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A simplified hybrid force/position controller method for the walking robots

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SUMMARY

Force and position sensors have been widely used in robots to realize compliance and precise control. Traditional force/position control methods were studied and developed by the inverse dynamics for decades. Generally speaking, the controller contains two parts: One is the error-driven part that guarantees system stability; another is the identification model of inverse dynamics that can compensate for system influence. In practical control engineering, a system inverse dynamics or its identification model is not easy to obtain, even when using nonlinear estimation methods. Moreover, the complicated control algorithm cannot be implemented in on-board microprocessors because of the limited speed and memory. Thus, a simplified control method using a forward system model is introduced in this paper. Since the direct dynamics of the system can be more easily obtained than the inverse dynamics, this, in turn, simplifies the control structure and increases control speed. Therefore, the proposed control policy has a wider practical application.

KEYWORDS: Hybrid control; Force control; Walking robots.

1. INTRODUCTION

Robot compliant control has been developed for decades and it is still our main aim. This is because the requirements of human beings keep increasing, and the tasks the robot undertakes become more complex. Thus, how to improve robot control performance is always the research aim of our work.

Currently, the booming development of scientific technology offers us two power tools to improve control performance. The first is the development of hardware, such as new sensors, more powerful microprocessors, and high performance servo systems. The other is the development of control techniques and theories, such as adaptive control and intelligent control.

In recent years, theoretical research on force/position control has been well studied. Based on the application of the relationship between position/applied force or between velocity/applied force, the control method can be classified as stiffness control, damping control, impedance control, explicit control and hybrid position/force control.[1–3] In hybrid control, some modified control methods have been well studied. Pandian and Kawamura[4] and Cheah *et al.*[5] introduced a PD based learning force control law in the continuous and discrete domains, respectively. Jeon and Tomizuka[6] present a learning hybrid force/position control policy, which can online update its inverse dynamics model. In order to identify inverse system models, a Kalman Filter identification control method is introduced in reference [7].

Some intelligent control methods have also been applied to robotic control. The first is an adaptive fuzzy control; one advantage of this controller is in its non-model based control policy; the second is an adaptive control policy by on-line adjusting its components.

Another main applied intelligent control method is neural networks (NN) control.[2,8–10] In reference [8], a direct NN control method is proposed (an indirect NN control method may be more suitable in actual engineering applications); the neural network is an ordinary feedforward network. A CMAC neural network control method is given in reference [2], where the function of the network is an identification of a nonlinear inverse system. Similar cases are in references [9] and [10], where the neural network learns an inverse model of the system.

Some other control methods, such as model based control[11] variable structure control[12] have also been widely studied. The system stability analysis is also presented in references [5], [6] and [13]–[15]. Most of these control methods, except fuzzy control, are based on an inverse model dynamics. The hybrid control output is a motor driven torque. This torque is the input signal of the leg so as to reach the desired position/force. From a theoretical view, it works quite well, but it is very hard to realize it in practical control engineering. One reason is that the inverse model of the leg is too complicated to be obtained, even by using nonlinear identification methods. Another reason is that a walking robot control is a fast speed control system, and the complicated algorithm cannot be realized on-line owing to the memory and speed limitation of the on-board microprocessor of the mini-walking robot. Therefore, a new and simplified method is introduced in this paper. The proposed hybrid force control for a walking robot is based on ordinary forward system dynamics, which is relatively easy to obtain. Due to the simple control structure, more versatile control methods can be applied.

The contents of the paper are arranged as follows: In section 2, current difficulties are presented. In section 3, a force control method is studied. In section 4, motor control policy is analyzed. In section 5, an overall force control system structure is produced. In section 6, simulation results

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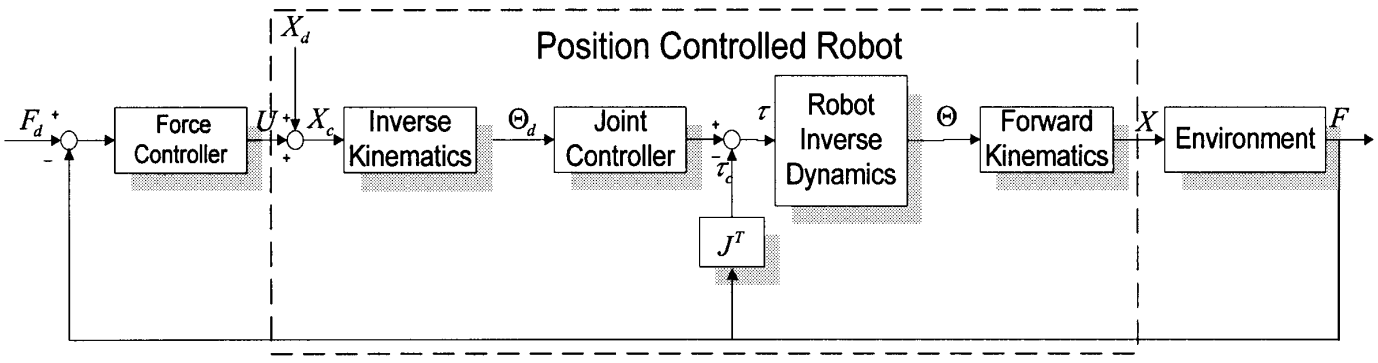


Fig. 1. Hybrid force/position control system.

are given to illustrate the validity of the proposed methodology.

