A Novel Constant Damping and High Stiffness Control Method for Flexible Space Manipulators Using Luenberger State Observer

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Abstract: This paper presents a novel control strategy for transferring large inertia loads using flexible space manipulators in orbit. The proposed strategy employs a Luenberger state observer and damping-stiffness controller to address issues of large tracking error and vibration. A comprehensive joint dynamics model is developed to identify the main sources of disturbance, and a Luenberger state observer is designed to estimate unmeasurable transmission deformation. Transmission stiffness and load inertia perturbations are identified based on the estimated results. By adjusting velocity damping and the gain of the forward channel, perturbations are suppressed to maintain optimal system damping and stiffness. Simulation and physical experiments demonstrate the effectiveness of the algorithm, with simulation experiments showing smoother joint output characteristics and minimal vibration under large load inertia changes, and a 97% reduction in internal deformation. Physical experiments demonstrate improved joint dynamic command tracking performance, with an 88% reduction in position tracking error. The algorithm provides a practical and efficient approach for transferring large inertia scientific payloads in space.

Keywords: space manipulator; flexible joint; dynamic; Luenberger observer; automatic control

1. Introduction

The space manipulator is a powerful tool for on-orbit space services due to its large working range, high positioning accuracy, and strong load capacity [1]. However, the joint—a key component of the space manipulator—shows obvious flexibility characteristics due to the application of harmonic reducers that increase output torque. During the transfer of a target object for a science experiment in orbit, nonlinear changes in the transmission stiffness of the joint harmonic reducer and the load inertia can cause perturbations in the dynamic model, leading to out-of-tolerance joint trajectory tracking and flexible vibration, as shown in Figure 1. Reducing motion speed and modal analysis have been used to avoid violent flexible vibration of the space manipulator. In addition, the dynamic control of flexible joints is a point of difficulty in the control of exoskeleton robots, medical robots, and other equipment that are in direct contact with the human body. Therefore, the high-performance control of flexible joint robots has always been a research hotspot in the industry [2].
1.1. Related Works

Scholars have proposed various control strategies, such as full-state feedback control (FSFB), backstep control, compensation control based on state observer, synovial membrane control, and neural network control, to address the motion control of flexible joints with nonlinear time-varying load inertia [3–5]. The backstep method compensates for the interference of the contained severe uncertainty by building a state feedback controller [6]. The state observer is capable of compensating for model disturbances and thereby reducing their impact on joint control. Jian Li, for a class of uncertain flexible joint robots with variable stiffness actuators (VSAs), explicitly constructed a state feedback controller through backstepping and disturbance learning mechanism [7], and designed a key switching mechanism to adjust online parameters in the controller, which achieved good control effect. However, when the order of the controlled system is high, the calculation of the partial derivative of the virtual control quantity will have the disadvantage of differential explosion [8], which is not suitable for space occasions with limited computing resources [9]. The FSFB method has a simple structure and a small calculation amount; however, due to the general effect on the flexible time-varying inertial control system, the flexible vibration phenomenon occurs easily when the gain is large [10–12]. Feedback linearization control is an effective means to solve the nonlinear links in the control system; however, this method relies on high-precision mathematical models, and the control effect is greatly reduced once the model is biased [12]. The synovial membrane controller has the characteristics of fast response and strong robustness to disturbances. However, when the state trajectory reaches the sliding modal plane, it does not easily slide strictly along the sliding mode towards the equilibrium point. Rather, it crosses back and forth on both sides to approach the equilibrium point, resulting in jitter [13]. The intelligent algorithm based on a neural network also has the problem of excessive computation and is difficult to apply in space engineering [14].

