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Design, Simulation, and Testing of Active Cooperative Control Strategies for a Light Sensation Transfer Nursing Robot

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Abstract: The transfer of patients, especially elderly or long-term bedridden individuals, has emerged as an important problem due to the growing aging population. The advancement of transfer nursing robots provides an intelligent solution to this problem. This paper presents a Parallel Master–Slave Cross-Coupled (PMSCC) cooperative control strategy based on adaptive fuzzy controllers to address the motion control challenges of a self-developed light Sensation Transfer Nursing Robot (LSTNR). First, the working principle of the LSTNR is introduced, followed by the establishment of its motion model. Next, the robot's velocity is designed based on PMSCC cooperative control strategies, with an adaptive fuzzy controller performing motion control. Finally, the proposed cooperative control strategy is simulated and analyzed, and the robot is tested for patient transfer. The results show that the proposed control strategy reduces the velocity cooperation error between the robot's motors. The average velocity error of the robot is reduced by 92.69%, 92.08%, 47.35%, and 87.78%, respectively, compared to the non-cooperatively controlled robot. This significantly addresses issues such as belt slack, tightness, and patient position deformation during operation, improving the transfer efficiency and effectiveness of the LSTNR.

Keywords: transfer nursing robot; motion modeling; active cooperative control; PMSCC; velocity cooperation



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1. Introduction

According to the World Health Organization's Global Progress Report on Aging and Health, the global population of individuals over 60 is expected to increase from 1 billion to 1.4 billion between 2020 and 2030 and is projected to reach 2.1 billion by 2050 [1]. This has made the caregiving of elderly or bedridden patients an increasingly difficult challenge [2]. Among all caregiving tasks, patient or elderly transfer is one of the most demanding, time-consuming, and labor-intensive [3,4]. Traditional transfer methods typically require multiple caregivers or family members, which not only increases their caregiving burden but also risks causing discomfort or even secondary injuries to patients [5,6]. Therefore, the development of transfer devices that alleviate caregivers' workload while enhancing patient safety has gained significant attention and support from hospitals, companies, and researchers [7–10].

Various nursing robots have been developed and applied for patient transfer [11,12]. These robots can be broadly classified into five categories based on their mechanisms: board-type, humanoid-type, lifting-type, bed-and-chair combination type, and wearable type [13]. Among these, the board-type of transfer nursing beds is favored by hospitals, companies, and researchers due to its simple design, low risk of use, and wide range of applications [13,14]. The integrated transfer device MOBILIZER 3 [15] was designed by the Italian SA.VIR consists of two components: a moving panel and a delivery mechanism. The transfer process is performed by the coordinated movement of the traverse mechanism and the enclosed transport belt. However, the mechanism is limited to unilateral transfer. Wang et al. [16] developed the E-pat-plus, which also uses the enclosed transfer belt. However, the difference is that the E-pat-plus features a double-layer belt that enables bidirectional transfer. Nevertheless, its transfer and delivery are two independent systems. Similar products include the PowerNurse from Astir Technologies (USA) [17] and the C-Pam from DAIHEN (Japan) [18], which both use an enclosed belt and a layered drive to achieve patient transfer. The transfer and delivery mechanisms are designed as separate modules.

Building on the research advances in board-type transfer beds and the results of hospital demand studies, we designed an integrated bidirectional transfer nursing robot with a single-layer open-belt structure. This design enables bidirectional transfer and rapid transport [19]. The LSTNR relies on the friction between the belt and the patient for transfer. This makes it susceptible to problems such as individual differences, flexible belt stretching, uneven force distribution, and changes in the radius of the gyration of the open belt. These factors complicate the accurate control of the patient's position and the velocity and torque of the robot motors during operation. No studies on the control strategies for plate-type transfer robots have been found in the existing literature. Instead, there has been some research into the problems of modeling flexible material stretching, multi-motor co-control, and torque control that exist in the study. In [20], a novel hybrid-mesh model was proposed to simulate the behavior of multi-layer woven fabrics subjected to medium-velocity impact; this method ensures accuracy and reduces the consumption of computational resources. In [21], a novel multiscale modeling method for plain woven fabrics is proposed, and the theoretical and simulation results are verified by experiments. In [22], a belt transmission was dynamically analyzed based on the Generalized Maxwell Slip friction model, and a flat transmission model was proposed. In [23], an analytical model of a steady-state flat belt drive with multiple driving and driven pulleys is presented; it can be used to estimate the belt tension, speed, and strain of any belt drive. In [24], an adaptive speed control strategy for DC motors using a DC/DC converter based on the inverse optimal control approach is presented. This method, compared to traditional cascaded PI control, offers faster response times and improved efficiency in regulating the speed of DC motors. In [25], a speed tracking and synchronization control approach is proposed for a multi-motor system based on fuzzy active disturbance rejection control (FADRC) and an enhanced adjacent coupling scheme; the chattering problem in traditional sliding mode control is mitigated by adaptively estimating the control gain.

Building on the aforementioned references, this paper proposes a PMSCC cooperative control strategy based on an adaptive fuzzy controller to address the technical challenges encountered in the practical operation of the LSTNR, such as slack in the transfer belt, poor inter-module coordination, and the deformation of the patient's body position.

The paper is structured as follows: Section 2 introduces the design principles of the LSTNR, establishes the robot's motion model, designs a PMSCC velocity cooperative control strategy, and builds a PMSCC cooperative control model based on adaptive fuzzy controllers. In Section 3, we use Simulink to simulate and test the variations in the motor

velocity and torque of the robot under different operational states. Section 4 is the prototype system introduction and human transfer test. Section 5 is the conclusion. The main contributions are as follows:

- (1) A PMSCC cooperative control strategy based on adaptive fuzzy controllers was designed for a board-type transfer nursing robot.
- (2) The LSTNR motion model was established, and the issues of belt slack and poor synergy encountered during the open-belt drive process were addressed.

2. Methods

2.1. The LSTNR Design Principles

The transfer process was simplified into a two-degrees-of-freedom model, comprising translation and overturning, based on the transfer performed by paramedics for long-term bedridden patients. This model utilizes the cooperative motion of the moving plate and the belt to realize bidirectional patient movement [19]. The specific principle is shown in Figure 1.

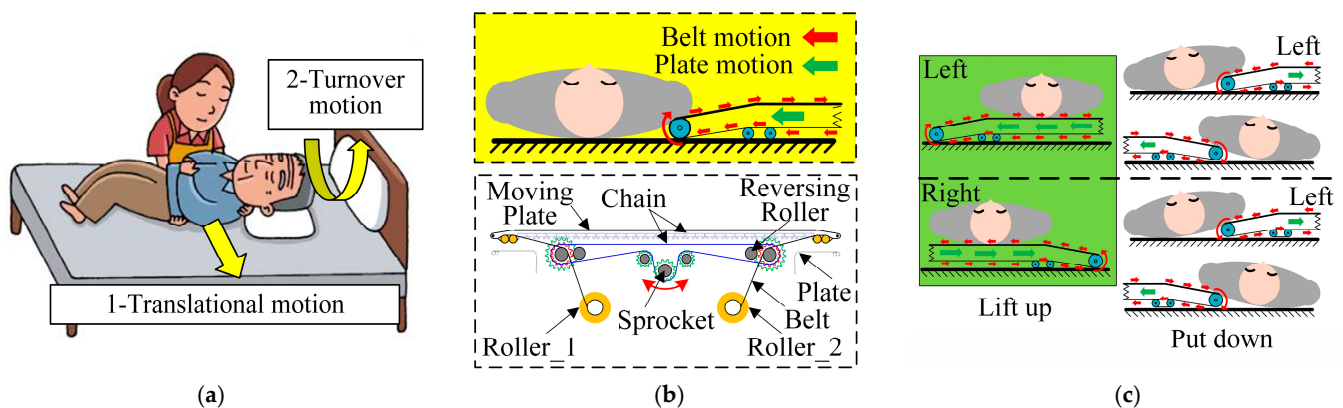


Figure 1. Working principle and transportation process of the LSTNR. (a) Simplified model of working principle; (b) Working Principle of the LSTNR; (c) Transportation process of the LSTNR.

The moving plate is divided into two modules based on clinical needs and usage scenarios: a horizontal plate and a support backplane module. The support backplane module can work in conjunction with the horizontal plate to achieve translational movement and also assists with lifting and support when the patient needs to sit up. Additionally, the robot can perform patient transfers in confined spaces when the support backplane module is raised, allowing the moving plate to move with the belt, as shown in Figure 2.

