in Fig. 3 b) and c) is 2.4% and 1.85% respectively, and the response time is no more than 0.2 second. With the proposed method, the inner suspension can hold a relatively constant angle, which can ensure a good imaging effect of spherical robot in unstructured environment. The enlarged drawing shown in Fig. 3 b) further demonstrates that the actual value can converge to the desired value quickly even though the white noise is introduced, which demonstrate the robustness of the proposed control scheme.

Table 1. Spherical robot parameters

Spherical robot	Value
Mechanical parameters	$m_1 = 3$, $m_2 = 5$, $r = 0.175$, $l = 0.094$, $g = 9.81$.
Control coefficients	$\lambda_1 = \lambda_2 = 20$, $\lambda = 90$, $\delta_1 = 0.1$, $\delta_2 = 50$, $\kappa = 50$.

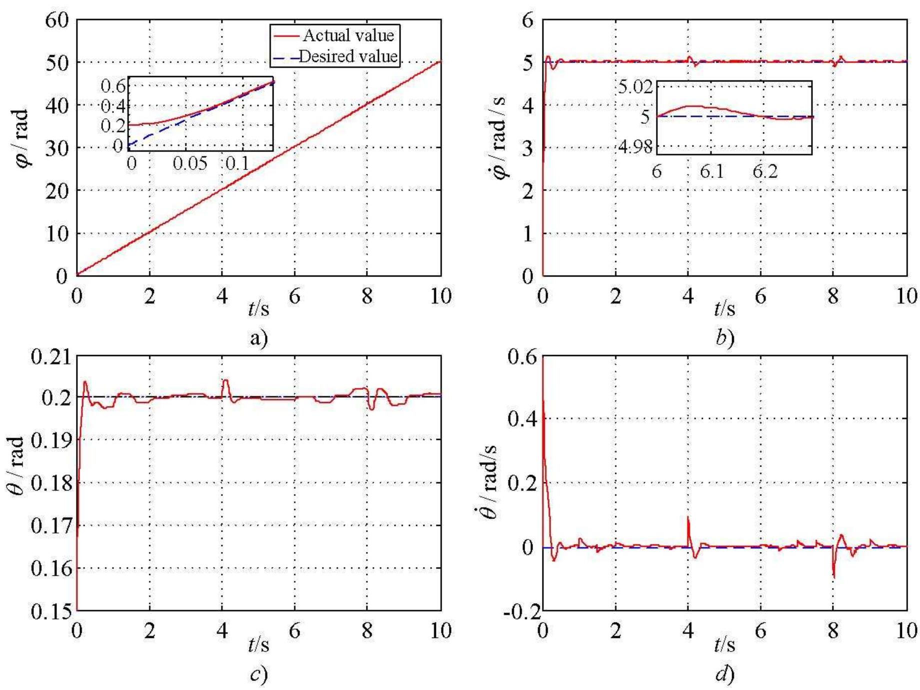


Fig. 3. States variables of the controlled spherical robot

Fig. 4 provides error curves of the shell angular velocity and the inner suspension swing angle. The errors can converge to zero globally even when the disturbances change violently in 4 seconds and 8 seconds. The enlarged drawings, which are shown in Fig. 4 a) and b), demonstrate that the proposed control scheme can deal with white noise effectively demonstrating strong robustness of the control methods.

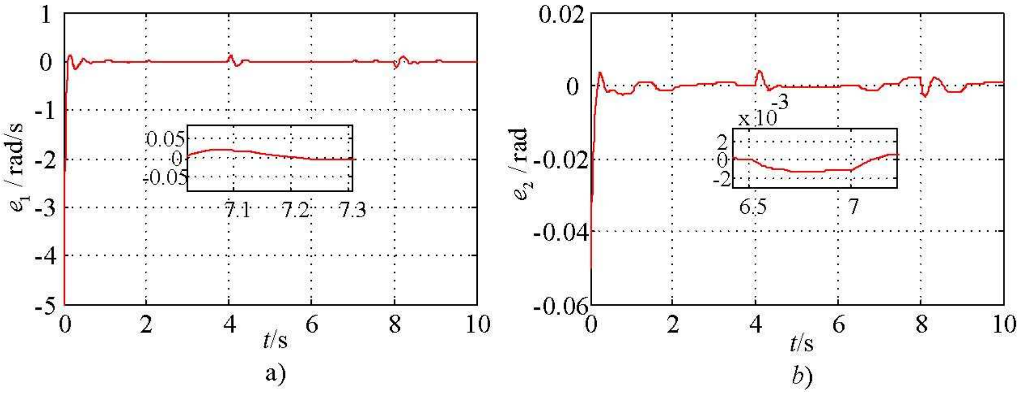


Fig. 4. Tracking errors of $\dot{\varphi}$ and θ

Fig. 5 describes the estimation curves of disturbances. Here, the disturbances with step form are supposed to affect both the shell system and the inner suspension system thereby representing an extremely unfavorable condition. The disturbance w_1 acting on shell subsystem occurs between 2 N and 4 N at 4 seconds and 8 seconds. The disturbance w_2 acting on inner suspension subsystem occurs between 0.5 N and 1.5 N at 4 seconds and 8 seconds. It implies that the converging time and accuracy can be improved by increasing λ, while the overshoots would increase abruptly. Slight fluctuation occurs after the disturbances are estimated well owing to the white noise. However, the estimation can quickly converge to the estimated value.