The state observer can compensate the model to reduce the impact of model disturbance on the control system, and there is no differential explosion problem. Z. Bowen et al. propose an accurate estimation of the uncertainty of the velocity state of the manipulator and the stiffness of the joint by the Extended State Observer (ESO) [15]. M. J. Kim et al. use the inverse method to generate adaptive controllers, in which dynamic uncertainty is compensated for by a radial basis function neural network (RBFNN) and joint-stiffness uncertainty is eliminated by ESO estimation. The articulated motor side interference ob-
server is proposed and fed back to the proportion differential controller, which, in turn, introduces a nominally stable controller input [16]. A. Fagiolini et al. achieve linear state observation of the plastic deformation of the flexible joint reducer by measuring the joint and motor position [17]. L. Dou et al. propose a terminal sliding mode control (TSMC) strategy based on fuzzy interference observer to target liquid shaking interference of a flexible liquid-filled spacecraft [18]. C. Pan et al. design a state observer for single-degree-of-freedom flexible joint manipulator disturbance to compensate for interference, turning the nonlinear system into a linear integral sequence system [19]. Y. Lin et al. propose a linear expansion state observer for industrial robotic arms to estimate joint flexibility and torque [20]. Yong Nie developed two low-order extended state observers to handle the external load force and the impact of the pressure compensator in a high-order nonlinear hydraulic system. Additionally, backstepping methods were designed to ensure robust stability of the system [21]. Due to the difficulty of modeling nonlinear and flexible environments, some scholars propose the use of artificial neural networks to control the flexible joints [22–25], and W. Quanwei et al. propose a new neural network based on a disturbance observer-based integrated sliding mode controller that is only numerically simulated [26]. However, the state observer method can only realize the estimation of the internal state of the model, and must be combined with other closed-loop control methods to build a stable control system. Therefore, it is very important to choose a suitable observer and control strategy.

1.2. Motivations and Contributions

This paper investigates and proposes a new high-performance tracking control method for flexible space manipulator joints with a simple model structure, moderate calculation requirements, and practical applications. This method maintains the damping and stiffness of the control system at the desired state, despite simultaneous disturbances from external load inertia and internal transmission stiffness in the joint. To achieve this, the paper designs a Luenberger state observer to estimate the internal flexible deformation of the joint reducer and observe real-time transmission stiffness and load inertia. By simplifying the model, the paper analyzes the influence of parameter changes on the control characteristics, improving on traditional three-loop feedback control algorithms that are sensitive to changes in model parameters. The paper introduces speed dampers and feed-forward gain regulators to keep the damping and stiffness of the flexible joint control system at the desired state, Henceforth, this strategy is referred to as Constant Damping and High Stiffness (CDHS) algorithm. Thereby improving the joint control system’s robustness and the ability of the flexible space manipulator to transfer large-inertia scientific payloads in orbit. The paper’s contributions to the control of flexible space manipulators include:

- A comprehensive state-space dynamic modeling method for flexible joints is proposed, and the perturbation parameters of the flexible joint model are comprehensively analyzed.
- A Luenberger state observer [27] based on the joint dynamics model is constructed, which enables the accurate estimation of the internal flexible deformation of a joint that cannot be directly measured.
- The dynamic identification of joint transmission stiffness and external inertia is realized according to the estimated value of joint flexible deformation and joint physical motion characteristics.
- A control algorithm for flexible joints with constant damping and high stiffness is proposed, based on a dual-adjustment mechanism of speed damping and feed-forward gain. The algorithm is proposed and its effectiveness is verified by simulation experiments and physical experiments.

The remainder of this paper is organized as follows: In Section 2, we present the problem formulation and the comprehensive joint dynamics model. Section 3 describes the design of the CDHS controller with a Luenberger observer. In Section 4, we compare and
discuss the simulation results and physical experiment results. Finally, Section 5 contains the conclusions of this study.

2. Dynamic Modeling of Flexible Joints

Due to the limitations of space transportation and the usage environment, space manipulators are longer but lighter in weight compared to industrial manipulators, resulting in significantly lower structural rigidity [28]. The flexible space manipulator studied in this paper is illustrated in Figure 2a. It has an arm length of approximately 3300 mm, with a weight of only 60 kg. The joint structure of the manipulator, as shown in Figure 2b, is driven by a brushless DC motor with a harmonic reducer as the transmission part. Both the motor and the output shafts of the reducer are equipped with position sensors. The reducer has the lowest stiffness among the manipulator’s components. Hence, this paper only considers the flexibility of the space manipulator caused by the joint harmonic reducer while disregarding other factors.

