Design and Experimental Study on Telescopic Boom of the Space Manipulator

Shicai Shi(✉), Qingchao He, and Minghe Jin

State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China
sschit@hit.edu.cn, heqingcao123@163.com

Abstract. This paper achieves the design of the key component of space manipulator – the telescopic boom and develops the principle prototype, to solve the contradiction between large working space, small load and fine operation, high rigidity, high precision in space manipulator handling operations. The stiffness test platform is developed for the telescopic boom, and through the test the boom meets the design requirements. The control strategy used to stretch the boom is also discussed in detail. Relevant experiments show that the telescopic boom can successfully achieve the telescopic movement.

Keywords: Space manipulator · Telescopic boom · Test platform · Telescopic strategy

1 Introduction

Space environment with high vacuum, large temperature difference, strong radiation and other characteristics, will pose a threat to the safety of astronauts working in space [1]. By space robots to complete the above operations can effectively avoid the problem, which can improve the safety, economic benefit, efficiency and quality of the task [2]. The most widely used space robot system is the space manipulator, such as the Canadarm and Canadarm2 [3, 4].

Nowadays, the mature space manipulators all use fixed length arm, which brings the problem of large occupied space, high cost and fixed working space [5]. Although the Canadarm2 uses a collapsible structure that reduces the need for launch space and improves operational flexibility, it needs the astronaut's extravehicular operations to assist its development, which brings some risks. Therefore, the retractable space manipulator is the future direction of development. The main advantages of retractable space manipulator mainly include: (1) it occupies a small size when shrank, and has a large working space after being stretched. (2) it is more flexible and can be competent for more complex tasks. (3) it reduces the cost of launch.

Y. Huang et al. (Eds.): ICIRA 2017, Part III, LNAI 10464, pp. 707–716, 2017.
DOI: 10.1007/978-3-319-65298-6_63

2 Design of the Telescopic Boom

2.1 Design Specifications

The telescopic boom has the characteristics of light weight and small space occupation, and it also needs to have enough rigidity, strength, reliability and security, to meet the needs of the complex space mission. In this paper, the design index of telescopic boom of space manipulator is shown in Table 1.

Table 1. Design index

Serial Number	Property	Index
1	Weight	≤ 8 kg
2	Torsional stiffness	3×10^4 Nm/rad
3	Bending stiffness	7×10^4 Nm/rad
4	Tensile stiffness	2.5×10^5 Nm/rad
5	Telescopic ratio	$\geq 3:2$

2.2 Overall Design of the Telescopic Boom

In this paper, several telescopic structures are compared. It can be seen from the results of Table 2 that the sleeve telescopic mast has the advantages of moderate length, high carrying capacity, high reliability and low complexity [6, 7]. The telescopic scheme of the boom is divided into two types: the active telescopic scheme and the passive telescopic scheme according to the power source. Although the active telescopic scheme has the advantages of strong versatility, large proportion of boom extension and easy change of arm length, it has the characteristics of complex structure, large volume and heavy weight. As for passive scheme, the arm is not driven by a separate drive source, but is rotated by the rotation of the joint, mounted on both ends of the boom, to drive the boom to achieve a change in the length of the arm. Therefore, the passive scheme is simpler and lighter. After comparison, the telescopic boom developed in this paper adopts the sleeve structure, using the passive telescopic scheme.

Table 2. Comparisons of the telescopic strategies

Strategy	Stretching length	Carrying capacity	Reliability	Complexity
Collapsible Tubular mast	Short	Small	Low	Low
Telescopic Sleeve mast	Moderate	Large	High	Low
Coilable mast	Long	Larger	High	High

Figure 1 shows the overall design of the telescopic boom. The telescopic arm system consists of two sets of telescopic boom, two active joints and one driven joint, arranged symmetrically. An active joint is mounted at the end of each boom, and two

