A Light Space Manipulator with High Load-to-Weight Ratio: System Development and Compliance Control

Zhiwei Wu,1 Yongting Chen,1 and Wenfu Xu1,2

1The School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen 518055, China
2The State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China

Correspondence should be addressed to Wenfu Xu; wfxu@hit.edu.cn

Received 24 May 2021; Accepted 22 August 2021; Published 28 September 2021

1. Introduction

Space robots are developing in the direction of intelligence and lightweight [1]. The lightweight space manipulator not only meets the weight reduction needs of aerospace, but also has the characteristics of high load-to-weight ratio. It can make the space manipulator have a smaller inertial force when operating the space manipulator in space, thereby improving the response speed of the space manipulator [2–6].

The main methods to realize the compliance control of the manipulator are active compliance and passive compliance. Passive compliance is realized by installing a flexible body or elastomer at the end, and active compliance is realized by force-position hybrid control, impedance control, etc. [7, 8]. Impedance control is to adjust the system impedance parameters including inertia parameters, damping parameters, and stiffness parameters according to the position, speed, acceleration, force, and moment feedback of the end of the manipulator, so as to achieve the purpose of controlling the end force and torque. Impedance control is divided into impedance control of joint force control and admittance control of joint position control [3]. Impedance control based on joint force control requires dynamic model parameters of the manipulator, so the manipulator must support the force control mode. However, for admittance control, the robot arm only needs to provide a position control mode, so its application range is wider [9]. When the actual stiffness, damping, actual position, and other parameters of the environment are inconsistent with the theoretical values, the given desired position does not match the environmental position, resulting in poor end force control effect. Therefore, the researcher introduces an adaptive term to adjust the desired position or desired speed in real time according to the force error [10]. The adaptive term is a discrete compensation term related to the force error, which can be added to the speed error term or the position error term. The update rate in the adaptive item has a great impact on the control performance. Researchers use neural network, fuzzy control, and other theories to obtain an appropriate update rate to improve the performance of adaptive impedance control [11–14]. By adding discrete compensation items, constant force control can be realized and control responsiveness can be improved. However, the discrete compensation term turns the admittance expression into a nonlinear expression, and it is difficult to convert to the frequency domain for parameter analysis, and it is...
impossible to use hyperbolic transformation to z-function to obtain the differential equation solution. It can only be solved by the iterative method, which has poor accuracy [15].

In addition, Karami et al. proposed an observer-based state feedback stabilizer design for a class of chaotic systems with external disturbances and Lipschitz nonlinearity. They used linear matrix inequalities to obtain the stabilizer and observer parameters, which made the state error converge to origin [16]. Esmaeilzadeh et al. proposed a new controller and adaptive mechanism to solve the problem of fixed-time attitude control of flexible spacecraft under the effect of actuator failure, external disturbance, and flexible mode coupling [17]. Pujol-Vazquez et al. use linear matrix inequality technology to design effective output feedback control and propose a robust delay-dependent controller based on H∞ theory [18]. Rasoolinasab et al. proposed a robust stabilizer for nonholonomic systems with time-varying time delays and nonlinear disturbances. And use the Lyapunov-Krasovskii function to derive the asymptotic stability of its feedback control method [19].

In view of the drawbacks of the above method due to the addition of discrete compensation terms, this paper proposes an integral adaptive control algorithm based on admittance, which is a third-order linear system that does not contain discrete compensation terms. Integral adaptive admittance control adds a force error integral term, which solves the problem of steady-state error of force control in traditional admittance. And the control system is a third-order linear system without nonlinear time terms. Performance analysis can be performed in the frequency domain. Simplify the environment to a spring model. The expected force response transfer function and the environmental error response transfer function are derived, and the step response is used as the evaluation index to analyze the influence of the control parameters on the control performance.

| Table 1: The overall design index of the robotic arm. |
|-----------------------------------------|
| Index                                      |
| Degree of freedom                     | 7          |
| Operating range                        | 800 mm     |
| Robotic arm quality                    | 9.23 kg    |
| Load capacity                          | 2 kg       |
| Repeatability                          | 0.12 mm    |
| Sensor                                  | Position encoder |

2. Lightweight Space Manipulator Structure Design

The index of the manipulator designed in this paper is shown in Table 1.