![Developed space manipulator](image)

**Figure 2.** Developed space manipulator. (a) Prototype; (b) Model of the flexible joint.

*Full-Elements Joint Dynamics Model*

The flexible joint of the space manipulator is composed of several components, including the motor, motor position sensor, joint position sensor, and harmonic reducer, as shown in Figure 2b. To simplify the engineering analysis, the model is divided into three parts: the motor unit, transmission unit, and output unit, as depicted in Figure 3. The inertia and damping of the motor position sensor and its associated structure are included in the motor unit, while the inertia and damping of the output position sensor and its subsidiary structure are included in the output unit. The equivalent inertias and damping of the joint unit, transmission unit, and output unit are denoted by \( I_m, I_g, I_l \), and \( d_m, d_g, d_l \), respectively. The rotation angles are \( q_m, q_g, q_l \), and the moments are \( \tau_m, \tau_g, \tau_l \). Additionally, to account for the stiffness and damping characteristics of the output shaft and reducer, an ideal torsion spring-damping link is introduced between the motor unit and the transmission unit and between the transmission unit and the output unit. The equivalent stiffness and damping between the motor unit and the transmission unit are denoted by \( k_g \) and \( d_{mg} \), respectively, while the equivalent stiffness and damping between the transmission unit and the output unit are denoted by \( k_g \) and \( d_{gL} \), respectively.
The dynamics model of the flexible joint consists of two parts: an electrical model and a mechanical model. The electrical model describes the characteristics of motor current input and torque output, while the mechanical model describes the characteristics of motor torque input and joint load torque output, which is further divided into linear and nonlinear parts. The dynamic model of the flexible joint can be described as follows:

\[ \tau = Kq + Dq + Iq \]  \hspace{1cm} (1)

\[ q = [q_m, q_g, q_l] \]  \hspace{1cm} (2)

The joint stiffness matrix \( K \), the inertia matrix \( I \), and the damping matrix \( D \) are defined as follows:

\[ K = \begin{bmatrix} k_g & -k_g & 0 \\ -k_g & k_g + k_b & -k_b \\ 0 & -k_b & k_b \end{bmatrix} \]  \hspace{1cm} (3)

\[ I = \begin{bmatrix} I_m & 0 & 0 \\ 0 & I_g & 0 \\ 0 & 0 & I_l \end{bmatrix} \]  \hspace{1cm} (4)

\[ D = \begin{bmatrix} d_m + d_{mg} & -d_{mg} & 0 \\ -d_{mg} & d_g + d_{mg} + d_{gl} & -d_{gl} \\ 0 & -d_{gl} & d_l + d_{gl} \end{bmatrix} \]  \hspace{1cm} (5)

The nonlinear part of joint dynamics mainly includes joint viscous friction \( f_{vis} \) and coulomb friction \( f_{coul} \).

\[ f_{vis} = [0, 0, 0, d_{mn} - d_m, d_{gn} - d_g, d_{ln} - d_l] q^T \]  \hspace{1cm} (6)

\[ f_{coul} = \frac{e^{k_d} - e^{-k_d}}{e^{k_d} + e^{-k_d}} q^T \]  \hspace{1cm} (7)

\[ k_d = [0, 0, 0, d_m, d_g, d_l] \]  \hspace{1cm} (8)

According to the dynamic model, the flexible joint of a space manipulator is a dynamic system of multi-variable inputs and outputs, and the joint dynamics model shown in Figure 4 is established by the state space method. In order to clarify the physical meaning of the model, the position and velocity of the joint motor unit, transmission unit, and output unit are selected as the state vector \( X \).
Figure 4. State space model of flexible joint.