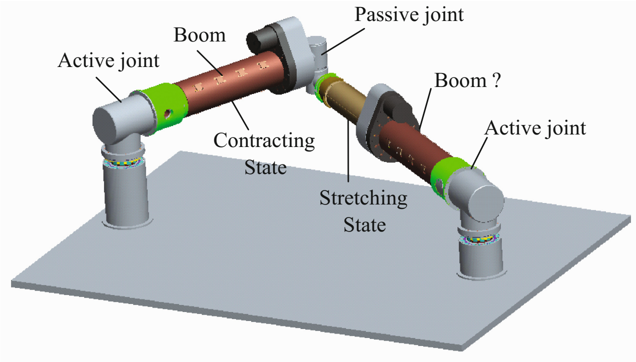


Fig. 1. The overall structure of the boom

sets of booms are connected by a driven joint. In the initial state, the booms are contracted and locked. The stretching process is as follows: positions of two active joint are fixed, unlock the arm to be expanded, the joint at the end of another boom rotates, another active joint follows the movement, passive extension starts, stop joint's operation after reaching the designed position and then lock booms again. The constriction process is similar to the above procedure, with the reverse rotation of the joint.

2.3 Internal Structure of the Boom

The structural design of the telescopic mechanism is shown in Fig. 2, consisting mainly of internal and external booms. In order to ensure smooth sliding between the inner and outer booms, the outer boom is equipped with a pulley, and the inner boom has a corresponding guide rail. The inner part of the boom is provided with a locking mechanism which is driven by a locking motor, to lock booms after the telescopic motion. A stroke switch is arranged at the limit position of the extension and contraction of the boom to control the start and stop of the joint motor and the locking motor.

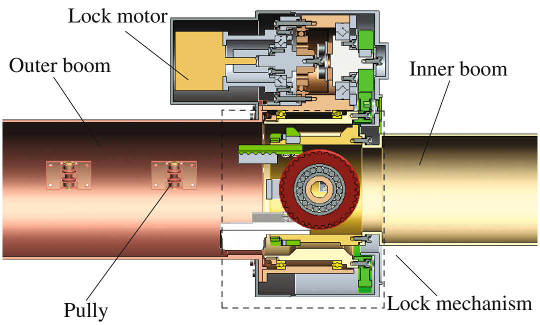


Fig. 2. The inner structure of the boom

3 Control Strategy of the Telescopic Motion

3.1 Establishment of the Joint Dynamic Model

Passive stretching strategy is mainly achieved through joint motion. For joint control, it is necessary to create a dynamic model of the joint. In this paper, the active joint is equipped with harmonic reducer and torque sensor. When the joint movement, harmonic reducer flexible wheel and torque sensor will be deformed, so that the joint with a certain degree of flexibility. Based on the assumption of Spong [8], the flexible joint can be regarded as a simple two body system: there is a zero inertia torsion spring between the two bodies, and the flexibility of the joint is simulated by the stiffness and damping of the torsional spring, which is shown in Fig. 3. Dynamic model of flexible joint is as follows:

$$\begin{aligned} &\tau_{\mathrm{m}} - \tau_{f1} = J_1\ddot{q}_1 + D(\dot{q}_1 - \dot{q}_2) + K(q_1 - q_2) \\ &\tau = K(q_1 - q_2) \\ &K(q_1 - q_2) + D(\dot{q}_1 - \dot{q}_2) + \tau_{\mathrm{ext}} = J_2\ddot{q}_2 + \tau_{f2} \end{aligned} \tag{1}$$

Where q_1 and q_2 denote the rotation angle of the motor and the load, J_1 and J_2 are the inertias of the motor and the load separately. τ_{f1} and τ_{f2} represent the friction torque respectively applied on motor and load, K and D are the stiffness and damping coefficients of the sensor. τ_m and τ_{ext} respectively represent the input torque of the motor and the torque applied to the load. τ is the measured value of the torque sensor.

