A Walking-assistant Robot Controlled by Tactile-Slip Sensation

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Abstract:
A walking-assistant robot guided by the intention and power-driven is presented, its purpose is to provide physical support and walking assistance for the elderly to meet their needs of walking autonomy, friendliness, and maintaining the ability of walking and taking care of themselves. Tactile and slip sensor is selected as the human interface to perceive the user’s walking intent, and the sensor is also used to detect the user’s slip trend. And the paper researches the feature representation and extraction method of tactile and slip signal for driving control pattern recognition. An improved classification and identification method combining K-means in clustering and K-nearest neighbor algorithm in classification is proposed. The paper introduces the overall design schemes of tactile and slip drive control system of walking-assistant robot, perception system, motion control system. Finally the feasibility and effectiveness of the entire system are verified by experiment.

Keywords:
Tactile Sensor; PVDF; Walking-assistant Robot

1. INTRODUCTION

With the arrival of an aging society, the nursing care of elderly people has become an intractable social problem. The walking-assistant robot, which can effectively resolve the elderly problems with mobility difficulty caused by physical decline, function atrophy of sport organ and many other reasons, becomes one of the research focus in recent years. Therefore, it is essential to study a waking assistant robot which can capture the motion behavior and perceive movement intention and falling trends of the elderly people. So the elderly people’s quality of life will be greatly improved.

In recent years, although many studies have been performed on the walking-assistant robot, the walking-assistant robot is relatively rare which can sense the users’ walking intentions flexibly and intelligently [1–5]. The following studies: (1) Dubowsky developed Smart Cane [6], through a microphone & speaker and touch handle torque sensor sensed the users’ walking intentions. Using navigation map and user’s commands realized navigation. But this walking-assistant robot can only work on general flat ground or less than five degrees slope. (2) MacNamara (Irish), developed PAM-AID walker under the sponsorship of the National Rehabilitation Commission and EU information communication application [7]. This walking-assistant robot was designed to help the patients with poor vision or hypodynamic.
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control system used a handle which was suitable for the elderly and easy to operate as a human-machine interface. (3) In country-region China, Shanghai Jiao Tong University completed preliminary walking-assistant robot’s concept prototype [8], the prototype installed control handles on both ends above the carriage body frame to provide buttons to control the robot’s direction.

This paper proposes the overall design schemes of walking-assistant robot system, designs and develops tactile and slip perception system and control system. And finally it is feasible and effective for the studied walking-assistant robot through experiments.

2. THE OVERALL DESIGN OF WALKING-ASSISTANT ROBOT

Walking-assistant robot is a kind of robot system being intention-guided and power-driven, its purpose is to provide physical support and walking assistance for the elderly to meet their needs of autonomous walking, friendliness, and maintaining the ability of walking and taking care of themselves. The walking-assistant robot’s tactile and slip driving control system consists of tactile and slip perception system, control system, mechanical structure and so on. The entire system block diagram is shown in Figure 1.

Figure 1. The overall system block diagram of walking-assistant robot.

The tactile and slip sensor array is placed on the walk-assistant robot’s handle. The signals which the sensors collect through signal processing, signal acquisition, feature extraction and pattern recognition are sent to the robotic controller based on DSP2812. The controller is mainly responsible for processing of sensor information and motor control, thus it achieves the control of the robot’s speed and direction.

3. PERCEPTION SYSTEM OF WALKING-ASSISTANT ROBOT

The main task of the detecting system is to perceive user's movement intention exerted on the robot. After recognition of walking intention, the results achieve robot control strategies through the robot drive control unit, and make the robot move in accordance with the user’s walking intention, meanwhile realize real-time feedback and interaction between the walker and robot. After considering the sensors’ installation and user’s operation mode, tactile and slip sensor is chosen as the primary interface to detect users’ walking intentions [9].
3.1 Design and Development of Tactile and Slip Detection System of Walking-assistant Robot

Tactile and slip sensor, which has a tactile-slip sensation function, is a direct essential medium between the user and the robot. The sensitive material PVDF piezoelectric film is selected as the medium of tactile and slip sensor. PVDF piezoelectric film is the organic polymer material with most potential and has many advantages such as high toughness, high sensitivity, fast response, wide frequency range, high chemical stability, etc. These good performances make them widely adopted as a new type of intelligent sensor. It has a unique dielectric effect, piezoelectric effect, and also has good mechanical properties and flexibility. It is currently considered the best sensitive materials of robot’s tactile and slip sensors. Comparing with conventional piezoelectric material, it has wide frequency response, dynamic range, high sensitivity of electromechanical conversion, high strength of mechanical properties, and easy matching of acoustic impedance etc [10–14]. So it is suitable for this PVDF to be chosen as the robot’s tactile and slip sensor.