The shoulder and elbow joints adopt the same design scheme, adopting an integral harmonic design, and the wrist joint adopts a split harmonic design. The shoulder joint is shown in Figure 1(a). The absolute encoder is installed at the end of the motor to facilitate the connection of the drive with the encoder and the electrical wires of the motor. The motor shaft adopts a hollow design, which reduces the quality and realizes internal wiring. The wire tube is 3D printed and fixed to the shell to prevent the high-speed rotating motor shaft from damaging the wires. The improved design LCD type integral harmonic reducer is adopted, the center hole is enlarged, and the hollow wiring is realized. We use frameless torque motor, which has stable output torque, simple structure, and low quality. The wrist joint design is shown in Figure 1(a). Use a separate harmonic reducer. Its circular spline is fixed on the joint shell, the wave generator is connected with the motor shaft, and the flex spline is connected with the output shaft. Among them, the wave generator expands the center hole and realizes the hollow wiring. The output shaft is fixed by cross roller bearings to improve accuracy and reliability. The rest of the design is the same as the shoulder joint.

In this paper, the curved cylinder shown in Figure 2 is used to achieve 90° steering. The electrical circuit is installed inside, which improves the force of the L-shaped adapter and increases the aesthetics. The connecting rod adopts a hole on the circumference in the vertical direction, which is convenient for installation and disassembly. In the lateral direction, the axial opening is adopted to improve the connection reliability, and the thin covering part is designed to realize the closure of the lateral joint. A large space is reserved in the vertical direction of the connecting rod to install the driver and realize the separation of the driver and the joint. The robot arm adopts the SRS configuration, and 6 curved connecting rods are connected to 7 joints in sequence. It is connected to the optical platform through a base, and its core components are mainly joints, curved connecting rods, bases, and 3D shells. The overall mass of the robot arm is 9.23 kg, the rated load is 2 kg, and the repeat positioning accuracy is 0.12 mm, which meets the design index requirements.

3. Integral Adaptive Admittance Control Algorithm

There are mainly two existing admittance adaptive control methods. The first is compensation in the position term, and the single degree of freedom control formula is as follows:

\[
m(x - \dot{x}_d) + b(x - \dot{x}_d) + k(x - \dot{x}_d + \Omega) = f - f_d. \tag{1}
\]

The compensation term in the formula is as follows:

\[
\Omega(i + 1) = \Omega(i) + \eta \frac{f_d(i + 1) - f(i + 1)}{k}, \tag{2}
\]

\[
0 < \eta < \frac{Tb}{Tb + m} < 1, \tag{3}
\]

where \( \eta \) is the update coefficient and \( T \) is the control period.

The second type is compensation in the speed term, and the formula given is as follows:

\[
m(\ddot{x} - \ddot{x}_d) + b(\ddot{x} - \ddot{x}_d + \Omega) = f - f_d. \tag{4}
\]
Figure 1: Joint structure diagram. (a) Shoulder joint structure. (b) Wrist joint structure.

Figure 2: Structure diagram of light space manipulator.
The compensation term in the formula is shown in the following formula:

\[ \Omega(i + 1) = \Omega(i) + \eta \frac{f_d(i + 1) - f(i + 1)}{b}, \]  
\[ 0 < \eta < \frac{T_B}{T_B + m}. \]  

Equations (1) and (4) contain discrete compensation terms. The theoretical analysis is difficult, and it can only be solved by iteration, and the solution error is relatively large. Now derive the two compensation terms, assuming that the period is infinitely small, based on the differential theory, we can get the following:

\[ \begin{align*}
\Omega(i + 1) & = \Omega(i) + \frac{f_d(i + 1) - f(i + 1)}{k} \\
\Omega(i + 1) & = \Omega(i) + \frac{f_d(i + 1) - f(i + 1)}{b}
\end{align*} \]