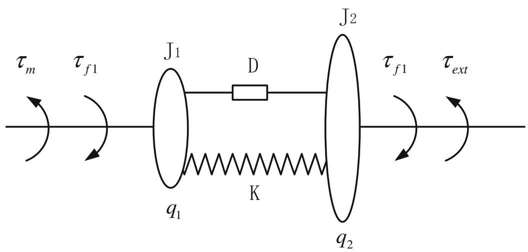


Fig. 3. The flexible joint model

Without considering the damping of the joint and ignoring the influence of the friction torque at the motor end and the load, the joint dynamics model can be simplified as:

$$\begin{aligned} &\tau_{\mathrm{m}} = J_1\ddot{q}_1 + K(q_1 - q_2) \\ &\tau = K(q_1 - q_2) \\ &K(q_1 - q_2) + \tau_{\mathrm{ext}} = J_2\ddot{q}_2 \end{aligned} \tag{2}$$

3.2 Position Control of the Active Joint

It is the basis for the telescopic motion of the boom to carry out the accurate position control of the active joint, which makes it follow the planned path precisely. When the joint position control is concerned, it often involves the rapid start and stop or the large change of the joint setting value. The introduction of integral controller will cause the system overshoot, and even the system of shock. Therefore, this paper uses the PD control strategy. By the Lyapunov stability theorem and LaSalle theorem, PD control has the asymptotic stability, and its control law is:

$$\tau = k_{\mathrm{P}}(q_{\mathrm{d}} - q) + k_{\mathrm{D}}(\dot{q}_{\mathrm{d}} - \dot{q}) \tag{3}$$

Where k_p and k_p are scale factor and derivative coefficient. q_d and $\dot{q}_d$ denote the desired position and speed of the joint angle. q and $\dot{q}$ represent the actual position and speed.

3.3 The Impedance Control of the Joint

When an active joint is moved by position control, the other active joint follows the movement by impedance control. By establishing the relationship between the force and the position, the impedance control makes the joint flexibility [9], the expression is:

$$M_\theta(\ddot{\theta} - \ddot{\theta}_r) + D_\theta(\dot{\theta} - \dot{\theta}_r) + K_\theta(\theta - \theta_r) = \tau \tag{4}$$

Where M_θ, D_θ and K_θ represent the inertia matrix, damping matrix and stiffness matrix of the desired impedance model.

Since the joint in this paper does not have the acceleration sensor, and the acceleration information obtained by the second derivative of the position information will produce very strong noise. Therefore, the inertia term is neglected in this paper. The impedance control expression becomes:

$$D_\theta(\dot{\theta} - \dot{\theta}_{\mathrm{r}}) + K_\theta(\theta - \theta_r) = \tau \tag{5}$$

In order to obtain smaller ideal stiffness and damping, this paper adopts the impedance control strategy based on joint force, which consists of impedance control outer ring and force control inner ring [10], and uses internal force controller to compensate the nonlinear dynamic influence of manipulator.

Because of the flexibility of joints, the stiffness of joints and the effective moment of inertia of the rotor will affect the accuracy of the mechanical model. For this reason, this paper introduces the output torque of the torque sensor as the feedback of the force controller, so that the effective inertia of the rotor of the force closed loop system is smaller, and the model is shown in Fig. 4. The motor output torque is:

$$\tau_{\mathrm{m}} = J_1 J_{1\theta}^{-1} \tau_1 + (1 - J_1 J_{1\theta}^{-1})\tau \tag{6}$$

Where $J_{1\theta}$ represents the effective moment of rotation of the motor, and τ_1 is a new control input whose expression is $\tau_1 = K_\theta \theta + D_\theta \theta$. K_θ and D_θ mean the ideal stiffness

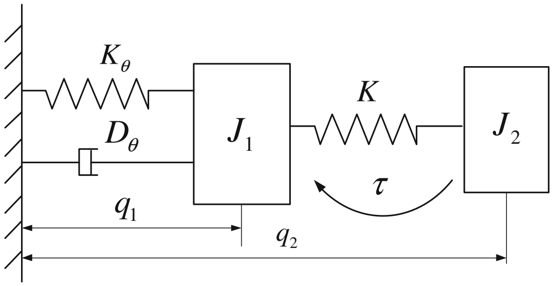


Fig. 4. Introducing moment negative feedback

and ideal damping of joints in impedance control respectively. According to (2), the impedance control strategy is:

$$\begin{aligned} & K_\theta \theta + D_\theta \dot{\theta} = J_{1\theta} \ddot{q}_1 + K(q_1 - q_2) \\ & \tau = K(q_1 - q_2) \\ & K(q_1 - q_2) + \tau_{\text{ext}} = J_2 \ddot{q}_2 \end{aligned} \tag{7}$$

4 Experimental Verification of the Telescopic Boom

4.1 The Stiffness Test of the Boom

In order to test the actual operation of the telescopic boom and its stiffness, this paper has worked on the principle prototype of the boom and developed the corresponding rigidity test platform, which is shown in Fig. 5.

