Ultrasonic Sensor-based Rehabilitation Training of Finger Exoskeleton Robots

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Abstract. Finger exoskeleton robots are gradually gaining attention as the demand for rehabilitation increases. Due to the limitations of traditional rehabilitation means, research on finger exoskeleton robot rehabilitation using ultrasonic sensors is particularly necessary. This thesis explores the application of finger exoskeleton rehabilitation robots with ultrasonic sensors in the field of medical rehabilitation and its potential impact. By combining precise ultrasonic sensing technology and intelligent control algorithms, this exoskeleton robot can provide patients with personalized rehabilitation training programs, thus improving rehabilitation efficiency and quality of life. The study shows that the exoskeleton robot not only meets the growing demand for care in an aging society but also effectively assists athletes in their post-injury recovery. In addition, combined with telemedicine and big data analytics, the technology helps to advance research and optimization in rehabilitation science. Therefore, the ultrasonic sensor finger exoskeleton rehabilitation robot will play an important role in facilitating patient rehabilitation, enhancing the independence of life, and promoting medical science and technology innovation.

Keywords: Rehabilitative, finger exoskeleton, curing.

1. Introduction

With the change in working style and living habits in modern society, the number of patients with finger dysfunction has been increasing year by year, and the demand for their rehabilitation has gradually increased. However, traditional rehabilitation training methods, such as manual assisted training and simple device training, usually have problems such as long rehabilitation periods and low precision. The rapid development of ultrasonic sensor technology in recent years, with its advantages of high precision, non-invasiveness, and real-time monitoring, has brought new possibilities for rehabilitation training of finger exoskeleton robots, which is expected to improve the rehabilitation effect.

Finger exoskeleton rehabilitation robots have made remarkable progress in domestic and international research. Foreign research mainly focuses on control systems, material application, and human-robot interaction, and a variety of types of robots have been developed that utilize advanced sensors and control algorithms to achieve precise support. For example, the bilaterally independent robotic motion-assisted finger exoskeleton robot for home rehabilitation developed by Tony et al. is highly practical [1]. Domestic research is gradually emerging, combining traditional rehabilitation methods with intelligent technology to improve the rehabilitation effect and user experience. With the development of machine learning and artificial intelligence, researchers are beginning to apply these technologies to achieve smarter and personalized rehabilitation programs. For example, a human-machine-integrated finger exoskeleton robot was developed by researchers such as Yu Jinsu [2]. As well as Sun et al.'s personalized exoskeleton system for fingers with a non-contact leader-follower control strategy both cutting-edge as well as moving towards being more convenient and intelligent [3]. Overall, finger exoskeleton rehabilitation robots are moving towards being smarter, more efficient, and user-friendly.

The purpose of this paper is to investigate the application and optimization of ultrasonic sensors in finger exoskeleton robot rehabilitation training. The subsequent paper will first give the overall system architecture, then describe the proposed innovative application methodology, which mainly utilizes the dynamics and control system to realize the study, and finally analyze the pros and cons and the future outlook of the study and its main future work.

2. System design

2.1. System architecture

The system architecture of this study includes a finger exoskeleton robot body, an ultrasonic sensor module, and a control and data processing unit. The exoskeleton robot is responsible for providing the required motion assistance and support for rehabilitation training [4]; the ultrasonic sensor module accurately detects the position and motion status of the finger; and the control and data processing unit analyzes the sensor data, generates control commands according to the preset algorithms, and adjusts the robot's motion parameters in real-time to achieve personalized and precise rehabilitation training and to ensure that the system operates efficiently and stably.

In this study, TURCK ultrasonic sensors RU600U-M30E-2UP8X2T are used, and their excellent stability and reliability are suitable for long-term accurate monitoring. The sensors are installed in the finger joints fingertips and other key positions, which can monitor the finger movement status in real time and provide accurate distance measurement and feedback information, providing data support for the rehabilitation training algorithm and robot control.

2.2. Structural design of finger exoskeleton rehabilitation robot

The design of the finger exoskeleton rehabilitation robot in this study takes into full consideration the physiological structure and movement characteristics of human fingers, aiming to provide patients with an efficient, comfortable, and personalized rehabilitation training experience. Lightweight materials are used to reduce the wearer's burden and ensure that patients can move their fingers easily.