Bring (7) into (2) and (5), the following formula can be obtained:

\[ \begin{align*}
m(\ddot{x} - \ddot{x_d}) + b(\dot{x} - \dot{x_d}) + k(x - x_d) &= f - f_d + \eta \int_0^t (f - f_d)dt, \\
m(\ddot{x} - \ddot{x_d}) + b(\dot{x} - \dot{x_d}) &= f - f_d + \eta \int_0^t (f - f_d)dt.
\end{align*} \]

Based on the above derivation and extended from single degree of freedom to 6 degrees of freedom, a new adaptive impedance expression (9) is obtained, and its control block diagram is shown in Figure 3, where \( K_i \) is the force error integral coefficient; \( X_i \) is the modified outer loop control law.

\[ M(X_i - \dot{X_i}) + B(X_i - \dot{X_i}) + K(X_i - X_d) = F - F_d + K_i \int_0^t (F - F_d)dt. \]

As shown in Figure 3, we consider the impact of input saturation, and define the saturation function as shown below.

\[ \text{sat}(u) = \begin{cases} 
\text{sign}(u)|u_M|, & |u| \geq |u_M|, \\
u, & |u| \leq |u_M|,
\end{cases} \]

\[ u = F - F_d + K_i \frac{\int_0^t (F - F_d)dt}{s}, \]

where \( u_M \) is the saturation bound of \( u \).

Equation (9) can be regarded as the proportional integral control of the force error, and the steady-state error is eliminated by the integral term. Compared with the traditional adaptive admittance control algorithm, the integral adaptive admittance control algorithm does not include the discrete compensation term and is a third-order linear system. The steady-state and dynamic performance of the integral adap-

Through hyperbolic transformation, you can get the following:

\[ \begin{align*}
H(z) &= E_x(z) \\
E_y(z) &= E_f(z)
\end{align*} \]

In Equation (9), the single degree of freedom Laplace transform is as follows:

\[ (ms^2 + bs + k)E_x = \left(1 + k_i \frac{1}{s}\right)E_f \Rightarrow H(s) = \frac{E_x}{E_f} = \frac{1}{s + k_i}. \]
The discrete difference expression for obtaining the correction is as follows:

$$
e_\alpha(k) = \frac{T^2}{2\Delta t} \left[ b_0 e_\alpha(k) + b_1 e_\alpha(k-1) + b_2 e_\alpha(k-2) + b_3 e_\alpha(k-3) \right] - \frac{1}{a_0} (a_1 e_\alpha(k-1) + a_2 e_\alpha(k-2) + a_3 e_\alpha(k-3)).$$

(14)

According to Figure 3, it can be seen that the input of the position inner loop control is the deviation of the corrected joint angle ($\theta_\alpha$) and the actual output angle ($\theta$) of the robot. The output of the position inner loop control is the current joint angle of the robot system. According to the above deviation, the motor controller of each joint in the robot is based on the position loop PID control to make each joint of the robot reach the desired joint position, so as to realize the impedance inner loop control.

In order to facilitate parameter selection and theoretical analysis, only the outer loop of admittance control is considered. The above control block diagram is simplified as a control system with expected force as input, actual force as output, and the difference between the expected position and the environmental position as a disturbance. This article makes the following assumptions:

1. The robotic arm is an ideal robotic arm, which can achieve perfect tracking of a given position: $X = X_r$
2. The difference between the expected position and the static position of the environment is regarded as a disturbance term: $N = X_e - X_d$
3. The mechanical arm can be replaced with a spring model for the environment

$$F = K_e(X_e - X),$$

(15)

where $X$ is the actual position of the end effector of the robotic arm, $X_r$ is the resting position of the environment, $F$ is the force exerted by the robotic arm on the environment, and $K_e$ is the equivalent stiffness of the environment and the robotic arm.