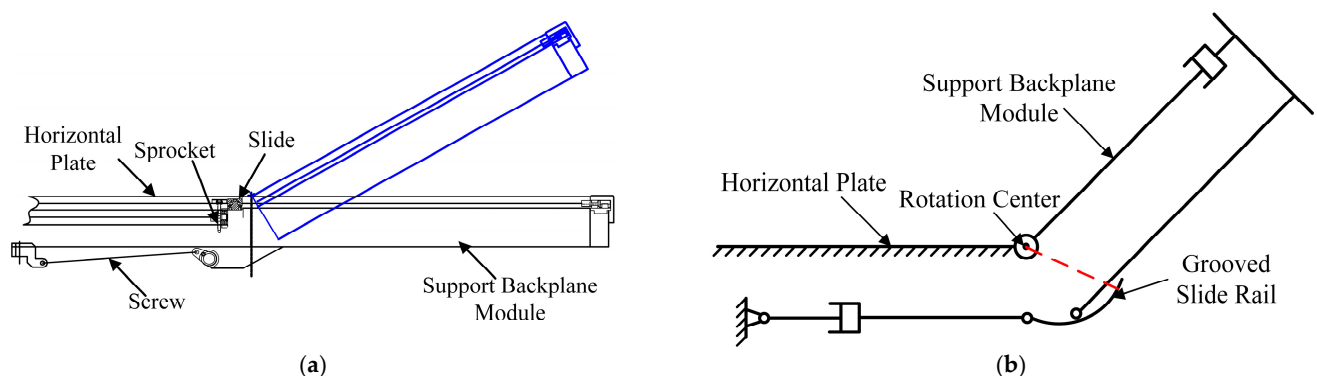


Figure 2. The support backplane module. (a) Support backplane module diagram; (b) Support backplane module motion principle.

Based on the above analysis, the LSTNR was designed as shown in Figure 3. The robot consists of a transfer module and a walking module. The transfer module enables bidirectional patient transfer, while the walking module helps move between different places. The transfer module consists of a moving plate and a transfer belt. The motion of the moving plate is controlled by a closed-chain system and a drive motor, enabling left/right movement. The transfer belt uses an open-belt transmission, consisting of a support backplane transfer belt and a horizontal transfer belt, and adopts independent electrical systems to control the motion of two motors respectively. The folding pusher controls the bending of the support backplane module.

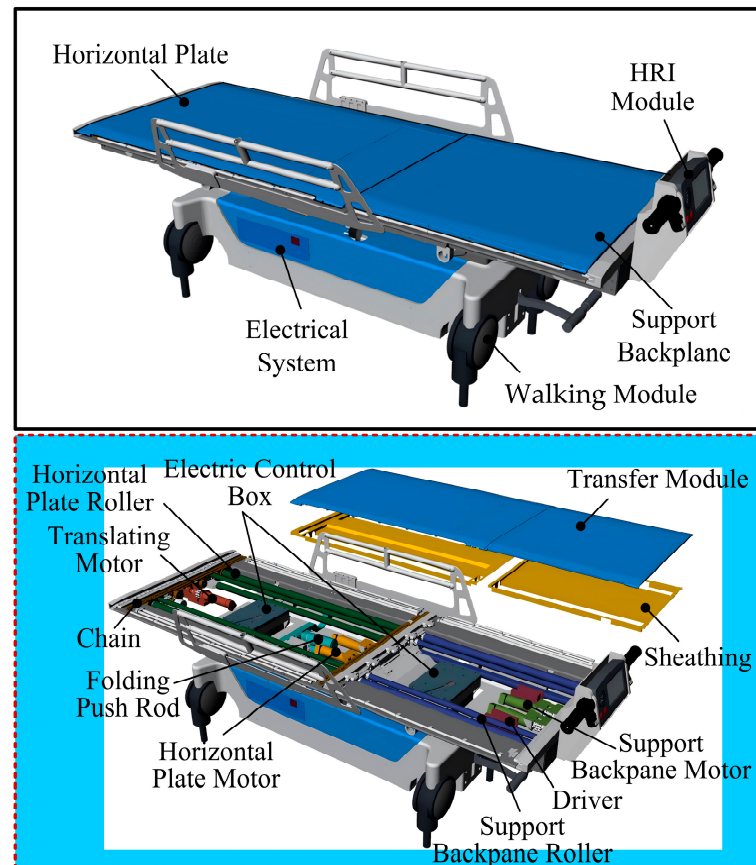


Figure 3. The LSTNR system model.

2.2. Motion Modelling

Based on the robot's working principle, a force analysis and modeling of the human–robot coupled system was conducted. The results are shown in Figure 4. In Figure 4, ω_1 and ω_2 represent the angular velocity of Roller_1 and Roller_2, respectively. ω_p is the angular velocity of the moving plate motor. v is the belt's velocity. G_1 and G_2 represent the patient's weight on the bed and the moving plate, respectively. $G = G_1 + G_2$ is the total weight. f_{h-b} is the static friction between the patient and the belt. f_{p-b} is the dynamic friction between the moving plate and the belt. f_{h-s} is the friction between the patient's body and the sickbed. F_p is the insertion force of the moving plate. Further, the system is subjected to the belt pulling force f_b and the friction force f_{b-r} between the belt and the roller.

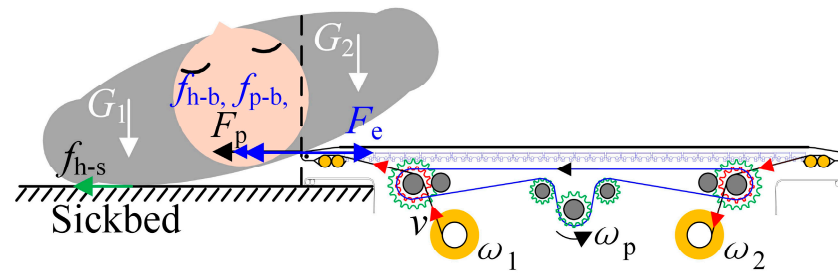


Figure 4. The mechanical model of a human–robot coupled transfer system.

When the transfer robot lifts the patient, the motion model of the human–robot coupled system is:

$$\begin{cases} F_e = \frac{P_{R_2}}{\omega_2 r_2} + f_b - f_{h-b} - f_{p-b} - f_{h-s} - f_{b-r} - F_p \\ F_p = \frac{P_s}{\omega_p R} \end{cases} \quad (1)$$

where P_s is the sprocket motor power. R is the sprocket radius. P_{R_2} is the Roller_2 motor power. r_2 is the radius of the Roller 2 + belt.

When the transfer robot puts the patient down, the motion model of the human–robot coupled system is:

$$F_e = \frac{P_{R_1}}{\omega_1 r_1} + f_b - f_{h-b} - f_{p-b} - f_{h-s} - f_{b-r} \quad (2)$$

where P_{R_1} is the Roller_1 motor power. r_1 is the radius of the Roller 1 + belt.

When the transfer robot works, to keep the belt velocity v constant, establishing the roller Roller_1 and Roller_2 angular velocities ω_1 and ω_2 relational equations K_ω based on the change in the roller Roller_1 and Roller_2 rotational radii r_1 and r_2 is:

$$K_\omega = \frac{r_2}{r_1} = \frac{2\pi r_{\min} + (\omega_2 t + 2\pi)d}{2\pi r_{\max} - \omega_1 t d} \quad (3)$$

where d is the belt thickness 0.5 mm. t is the time. r is the radius of the Roller+belt, $r = r_0 + (n + 1)d$. r_0 is the roller radius. n is the number of belt-wrapping turns.

According to the relationship between motor voltage and angular velocity [26], the robot roller's control model is:

$$\frac{W_r(s)}{U_r(s)} = \frac{nk_{rt}}{(n^2 R_r J_{r1} + R_r J_{r2})s + (n^2 R_r B_{r1} + R_r B_{r2}) + n^2 k_{rt} k_{rb}} \quad (4)$$

where J_{r1} and J_{r2} are the moments of inertia of the motor and reducer, respectively. B_{r1} and B_{r2} are the damping coefficients of the motor and reducer, respectively. n is the velocity ratio. k_{rt} is the torque constant. k_{rb} is the counter-electromotive force constant. R_r is the armature resistance.