The input vectors of the state-space model are the motor torque and the total output torque.

\[
U_f = \begin{bmatrix} \tau_m & \tau_l \end{bmatrix}^T
\]

(12)

The joint model state transformation matrix \( A_f \), input matrix \( B_f \), and output matrix \( C_f \) are, respectively:

\[
A_f = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
-k_g l_k & -k_g l_k & 0 & -d_{mg} d_m & d_{mg} d_m & 0 \\
-k_g l_k & -k_g l_k & 0 & d_{mg} d_m & -d_{mg} d_m & 0 \\
0 & 0 & 0 & 0 & d_{lg} l_l & -d_{lg} l_l
\end{bmatrix}
\]

(13)

\[
B_f = \begin{bmatrix}
0 & 0 & \frac{1}{m} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{l}
\end{bmatrix}
\]

(14)

\[
C_f = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

(15)

3. CDHS Controller with Luenberger Observer

3.1. Structure of CDHS

Based on the analysis of Equation (9), the disturbances of the dynamic model of the flexible joint of the space manipulator are primarily caused by changes in internal parameters, such as the load inertia disturbance \( l_l \) caused by manipulator configuration changes, the stiffness disturbances \( k_g \) and \( k_{gl} \) resulting from harmonic reducer stiffness...
changes, and the friction coefficient. Additionally, there is a nonlinear damping disturbance caused by changes in \( d_m \) and \( d_g \). While the position–speed–current (torque) three-loop feedback control algorithm utilized in transmission flexible joint control can adapt to nonlinear disturbances caused by friction changes, significant changes in load inertia and transmission stiffness can result in significantly worse control characteristics, larger tracking errors of motion trajectory, and flexible joint vibrations [29].

The constant damping and high stiffness control algorithm proposed in this paper is based on the three-loop feedback control algorithm, and addresses the limitation that the latter cannot handle time-varying loads with large inertia and flexibility [30,31]. To overcome this, we incorporate a system-stiffness controller and a system-damping controller to mitigate perturbations caused by changes in joint inertia and transmission stiffness, thus ensuring that the damping and stiffness parameters of the flexible joint dynamics control system are always maintained in the desired state. The schematic diagram of the constant damping–high stiffness controller is presented in Figure 5 to illustrate its design and implementation for achieving high quality control performance.

![Figure 5. The structure of CDHS controller.](image)

### 3.2. The Luenberger Observer

The flexible deformation of the joint harmonic reducer is the most sensitive component that reacts to changes in joint stiffness and external load inertia. However, due to the reliability requirements of the space environment, a sensor for detecting harmonic deformation cannot be installed inside the joint. Instead, the working state of the internal transmission mechanism of the joint can be estimated through a state observer [32]. In this paper, a Luenberger state observer is constructed based on the joint dynamics model. The specific calculation process is as follows:

Take the reducer position \( q_g \) and the reducer speed \( \dot{q}_g \) as the state observation vector \( x \), and take the motor position \( q_m \), motor speed \( \dot{q}_m \), motor acceleration \( \ddot{q}_m \), joint output position \( \dot{q}_l \), and joint output speed \( \dot{q}_l \) that can be directly measured as the input vector \( U \).

\[
X = \begin{bmatrix} q_g \ \\ \dot{q}_g \end{bmatrix}^T
\]

\[
U = \begin{bmatrix} q_m \\
\dot{q}_m \\
\ddot{q}_m \\
\dot{q}_l \\
\dot{q}_l \end{bmatrix}
\]
According to the joint dynamics state space model Formula (5), the following formula is obtained.

\[ \dot{x}_1 = x_2 \]  

\[ \dot{x}_2 = -\frac{k_g + k_b}{I_g} x_1 - \frac{d_{mg} + d_{gl} + d_g}{I_g} x_2 + B U \]

\[ Y = -k_g x_1 - d_{mg} x_2 + D U \]

where \( B \) and \( D \) are the coefficients corresponding to the state observer.

\[ B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ k_g \frac{l_e}{I_g} & k_b \frac{l_e}{I_g} & 0 & 0 & 0 \end{bmatrix} \]  

\[ D = \begin{bmatrix} k_g \frac{l_e}{I_g} \\ d_{mg} \\ d_m \\ 0 \\ I_m \end{bmatrix} \]

Define a Luenberger state observer based on the above calculation.

