SCIENCE CHINA
Information Sciences

• LETTER •
Special Focus on Human-Robot Hybrid Intelligence

May 2019, Vol. 62 050210:1–050210:3
https://doi.org/10.1007/s11432-018-9666-y

A stiffness-adaptive control system for nonlinear stiffness actuators

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Received 30 August 2018/Accepted 30 October 2018/Published online 27 February 2019

Citation Zhao Y R, Song Z B, Ma T Y, et al. A stiffness-adaptive control system for nonlinear stiffness actuators. Sci China Inf Sci, 2019, 62(5): 050210, https://doi.org/10.1007/s11432-018-9666-y

Dear editor,
In human robot interaction (HRI), actuators with high stiffness can realize high bandwidth at the cost of safety performance, whereas actuators with low stiffness can decrease response oscillation and enhance stability and safety performance [1]. Variable stiffness actuators (VSAs) can realize a trade-off between the two contradictory performances. However, some VSAs, e.g., antagonistic-type models with decoupled stiffness and load, require auxiliary motors to realize stiffness adjustment, leading to high energy consumption and system complexity [2, 3]. Actually, it is valuable to design nonlinear stiffness actuators (NSAs) with coupled stiffness and load based on the "high stiffness corresponds to large loads, whereas low stiffness corresponds to small loads" strategy [4]. Therefore, we designed a load-dependent NSA (LDNSA) whose stiffness obeys this strategy [5]. However, like many compliant actuators that employ classical proportional-derivative (PD) controllers to improve the control bandwidth and response stability, obvious limitations for NSAs still exist.

PD parameters have a major influence on the nonlinear system [6], but they must be tuned manually and cannot be adjusted during each torque/position response [7]. Specifically, during each response of LDNSA, the constant PD parameters set manually are not always appropriate for all stiffness values, causing weakening of the control bandwidth and torque/load tracking stability. Although some advanced methods used for compliant actuators, e.g., active damping control and output feedback control, are available, they are inapplicable to actuator systems with high nonlinearity and variable stiffness in real time [6].

This study proposes a novel stiffness-adaptive control system with a nonlinear compensation term and an auto-tuning feedback controller to adaptively compensate for nonlinearity and tune control gains along with the variable stiffness based on an optimum damping ratio ($\zeta = 0.707$). This allows the actuators to realize a high control bandwidth and relatively high response stability [8]. The contributions of this study are that the control system is proposed for the first time in the control of NSAs, and for any given actuator, the auto-tuning feedback control gains corresponding to torque/stiffness are determined and do not need to be set manually, thereby considerably improving the work efficiency of the actuators. Furthermore, the stiffness-adaptive control system can adapt the nonlinearity of NSAs and optimize their control performance to achieve the optimum damping ratio.

Principle and design. Figure 1(a) shows the structure of LDNSA. It comprises a support frame, motor combination (including a motor, gearbox, and encoder), a pulley, an inner cylinder, an outer cylinder, wires, a magnetic linear encoder, and three uniform elastic structures. The motor combination as a power source transmits ro-

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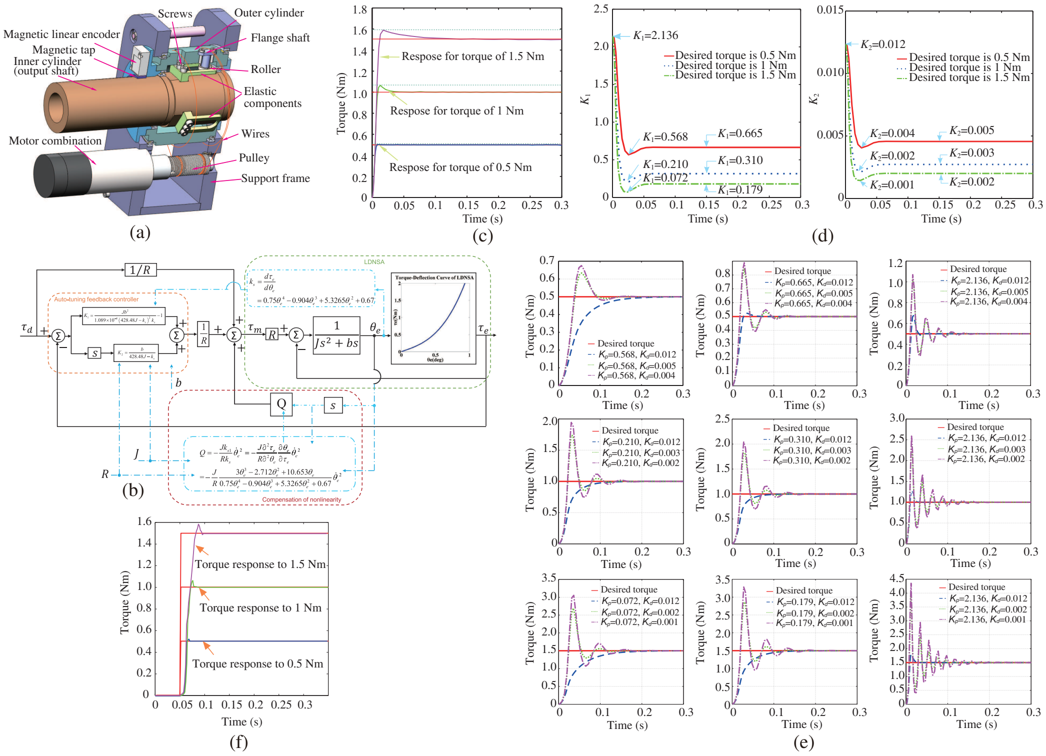