The control model of the moving plate is:

$$\begin{cases} \frac{W_p(s)}{U_p(s)} = \frac{k_p}{J_p s + B_p} \\ k_p = \frac{k_{pt}}{R_p} \\ J_p = n_1^2 n_2^2 J_{p1} + \frac{n_2^2}{n_1} J_{p2} + \frac{1}{n_2} J_{p3} \\ B_p = (n_1 n_2 B_{p1} + \frac{n_2}{n_1} B_{p2} + \frac{1}{n_2} B_{p3}) + \frac{n_1 n_2 k_{pt} k_{pb}}{R_p} \end{cases} \quad (5)$$

where J_{p1} , J_{p2} , and J_{p3} are the moment of inertia of the motor, reducer, and sprocket, respectively. B_{p1} , B_{p2} , and B_{p3} are the damping coefficients of the motor, reducer, and sprocket, respectively. n_1 and n_2 are the velocity ratios of the reducer and sprocket, respectively. k_{pt} is the torque constant. k_{pb} is the counter-electromotive force constant. R_{pr} is the armature resistance.

2.3. PMSCC Velocity Cooperative Design

Figure 5 shows the workflow of the LSTNR during a left-side patient transfer. The specific operations are as follows:

- (1) The moving plate extends to the left, the sprocket in reverse (green arrow), while Roller_1 rotates forward to loosen the belt (red arrow); Roller_2 rotates in reverse to loosen the belt (red arrow).
- (2) After the moving plate contacts the patient, it continues to move to the left and inserts beneath the patient. While Roller_1 continues to rotate forward to loosen the belt (red arrow), Roller_2 rotates forward to tighten (red arrow), and the transfer operation begins.
- (3) When the patient is completely transferred onto the moving plate, the sprocket rotates forward (green arrow), the moving plate resets, while Roller_1 rotates in reverse to tighten (red arrow); Roller_2 rotates forward to tighten (red arrow), preparing for patient transportation.
- (4) When the patient is transported to the destination, the patient needs to be transferred to the sickbed. The moving plate performs action (1) again.
- (5) When the moving plate extends to the center of the sickbed, the sprocket rotates forward (green arrow), the moving plate retracts, while Roller_1 rotates in reverse to tighten the belt (red arrow); Roller_2 rotates in reverse to loosen the belt (red arrow); the transfer operation begins.
- (6) When the patient is completely transferred onto the sickbed, the moving plate continues to retract, while Roller_1 rotates in reverse to tighten the belt (red arrow); Roller_2 rotates forward to tighten the belt (red arrow), and the robot resets. The entire transfer process is completed.

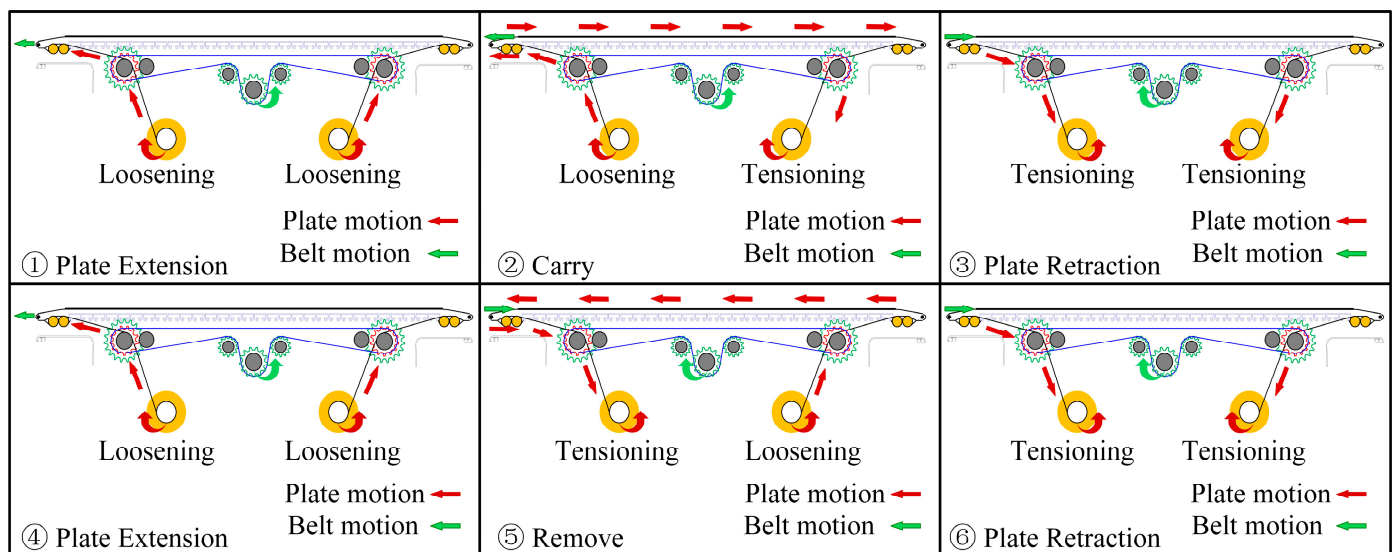


Figure 5. The workflow of the LSTNR during a left-side patient transfer.

The entire process requires coordinated movement of one moving plate control motor, two support backplane roller motors, and two horizontal plate roller motors. Therefore,

this paper proposes a PMSCC cooperative control strategy based on the traditional parallel cooperative, master–slave cooperative, and cross-coupled cooperative strategies.

It is set in the design of the cross-coupled synergistic strategy by introducing the velocity evaluation function and setting the velocity compensator to be:

$$\begin{cases} \Delta\omega = \eta_i(\omega_i - \omega_{\min}) + (\omega_i - \frac{1}{n} \sum_{i=1}^n \omega_i) \\ \eta_i = \frac{I_i \sum_{k=1}^n I_k}{\prod_{k=1}^n I_k} \quad i, k = 1, 2, 3, \dots, n, \quad i \neq k \end{cases} \quad (6)$$

where ω_i is the velocity of the i th motor. n is the number of motors. $\omega_{\min}$ is the velocity of the motor with minimum speed. I is the moment of inertia of the motor.

The PMSCC cooperative control strategy based on the fuzzy controller is established for the LSTNR, as shown in Figure 6. In Figure 6, a master–slave cooperative control strategy controls the two reel motors that govern the motion of the belts on the horizontal and support plates. A parallel cooperative control strategy controls the interaction between the driving motors of the two flat plates and the active motors of the reels. In addition, a cross-coupled system motion strategy is applied respectively between the three active motors and the two slave motors involved in the motion. When load fluctuations occur in the system, the average speed and rotational speed error compensation can be used to adjust the motion speed between the motors, thereby reducing system oscillations.

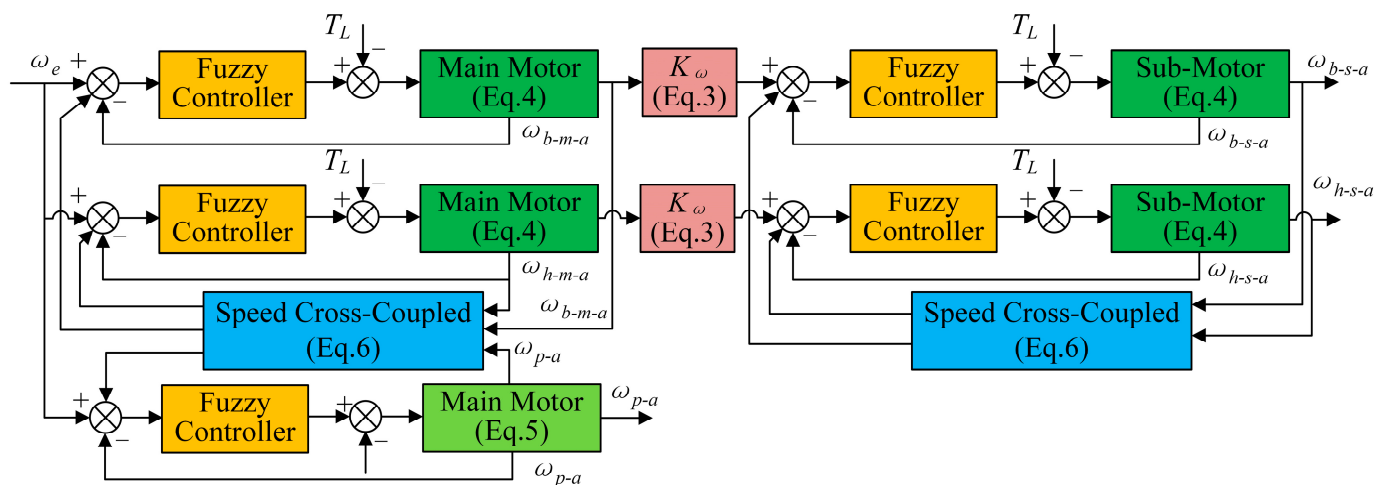


Figure 6. The PMSCC cooperative control strategy based on the fuzzy controller of the LSTNR.