The structure of the robot is divided into several parts, each corresponding to a different joint of the finger. The joints are designed to be flexible and adjustable to adapt to different finger sizes and shapes of patients, ensuring a snug fit without causing compression and enhancing comfort.

In terms of the design of the drive mechanism, this study skillfully integrates it into the structure to realize the precise control of finger movement. The drive mechanism smoothly transmits power to the joints, simulating the natural movement of the fingers, and accomplishing complex movements such as flexion, extension, adduction, and abduction.

This study also focuses on the appearance design to ensure that it is ergonomic, simple, and smooth, enhancing patient acceptance and facilitating clinical and home use. The overall structure has been optimized and verified many times to ensure its effectiveness and reliability in rehabilitation training and to provide strong technical support for finger rehabilitation therapy.

Fig. 1 shows a system analysis framework based on ultrasonic sensors. The ultrasonic sensor is in the core position, which on the one hand provides key motion parameters and data support for dynamics analysis, helping it to derive the robot's motion law and mechanical properties; on the other hand, it provides target position information and auxiliary positioning, as well as feedback information for control system analysis. On the other hand, it provides target position information and auxiliary localization, as well as feedback information for the control system analysis. The results of the dynamics analysis can provide the data basis for the control system analysis, to design a reasonable control strategy. The whole figure shows the interrelated and synergistic relationship among the three.

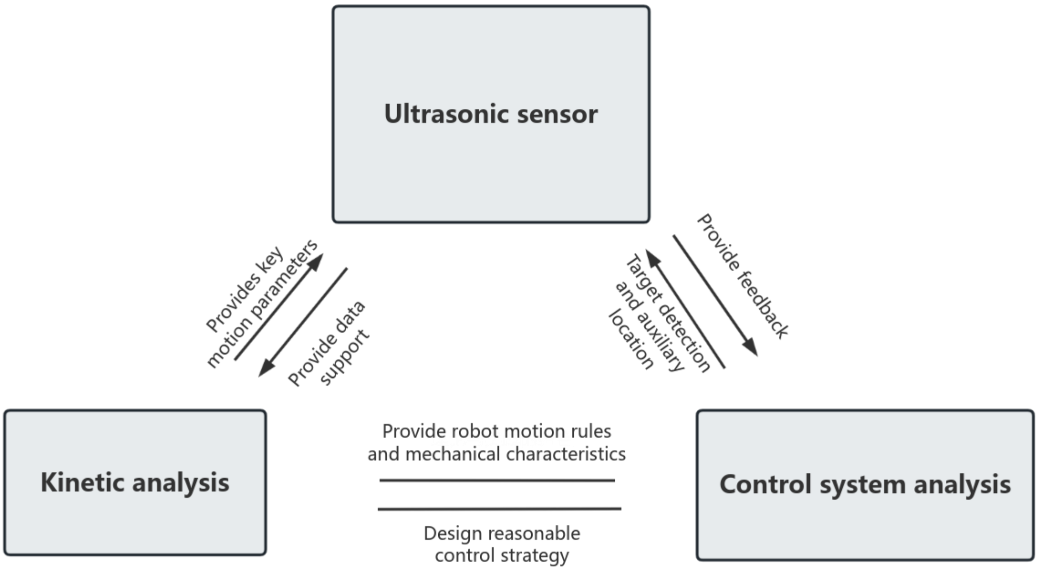

Fig. 1 Relationship of components in the study

2.3. Kinetic analysis

2.3.1 Overview of kinetic analysis

In the study of finger exoskeleton robots, the dynamics analysis based on ultrasonic sensors shows great value. Ultrasonic sensors provide a powerful tool for this study to deeply understand the motion characteristics of finger exoskeleton robots by their non-contact measurement, high accuracy, and fast response [5]. By establishing an accurate dynamics model that incorporates key parameters such as distance, angle, and velocity obtained from ultrasonic sensor measurements, this study can more accurately characterize the dynamic relationship between the finger and the exoskeleton. Using advanced dynamics analysis methods and Lagrangian equation solving, this study can deeply investigate the effects of different parameters on the dynamic performance of the finger exoskeleton robot and provide a solid theoretical foundation for optimizing the design and control strategies.