Based on the above assumptions, the outer loop of the integral adaptive admittance control can be regarded as an independent control system whose input is the desired force $F_d$ and the output is $F$. The control block diagram is shown in Figure 4.

The environment is assumed to be a spring model. After the simplified system, the relationship between single degree of freedom output and input and disturbance is as follows:

$$F = \frac{k_e(s + k)}{ms^3 + bs^2 + (k + k_e)s + k_k_e} F_d$$

$$+ \frac{k_e(s + k)}{ms^3 + bs^2 + (k + k_e)s + k_k_e} N.$$

(16)

When only considering the relationship between the expected input force and the output force, the closed-loop transmission formula is as follows:

$$G_b^f = \frac{F}{F_d} = \frac{k_e(s + k)}{ms^3 + bs^2 + (k + k_e)s + k_k_e}. $$

(17)

When only considering the relationship between disturbance and output force, the closed-loop transmission formula is as follows:

$$G_b^n = \frac{F}{N} = \frac{k_e(s + k)}{ms^3 + bs^2 + (k + k_e)s + k_k_e}. $$

(18)

It can be seen from formula (16) that the simplified system is a third-order linear system, and the Routh criterion can be used to analyze its stability directly, without using the Lyapunov function to find its stability. Since the parameters of the system are all diagonal matrices, only one degree of freedom of the system can be considered. The characteristic
equation of the closed-loop function of the system is as follows:

\[ D(s) = ms^3 + bs^2 + (k + k_3)s + k_1k_2. \]  \hspace{1cm} (19)

Since the impedance parameters \( m, b, \) and \( k \) and the environmental stiffness parameter \( k_e \) are nonnegative, the necessary and sufficient condition of the criterion is established. The necessary and sufficient condition of the criterion is that the first column of the Routh matrix is greater than zero. Find the first column of the Routh matrix:

\[
\begin{align*}
  a_1 &= m, \\
  a_2 &= b, \\
  a_3 &= \frac{b(k + k_e) - mk_1k_2}{b}.
\end{align*}
\]  \hspace{1cm} (20)

Since \( a_3 > 0 \), the value range of \( k_1 \) can be obtained.

\[ 0 < k_1 < \frac{b(k + k_e)}{mk_e}. \]  \hspace{1cm} (21)

For a rigid environment, the environment stiffness \( k_e \) is much greater than the impedance stiffness \( k \), and the following formula can be obtained:

\[ 0 < k_1 < \frac{b}{m}. \]  \hspace{1cm} (22)

It can be seen from Equations (20) and (22) that as long as the appropriate value of \( k_1 \) is selected, the integral adaptive admittance control system can remain stable. It can be seen from formulas (8) and (9) that the integral parameter in the integral adaptive admittance control is the same as the update rate parameter of the adaptive admittance control in the reference \( k_1 = \eta \), but because the traditional adaptive admittance control includes discrete compensation items, it is impossible to use a more accurate solution method, and its value range is \( 0 < \eta < 1 \). After adopting integral adaptive admittance control, the value range of the integral parameter is \( 0 < k_1 < b/m \), so the stability of integral adaptive admittance control is better.

In order to study the influence of integral adaptive admittance control parameters, this paper selects a set of parameters \( m = 1, b = 200, k = 1000, k_1 = 5, \) and \( k_e = 27000 \) as fixed quantities. When analyzing the influence of one of the parameters, the other parameters are, respectively, fixed values.

Select a set of values and draw the desired force step response graph to study the influence of each parameter. As shown in Figure 5, as the inertia parameter \( m \) increases, the overshoot increases and the response slows down, so the inertia parameter usually chooses \( m = 1 \). As the damping parameter \( b \) increases, the overshoot decreases and the response slows down, so the damping parameter is usually selected as \( b = 200 \). As the admittance stiffness parameter \( k \) increases, the response speed will be slowed down. Therefore, in the constant force control, if the admittance stiffness parameter is set to \( k = 0 \), the dynamic response performance will be better. The integral term mainly affects the fast response of power tracking, but as the integral parameter \( k_i \) increases, the overshoot increases obviously. Generally, 1 to 10 are more appropriate.