\[ \begin{cases} \dot{X} = AX + Bu_q + L(y - Cx) \\ Y = CX + DU \end{cases} \]

\[ A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{k_g + k_b}{I_g} & -\frac{d_{mg} + d_{gl} + d_g}{I_g} & 0 & 0 & 0 \end{bmatrix} \]

\[ C = \begin{bmatrix} -k_g \\ -d_{mg} \end{bmatrix} \]

Let the estimation error be \( e = x - \hat{x} \). Then, the observation error dynamic equation is as follows:

\[ \dot{e} = (A - LC)e \]

The characteristic state equation of the system is as follows:

\[ |\lambda I - (A - LC)| = 0 \]

\[ L = \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} \]

\[ \lambda^2 + \left( k_g + \frac{(1 + I_g)d_{mg} + d_g + d_{gl}}{I_g} \right) \lambda + \frac{(1 + I_g + d_g + d_{gl})k_g + k_b(1 - d_{mg})d_g}{I_g} = 0 \]

The characteristic equation of the state observer is calculated to obtain \( \lambda_1 \) and \( \lambda_2 \), and then the estimated value \( \hat{x} \) of the state observation vector \( x \) is calculated in real-time according to Equation (29).

3.3. CDHS Control Layer

3.3.1. Realtime Stiffness and Load Inertia Identification

The real-time load inertia and real-time stiffness of the joint are identified according to the estimated value of the joint’s flexible deformation by the observer. The equivalent stiffness \( k_g \) on the input side of the motor is related to the position \( q_m \) of the motor and the position \( q_g \) of the reducer, and the equivalent stiffness \( k_{gl} \) on the output side of the
The joint real-time stiffness $k_t$ is determined by the series connection of two elastic links, and the estimated value of the stiffness $\hat{k}_{gl}$ is calculated as follows:

$$\hat{k}_{gl} = \frac{\hat{k}_g \times \hat{k}_{gl}}{\hat{k}_g + \hat{k}_{gl}}$$ (31)

The real-time load inertia of the joint is determined by the quotient of the joint output load moment and the load acceleration. The calculation formula is as follows:

$$\hat{J}_l = \frac{k_{gl}(\hat{x}_1 - U_2) + d_{gl}(\hat{x}_2 - U_4)}{\dot{q}_l}$$ (32)

3.3.2. CDHS Controller

Due to the limited computing power of the processor used in a space manipulator, a simplified model must be used. Given that the stiffness of the joint’s output unit is significantly greater than that of the transmission unit, the stiffness and damping of the output and transmission units can be combined. Assuming constant joint transmission stiffness and only considering viscous friction, the joint’s dynamic equation can be simplified to a transfer function model, where the motor input angle is $\theta_i$, the joint output angle is $\theta_o$, the joint equivalent stiffness is $k_t$, the equivalent inertia is $J_t$, and the viscous friction system is $f$. The transfer function model is as follows:

$$\theta_o(s) = \frac{k_t}{J_t s^2 + f s + k_t}$$ (33)

The undamped oscillation frequency $\omega_n$ and damping ratio $\xi$ of the system can be calculated using the following equations:

$$\omega_n = \sqrt{\frac{k_t}{J_t}} \xi = \frac{f}{2 \sqrt{J_t k_t}}$$ (34)

According to the above formula, it can be observed that an increase in load inertia leads to a decrease in system damping and a decrease in undamped oscillation frequency, which may result in joint motion overshoot or instability. To address this issue, a closed-loop damping control system is introduced via speed damping feedback, and a position variable gain controller is added to adjust the closed-loop stiffness of the system. Here, $k_1$ represents the position control gain, $k_s$ represents the damping control gain, and the transfer function of the joint closed-loop control system is as follows:

$$\theta_o(s) = \frac{k_1 k_s}{J_t s^2 + f s + k_t}$$ (35)