Figure 1 (Color online) (a) Sectional view of the LDNSA structure; (b) block diagram of the stiffness-adaptive control system; (c) torque tracking performance of the LDNSA with the proposed control system; (d) variation of the auto-tuning feedback control gains during torque tracking; (e) simulation results of LDNSA with classical PD controller responding to different torques (0.5, 1 and 1.5 Nm) where t_r and M_p represent the rise time (ms) and maximum overshoot (Nm), respectively; (f) experimental results of LDNSA with the proposed control system.

tation to the outer cylinder through wires. The transmission ratio can be expressed by R. Each elastic structure includes a roller fixed onto the outer cylinder through a flange shaft and an elastic component with two symmetrical elastic elements fixed onto the inner cylinder by screws. The roller is always in contact with the elastic element. The nonlinear stiffness characteristic can be realized by designing the profile of the elastic element based on the analysis of the interaction between the roller and the elastic element [4]. When loads act on the inner cylinder, the elastic elements will deflect and a relative rotation (θ_e) between the inner and outer cylinders will be detected by the magnetic linear encoder. Next, we obtain load through the nonlinear stiffness relation $\tau_e = 0.15\theta_e^5 - 0.23\theta_e^4 + 1.78\theta_e^3 + 0.67\theta_e$.

The proposed stiffness adaptive control system is shown in Figure 1(b). Through dynamic analysis of LDNSA with a nonlinearity compensation term, the relationship between the actual output torque τ_e and the desired torque τ_d can be expressed as $\frac{J}{k_s}\ddot{\tau}_e + (RK_2 + \frac{b}{k_s})\dot{\tau}_e + (K_1R+1)\tau_e - \frac{Jk_{s_1}}{k_s^3}\dot{\tau}_e^2 = (RK_1+1)\tau_d + RK_2\dot{\tau}_d + RQ$, where Q is a nonlinearity compensation term chosen as $Q = -\frac{Jk_{s_1}}{Rk_s^3}\dot{\tau}_e^2 = -\frac{Jk_{s_1}}{Rk_s}\dot{\theta}_e^2$ with $k_{s_1} = \frac{\partial^2\tau_e}{\partial^2\theta_e}$ and $k_s = \frac{\partial\tau_e}{\partial\theta_e}$. Next, based on above response relation, the formula for the optimal damping ratio, and its corresponding maximum overshoot (6%) [9], the auto-tuning feedback control gains K_1 and K_2 should be designed as

$$\begin{aligned} K_1 &= \frac{Jb^2}{1.089\times10^{-5}(428.48J-k_s)^2k_s} - 1, \\ K_2 &= \frac{b}{428.48J-k_s}, \end{aligned} \quad (1)$$

where J and b are system equivalent rotational inertia and damping respectively.

Results and decisions. The simulation results for LDNSA with the proposed stiffness-adaptive control system for loads of 0.5, 1, and 1.5 Nm are shown in Figure 1(c). Because the damping ratio of the system contains a constant and the stiffness varies within a relatively small range (1.9–4.13 Nm/deg), the rise times of the above responses are close to 7.898 ms and the control bandwidth is 44.3 Hz, for which the maximum overshoots are 0.03, 0.06, and 0.09 Nm, respectively. The variations of the auto-tuning feedback control gains are illustrated in Figure 1(d). The control gains always decrease when stiffness increases. At the beginning of the response, because the stiffness is minimal, feedback control gains are maximal.

Further, when the actual torque of LDNSA reaches maximum overshoot, feedback control gains become minimal. Finally, these gains attain stability corresponding to a constant stiffness and a desired torque. The larger the desired load/torque, the smaller the auto-tuning feedback control gains.