In order to study the influence of the environment and the equivalent stiffness parameters of the manipulator, this paper selects a set of equivalent stiffness parameter \( k_e \) and obtains the desired force unit step response diagrams, respectively. The response diagrams are shown in Figure 5(e), which can be seen. The smaller the equivalent stiffness of the environment and the robotic arm, the slower the response. As the equivalent stiffness increases, the system response speeds up and the overshoot increases. The equivalent stiffness of the environment and the robot cannot be changed, so it is necessary to adjust the 4 parameters of the integral self-adaptation to match the environment and achieve the best response control.

4. Simulation of Integral Adaptive Admittance Control

The simulation is carried out with conditions similar to the actual control, the environment is replaced by a spring model, and a changeable curved surface environment is designed to study the rapid response. The environmental stiffness is set to pass the actual measured value of the equivalent stiffness, the feedback force is added with random ±0.2 N noise, and the noise-contaminated data is restored through a low-pass filter. The simulation block diagram is shown in Figure 6.

This article only considers a single degree of freedom, the force controls the \( z \)-axis direction, the \( y \)-direction is a constant value, and the \( x \)-axis direction is a linear motion.
Figure 5: The relationship between system step response and various parameters. (a) Influence of inertial parameters. (b) Influence of damping parameters. (c) Influence of stiffness parameters. (d) Influence of the integral term. (e) Influence of environmental stiffness.
Set the sine function in the axis direction environment to simulate the robot arm walking in a straight line in an unknown environment. Set the environment as shown in the curve shown in Figure 7(a), the first 10 s is a fixed position, the last 20 s is the position of sinusoidal change, there is a sudden change in environmental curvature at 10 s, the
expected force is the curve shown in Figure 7(b), the first 10 s is a fifth-degree polynomial smooth loading force, and maintain constant force after 20 s. Respectively, verify the effect of fixed environmental force tracking, the robustness of curvature mutation, and the constant force tracking effect of unknown environment.

Assuming $k_e = 27000$ N/m, using the second expression of traditional adaptive admittance control, set the admittance parameters $m = 0.4$, $b = 60$, $k = 0$, and $\eta = 0.5$, and the force tracking obtained after simulation is shown in Figure 8. It can be seen that the response is too slow to quickly track the changing environment.

Using the integral adaptive admittance control method proposed in this paper, set the admittance parameters $m = 0.4$, $b = 60$, $k = 0$, and $\eta = 0.5$, and the force tracking obtained after simulation is shown in Figure 10. It can be seen that the response is too slow to quickly track the changing environment.

![Figure 9: Integral adaptive admittance control force tracking diagram. (a) Tracking force. (b) Tracking force error.](image)

![Figure 10: Integral adaptive admittance control fixed-point force tracking experiment. (a) Tracking force. (b) Tracking force error.](image)

![Figure 11: Constant force tracking experiment on unknown surface.](image)
m = 1, b = 300, k = 0, and k_i = 20, and the force control curve is shown in Figure 9. In the fixed-point constant force tracking stage, the force curve can be perfectly tracked. When t = 10 s, the environmental curvature has a sudden change. Compared with the traditional adaptive admittance, through the integral adaptive admittance control, the mechanical arm converges faster after a sudden change in force. In an unknown curved surface environment with continuous curvature, the environment fluctuates within ±10 mm, but the robotic arm can still track the environment well, keeping the tracking force error at ±0.1 N, and the tracking effect is good.

Comparing integral adaptive admittance and traditional adaptive admittance control, it can be seen that they can track well when the expected force changes at a fixed position. However, when the environmental curvature is abrupt or the frequency of environmental position changes is high, the effect of integral adaptive admittance control is obviously better than that of traditional adaptive admittance control.