Tactile and slip sensor conditioning circuit block diagram is shown in Figure 2. The signal conditioning circuit includes charge conversion module, low-pass filter module, trap filter module, amplifier module, and protection circuit. Tactile and slip sensor under the external force will produce the charge. So firstly charge is converted to the corresponding voltage. Because the tactile signal frequency is generally not more than 100Hz, low-pass filter is selected for filtering the high frequency noise of the signal source. The output signal has the interference of 50Hz alternating current. To eliminate the interference of 50Hz alternating current, a notch filter is designed. Because the maximum sampling voltage of AD sample port is 3V, the collected signal must be processed to make the input voltage range in normal sampling range. The 2 zener diodes IN4007 are selected to limit the output voltage. The tactile and slip sensor conditioning circuit diagram is shown in Figure 3.

For experimental convenience, tactile and slip sensor offline detection system was set up, as shown in Figure 4. The AD of TMS320F2812 achieves signal of six tactile and slip sensors real-time acquisition and processing. The converted data is transmitted to high-speed USB communication chip CY7C68013 FIFO cache, and then is transferred to PC via the USB data bus to achieve data storage, display and data processing. The offline system can fully meet the requirements for high accuracy and real time, and meet the needs of data transmission.

![Figure 2. Tactile and sliding sensor conditioning circuit block diagram.](image)

3.2 Discrimination Technology of Walking-assistant Robot Perception System

3.2.1 Tactile and Slip Signal Feature Extraction and Representation

The tactile signal is produced when the object contacts with the sensor and produces contact force. Slip signal produces when the object and the sensor are relatively slipping and produces the tangential force between the surface of object and sensor along the slip direction. Tactile and slip sensors share the
same signal source. In order to separate the tactile and slip signal in the same signal, the characteristics of tactile and slip signal are derived. Tactile and slip signal characteristics are as follows:

\[
\max = \max(x_i) \tag{1}
\]

The signal minimum value:

\[
\min = \min(x_i) \tag{2}
\]

The signal mean value:

\[
\text{mean} = \frac{1}{N} \sum_{i=0}^{N-1} x_i \tag{3}
\]

The signal variance:

\[
\text{Var} = \frac{1}{N} \sum_{i=0}^{N-1} (x_i - \text{mean})^2 \tag{4}
\]

Experimental system collects tactile and slip signal when the user manipulates the robot and analyzes them as the research object. Figure 5 and Figure 6 show the experimental results of typical tactile and slip response signal when a user grasps handrail. Evidently, they have the obvious difference.
Through the data analysis, it is clear that the tactile signal has a single high peak, and the amplitude is higher than slip signal, so the mean of a certain length signal is chosen as tactile characteristic value. Slip signal has a number of smaller amplitude peaks in the unit time, so the variance of a certain length signal is chosen as the slip characteristic value. The generation of tactile and slip is judged through the threshold method. When the tactile feature value is greater than the threshold, it is suggested that tactile generates; when the slip characteristic value is greater than the threshold, it is suggested that slip generates.

Therefore, the output signal means of six-channel tactile and slip sensors are as characteristic and form the feature vector to use action pattern recognition of the experimenter. The feature vector is expressed as $X_k$: $X_k = [x_{k1}, x_{k2}, x_{k3}, x_{k4}, x_{k5}, x_{k6}]$. $x_{k1}, x_{k2}, x_{k3}, x_{k4}, x_{k5}, x_{k6}$ are respectively tactile and slip signal mean of the 1-6 sensor.