The experiment platform can fix the boom in the vertical direction, and exert force on the boom in all directions through the pulley, cable and weight. Apply the vertical and horizontal forces on the boom to obtain the corresponding deformation. Through the linear fitting of the experimental data by MATLAB, we can get the stiffness data of

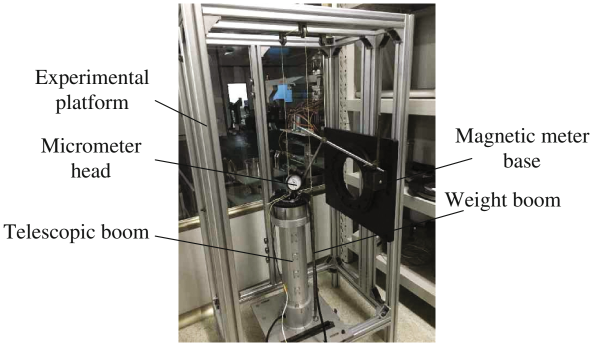


Fig. 5. The stiffness test platform of the boom

Table 3. Stiffness index of the boom

	Contraction	Stretching	Units
Compression stiffness	2.75×10^6	2.48×10^6	N/m
Tensile stiffness	3.38×10^6	2.22×10^6	N/m
Bending stiffness	9.83×10^4	7.86×10^4	Nm/rad
Torsional stiffness	–	3.05×10^4	Nm/rad

different states of the boom, as shown in the Table 3. By comparing with Table 2, we can see that the stiffness of the boom can reach the design target.

4.2 The Test of the Position Control of the Active Joint

The whole telescopic motion of the boom contains the following stages, as shown in Table 4.

Table 4. Boom movement stage

	Joint 1	Joint 2	Boom 1	Boom 2
Phase 1	Active	Passive	Locked	Stretch
Phase 2	Passive	Active	Stretch	Locked
Phase 3	Passive	Active	Shrink	Locked
Phase 4	Active	Passive	Locked	Shrink

In order to test the actual effect of the PD and impedance control strategy applied in the telescopic boom, the experimental system is set up in Fig. 6. The joints mounted on both ends of the telescopic arm are secured to the horizontal test platform.

This paper first adjusts the PD controller parameters, to ensure the accuracy of the boom telescopic movement. At the same time to ensure the stability of the system, we should minimize the steady-state error of the system and speed up the system. In this paper, different values of k_p and k_D are selected, and the reasonable parameters are obtained by comparing the actual trajectories with the given trajectories. For the active

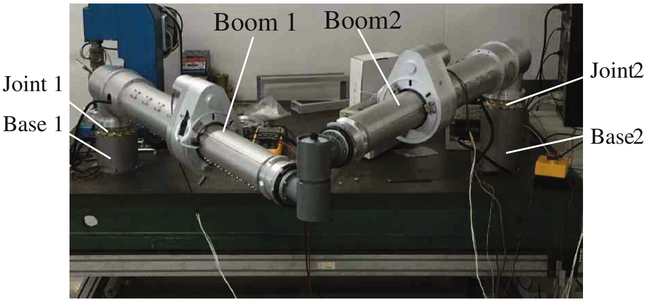


Fig. 6. The experimental system of the boom

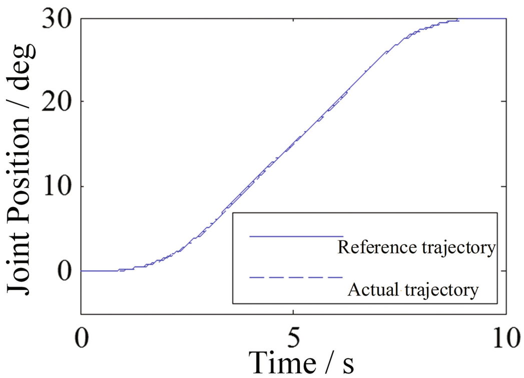


Fig. 7. Reference trajectory and actual trajectory of joint

joint, the actual trajectory can track the target trajectory well, as shown in Fig. 7, the maximum position error does not exceed 0.1°.