2. EXISTING DIFFICULTIES

As illustrated in Figure 1, the dynamic model of a robot leg in the free space can be derived using the Lagrange's method and it is expressed as[16]

$$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau \tag{1}$$

where $M \in R^{n\times n}$ is a positive-definite symmetrical inertia matrix of the i-th leg; $C(\theta, \dot{\theta}) \in R^{n\times n}$ the Coriolis and centrifugal terms; $G \in R^{n\times 1}$ the gravitational term; $\tau \in R^{n\times 1}$ the vector of actuator torque; $\theta, \dot{\theta}, \ddot{\theta} \in R^{n\times 1}$ are vectors of joint position, velocity and acceleration, respectively; n is the number of joints for each leg.

The dynamic model of a robot leg in the constraint coordinate can be expressed as[6]

$$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau-J^T F_f \tag{2}$$

where $J^T \in R^{n\times 1}$ is the transpose of the Jacobian matrix for the i-th leg; $F_f \in R^{n\times 1}$ is the foot contact force of the i-th leg.

The compliant control contains force and position control. To an internal joint controller, the given control input is the desired rotation angle, while the controller output is driven torque. The control law is given by[6]

$$\tau=W_d(t)+f_d(t)+K_p e(t)+K_v \dot{e}(t)+q_n(e,\dot{e}) \tag{3}$$

where, $W_d(t)=M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)$ is the inverse dynamics. Suppose that identification model of inverse dynamics $W_d(t)$ can be represented by $\hat{W}_d(t)$, then the controller can be written as

$$\tau=\hat{W}_d(t)+f_d(t)+K_p e(t)+K_v \dot{e}(t)+q_n(e,\dot{e}) \tag{4}$$

Please note that $\hat{W}_d(t)=\hat{M}(\theta)\ddot{\theta}+\hat{C}(\theta,\dot{\theta})\dot{\theta}+\hat{G}(\theta)$ can compensate for the system model influence. Also, $f_d(t)$ is the feedforward item; $K_p, K_v > 0$ the PD controller gain; $e=F_d-F$ the force error; $q_n(e,\dot{e})$ the disturbance. The function of PD controller is to guarantee that system converges to zero at the right time.

Substitution of equations (4) into (1) yields

$$W_d(t)=\hat{W}_d(t)+f_d(t)+K_p e(t)+K_v \dot{e}(t)+q_n(e,\dot{e}) \tag{5}$$

where $\hat{W}_d(t)$ is the identification model of $W_d(t)$, by assuming $\| \hat{W}_d(t)-W_d(t) \| \le \epsilon$, $\| q_n(e,\dot{e}) \| \le \eta$, and ϵ, η are small positive constant. By neglecting the influence of forward item $f_d(t)$, the condition $\lim_{t\to\infty} | \hat{W}_d(t)-W_d(t)+K_p e(t)+K_v \dot{e}(t)+q_n(e,\dot{e}) | = 0$ can be guaranteed, which implies that the system can converge to its desired force or position.

From a theoretical point, the above control method should produce a desired control result. In most mini-robot control systems, due to the weight and dimension limitations, a powerful industrial PC is often not required and only microprocessors, such as BASIC STAMP I/II and PIC motion controllers, can be mounted on its body. For such systems, precise inverse nonlinear dynamics is impossible to obtain, nor is its identification model. Furthermore, even when the model can be obtained, this complicated control algorithm based on inverse dynamics cannot be implemented through an on-board microprocessor because of its speed and memory limitations. Thus, a new simplified hybrid force control design method is proposed and introduced in the following sections.

3. FORCE CONTROL

Firstly, a single-joint leg in X-Y coordinate is given in Figure 2, where θ is the joint angle, L the length of the leg, and M the mass of a weight. In order to highlight the environment's influence, a basic system made with a linear actuator in contact with the ground is illustrated in Figure 3, where F_c is the actuator force, D the damping coefficient, x the actuator position, F the reaction force produced by the wall and K_e the sensor elastic coefficient.