![Tactile signal acquisition diagram.](image1)

![Slip signal acquisition diagram.](image2)

### 3.2.2 Walking Intention Recognition Method Based on the Improved KNN Classification

KNN classification algorithm is a very effective nonparametric classification algorithm. The algorithm is that: by calculating nearest distances between the unknown sample and the training samples to find the k nearest neighbors, the category of an unknown sample is determined according to the category of
k nearest neighbors [15–20]. Although the advantage of KNN algorithm is high accuracy, it requires some known category data as training samples. And artificial category is laborious and time-consuming. Clustering algorithm is a kind of automatic learning method, and it does not require to label the category for the learning sample. But the learned model is not accurate enough under the absence of supervisory information, and it will not get satisfactory learning results. According to this characteristic, we propose the classification and recognition method that classification algorithm are combined with clustering algorithm. The main steps of the algorithm are as follows:

1. A clustering algorithm is selected to cluster the training samples, and the cluster centers are found;
2. According to a method, representative data is selected from each class as the training samples;
3. The training samples are used to construct classification algorithm;

The method does not need the category of the known samples. And after clustering, a part of data is selected as learning samples. So it greatly saves the calculation time. So in order to improve the efficiency of KNN, this paper adopts the improved KNN classification algorithm, and the efficiency of classification is greatly improved. The method based on clustering and classification method uses K-means to cluster the unknown category data, and then uses k-nearest neighbors to predict judgment, and achieves rapid classification purpose.

According to definition of the walking intentions, there are 5 different types, namely, “forward”, “backward”, “turn left”, “turn right” and “no operation”. A group data sets have been collected $Y = \{Y_1, Y_2, ..., Y_N\}$, $Y_i$ represents a sample;

Algorithm steps: (1) using K-means to cluster the data sets $Y$:

a) The initial cluster centers are selected: $X_1^1, X_2^1, X_3^1, X_4^1, X_5^1$ (The code of right foot is the iteration that finding the clustering centers). $X_1^1 = [0.448, 0, 0.235, 0, 0, 0]$; $X_2^1 = [0, 0.492, 0, 0.184, 0, 0]$; $X_3^1 = [0, 0.252, 0.174, 0, 0, 0]$; $X_4^1 = [0, 0.535, 0, 0.182, 0, 0]$; $X_5^1 = [0, 0, 0, 0, 0, 0]$. $X_1^1, X_2^1, X_3^1, X_4^1, X_5^1$ are respectively the standard forward, backward, left, right, static pattern feature vector. They are used as the initial cluster center.

b) The remaining data is classified. Take a sample $Y_i$, if $|Y_i - X_m^j| < |Y_i - X_m^l|$ (i =1,2,..,N; j =1,2,..,S; l=1,2,..,S; j ≠ l; m is the iteration),$Y_i \in S_m^j$. $S_m^j$ is the sample set that the cluster center is $X_m^j$.

c) Calculate the new cluster centers:

$$X_m^{j+1} = \frac{1}{n_j} \sum_{Y \in S_m^j} Y_i (j = 1, 2, ..., 5)$$

(5)

$n_j$ is the sample number of $S_m^j$.

d) If $X_m^j = X_m^{j+1}$, the program ends, otherwise let m = m+1 and go b).

Through the above method, it is got that $Y = S_1 \cup S_2 \cup S_3 \cup S_4 \cup S_5$ (the data sets $Y$ is divided into 5 categories, $S_1, S_2, S_3, S_4, S_5$ represent forward, backward, turn left, turn right, no operation);

(2) Using improved KNN method to classify unknown data.

a) In Step (1), the data quantity of $S_1, S_2, S_3, S_4, S_5$ is $n_1, n_2, n_3, n_4, n_5$, calculating the cluster centers $Y_i$.

$$\max = \max(x_i)$$

(6)
b) Calculating the Euclidean distance from clustering center of all the categories $\overline{Y}_i$ to the point $Y_i$ in that category, calculating the maximum Euclidean distance of each category $d_i$ and the maximal value \( d = \max_{i=1,2,\ldots,5} \{d_i\} \) in the 5 categories.

c) Each category clustering center and the distance between each point in its category divided by \( l \times d \) \( l \) is large enough to make the regional formed by all categories small enough.

d) Selecting \( k \) to satisfy the condition \( k = \min (n_1, n_2, n_3, n_4, n_5) \), \( k \) is integer.