2.4. Based on Adaptive Fuzzy Controller for Transfer Control

A selector is integrated into the robot control system to set and adjust the parameters for different states (Figure 5) during patient transfer, as shown in Figure 7.

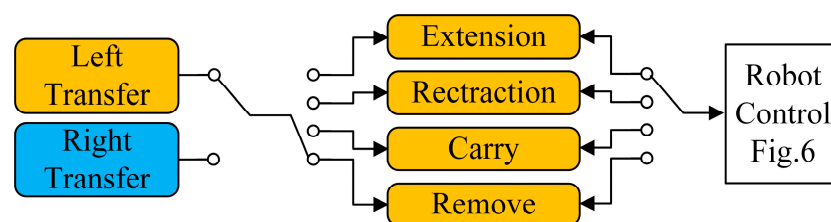


Figure 7. The selection controller for the LSTNR.

In Figure 7, this paper designs a control system based on adaptive fuzzy control to accommodate the varying transfer needs of patients in different environments. The system is optimized to meet the dynamic performance requirements and to enhance the cooperative and tracking effectiveness between the motors [27–29]. The fuzzy adaptive control law is defined as:

$$\tau = D(q)\ddot{q}_r + C(q, \dot{q})\dot{q}_r + G(q) + \hat{F}(\dot{q}|\theta) - K_D e \quad (7)$$

where $D(q)$ is the inertial force matrix. $C(q, \dot{q})$ is the centripetal force matrix. $G(q)$ is the gravity matrix. $\hat{F}(\dot{q}|\theta)$ is the disturbance force generated by friction. $K_D = \text{diag}(K_i)$, $K_i > 0$, $i = 1, 2, \dots, n$. $e = \dot{q} - \dot{q}_r + \Lambda e_q$.

Construct fuzzy systems as:

$$\hat{F}(\dot{q}|\theta) = \begin{bmatrix} \hat{F}_1(\dot{q}_1) \\ \hat{F}_2(\dot{q}_2) \\ \vdots \\ \hat{F}_5(\dot{q}_5) \end{bmatrix} = \begin{bmatrix} \theta_1^T \xi^1(\dot{q}_1) \\ \theta_2^T \xi^2(\dot{q}_2) \\ \vdots \\ \theta_5^T \xi^5(\dot{q}_5) \end{bmatrix} \quad (8)$$

Design adaptive laws as:

$$\dot{\theta}_i = -\Gamma_i^{-1} e_i \xi(\dot{q}), \quad i = 1, 2, \dots, n \quad (9)$$

To ensure that $e \rightarrow 0$, define the Lyapunov function as:

$$V(t) = \frac{1}{2} e^T D e \quad (10)$$

Then

$$\dot{V}(t) = -e^T K_D e - e^T \omega \quad (11)$$

when $K_D \rightarrow \infty$ and the fuzzy approximation error $\omega \rightarrow 0$, $\dot{V}(t) \leq 0$.

When $\dot{V}(t) \equiv 0$, $e \equiv 0$. According to LaSalle's principle [30], the closed-loop system is asymptotically stable and the convergence rate of the system depends on the K_D . Since $V \geq 0$, $\dot{V} \leq 0$, then $t \rightarrow 0$, V is bounded and θ_i is bounded.

In summary, the adaptive fuzzy controller-based PMSCC cooperative control strategy for the LSTNR is established, as shown in Figure 8.

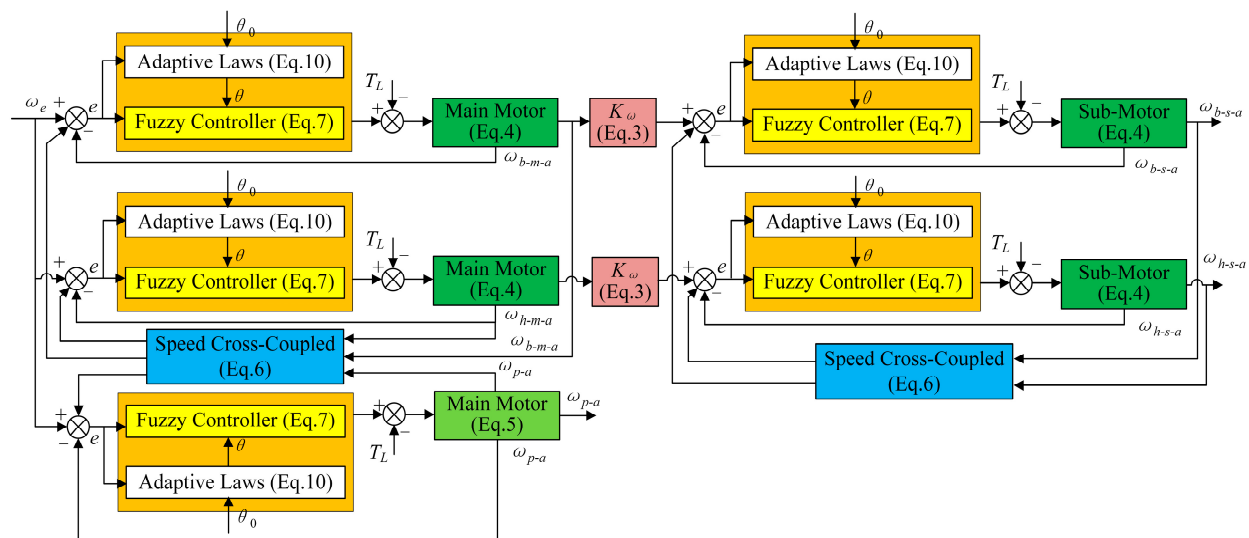


Figure 8. The adaptive fuzzy controller-based PMSCC cooperative control strategy for the LSTNR.

3. Simulation and Analysis

According to the transfer workflow of the robot (Figure 5), the adaptive fuzzy controller-based PMSCC cooperative control strategy for the LSTNR (Figure 8) built in this paper is simulated and analyzed.

The motor velocity is set as ω_e , the friction factor μ_{h-s} between the patient and the bed is 0.5, the friction factor μ_{h-b} between the patient and the belt is 0.5, the friction factor μ_{p-b} between the belt and the moving plate is 0.3, the friction factor μ_{b-r} between the belt and the drum is 0.2, and the belt deformation Δx is 3mm. The number of belt winding turns n_{max} is 17. The dynamic performance of the LSTNR was analyzed in two states, no-load and loaded; the results are shown in Figures 9 and 10, respectively, where AMV is the velocity of the active motor, and SMV is the velocity of the slave motor. The expected velocity of the active motor is 40 r/min, and the expected velocity of the slave motor is the output velocity of the active motor. The given load torque is 40 Nm.

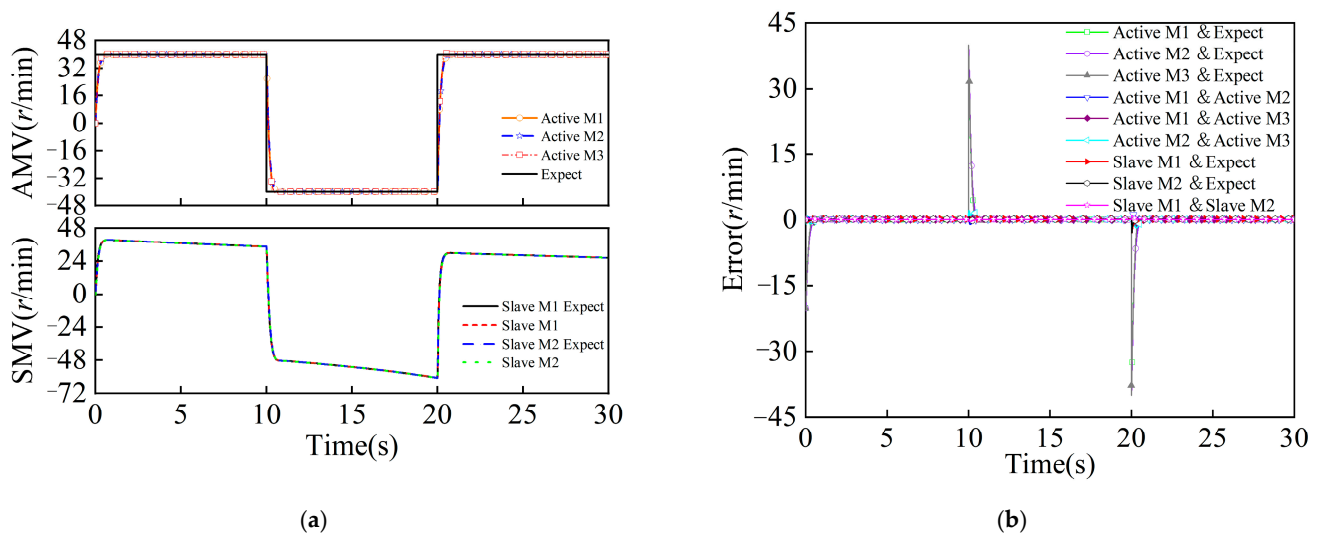


Figure 9. The LSTNR dynamic performance under no load. (a) Velocity curve; (b) Velocity error curve.