The new system undamped oscillation frequency $\omega_n$ and system damping $\xi$ are calculated as follows:

$$\omega_n = \sqrt{\frac{k_1 k_s}{J_t}} \xi = \frac{f}{2 \sqrt{J_t k_t k_1}} + \frac{k_s}{2} \sqrt{\frac{k_1 k_s}{J_t}}$$ (36)

The above formula shows that the speed damping feedback introduces an additional term of $\frac{k_s}{2} \sqrt{\frac{k_1 k_s}{J_t}}$ compared to the original system. By setting a desired reference inertia
For the joint, the speed damping feedback coefficient $k_s$ can be adjusted to maintain a constant closed-loop damping of the joint.

$$k_s = \frac{f}{k_t k_1} \left( \sqrt{\frac{f}{I_{\text{exp}}} - 1} \right)$$  \hspace{1cm} (37)

In the same way, changing the position gain $k_1$ can make the system undamped oscillation frequency $\omega_n$ stable at the expected value $\omega_{n\text{exp}}$.

$$k_1 = \frac{\hat{I}_t \times \omega_{n\text{exp}}^2}{\hat{k}_t}$$  \hspace{1cm} (38)

4. Experiments and Analysis

The flexible joint used in the experiment is the self-developed manipulator joint module with a rated output torque of 40 N.m and a self-weight of 3.5 kg. The motor of the joint has six pairs of poles, and the coil resistance $r$, coil inductance $L_q$, and Torque constant $k_t$ are shown in Table 1. The joint is equipped with various sensors, including a motor resolver, joint angular position sensor, joint angular velocity sensor, and harmonic end resolver (output position sensor). The main characteristic parameters of the joint are shown in Table 1.

<table>
<thead>
<tr>
<th>$m$ [kg]</th>
<th>$I_m$ [kg·m²]</th>
<th>$I_l$ [kg·m²]</th>
<th>$d_m$ [N·s/m]</th>
<th>$d_g$ [N·s/m]</th>
<th>$d_l$ [N·s/m]</th>
<th>$k_g$ [N·s/rad]</th>
<th>$L_q$ [H]</th>
<th>$R$ [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.23</td>
<td>0.0717</td>
<td>0.0036</td>
<td>0.002</td>
<td>0.0003</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{mg}$ [N·s/m]</td>
<td>$d_{gl}$ [N·s/m]</td>
<td>$P$ [pairs]</td>
<td>$k_b$ [Nm/rad]</td>
<td>$k_1$ [Nm/A]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.001</td>
<td>0.002</td>
<td>6</td>
<td>16,000</td>
<td>0.78</td>
<td>0.002</td>
<td>15.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1. The Simulation Experiment

To verify the effectiveness of the high stiffness constant damping control algorithm, a comparative experiment was conducted between the traditional three-loop feedback controller and the CDHS controller using a typical excitation signal for fast track applications in orbit. The joint servo system was set to a sinusoidal signal with a frequency of 0.05 Hz and an amplitude of 0.1 rad, while the load inertia signal was set to a sinusoidal signal with a frequency of 0.01 Hz and an amplitude of 100 kg·m².

The position command tracking curve and position tracking error curve obtained using the traditional three-loop feedback controller are presented in Figures 6 and 7, respectively. The curves indicate the occurrence of flexible vibration when the algorithm is used to control the flexible joint to track the sinusoidal position command signal, particularly at the peak and trough of the signal. Notably, the algorithm fails to adapt to changes in joint stiffness. Additionally, the position tracking error curve reveals that the error in joint position at different times, such as 30 s and 50 s, is inconsistent. This indicates that the command tracking error is not solely dependent on the joint position but is also influenced by the load inertia, with the maximum error being $\pm 1.5^\circ$.

The position command tracking curve and position error curve of the CDHS algorithm are presented in Figures 8 and 9, respectively. As shown in the command tracking curve, the CDHS algorithm effectively eliminates flexible vibrations, indicating its ability to adapt to changes in joint stiffness. Furthermore, the position tracking error curve indicates that the command tracking error is consistent for the same joint position at different times, indicating that the algorithm is not affected by load inertia. The maximum error is only $\pm 0.5^\circ$, highlighting the improved tracking performance achieved by the CDHS algorithm. Figure 8 shows that the position feedback and the position command basically overlap when the joint tracks the position sinusoidal excitation signal. Figure 9 shows that the
position tracking error is also similar to a sinusoidal waveform, and the tracking error peak appears at the peak and trough commutation moments of the position command.