2.3.2 Kinetic modeling

In the process of modeling the dynamics of this finger exoskeleton robot, the Lagrangian method is chosen in this paper [6]. The Lagrangian method can provide strong support for the study with its unique advantage of characterizing the dynamics based on the energy of the system. By properly defining the generalized coordinates, the kinetic and potential energies of the system can be accurately calculated, and then the robot dynamics equations can be deduced based on the Lagrangian equations. This not only reflects the beauty of mathematics but also reflects the interactions between robot components and the laws of motion, which lays a theoretical foundation for control strategy design and performance analysis.

For the ultrasonic exoskeleton rehabilitation robot, it can take the hand-finger joint angle as the generalized coordinate and set it as n finger joints, and the generalized coordinate is $q = [q1, q2, ..., qn]$. Kinetic energy and potential energy including the part of finger joints and exoskeleton are calculated by using the Lagrangian function $L = T - V$. The generalized force Qi is calculated by external forces and moments (e.g., the driving moment of finger joints and external force of exoskeleton), which is substituted into the Lagrangian equation to get the equation of motion of the system, and solving it can be obtained as the rule of change of the angle of hand-finger joints over time to describe the robot's motion.

2.4. Control system design

2.4.1 The role of ultrasound in control systems

Ultrasonic sensors can measure the distance and posture between the finger and the exoskeleton in real time to achieve three-dimensional position and posture detection, as well as obstacle detection and force feedback control, and the data is fed back to the control system to optimize rehabilitation training [7].

2.4.2 Control system design

According to the structure and motion characteristics of the robot, the ultrasonic sensors are reasonably arranged to ensure that information such as the distance between the finger and the exoskeleton, posture, and contact force can be accurately detected. The signals collected by the ultrasonic sensors are processed to remove noise and interference and extract useful information [8]. Techniques such as digital filtering and signal amplification can be used to improve the quality of the signal. Based on the feedback signals from the ultrasonic sensors, a suitable control algorithm is designed to realize the precise control of the robot. Advanced control algorithms such as proportional-integral-derivative (PID) control, fuzzy control, sliding mode control, etc. can be used to improve the performance and stability of the control system.

2.4.3 Principle of the PID algorithm

Define the control goals of the ultrasound exoskeleton rehabilitation robot to precisely control the angle of the finger joints, the speed of movement the amount of force, etc. These objectives can be determined according to the needs of rehabilitation therapy and the specific situation of the patient. Ultrasonic sensors are utilized to collect real-time information about the robot's state, such as the distance, angle, and speed between the fingers and the exoskeleton. These data will be fed into the PID controller as feedback signals. The actual values collected by the sensors are compared with the set target values and the error signal is calculated. If the goal is to control the angle of the finger joints at a specific angle, then the error is the difference between the actual angle and the target angle.

Proportional term (P): A proportionality control signal is obtained by multiplying a proportionality coefficient according to the size of the error. The size of the proportionality coefficient determines the speed of response to the error. A larger proportionality coefficient will make the system respond faster to the error but may lead to overshoot.

Integral term (I): integrates the error, i.e., accumulates the error over time. The integral term eliminates the steady state error, but if the integral coefficient is too large, it may result in a slower system response or integral saturation. Calculation formula:

$$\int_0^t e(T)dT \tag{1}$$

The integral term is approximated:

$$\mathrm{I(k) = I(k-1) + e(k)\Delta t/T_i} \tag{2}$$

Differential term (D): calculates the rate of change of the error, i.e., the difference between the current error and the error at the previous moment divided by the time interval. The differential term can improve the stability and dynamic performance of the system, but it is more sensitive to noise. Calculation formula:

$$\mathrm{D(t)} = \frac{de(t)}{dt} \tag{3}$$

Differential term approximation:

$$\mathrm{D(k) = (e(k) - e(k-1))/\Delta t \times Td} \tag{4}$$

The proportional, integral, and differential terms are summed to obtain the final PID control signal. The PID control signal is sent to the robot's drive actuators, such as motors or hydraulics, to adjust the motion of the exoskeletontoward the target state. In practice, the parameters of the PID algorithm (proportional, integral, and differential coefficients) need to be adjusted according to the performance of the robot and the effect of the rehabilitation treatment. In addition, MINIPC acquires the data from the ultrasonic sensors and uses a single-loop PID controller to regulate the movement speed of the fingers to ensure the accuracy and consistency of the movements [9].