The sensor reaction force is

$$F(t)=-K_e(x(t)-x(t=0)) \tag{6}$$

If $x(t=0)=0$, $x(t)=x$, and $F(t)=F$, we have

$$F=-K_e x \tag{7}$$

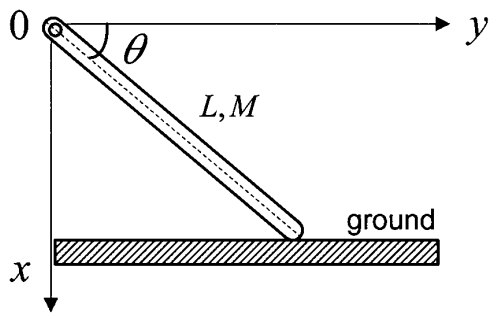


Fig. 2. A single-joint leg.

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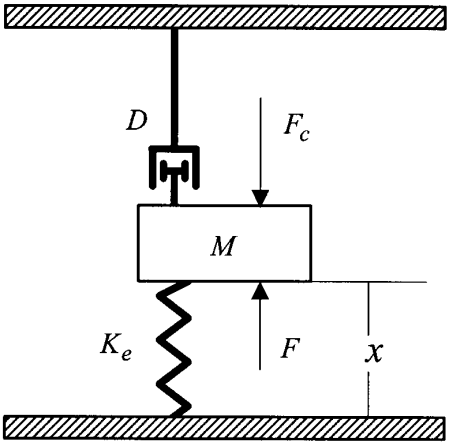


Fig. 3. Basic environmental model.

and

$$M\frac{d^2x}{dt^2}+D\frac{dx}{dt}=F_c-F \tag{8}$$

The force control structure can be obtained and its control diagram is given in Figure 4.

Many advanced control methods can be used in force control, such as fuzzy, adaptive and neural network control. For simplicity, PID or PI control is introduced. Select a controller as follows:

$$G_c(s)=\frac{T_cs+1}{a_cT_cs+1} \tag{9}$$

The open-loop transfer function for the control object is given by

$$G_f(s)=\frac{F(s)}{F_c(s)}=\frac{K_e}{Ms^2+Ds+K_e} \tag{10}$$

The closed-loop transfer function can then be obtained

$$H(s)=\frac{K_e(T_cs+1)}{a_cT_cMs^3+(a_cT_cD+M)s^2+(a_cT_cK_e+T_cK_e+D)s+2K_e} \tag{11}$$

in which the selection of controller parameters of T_c and a_c must satisfy the system's stability condition.

4. MOTION CONTROL

By adjusting the input voltage or current of the motor, a desired angle or position of the leg can be obtained. Without losing its generality, assume the force actuator is a DC motor (same for a hydraulic motor), as is shown in Figures 5 and 6.

The electric equation of motor is given as follows:

$$L_a\frac{di}{dt}+R_ai+E=U_a \tag{12}$$

where L_a is the inductance, R_a the resistance, i the current, U_a the voltage supplied, and E the armature voltage. Suppose that the motor driven payload torque $M_L \neq 0$, the motor dynamics can be simplified according to Newton's law as

$$T_M\frac{d^2\theta}{dt^2}+\frac{d\theta}{dt}=K_MU_a-K_fM_L \tag{13}$$

where θ is the motor angle, T_M, T_M and K_f are the relative electronic parameters.

The motor control system can then be generated by virtue of Figure 7. The payload torque M_L imposed on the motor can be viewed as a disturbance, which is a nonlinear function given as

$$\tau(\ddot{\theta},\ \dot{\theta},\ \theta)=M_L \tag{14}$$

The PID or PI control is commonly used for motor control. The transfer function of the controller is given by

$$G_u(s)=\frac{T_us+1}{a_uT_us+1} \tag{15}$$

Without losing generality, by assuming motor payload $M_L=0$, the internal motor closed-loop system can be obtained.

$$H_u(s)=\frac{K_M(T_us+1)}{a_uT_uT_Ms^3+(a_uT_u+T_M)s^2+(K_MT_u+1)s+K_M} \tag{16}$$

The characteristic equation $a_uT_uT_Ms^3+(aT_u+T_M)s^2+(K_MT_u+1)s+K_M=0$ must satisfy the Hurwitz stability criteria. On the other hand, in order to eliminate the influence of the external payload, M_L, the feedback error proportional gain in the PID controller should be selected as large as possible within the stability range.

5. OVERALL FORCE CONTROL SYSTEM DESIGN

With the force control and motor control models discussed earlier, the whole control system can be established as shown in Figure 8. It is noted that the main difference between Figures 1 and 8 lies in the object's internal control. In Figure 1, the controlled object is the inverse model of leg, while the controller output is the torque. In Figure 8, the

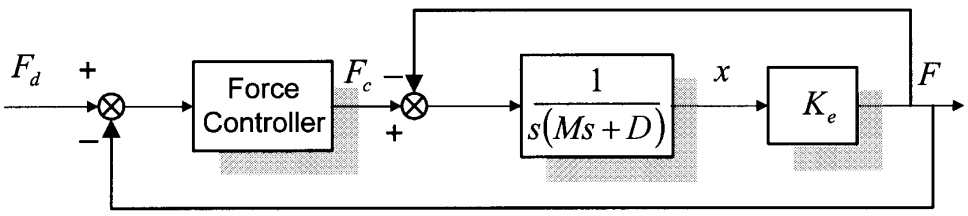


Fig. 4. Force control structure diagram.