5. Experiments and Results

The purpose of the fixed-point force tracking experiment is to study whether the integral adaptation can track the expected force of the transformation. Using integral adaptive admittance control, only the z-axis direction is considered, given control parameters m = 1, b = 300, and k = 0 and desired joint angle = [0°, 60°, 0°, 60°, 60°, 0°]. The expected force \( f_d = -10 + 10 \cos(0.4\pi t) \), and the expected force and the tracking force are shown in Figure 10(a). The actual tracking force contains high-frequency noise. In this paper, a finite impulse response FIR filter is used to filter high-frequency noise. The filters in the following text all use this filter. The difference between the expected force and the actual contact force is used to obtain the tracking force error as shown in Figure 10(b). The tracking error is ±0.8 N, and the tracking effect is good.

Using the integral adaptive admittance control method proposed in this paper can solve complex practical problems, such as surface polishing. In the past, constant force control mostly focused on constant force control in a flat environment. For the constant force control of a plane, the direction of the control force is constant, but for a curved surface in an unknown environment, its normal vector is often changed in real time, so the traditional method will fail. In order to overcome this difficulty, the paper proposes integral adaptive admittance control can realize real-time correction of the desired position of the end of the manipulator, so that it is in full contact, and realizes constant force control. Traditional admittance can convert force error to position error and correct a certain amount of error between the expected position and the environment, but the correction range is limited, and it will produce a steady-state error of force control. The integral adaptive admittance control in this paper can be used for constant force control when the environment position is unknown. The integral term eliminates the steady-state error of force control and continuously corrects the desired position to make it contact with the surface. The experimental scene is shown in Figure 11. An unknown curved surface is placed on the optical platform, the end of the robotic arm is moved to the small plane on the left, and the fixed-point constant force control is used to make the robotic arm reach a stable constant force and then start to walk a straight line to the right (the given desired position is a straight line). The given desired position and desired force are shown in Figure 12. Through the integral adaptive admittance control, real-time correction of the desired position of the end of the manipulator is realized, so that it is in contact with the surface, and constant force control is realized.
The integral adaptive admittance control parameters are set to $m = 1$, $b = 300$, $k = 0$, and $k_i = 5$, and the actual tracking effect is shown in Figure 13. Due to the high-frequency force in the acquisition process, in order to obtain the original signal, this paper uses a finite impulse response filter (FIR) to filter the data. In the unknown surface stage, the error is expected to be within $\pm 0.8$ N and the tracking effect is good.

6. Discussion

In this paper, a lightweight space manipulator is developed, which has the characteristics of compact structure and high load-to-weight ratio. In addition, an integral adaptive compliance control method is proposed, and the adaptive admittance system is expressed as a third-order linear system. It solves the shortcomings of traditional admittance control with steady-state errors and adaptive environment changes and overcomes the nonlinear problems caused by the traditional adaptive admittance discrete compensation term. Integral adaptive admittance control can be converted to frequency domain by Laplace to analyze control performance and can be converted to z-function by hyperbolic to obtain differential expression and improve calculation accuracy. Finally, the integral adaptive admittance control experiment was completed, and a good force tracking effect was obtained. Based on the current research results, we will conduct research on robot force perception and compliance control methods in human-robot collaboration and dual-arm (or multiarm) coordination and compliance control algorithms in the future.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

This work was supported by the Key Research and Development Program of Guangdong Province (2019B090915001) and the Basic Research Program of Shenzhen (JSGG2020 0103103401723, JCYJ20190806142818365, and JCYJ2018 0507183610564).

Supplementary Materials

Integral adaptive admittance control has adaptability to unknown environments. The white board in the video is a 3D printed surface. The motion trajectory of the robot arm is a straight line trajectory from left to right in the plane. The expected contact force is 5 N. The obtained tracking force error is shown in Figure 13(b), and the error force is $\pm 0.8$ N. (Supplementary Materials)

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