e) The classification of unknown data: the assumption that unknown category data $Y_s = (y_1, y_2, y_3, y_4, y_5, y_6) \in \mathbb{R}^6$, according to the k nearest neighbor method, the distance is simply calculated between data and each cluster center $\overline{Y}_i$ (\( i = 1, 2, 3, 4, 5 \)), if \( \min_{1\leq i \leq 5} (d_{si}) = d_{si} \), you can determine $Y_s \in S_i$.

\[
d_{si} = d(Y_s, \overline{Y}_i) = \sqrt{\sum_{l=1}^{6} (Y_{sl} - \overline{Y}_il)^2}
\]  

(7)

4. THE MOTION CONTROL SYSTEM OF WALKING-ASSISTANT ROBOT

The quality of control system is directly related to its performance. In order to realize the speed without static error in steady state and have good dynamic characteristics, a double loop control system was chosen, in which a PI controller was adopted in the speed and the current loop, the overall structure is shown in Figure 7.

The walking-assistant robot control system is divided into three parts: control section, execution section and detection section. A double closed-loop scheme (current loop and speed loop) is adopted in the control system. The control section mainly includes motor control and movement algorithm. Execution section is mainly composed of a bodywork platform, two brushless DC motors and two universal wheels. The detection section includes the detection of output signals from the tactile sensors and the joystick, together with the detection of current, speed and fault. The users’ movement intentions are detected by making use of the tactile detection system. According to the intention recognition results, the robot control system achieves the corresponding control strategy. In addition, when users walk a long time or being inconvenient in walking, they can also sit in the seat to operate the robot.

The work process of the whole control system is as follows: The AD of TMS320F2812 achieve signals real-time acquisition and processing of tactile and slip sensors. And through the motor control algorithm they will be transformed into PWM output, at last the drive circuit module drives the two brushless DC motors and therefore can realize the movement of the walking robot.

5. EXPERIMENTAL VERIFICATION AND RESULT ANALYSIS

The elderly-assistant & walking-assistant robot is set up in the laboratory by the integration of tactile and slip detection system, tactile and slip signal analysis system and walking robot control system. And some experiments have been done. By using the parameter \( k \) (k-nearest neighbor method) obtained from each of the experimenter data under the highest off-line recognition rate, the online experiment
should be done for pattern recognition of each pattern, and the driving experiment of the walking-assistant robot should also be performed at the same time. The experiment focuses on the walking-assistant robot moving forward and backward, turning left and right, keeping static and action combination. So the walking-assistant robot is the driving and control object of the tactile and slip signals, and the driving control unit of the walking-assistant robot uses the recognition results of the tactile and slip signal to realize the corresponding action.

We do an online walking intention recognition experiment for one experimenter by using the detection and recognition system of tactile and slip. Figure 9(a) shows the result of the forward pattern. Figure 9(b) shows the result of the backward pattern. Figure 9(c) shows the result of turning left pattern. Figure
9(d) shows the result of turning right pattern.

![Figure 9. The result of the different pattern.](image)

Table 1. The highest online recognition rate.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Accuracy (%)</th>
<th>Average (%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>S₁</td>
<td>S₂</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>95</td>
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<tr>
<td>4</td>
<td>95</td>
<td>90</td>
</tr>
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The accuracy of offline classification of forward (S₁), backward(S₂), left(S₃) and right(S₄) was given.

We did the experiments on 4 experimenters when the experimenters sat in the seat and walked. And each experimenter repeats each action 50 times (30 times for training, 20 times for testing). According to the frequency of various patterns, the online recognition rate can be correctly obtained as shown in Table 1. The experiment also proves that the recognition rates of the experimenters under the two conditions are same. So the detection system and recognition method of the tactile and slip senses are effective so as to realize the driving control of the elderly walk-assistant robot.

6. SUMMARY

In this paper, the overall system, perception system and motion control system of the walking-assistant robot are introduced, and the results of the field experiment are given. From the experimental results, the robot system can accurately respond to the intention of users, and can guarantee the comfort and safety of the walking process. The assistant behavior can be implied efficiently and rapidly, so the effectiveness of
the robot can be verified.

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**References**