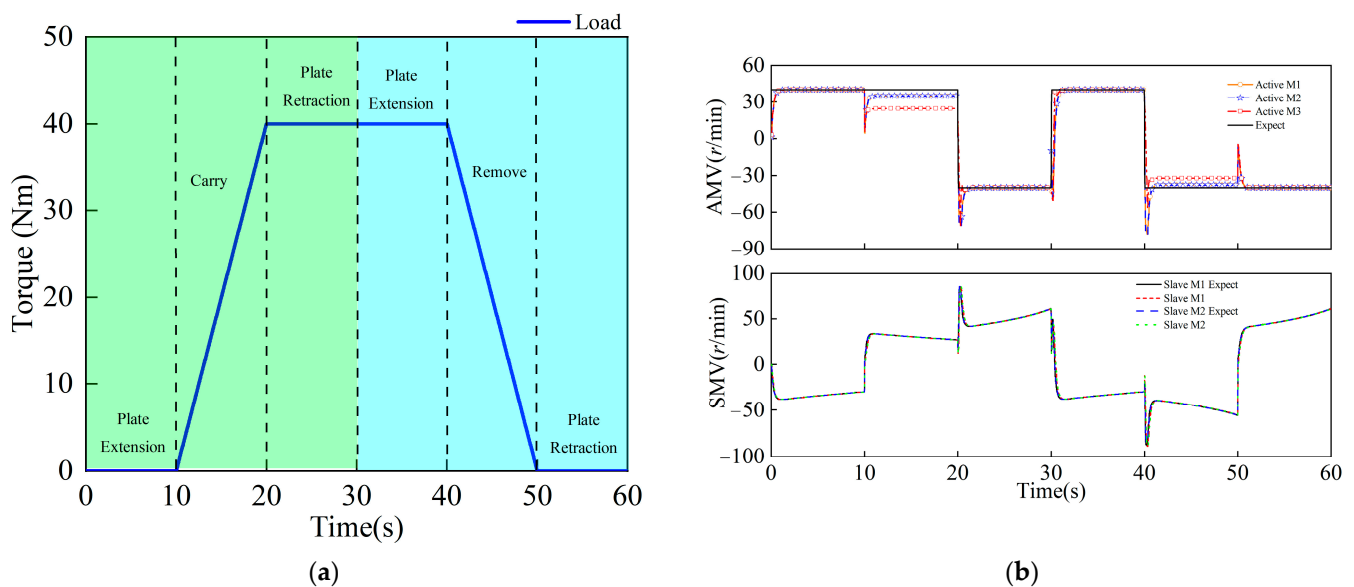


Figure 10. Cont.

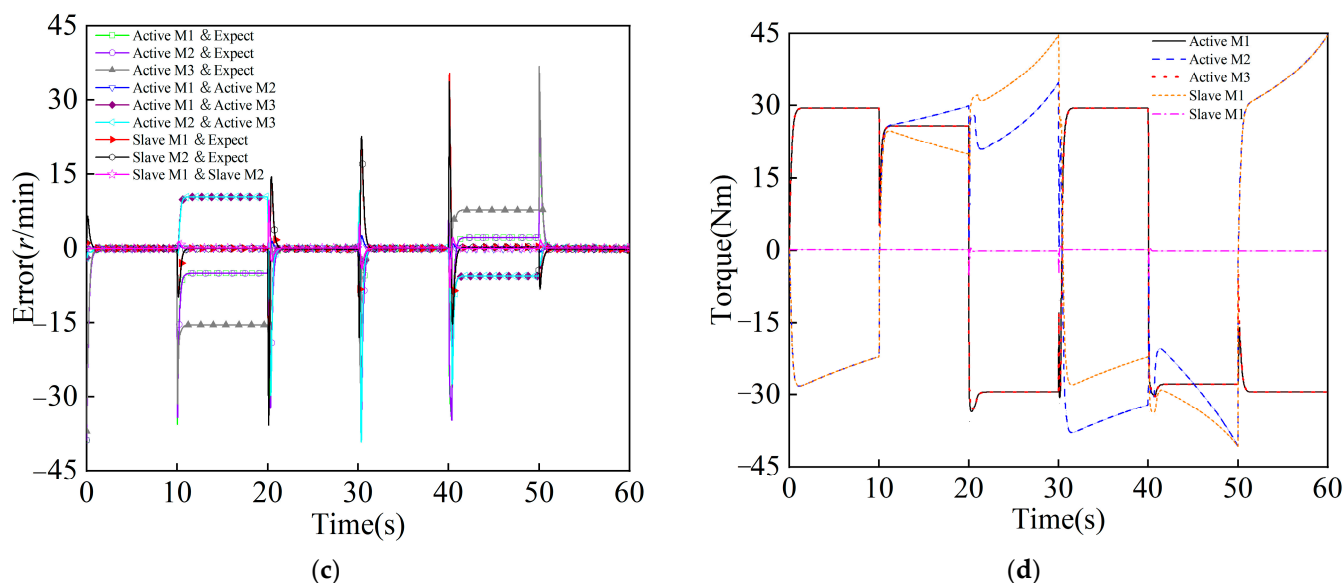


Figure 10. The LSTNR dynamic performance under load. (a) Load curve; (b) Velocity curve; (c) Velocity error curve; (d) Torque curve.

From Figure 9a, it is evident that the velocity curves of both the active and slave motors can converge quickly and with less fluctuation when the system is unloaded. When the velocity direction is changed, large errors occur in the velocity curves of the motors (Figure 9b). The maximum velocity errors of Active M1 and Active M2, Active M1 and the mobile plate control motor (Active-M3), and Active M2 and the mobile plate control motor (Active-M3) are 1.13 r/min, 1.81 r/min, and 2.09 r/min, respectively, and the maximum velocity error between Slave M1 and Slave M2 is 0.90 r/min.

As shown in Figure 10, when step load disturbances are imposed on the system, the robot's velocity closely follows the expected velocity, with a small error. Additionally, the motor torque remains stable, without significant fluctuations, and it aligns with the changes in load. The maximum velocity errors of Active M1 and Active M2, Active M1 and the mobile plate control motor (Active-M3), and Active M2 and the mobile plate control motor (Active-M3) are 1.59 r/min, 2.21 r/min, and 2.37 r/min, respectively, and the maximum velocity error between Slave M1 and Slave M2 is 1.83 r/min.

4. Experimental

4.1. The LSTNR Prototype

The LSTNR prototype and control system were built, encompassing the central processing unit, actuator unit, drive unit, sensing unit, data acquisition unit, power unit, remote operation, and human-machine interaction unit, as shown in Figure 11.

The electrical system of LSTNR uses the STM32 microcontroller (ESP32S3, Made in Guangzhou, China) as the central processing unit, which is connected to the data acquisition unit, drive unit (MLDS 3605C, SUD-36, CB6S MK2), handheld remote control, and the interactive screen of the lower computer via Controller Area Network (CAN). The drive unit controls the movement of the motor (SINBAD DC MOTOR32/36), electric actuator (KA19), lifting column (BL1), and booster wheels. The data acquisition unit collects positional information from the absolute encoder (Remido E6C3-AG5C). The power unit provides 24 V DC voltage to the entire system.