![Figure 6](image1.png)

**Figure 6.** Joint position command tracking curve using traditional three-loop feedback controller.

![Figure 7](image2.png)

**Figure 7.** Joint position tracking error curve using traditional three-loop feedback controller.

Figures 10 and 11 depict the flexible deformation curves of the joint reducer under the traditional three-loop feedback controller and CDHS controller, respectively. The curves indicate that the joint harmonic reducer is significantly affected by changes in load inertia under the three-loop feedback controller, resulting in noticeable fluctuations and a maximum deformation of ±0.05°. Conversely, the maximum deformation of the joint harmonic reducer under the CDHS controller is only ±0.004°, which is not comparable to the three-loop feedback controller; rather, it is reduced by an order of magnitude. This demonstrates the CDHS controller’s ability to achieve smooth transmission of the reducer under variable load conditions.
Figure 7. Joint position tracking error curve using traditional three-loop feedback controller.

The position command tracking curve and position error curve of the CDHS algorithm are presented in Figures 8 and 9, respectively. As shown in the command tracking curve, the CDHS algorithm effectively eliminates flexible vibrations, indicating its ability to adapt to changes in joint stiffness. Furthermore, the position tracking error curve indicates that the command tracking error is consistent for the same joint position at different times, indicating that the algorithm is not affected by load inertia. The maximum error is only ±0.5°, highlighting the improved tracking performance achieved by the CDHS algorithm.

Figure 8 shows that the position feedback and the position command basically overlap when the joint tracks the position sinusoidal excitation signal. Figure 9 shows that the position tracking error is also similar to a sinusoidal waveform, and the tracking error peak appears at the peak and trough commutation moments of the position command.

Figure 9. Joint position tracking error curve using CDHS controller.

Table 2 shows the statistics on the joint position tracking error and flexible deformation of the reducer as key indicators for evaluating the performance of the controller. The results show a big improvement in both indicators with the CDHS controller compared to the three-loop feedback controller. Specifically, the joint tracking error is reduced by 73.1% and the flexible deformation of the reducer is reduced by 97.9%. These results indicate that the CDHS controller improves the control accuracy and robustness of the joint system, particularly under variable load conditions.
In order to further validate the effectiveness of the control strategy, a physical test platform was constructed, as shown in Figure 12. The platform was used to simulate flexible joints controlling the displacement of large inertia target loads, with an inertia of about 10 kg·m². The platform was constructed, as shown in Figure 12. The platform was used to simulate variable load conditions.

### Table 2. Comparison of key indicators resulting from three-loop and CDHS controllers.

<table>
<thead>
<tr>
<th>Controller Method</th>
<th>Maximum Error/°</th>
<th>Average Error/°</th>
<th>Error Reduction Rate</th>
<th>Maximum Deformation/°</th>
<th>Average Deformation/°</th>
<th>Deformation Reduction Rate</th>
<th>Flexible Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-loop</td>
<td>±1.5</td>
<td>0.606</td>
<td>1</td>
<td>±0.05</td>
<td>0.019</td>
<td>1</td>
<td>Exist</td>
</tr>
<tr>
<td>CDHS</td>
<td>±0.5</td>
<td>0.163</td>
<td>73.1%</td>
<td>±0.004</td>
<td>0.0004</td>
<td>97.9%</td>
<td>None</td>
</tr>
</tbody>
</table>

**Figure 10.** The flexible deformation of harmonic reducer using three-loop feedback controller.

**Figure 11.** The flexible deformation of harmonic reducer using CDHS controller.

4.2. Physical Experiment

In order to further validate the effectiveness of the control strategy, a physical test platform was constructed, as shown in Figure 12. The platform was used to simulate
flexible joints controlling the displacement of large inertia target loads, with an inertia of about 100 kg·m². The joint driver utilized Altera’s FPGA A3PE300 as the core computing unit, which allowed for efficient operation of the algorithm through the parallel computing capability of the FPGA. The host computer sent continuous position commands with a period of 16 ms to the joint driver through the CAN bus. The joint driver then controlled the compliant joint to drive the simulated load to track the position command. The photoelectric encoder located between the joint and the load recorded the position response curve of the joint output.