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controlled object is a motor direct model, while the controller output is a motor driven voltage or current, and the payload torque is only viewed as a disturbance item.

The sub-system (dash frame) in Figure 8 is the force control object which has been discussed in section 3. Its transfer function is given in equation (16). By properly selecting the internal motor PID control parameters a_u and T_u, the transient system performance is dominated by a pair of main poles,

$$H_u(s) = \frac{K}{(s+a-ib)(s+a+ib)} = \frac{1}{Ms^2+Ds+K_e} \quad (17)$$

where

$$a, b>0,\ M=\frac{1}{K},\ D=\frac{2a}{K},\ K_e=\frac{a^2+b^2}{K}.$$

Accordingly, the closed-loop transfer function of the overall control system can be obtained by

$$H(s) = \frac{N_c(s)}{D_c(s)} = \frac{K_e(T_c s+1)}{a_c T_c M s^3+(a_c T_c D+M)s^2+(a_c T_c K_e+T_c K_e+D)s+2K_e} \quad (18)$$

Again, the selection of poles $D_c(s) = 0$ must satisfy the Hurwitz stability criteria. Furthermore, the control system in Figure 8 can be changed to a position control system by assuming $G_c(s)=1$, $K_e=1$ and $F_d=0$.

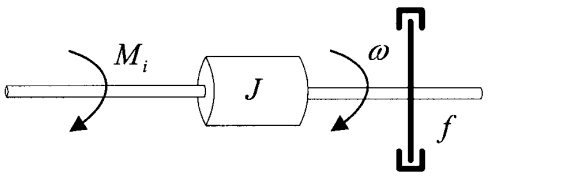


Fig. 5. Mechanism of a motor system.

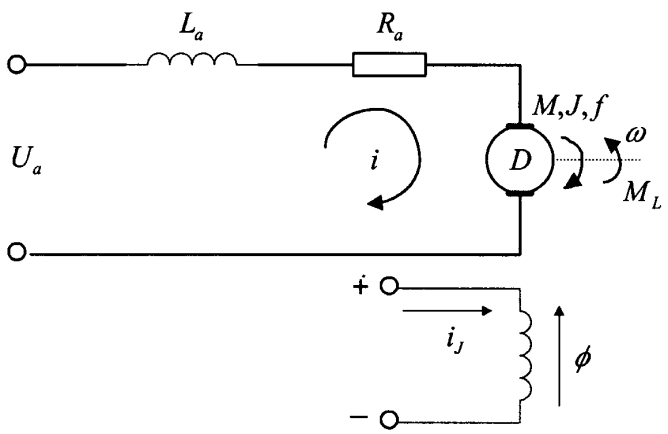


Fig. 6. Electricity diagram of a motor system.

6. SIMULATION RESULTS

6.1 Motor control

Consider the motor control system as shown in Figure 7.

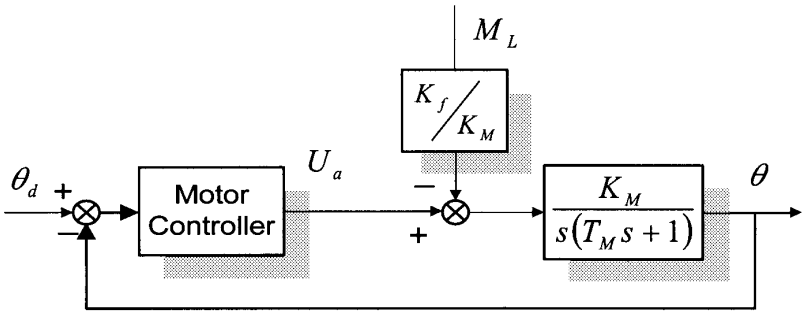


Fig. 7. Motor control system.