The PID algorithm is applied in this rehabilitation robot for motion control of the finger exoskeleton. The data from the ultrasonic sensors are obtained through MINIPC and a single-loop PID controller is used to regulate the movement speed of the fingers to ensure accuracy and consistency of the movements. In addition, the transfer function obtained using system identification is tuned in Simulink, which is also applicable to optimize the control performance of the exoskeleton to improve its responsiveness and accuracy (Fig. 2).

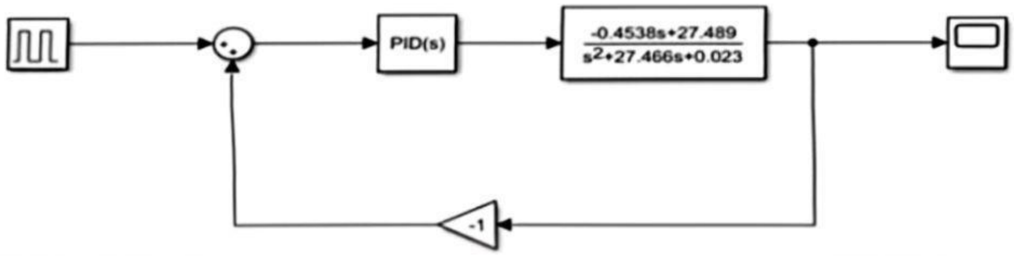

Fig. 2 Simulation of PID controller with Simulink [9]

2.4.4 YOLOv5 Target Detection and Recognition

In this study, the YOLOv5 target detection technique is applied to recognize the position and motion state of a finger in real-time.YOLOv5 is an efficient deep-learning model capable of detecting targets quickly and accurately in different environments. By training a specific dataset, its performance can be optimized so that it can effectively identify finger movement trajectories during rehabilitation training. The combination of this technology not only improves the feedback accuracy of finger exoskeleton robots but also provides patients with a more personalized rehabilitation experience and promotes the development of intelligent medical devices. Marker detection and recognition [10].

YOLOv5 is a single-stage target detection algorithm, which adds some new improvement ideas based on YOLOv4 so that its speed and accuracy have been greatly improved. The main improvements are as follows:

Input: In the model training phase, some improvement ideas are proposed, mainly including Mosaic data enhancement, adaptive anchor frame calculation, and adaptive image scaling;

Benchmark network: incorporating some new ideas from other detection algorithms, mainly including Focus structure and CSP structure;

Neck Network: The target detection network often inserts some layers between BackBone and the final Head output layer, FPN+PAN structure is added in Yolov5;

Head output layer: the anchor frame mechanism of the output layer is the same as that of YOLOv4, and the main improvements are the loss function GIOU_Loss during training and DIOU_nms for prediction frame screening.

3. Findings

3.1. The study design idea

This study aimed to evaluate the effect of finger exoskeleton robot rehabilitation training and designed a systematic experimental protocol. First, the purpose of the experiment was determined, i.e., to verify the facilitating effect of the exoskeleton robot on the recovery of finger function through data collection and analysis. Then, the preparation of the experiment was carried out, including the selection of suitable subjects, debugging of the finger exoskeleton robot and related ultrasonic sensors, PID controller, YOLOv5 detection system, and other equipment to ensure the stability and reliability of the experiment. During the experiment, the ultrasonic sensor collects the distance and attitude data between the finger and the exoskeleton in real-time. The YOLOv5 system detects the finger position and movement state. These data are transmitted to the control system, which analyzes and processes the data according to the PID algorithm and controls the movement of the exoskeleton robot. The data were recorded during the experiment and then sorted and analyzed after the experiment. The effect of the rehabilitation training was evaluated by comparing the functional recovery of the fingers and the changes in the movement parameters before and after the experiment, and the lessons learned were summarized according to the evaluation results, which provided a basis for the improvement of the subsequent research.

3.2. Challenges and perspectives of the study

In the design and optimization of a finger exoskeleton rehabilitation robot, the Lagrangian method was used to achieve dynamic modeling and motion analysis of the system. By establishing the equations of motion between robot components, the method not only provides in-depth kinematic characterization but also optimizes the motion control strategy to improve the efficiency and accuracy of rehabilitation training. For example, for the dynamic instability that may occur during complex tasks, the Lagrangian method provides a quantitative assessment tool, thus reducing the risk of falls for the user and ensuring safety. In addition, the method provides important data support for the development of personalized rehabilitation programs, enabling training plans to better meet the specific needs of patients, further enhancing rehabilitation outcomes. This research result provides a theoretical foundation and technical guarantee for the promotion of finger exoskeleton rehabilitation robots in clinical applications.