Compared with other board-type nursing robot systems [15–18,31–33] in terms of load, thickness, transfer direction, transfer posture, and equipment form, the results are shown

in Table 1. It can be seen that the LSTNR not only has a smaller thickness in design, but also can adapt to different transfer requirements in function.

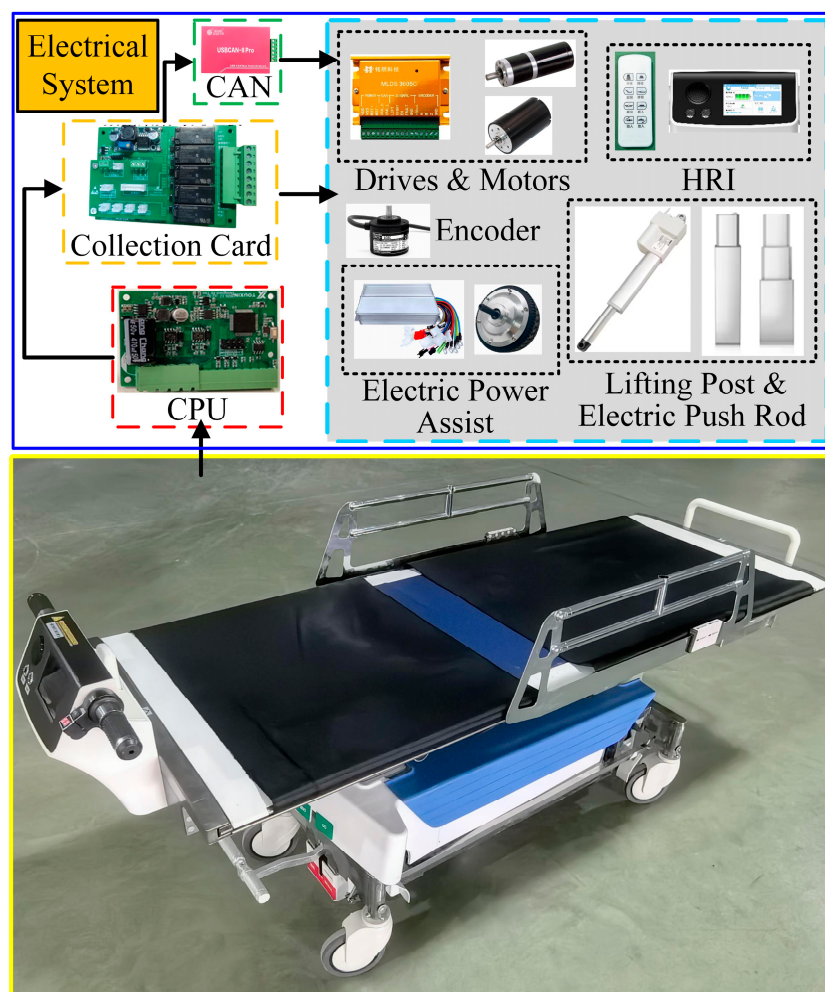


Figure 11. The LSTNR prototype and control system.

Table 1. Comparison summary of typical board-type of transfer nursing beds system.

Name	Load (kg)	Bed Thickness (mm)	Transfer Direction	Transfer Posture	Form
LSTNR	150	20	Bidirectional	Lying/Sitting	Integral
MOBILIZER3 [15]	-	30	Unidirectional	Lying	Split
E-PAT-plus [16]	120	350	Bidirectional	Lying	Split
PowerNurse [17]	-	400	Bidirectional	Lying	Split
C-Pam [18]	120	350	Bidirectional	Lying	Split
Hybrid system [31]	150	-	Unidirectional	Sitting	Integral
IWB [32]	90	-	Unidirectional	Sitting	Integral
E-Pat [33]	120	25	Unidirectional	Lying	Split

4.2. The LSTNR Transfer Experiment

A comparison and analysis of the cooperatively controlled and non-cooperatively controlled robots were conducted, and the transfer effect and motion velocity of the LSTNR were experimentally tested. The results are shown in Figures 12–17.

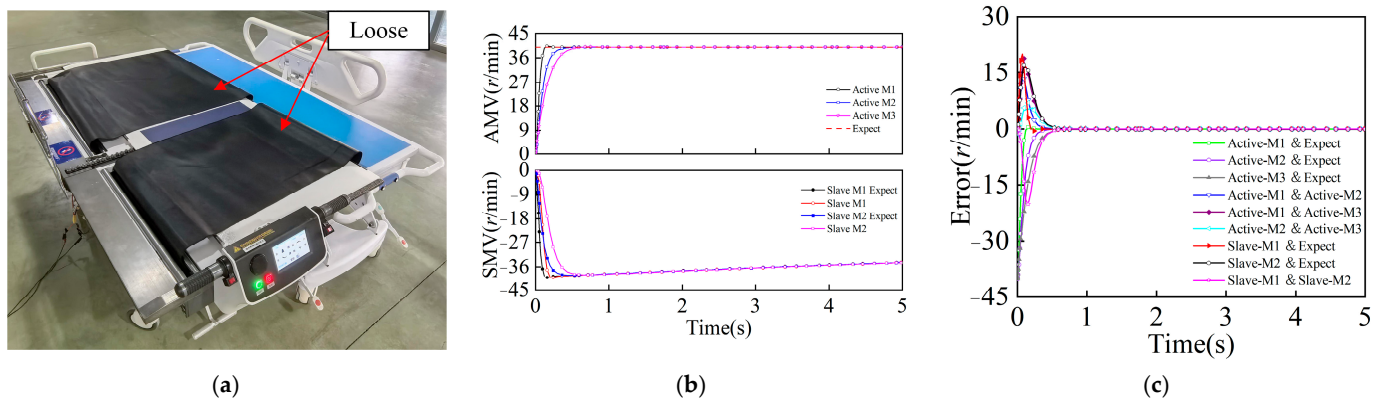


Figure 12. The non-cooperatively controlled robot. (a) LSTNR motion status; (b) Velocity curve; (c) Velocity error curve.

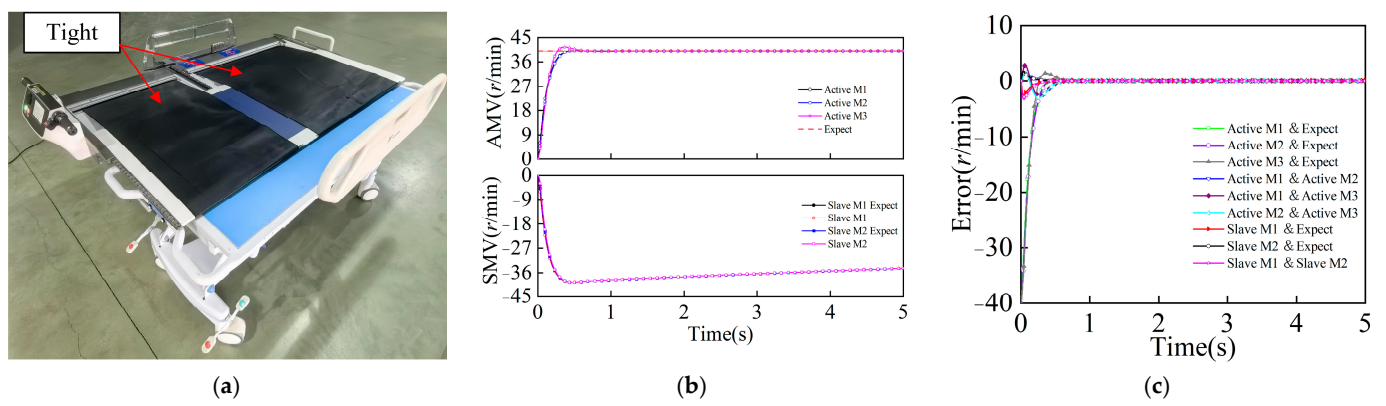


Figure 13. The cooperatively controlled robot. (a) LSTNR motion status; (b) Velocity curve; (c) Velocity error curve.