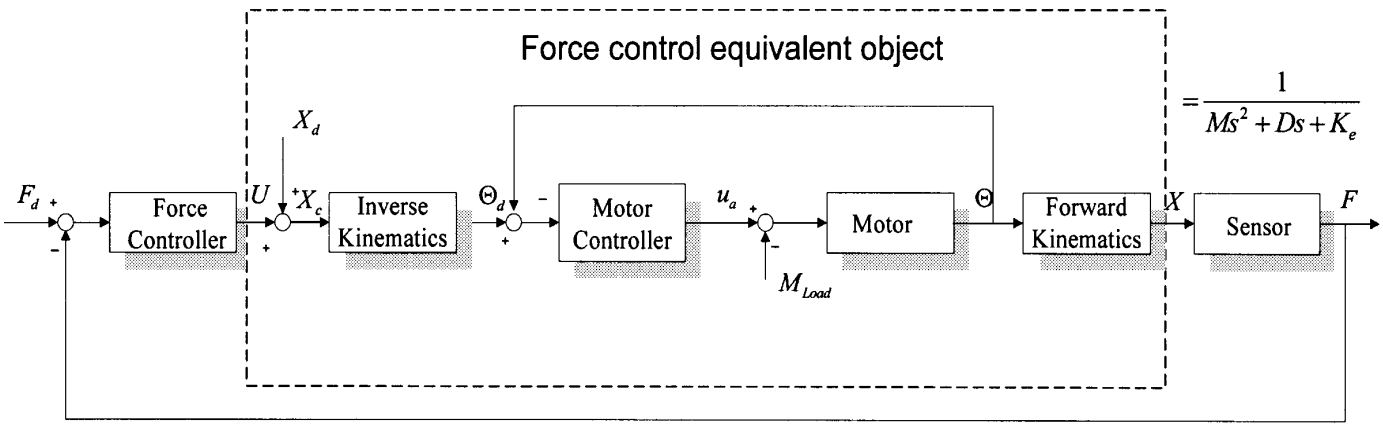


Fig. 8. Overall Force/Position control system diagram.

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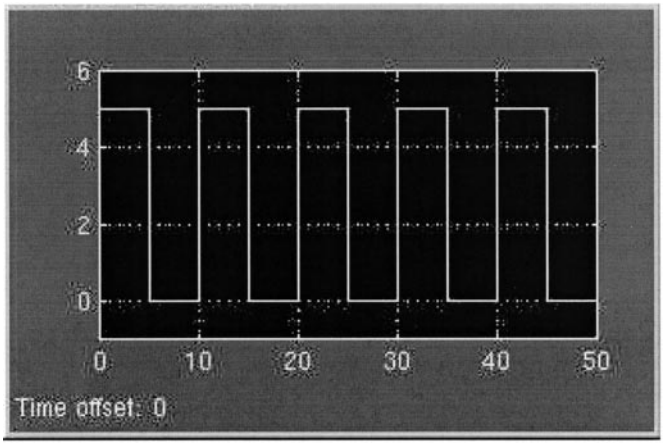


Fig. 9. Given motor angle.

Assume the motor transfer function is $G_M(s) = \dfrac{1}{s(s+0.5)}$, and the three parameters of PID control are $K_P = 2$, $K_I = 0.1$, and $K_D = 1$. The given trajectory is a squared wave as shown in Figure 9, and the payload is $M_L = 0.01\ddot{\theta} + 0.50\dot{\theta} + \theta$ (see Figure 10). Figures 11–13 illustrate the simulation results of motor rotation angle, angle error and controller output.

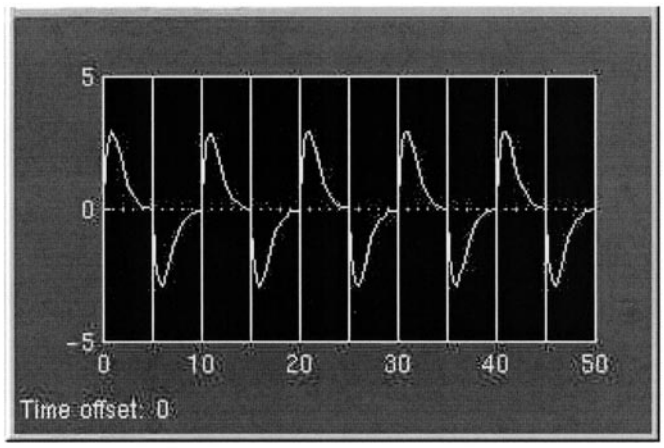


Fig. 10. Payload of the motor.

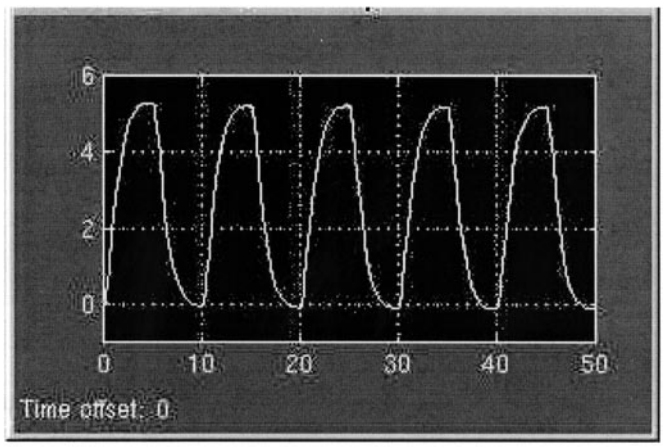


Fig. 11. Motor output angle for the motion control system.