For comparison, we also conducted some torque-tracing simulations of LDNSA with a classical PD controller whose parameters were chosen according to Figure 1(d). The results are shown in Figure 1(e). Although the two individual cases $K_p = 0.665$, $K_d = 0.012$ and $K_p = 0.568$, $K_d = 0.012$ can generate a lower maximum overshoot (i.e., a higher response stability performance) when the desired torque is 0.5 Nm, the overall rise time is much slower. Except for these two cases, the proposed control system can realize a much smaller overshoot with a shorter rise time, indicating a higher control bandwidth. This situation is similar to the LDNSA response for a torque of 1 Nm. The proposed control system can offer shorter rise times and lower overshoots than most PD controllers, except at $K_p = 0.310$, $K_d = 0.012$ and $K_p = 0.210$, $K_d = 0.012$, for which the response occurred with no overshoot and very slowly. Although the response with no overshoot realizes a high response stability performance, the slow response speed is not allowed in HRI. When LDNSA tracks a torque of 1.5 Nm, the rise times of PD controllers are much slower, except for the situations wherein $K_p = 2.136$, $K_d = 0.002$ and $K_p = 2.136$, $K_d = 0.001$, for which the response speed is almost the same as that of the proposed control system. However, the maximum overshoots of the two aforementioned situations are much larger and there exist severe oscillations, which are not advisable in HRI.

For classical PD controllers, it is common that high bandwidth performance and high response stability cannot be obtained simultaneously even when the PD parameters are matched repeatedly. The proposed control system can not only realize a quick response and high control bandwidth with high response stability but can also realize optimal performances without manual adjustment, improving the efficiency of NSAs.

Figure 1(f) shows the experimental results for LDNSA with the proposed control system. It can quickly track reference torques of 0.5, 1, and 1.5 Nm with rise times of 0.015, 0.021, and 0.032 s, respectively. The maximum overshoots are 0.026, 0.063, and 0.088 Nm, which also indicate high stability performance in the actual implementation.

Conclusion. We proposed a stiffness-adaptive control system to automatically tune feedback control gains and compensate for the nonlinear term during control. The relation between auto-tuning feedback control gains and nonlinear stiffness is established based on the optimal damping ratio and its corresponding maximum overshoot. Simulations of the proposed control system and classical PD feedback controller were conducted, which proved that the proposed stiffness-adaptive control system can adapt to the nonlinear stiffness of LDNSA and simultaneously realize high control bandwidth and high response stability. Finally, experimental results verified the feasibility of the proposed system.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 51475322, 51535008, 51775367, 51721003), Tianjin Municipal Science and Technology Department Program (Grant No. 17JCZDJC30300), and International Collaboration Programme (111 Program) (Grant No. B16034).

References

1 Zinn M, Khatib O, Roth B, et al. A new actuation approach for human friendly robot design. In: Proceedings of IEEE International Conference on Robotics and Automation, 2004
2 Sun J T, Guo Z, Zhang Y B, et al. A novel design of serial variable stiffness actuator based on an archimedean spiral relocation mechanism. IEEE/ASME Trans Mechatron, 2018, 23: 2121–2131
3 Sun J T, Guo Z, Sun D Y, et al. Design, modeling and control of a novel compact, energy-efficient, and rotational serial variable stiffness actuator (SVSA-II). Mech Mach Theory, 2018, 130: 123–136
4 Lan S B, Song Z B. Design of a new nonlinear stiffness compliant actuator and its error compensation method. J Robot, 2016, 2016: 1–8
5 Gao D, Song Z B, Zhao Y R. A novel concept and impedance schematic analysis for nonlinear stiffness compliant actuator (NSCA). In: Proceedings of IEEE International Conference on Mechatronics and Automation (ICMA), 2017. 1562–1566
6 Guo Z, Pan Y P, Sun T R, et al. Adaptive neural network control of serial variable stiffness actuators. Complexity, 2017, 2017: 1–9
7 Fahmizal, Surriani A, Budiyanto M, et al. Altitude control of quadrotor using fuzzy self-tuning PID controller. In: Proceedings of the 5th International Conference on Instrumentation, Control, and Automation (ICA), 2017. 67–72
8 Umland J W, Safiuddin M. Magnitude and symmetric optimum criterion for the design of linear control systems-what is it and does it compare with the others. In: Proceedings of IEEE Industry Applications Society Annual Meeting, 1998
9 Pavković D, Polak S, Zorc D. PID controller auto-tuning based on process step response and damping optimum criterion. ISA Trans, 2014, 53: 85–96