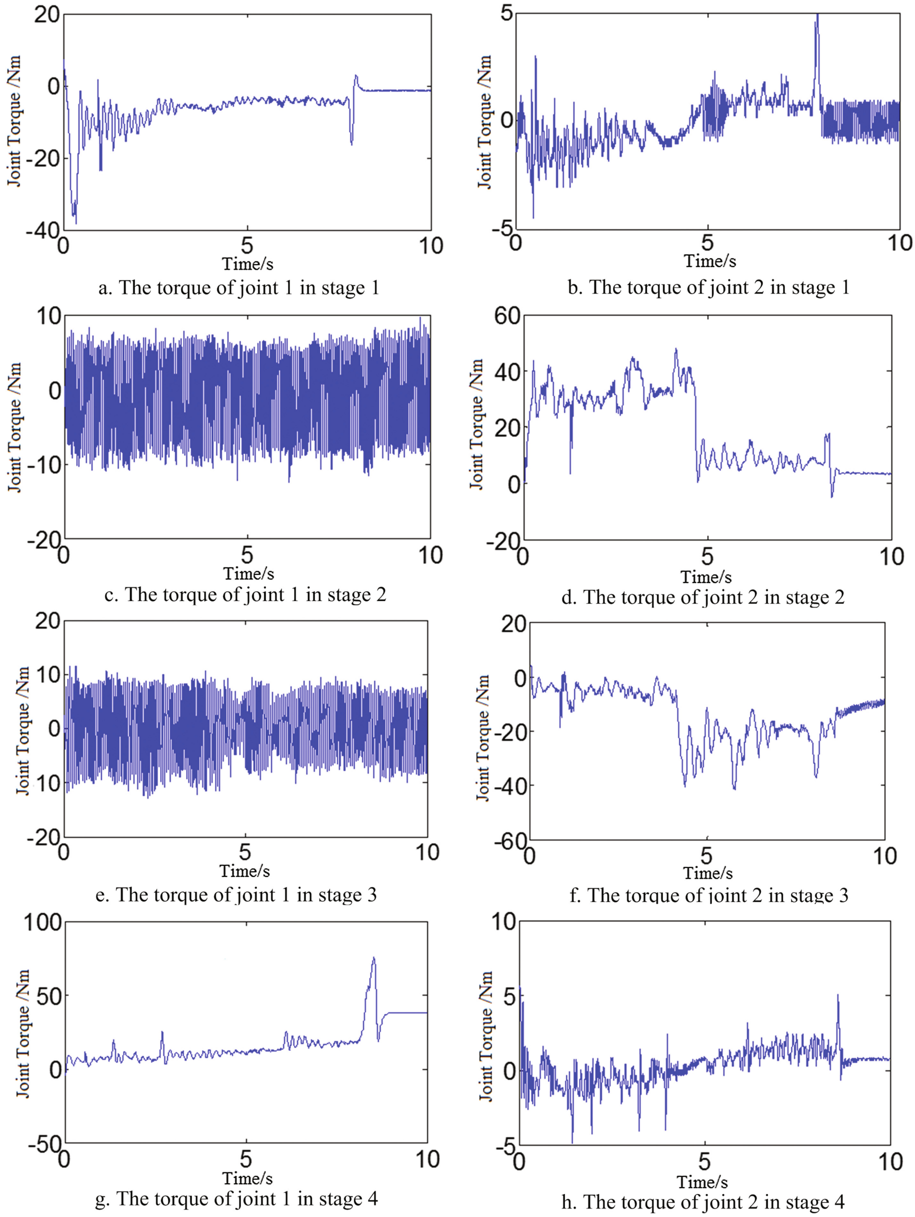
4.3 The Test of the Impedance Control of the Following Joint

For the joint that follows the movement, the stiffness and the damping coefficient in the impedance parameters are set to zero. The signal measured by the torque sensor is multiplied by the amplification factor as feedforward and input to the motor control terminal so that the effect of zero force tracking is as good as possible. Because the torque sensor has a certain noise, the amplification factor can not be taken too large, otherwise it will cause instability of the system.