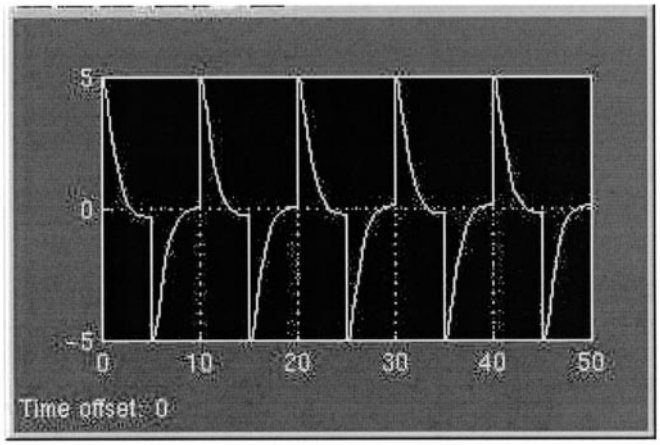


Fig. 12. Motor angle error for the motion control system.

6.2 Force control

For the force control system shown in Figure 8, the internal motor controller is assumed the same as the above motor controller; the external force controller is a PI controller, where $K_P = 2$ and $K_I = 0.1$. The given force signal is still a square wave as shown in Figure 14. The simulation output of force is given in Figure 15.

The force controller and motor controller outputs are displayed in Figures 16 and 17, respectively. From the

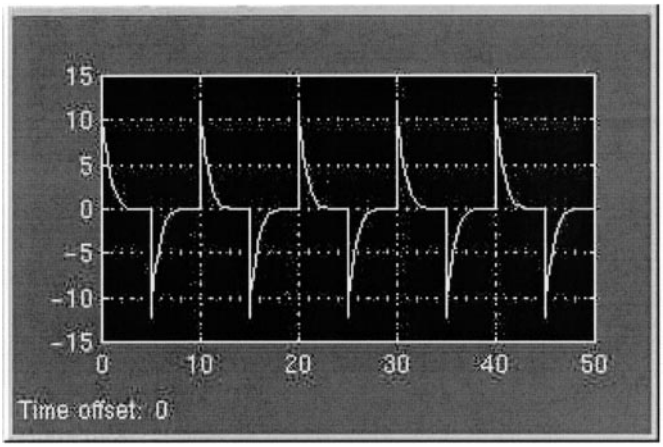


Fig. 13. Motor controller output.

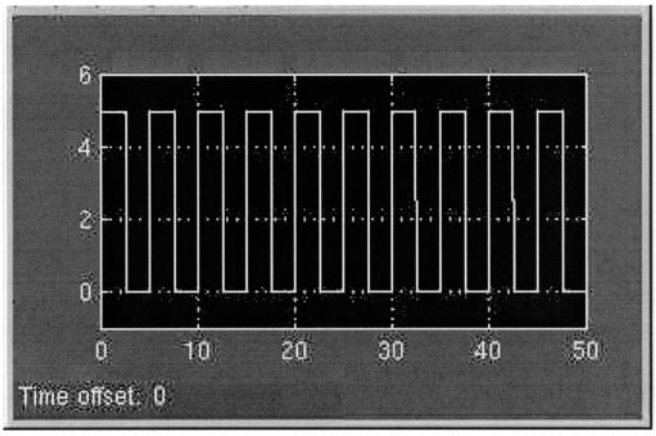


Fig. 14. Given force trajectory.

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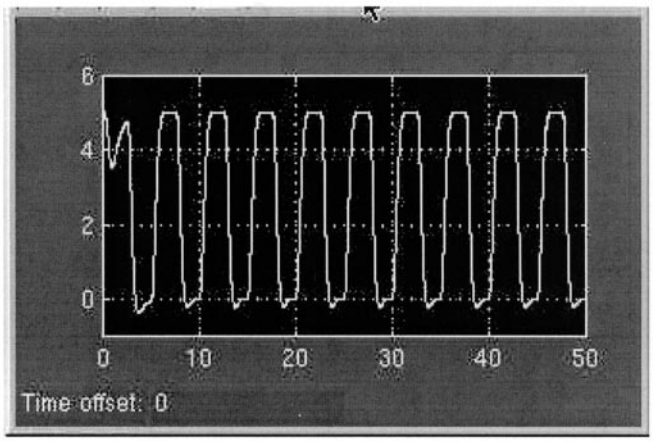


Fig. 15. Force output.

output of force control, a given motor command angle is generated as depicted in Figure 18, while Figure 19 is its tracking output. Figures 20 and 21 are the angle and force errors.

In view of the simulation results, the system control outputs are satisfied. Compared to the traditional robot force control, the proposed controller design method is quite simple. Furthermore, system stability can also easily be analyzed and guaranteed.