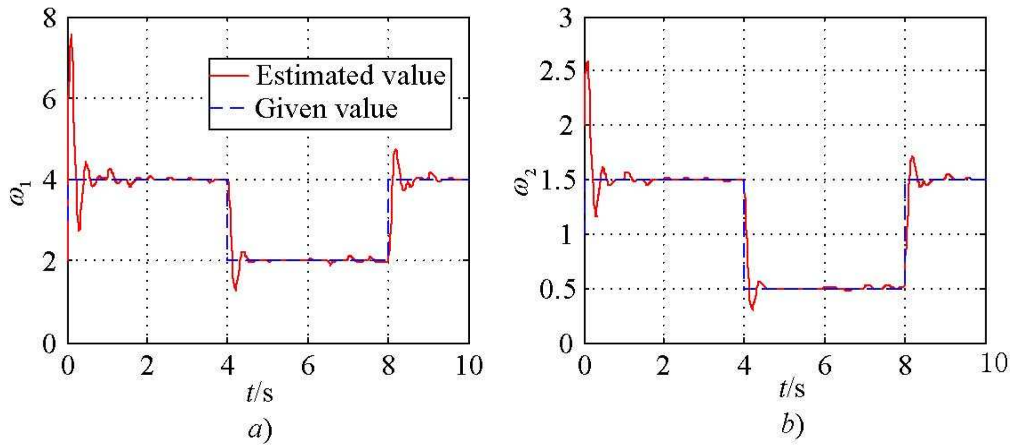


Fig. 5. Disturbance estimation process for an arbitrary step disturbance

Fig. 6 shows control torque of the shell subsystem and inner suspension subsystem. Overshoot occurs at the beginning due to the inertia of the system. The results indicate that τ_1, which drives inner suspension before introducing MR fluid actuator, is larger than τ_2. Therefore, τ_2 is transmitted from τ_1 and could be controlled by external magnetic fields, which are mentioned in section 1.

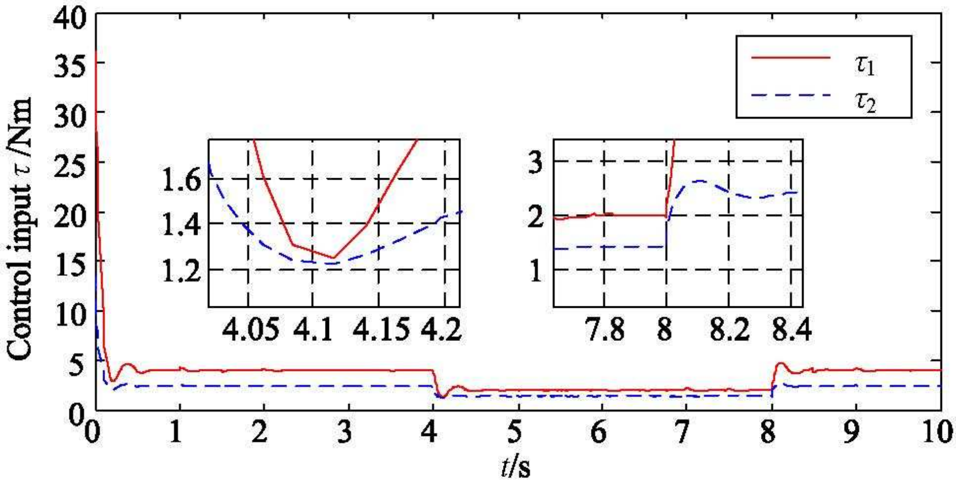


Fig. 6. System control input

Conclusion

A MR fluid actuator was introduced and an adaptive sliding mode control was proposed in this study. Firstly, we investigated a design method of the mechanical structure using MR fluid actuator to change the under-actuated suspension platform to the active one. This method can save more space and was proved to be more reasonable. Secondly, the dynamic model, which can describe the rolling ahead motion of the spherical robot, was derived. The models accounts for the sphere rolling and pendulum angles. Thirdly, an adaptive control scheme was proposed, which can estimate the uncertain disturbances in an adaptive manner. This adaptive control method may considerably enhance the robustness and adaptability of the spherical robot system. Such works will afford basic theoretical foundation for application of the MR fluid actuator, and further work will be concerned with experimental study in order to verify the proposed method by using a real-life spherical robot.

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