For the four movement stages in the previous section, the moments of the two joints are shown in Fig. 8. It can be seen from the image that the moment curves of the two joints also show some symmetry due to the symmetry of the four stages of motion: the stage one is similar to the stage four, and the phase two and the phase are similar. Therefore, we discuss only the joint moment curves of stage one and two.

The output torque of the active joint is both large at the beginning of stage 1 and stage 2, for the reason that the anti-twist block gets stuck in the card slot, causing a great friction resistance. Compared with stage two, the output torque of the active joint in stage one is smaller, and the tension of the boom is smoother. That is because, after the boom II is stretched, its arm of force becomes longer, so that the extension boom I requires a larger joint torque.

According to the experimental results, it can be seen that the performance of the impedance control strategy based on the joint torque is well, the passive joint can follow the rotation of the active joint and reflect the better flexibility.



a. The torque of joint 1 in stage 1

b. The torque of joint 2 in stage 1

c. The torque of joint 1 in stage 2

d. The torque of joint 2 in stage 2

e. The torque of joint 1 in stage 3

f. The torque of joint 2 in stage 3

g. The torque of joint 1 in stage 4

h. The torque of joint 2 in stage 4

Fig. 8. Joint torque of each movement stage

5 Conclusions

Aiming at the space manipulator, this paper designs a telescopic boom structure, which has the characteristics of small volume in launching, large working space on orbit, flexible operation and light weight. Compared with the traditional joint arm with a fixed length of the boom, it saves the launch cost, and is more suitable for the complexity of space missions in orbit.

In this paper, the structure of telescopic boom is introduced, and the sleeve type boom and the passive telescopic method are adopted to make the boom meet the requirements of high rigidity, light weight and multi working state. The dynamic model of joint is established, and the corresponding control strategy of joint is studied. Through the control of joint movement, the passive extension of the boom is realized. The experiment result shows that the stiffness of the boom can meet the requirements, and it can successfully complete the automatic telescopic movement.

Acknowledgements. This work is supported by the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (No. 51521003)

References

1. Zhang, W.H., Ye, X.P., Ji, X.M.: Development summarizing of space robot technology national and outside. Flight Mech. **31**(3), 198–202 (2013)
2. Yu, D.Y., Sun, J., Ma, X.R.: Suggestion on the development of Chinese space manipulator technology. Aerosp. Eng. **16**(4), 1–8 (2007)
3. Gibbs, G., Sachdev, S.: Canada and the international space station program: overview and status. Acta Astronaut. **51**(1–9), 591–600 (2002)
4. Marcotte, B.: Canadian ISS program involvement. Acta Astronaut. **54**(11–12), 785–786 (2004)
5. Wang, K., Liang, C.H., Lin, Y.C.: Design of reconfigurable space manipulator system based on telescopic mechanism. Manned Space Flight **22**(5), 537–543 (2016)
6. Li, D., Chu, Z.Y., Cui, J.: Design and adaptive control of a deployable manipulator for space detecting payload supporting. In: The 8th IEEE International Symposium on Instrumentation and Control Technology, London, UK, pp. 229–234. IEEE (2012)
7. Krimbalis, P.P., Djokic, D., Hay, G.: Design and validation of the primary structure and bonded joints for the next generation large Canadarm test bed. In: The 19th International Conference on Composite Materials, Montréal, Canada, pp. 544–554 (2013)
8. Spong, M.W.: Modeling and control of elastic joint robots. J. Dyn. Syst. Measure. Control **109**, 310–319 (1987)
9. Hogan, N.: Impedance control: an approach to manipulation. In: American Control Conference, pp. 304–313. IEEE Xplore (2009)
10. West, H., Asada, H.: A method for the design of hybrid position/Force controllers for manipulators constrained by contact with the environment. In: Proceedings of the IEEE International Conference on Robotics and Automation, pp. 251–259. IEEE (1985)