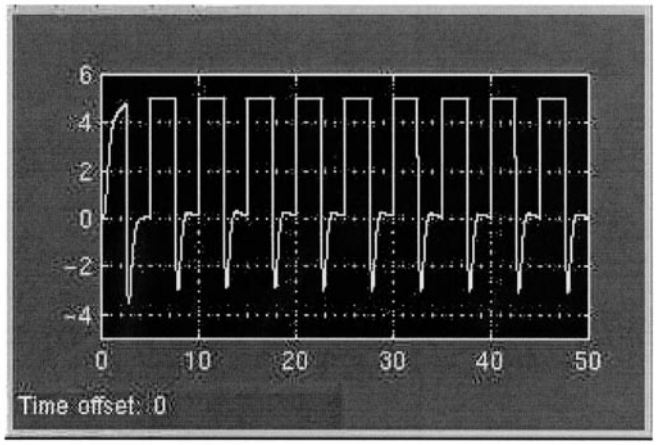


Fig. 16. Force controller output.

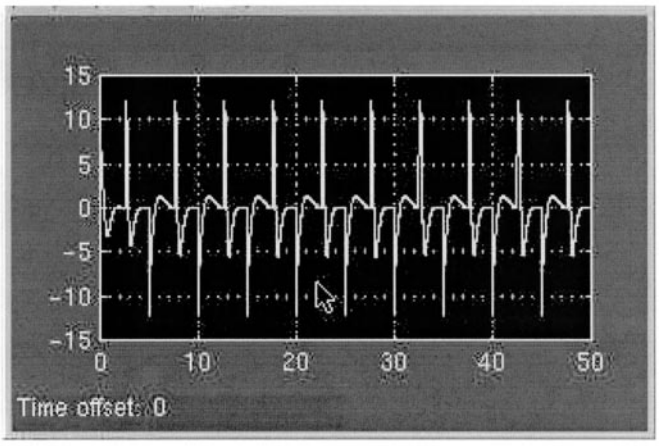


Fig. 17. Motor controller output.

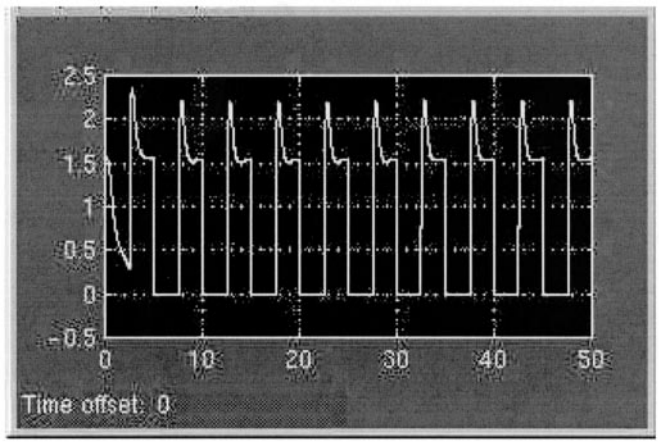


Fig. 18. Motor input angle for the force control system.

7. CONCLUSION

As a traditional force/position control method is based on the inverse model of system dynamics, which is complicated and difficult to obtain, a simple control policy based on ordinary forward dynamics is presented in this paper. In this method, the external force control generates an angle command signal which can directly drive the internal motor control. The internal control object is a motor and its direct

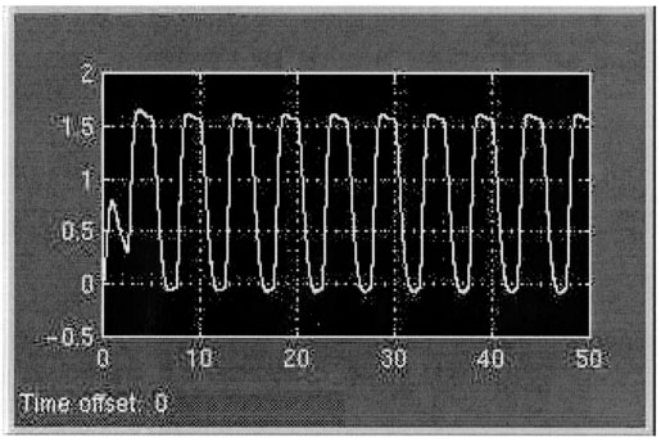


Fig. 19. Motor output angle for the force control system.

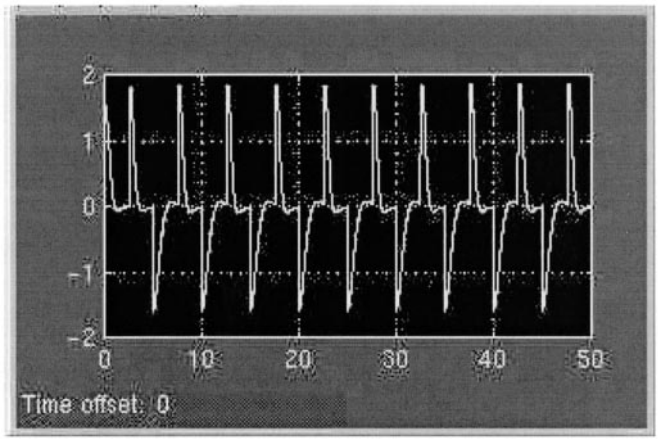


Fig. 20. Motor angle error for the force control system.