3.3. Future vision and main work of the project

For the finger exoskeleton robot rehabilitation training program, we have many ideas and planned the main direction of work in the future. On the one hand, we will continue to deepen the technology integration, further explore how to seamlessly integrate the PID algorithm, YOLOv5 technology, and Lagrangian method, solve the existing compatibility problems, and build a more stable and efficient control system architecture. On the other hand, we have invested more in algorithm optimization, such as in-depth study of adaptive PID algorithm based on deep learning, so that it can intelligently adjust the control parameters according to the patient's real-time rehabilitation status, and optimize the lightweight design of the YOLOv5 model to improve the detection speed and accuracy. At the level of sensor technology, we will focus on overcoming the problem of miniaturizing high-precision ultrasonic sensors, and actively research the integration of multi-sensor fusion, so as to realize a more comprehensive and accurate perception of patients' movement information by the finger exoskeleton robot. In addition, we plan to carry out large-scale clinical trials to collect abundant clinical data and improve the product based on the feedback of the data, so as to effectively improve the effectiveness and safety of rehabilitation training, and ultimately promote the widespread application and popularization of finger exoskeleton robots in the field of rehabilitation and medical treatment.

4. Discussion

In the study of the ultrasonic sensor finger exoskeleton rehabilitation robot, although the PID algorithm and Lagrangian method are used for system modeling and control, there are still some limitations. The Lagrangian method is applicable to linear systems, while the nonlinear nature of finger exoskeleton may lead to insufficient model accuracy. Meanwhile, the computational complexity may lead to real-time control delays and affect the dynamic responsiveness. In addition, performance fluctuations and measurement errors of ultrasonic sensors in different environments may also reduce the reliability and control accuracy of the system. Therefore, further research and improvement of control strategies are needed to achieve more efficient and safe rehabilitation training results.

Future research should focus on enhancing the performance of ultrasonic sensor finger exoskeleton rehabilitation robots. The accuracy and robustness of the system can be improved by exploring modeling methods (e.g., adaptive control and neural networks) applicable to nonlinear systems. In addition, combining multiple sensors for information fusion (e.g., IMU with vision sensors) can enhance environment sensing and improve adaptability in complex environments. Optimizing AI-based control algorithms (e.g., reinforcement learning) will enhance real-time responsiveness. Finally, personalization through user feedback will better meet the patient's rehabilitation needs.

Ultrasonic sensor finger exoskeleton rehabilitation robots show promising applications in the fields of personalized rehabilitation, aging social care, and sports medicine. The technology is capable of providing efficient rehabilitation training and assistive functions through real-time adjustment and intelligent control. Meanwhile, combined with telemedicine and data analysis, the exoskeleton robot not only customizes rehabilitation programs for patients but also promotes the in-depth development of rehabilitation research. With the advancement of technology, the robot will play an important role in improving patients' quality of life and accelerating the rehabilitation process.

5. Conclusion

This study focuses on the rehabilitation training of finger exoskeleton robots, and the integration of the PID algorithm, YOLOv5, and Lagrangian method is effective.

The PID algorithm collects ultrasound data with the help of MINIPC, accurately regulates the speed with a single-loop controller, and optimizes the performance through system identification and Simulink tuning to adapt to the patient and motion changes, while the YOLOv5 detects the state of the finger and accurately identifies the trajectory of the movement after training on a specific dataset, which is helpful for personalized rehabilitation and intelligent medical treatment. The Lagrangian method constructs a function to obtain the equations of motion, optimizes the design of the robot, and supports the control strategy to improve the rehabilitation effect.

Follow-up work will be promoted in various aspects, technically, PID algorithm to explore adaptive or intelligent algorithms, YOLOv5 optimization of structural parameters, Lagrangian method combined with modern control theory to expand; sensors, the study of high-precision and multi-sensor fusion, to provide an accurate basis for the rehabilitation training to enhance the quality of rehabilitation services for patients, and to promote the development of rehabilitation medicine.

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