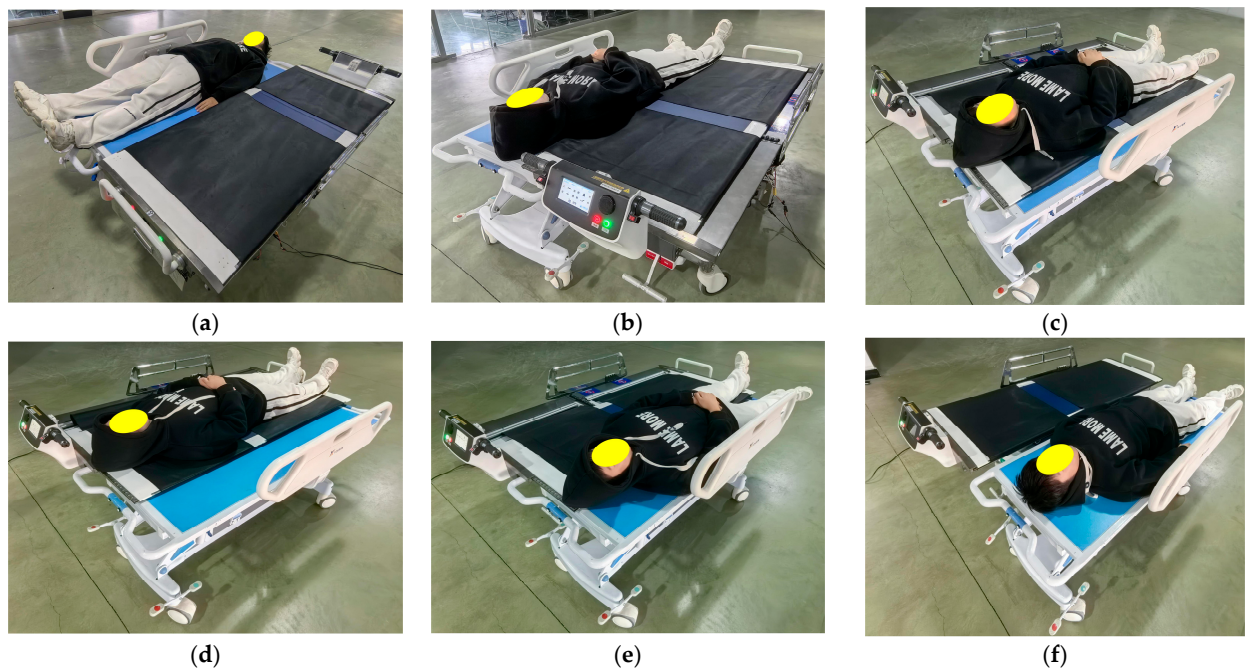


Figure 14. Transfer test. (a) Plate extension; (b) Carry; (c) Plate retraction; (d) Plate extension; (e) Remove; (f) Plate retraction.

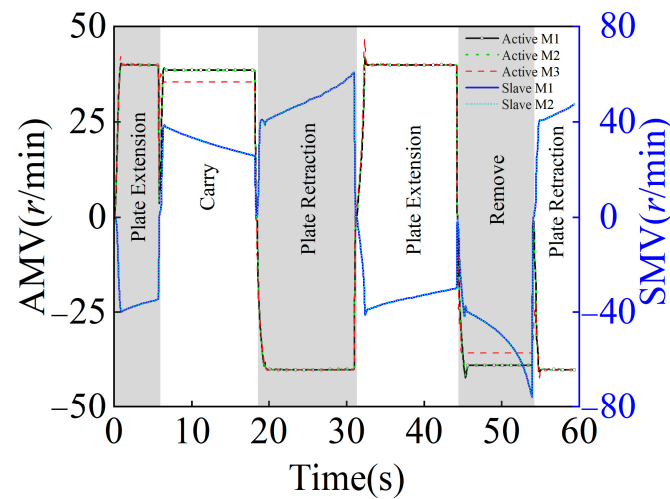


Figure 15. Motor velocity curve.

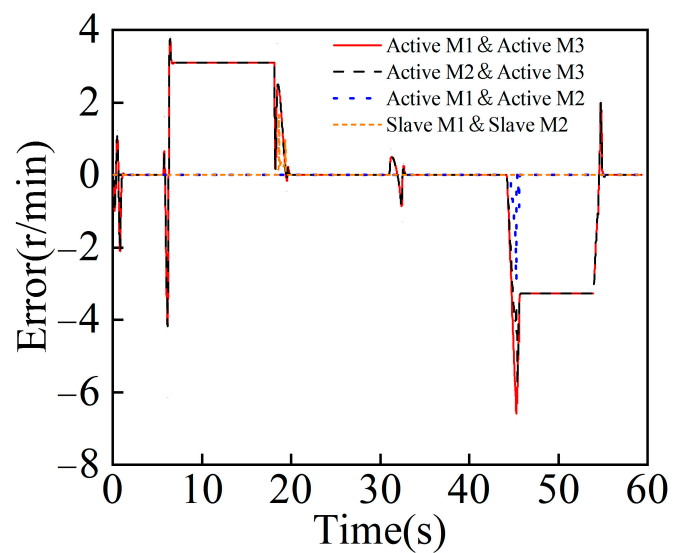


Figure 16. Velocity error curve.

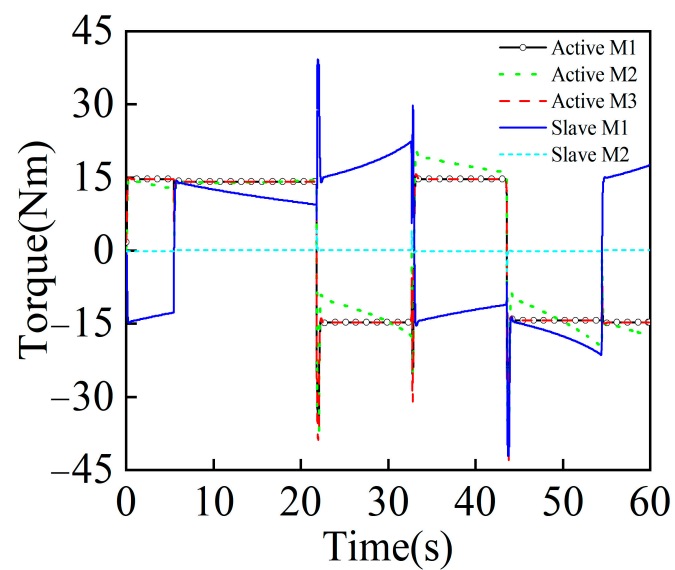


Figure 17. Torque curve.

Compared to Figures 12 and 13, it can be seen that the proposed cooperative control strategy effectively addresses the issues of belt slack and poor motion coordination during robot operation. In Figure 12, the maximum velocity errors between Active M1 and Active M2, and Active (M1, M2) and the mobile plate control motor (Active-M3) are 13.37 r/min, 18.90 r/min, and 6.86 r/min, respectively, and the maximum velocity error between Slave M1 and Slave M1 is 0.05 r/min. In Figure 13, the maximum velocity errors between Active M1 and Active M2, and Active (M1, M2) and the mobile plate control motor (Active-M3) are 1.48 r/min, 2.97 r/min, and 1.50 r/min, respectively, and the maximum velocity error between Slave M1 and Slave M1 is 0.01 r/min. The average velocity error was reduced by 92.69%, 92.08%, 47.35%, and 87.78%, respectively.

Figure 14 shows that the robot performed the transfer test without encountering issues of belt tightness or looseness and deformation of the patient's position. The motor velocity and torque variations were relatively smooth, without significant fluctuations during transport (Figures 15 and 17). It can be obtained from Figure 16 that the average velocity errors between Active M1 and Active M2, and Active (M1, M2) and the mobile plate control motor (Active-M3) are 0.0030 r/min, 0.0036 r/min, and 0.0065 r/min, respectively; the average velocity errors between Slave M1 and Slave M1 is 0.0046 r/min.

5. Conclusions

This paper proposes a PMSCC cooperative control strategy, based on an adaptive fuzzy controller, to address engineering challenges such as belt slack/tightness, poor cooperation, and patient position deformation during the operation of the LSTNR. We have introduced the working principle of the LSTNR, its established motion model, and a PMSCC velocity cooperative control strategy designed for this multi-motor system. Based on this, we propose a PMSCC control strategy with an adaptive fuzzy controller to address the problems encountered during the robot's motion. The results show that the proposed control strategy effectively resolves issues such as belt slack/tightness and patient position deformation caused by poor cooperation during the robot's movement. The average and maximum velocity errors are reduced, and the dynamic performance of the system is improved. In the future, we will continue to study the practical challenges of the LSTNR encountered in the clinical settings. We will integrate technologies such as autonomous navigation, trajectory planning, and decision making to enhance the intelligence of the LSTNR.