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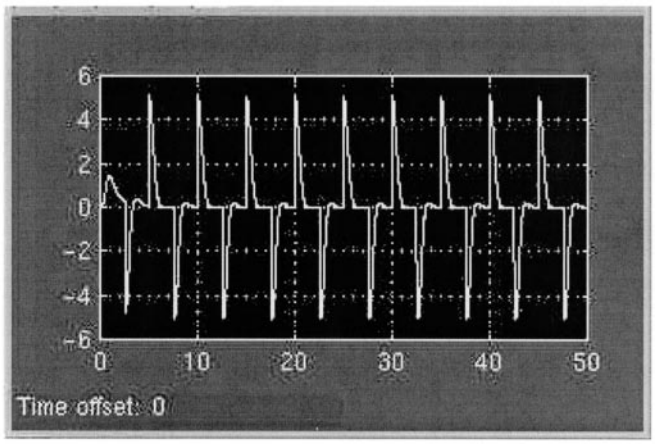


Fig. 21. Force error

dynamics is relatively easier to obtain than the leg's inverse dynamics. The control structure can also be simplified. Simulation results also illustrate the effectiveness of the adopted control policy.

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References

1. F.M. Kulakov, "Generalization of Force Control Theory for elastic Robot" *IEEE/RSJGI International Conference on Intelligent Robotics and Systems*, Munich, Germany (1994) pp. 1610–1617.
2. Yi Lin, and Shin-Min Song, "Learning Hybrid Position/Force Control of a Quadruped Walking Machine Using a CMAC Neural Network" *J Robotic Systems* **14**, No. 6, 483–499 (1997).
3. Ganwen Zeng and Ahmad Hemami, "An Overview of Robot Force Control", *Robotica* **15**, part 5, 473–482 (1997).
4. Shunmugham R. Panadian and Sadao Kawamura, "Hybrid Force/Position Control for Manipulators Based on a D-type Learning Law", *Robotica* **14**, Part 1, 51–59 (1996).
5. C.C. Cheah, Danwei Wang and Y.C. Soh, "Learning Control of Motion and Force for Constrained Robotics Manipulator" *Int. J. Robotics and Automation* **10**, No. 3, 79–88 (1995).
6. Doyoung Jeon and Masoyoshi Tomizuka, "Learning Hybrid Force and Position Control of Robot Manipulators" *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*, Nice, France (1992) pp. 1455–1460.
7. Friedrich Lange and Gerhard Hirzinger, "Iterative Self-improvement of Force Feedback Control in Contour Tracking" *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*, Nice, France (1992), pp. 1399–1404.
8. T. Yabuta and T. Yamada, "Force Control using Neural Networks" *Advanced Robotics* **7**, No. 4, 395–408 (1993).
9. Lilai Yan and C. James Li, "Robot Learning Control based on Recurrent Neural Network Inverse Model" *J. Robotic Systems* **14**, No. 3, 199–212 (1997).
10. M. Kemal Ciliz and Can Isik, "On-line Learning Control of Manipulator Based On Artificial Neural Network Models" *Robotica* **15**, Part 3, 293–304 (1997).
11. B. Bona and M. Indri, "Exact Decoupling of the Force-Position Control Using the Operational Space Formulation" *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*, Nice, France (1992), pp. 1394–1398.
12. Kangsik Lee, Sheri Coates and Victoria Coverstone-Carroll, "Variable Structure Control Applied to Underactuated Robots" *Robotica* **15**, Part 3, 313–318 (1997).
13. Byung-Ju Yi, Ian D. Walker, Delbert Tesar and Robert A. Freeman, "Geometric Stability in Force Control" *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, CA, USA (1991) pp. 281–286.
14. H.P. Qian and J. De. Schutter, "The Role of Damping and Low Pass Filtering in the Stability of Discrete Time Implemented Robot Force Control" *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*, Nice, France (1992) pp. 1368–1373.
15. P. Frisse, F. Pierrot and P. Dauchez, "Virtual Environment for Robot Force Control" *Proceedings of the IEEE International Conference on Intelligent Robotics and Automation*, Yokohama, Japan (1993) pp. 219–224.
16. M. Tarokh and S. Bailey, "Adaptive Fuzzy Force Control of Manipulators With Unknown Environmental Parameters" *J. Robotic Systems* **14**, No. 5, 341–353 (1997).

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