Figure 12. Flexible joint experiment platform.

The joint position control performance of the three-loop feedback controller and the CDHS controller was compared on a physical test platform. The controllers were configured with the same control parameters and tested on the joint’s range of motion from −135° to −125°, with varying speeds. The highest speed was reached at 40 s, followed by a gradual reduction in speed until the joint stopped. The joint driver recorded the position tracking curves and error curves for both controllers. Figures 13–16 show the results for different controller and speed configurations.

Figure 13. Physical joint position command tracking curve using three-loop feedback controller.

Figure 14. Physical joint position tracking error curve using three-loop feedback controller.
sturbance and transmission stiffness disturbance. Then, we designed a disturbance compensation control strategy based on a simplified model that is convenient for engineering application, which maintains the joint control system’s desired damping and stiffness under internal and external disturbances and improves control quality. Finally, we compare the new algorithm with the traditional three-loop feedback controller. The position tracking curve indicates that the tracking error of the three-loop feedback controller is larger than that of the CDHS controller. When the three-loop feedback controller is in operation, the average errors in the high-speed and low-speed sections are $0.7^\circ$ and $0.5^\circ$, respectively. In contrast, the CDHS controller operating in the high-speed and low-speed sections has average errors of $0.08^\circ$ and $0.05^\circ$, respectively. The position command tracking errors of the CDHS controller in the high-speed section and low-speed section are reduced by 88.6% and 90%, respectively, compared to the three-loop feedback controller.

5. Conclusions and Future Work

During space scientific load position transfer control, the joint load inertia and transmission stiffness change nonlinearly due to the manipulator arm shape, leading to flexible deformation of the joint harmonic reducer and nonlinear variation in joint transmission stiffness. These changes perturb the joint dynamics model and affect the control system’s key parameters, resulting in decreased damping and stiffness, which increase joint position tracking error and flexible vibration. To address this issue, we first established a full-element flexible joint dynamic model and used a Luenberger state observer to estimate joint flexible deformation, which cannot be directly measured, and to identify joint load inertia disturbance and transmission stiffness disturbance. Then, we designed a disturbance compensation control strategy based on a simplified model that is convenient for engineering application, which maintains the joint control system’s desired damping and stiffness under internal and external disturbances and improves control quality. Finally, we...
compared the new algorithm with the traditional three-loop feedback controller through simulation and physical experiments. The results show that the CDHS algorithm has more stable motion characteristics than the three-loop feedback control algorithm, reducing the joint’s flexible deformation by 97% and improving joint dynamic tracking performance, with an 88% reduction in position tracking error. These results are consistent with the theoretical analysis.

In the future, experiments will be conducted on an air-bearing platform to validate the effectiveness of the algorithm in controlling the real load displacement of space manipulators in microgravity, especially in the presence of multi-joint coupling disturbances. The research and experiments on the constant damping and high stiffness control method of flexible space manipulators based on the Luenberger state observer have positive implications for the future of space manipulators. These implications include the ability to capture, transfer, and maintain large spacecraft in orbit, and the capability to perform on-orbit servicing missions with high precision and reliability. The findings of this research will serve as a valuable guide for the development of advanced space manipulator technologies and contribute to the progress of space exploration and technology.

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References
23. Yan, G.; Zhao, B. Analytical Solution and Shaking Table Test on Tunnels through Soft-Hard Stratum with a Transition Tunnel and Flexible Joints. *Appl. Sci.* 2022, 12, 3151. [CrossRef]
27. Cheng, Y.; Li, C. Luenberger observer-based microgrid control strategy for mixed load conditions. *Energies* 2020, 15, 3655. [CrossRef]

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