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References

- World Health Organization. *Progress Report on the United Nations Decade of Healthy Ageing, 2021–2023*; World Health Organization: Geneva, Switzerland, 2023.
- Ophir, A.; Polos, J. Care Life Expectancy: Gender and Unpaid Work in the Context of Population Aging. *Popul. Res. Policy Rev.* **2022**, *41*, 197–227. [[CrossRef](#)] [[PubMed](#)]
- Brinkmann, A.; Böhlen, C.F.; Kowalski, C.; Lau, S.; Meyer, O.; Diekmann, R.; Hein, A. Providing physical relief for nurses by collaborative robotics. *Sci. Rep.* **2022**, *12*, 8644. [[CrossRef](#)] [[PubMed](#)]
- Czaja, S.J. The healthcare challenge for an aging population: The role of technology. *Innov. Aging* **2019**, *3*, S32. [[CrossRef](#)]
- Tiwari, M.K.; Prabhu, D.P.; Chavan, A. Design of an Indigenously Developed Patient Transfer Assistive Device. *Int. J. Health Sci. Res.* **2023**, *13*, 62–72. [[CrossRef](#)]
- Chae, H.D.; Choi, S.B. A new vibration isolation bed stage with magnetorheological dampers for ambulance vehicles. *Smart Mater. Struct.* **2014**, *24*, 017001. [[CrossRef](#)]
- Christoforou, E.G.; Avgousti, S.; Ramdani, N.; Novales, C.; Panayides, A.S. The Upcoming Role for Nursing and Assistive Robotics: Opportunities and Challenges Ahead. *Front. Digit. Health* **2020**, *2*, 585656. [[CrossRef](#)] [[PubMed](#)]
- Brimelow, R.E.; Gibney, A.; Meakin, S.; Wollin, J.A. Accessing care summaries at point-of-care: Implementation of mobile devices for personal carers in aged care. *Health Inform. J.* **2019**, *25*, 126–138. [[CrossRef](#)] [[PubMed](#)]
- Zhou, H.; Sang, L.; Luo, J.; Wang, H.; Feng, Y.; Zhang, X.; Chen, L. Development of a multifunctional nursing bed system for in-bed position recognition and automatic repositioning. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **2024**, *238*, 5437–5454. [[CrossRef](#)]
- Zhou, Z.; Qi, J.; Yang, Y. The Use of Mathematical Analysis in the Nursing Bed Design Evaluation. *J. Funct. Spaces* **2021**, *2021*, 5520813. [[CrossRef](#)]
- Wang, S.; Shi, W.; Liang, Y.; Huang, L.; Huang, Z. Design and manufacture of multi-function electric nursing bed. *J. Phys. Conf. Ser.* **2019**, *1213*, 052111. [[CrossRef](#)]
- Aslam, I.; Davis, S.A.; Feldman, S.R.; Martin, W.E. A Review of Patient Lifting Interventions to Reduce Health Care Worker Injuries. *Workplace Health Saf.* **2015**, *63*, 267–275. [[CrossRef](#)] [[PubMed](#)]
- Cheng, G.; Huang, Y.; Zhang, X.; Chen, H.; Ota, J. An overview of transfer nursing robot: Classification, key technology, and trend. *Rob. Auton. Syst.* **2024**, *174*, 104653. [[CrossRef](#)]
- Krishnan, R.H.; Pugazhenth, S. Mobility assistive devices and self-transfer robotic systems for elderly, a review. *Intell. Serv. Robot.* **2014**, *7*, 37–49. [[CrossRef](#)]
- Jin, J.; Jin, S.; Zhao, D.; Li, C. Self-Reliance Transfer Support Robot for Home-Based Care. In Proceedings of the 2022 7th International Conference on Robotics and Automation Engineering (ICRAE), Singapore, 18–20 November 2022.
- Tian, Y.; Wang, H.; Zhang, Y.; Su, B.; Du, J.; Wang, X.; Feng, Y.; Cheng, B.; Niu, J. Structural Design and Preliminary Tests of a Novel Patient Transfer Apparatus for Medical Scenarios. *J. Healthc. Eng.* **2021**, *2021*, 2770846. [[CrossRef](#)] [[PubMed](#)]
- Sang, L.; Yamamura, M.; Dong, F.; Gan, Z.; Fu, J.; Wang, H.; Tian, Y. Analysis, design, and experimental research of a novel wheelchair-stretcher assistive robot. *Appl. Sci.* **2019**, *10*, 264. [[CrossRef](#)]
- Wang, H.; Kasagami, F. A patient transfer apparatus between bed and stretcher. *IEEE Trans. Syst. Man. Cybern.* **2008**, *38*, 60–67. [[CrossRef](#)] [[PubMed](#)]
- Sang, L.; Wang, H.; Tian, Y. Analysis, Design and Experimental Research of a Novel Bilateral Patient Transfer Robot. *Machines* **2022**, *10*, 33. [[CrossRef](#)]
- Yang, E.C.; Linforth, S.; Ngo, T.; Tran, P. Hybrid-mesh modeling & validation of woven fabric subjected to medium velocity impact. *Int. J. Mech. Sci.* **2018**, *144*, 427–437.
- Chen, J.; Wen, X.; Tang, Q.; Du, Z.; Yu, W. A yarn-to-fabric multiscale modeling strategy for auxetic behavior analysis of negative Poisson's yarn-based fabric. *Compos. Struct.* **2024**, *347*, 118455. [[CrossRef](#)]
- Kubas, K.; Harlecki, A. Dynamic analysis of a belt transmission with the GMS friction model. *Meccanica* **2021**, *56*, 2293–2305. [[CrossRef](#)]
- Kumaran, V.U.; Weiss, L.; Zogg, M.; Wegener, K. Analytical flat belt drive model considering bilinear elastic behaviour with residual strains. *Mech. Mach. Theory* **2023**, *190*, 105466. [[CrossRef](#)]
- Acevedo, D.M.; Gil-González, W.; Montoya, O.D.; Restrepo, C.; González-Castaño, C. Adaptive Speed Control for a DC Motor Using DC/DC Converters: An Inverse Optimal Control Approach. *IEEE Access* **2024**, *12*, 154503–154513. [[CrossRef](#)]
- Tao, L.; Chen, Q.; Nan, Y.; Dong, F.; Jin, Y. Speed Tracking and Synchronization of a Multimotor System Based on Fuzzy ADRC and Enhanced Adjacent Coupling Scheme. *Complexity* **2018**, *2018*, 5632939. [[CrossRef](#)]
- Huang, J.; Lu, G.; Yao, X. Safe online optimization of motor speed synchronization control with incremental Q-learning. *Expert. Syst. Appl.* **2024**, *255*, 124622. [[CrossRef](#)]
- Yoe, R.Z. *Modelling and Control of Dynamical Systems: Numerical Implementation in a Behavioral Framework*; Springer: Berlin/Heidelberg, Germany, 2008.

28. Mohammadzadeh, A.; Sabzalian, M.H.; Zhang, C.; Castillo, O.; Sakthivel, R.; El-Sousy, F.F.M. *Modern Adaptive Fuzzy Control Systems*; Springer: Cham, Switzerland, 2023.
29. Zavala-Yoe, R.; Ramírez-Mendoza, R.A.; García-Lara, S. A 3-SPS-1S parallel robot-based laser sensing for applications in precision agriculture. *Soft Comput.* **2017**, *21*, 641–650. [[CrossRef](#)]
30. Mei, W.; Bullo, F. LaSalle Invariance Principle for Discrete-time Dynamical Systems: A Concise and Self-contained Tutorial. *arXiv* **2017**, arXiv:1710.03710.
31. Meng, N.; Mengxin, R.; Qinglin, F.; Lizhi, Z. Mechanism design of a robotic chair/bed system for bedridden aged. *Adv. Mech. Eng.* **2017**, *9*, 1–8.
32. Renming, G.; Jianjun, Y.; Songmin, J.; Xiuzhi, L. Design and Discussion on A Novel Intelligent Wheelchair Bed. In Proceedings of the IEEE International Conference on Robotics and Biomimetics, Kuala Lumpur, Malaysia, 12–15 December 2018; pp. 2013–2018.
33. Tian, Y.; Wang, H.; Zhang, Y.; Su, B.; Wang, L.; Wang, X.; Sang, L.; Feng, Y.; Niu, J. Design and Evaluation of a Novel Person Transfer Assist System. *IEEE Access* **2021**, *9*, 14306–14318. [[CrossRef](#)]

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