Intelligent Bed Robot System: Pose Estimation Using Sensor Distribution Mattress

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Abstract—In this paper, an Intelligent Bed Robot System (IBRS) is proposed, that is a special bed equipped with robot manipulator. To assist a patient using IBRS, pose and motion estimation process is fundamental. It is designed to help the elderly and the disabled for their independent life in bed without other assistants.

Index Terms—Intelligent bed robot system, pressure sensor distribution bed, pose and motion estimation.

I. INTRODUCTION

The increase in the life span of many elderly people means that there are more demands for aids to support them in normal life. It is a fact that the general improvement in living conditions has increased the number of elderly persons (over 60 years old) [1]. It is increasingly important that robots assist humans at home because of the forthcoming aging society problem.

Usually, one third or a quarter of life is spent for being in bed. Especially, peoples who need care usually spend the whole day for being in bed. If their movements are measured and evaluated quantitatively, not only robots can assist humans properly, but also theses data can be used for a health monitoring and an evaluation of rehabilitation progress.

Body movements are very important for humans to live. Moving the body makes humans take adaptive behavior to the outside world. It is said that physical conditions and mental conditions are buried in the body movements, because humans often move their bodies when they are in good health, but move rarely their bodies when they are in bad health. Therefore, it is thought that physical and mental conditions can be estimated by measuring the body movements.

Body movement can be classified by its size [2]. Fig. 2 shows the classification of body movement. The existence means only whether the human exists or not. The posture is a static pose. The articular movement means a dynamic motion such as twisting or bending motions. The body movement can be categorized into a gross movement and a slight movement. The gross movement is mainly produced by skeletal muscle. The slight movement is mainly produced by cardiac muscle or smooth muscle. Under the pulse, it includes small convulsion or internal organs’ movements.

A measuring system which has sensors attached to a human body directly is usually for the body movement or posture estimation. There is the system that can recognize postures using accelerometers [3]. Although this system can measure the body movement or posture accurately, many sensors must be attached to the body to measure accurate movements. Since attaching many sensors to the body produces mental burdens and restricts person’s activities, it is difficult to measure unaffected body movements. In order to measure unaffected body motions, sensors need to be attached not to the body but to an environmental side as a bed.

Many researches are performed for body motion tracking by using video camera [4], [5], [6]. However, it is difficult for these systems using video camera to extract motion features because the body is lost of sight in a quilt.

Static charge sensitive bed is famous for monitoring the body movements in bed. It can measure respiration, a heart rate and twitch movements [7]. Temperature sensors distribution bed can measure gross movements such as body turns [8]. Pressure sensor distribution bed is applied in many researches [2]. Harada et al. [2] has applied Pressure sensor distribution bed to estimate the body posture. His approach was based on the body model. This approach estimated the subtle posture and motion between main lying postures (supine and lateral posture). Since the body model had lots of model parameter determined, it takes lots of calculation time to determining the posture.

In our system, the control of manipulator is performed
from the result of patient’s posture and motion estimation. Therefore, short calculation time is required to control the manipulator based on posture estimation.

In this paper, we propose the IBRS, which is capable of estimating the patient’s posture and motion on bed in real-time and supporting the patient using manipulator. Section III briefly introduces the research background for designing IBRS and the proposed system. In Section IV, the algorithm for estimating the patient’s posture is described. Experimental results and conclusion are followed in Section V and VI.

II. SURVEY BEFORE SYSTEM DESIGN

We have asked several questions for designing the efficient bed robot system. In this paper, we will focus on below three questions. These questions relate to the life style of users and the function that they hope the bed to do. These questions played an important role in determining of the function and mechanism of bed robot system.

**Question 1: How much time do you spend in bed?**
This question is asked for the life style of users and is important for weighting the following question 2 and 3. The result of this question is as follows.

<table>
<thead>
<tr>
<th>Number of answerers</th>
</tr>
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<tbody>
<tr>
<td>Less than 10 hours</td>
</tr>
<tr>
<td>Less than 15 hours</td>
</tr>
<tr>
<td>More than 15 hours</td>
</tr>
</tbody>
</table>

From the this question, users who stay in bed for more than 10 hours is about two times as many as users who stay for less than 10 hours. This result means the following question 2 and 3 is meaningful.

**Question 2: What is the most inconvenient thing in bed?**
This question is asked for knowing the inconvenient thing in current bed system, and taking the design idea of bed robot system. The answerers had a chance to select multi-answer. The result of this question is as follows

<table>
<thead>
<tr>
<th>Number of answerers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement between bed and wheelchair</td>
</tr>
<tr>
<td>Movement on bed</td>
</tr>
<tr>
<td>Management of feces and urine</td>
</tr>
<tr>
<td>Reading book or newspaper</td>
</tr>
<tr>
<td>Avoidance of decubitus</td>
</tr>
<tr>
<td>Eating</td>
</tr>
<tr>
<td>Hobbies</td>
</tr>
</tbody>
</table>

This result shows that main inconvenient things of current bed system, which the disable feel, is the movement either on bed or between bed and wheelchair. It is because they cannot use his arms and legs freely, so that he tumbles down and slips on bed. So we think that the robotic structure with supporting bar is better.

**Question 3: Which of robotic system do you like?**
This question is asked for preference of robotic design and function. Three selection cases were offered. One is current comfortable bed system, which does not have robot arm, but only comfortable mattress. Another is the robot system with supporting structure, which is suggested from question 2. The other is the various-functional robot system with robot arm, which can help the user to do things such as eating, carrying cup or book, and so on.

<table>
<thead>
<tr>
<th>Number of answerers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current comfortable bed system</td>
</tr>
<tr>
<td>Pressure sensor distributed bed</td>
</tr>
<tr>
<td>Robot system with supporting structure</td>
</tr>
<tr>
<td>Various-functional robot system with robot arm</td>
</tr>
<tr>
<td>Etc.</td>
</tr>
</tbody>
</table>

From the results of the above three questions, we can summarize the requirements the disabled/elderly need on the bed as two following sentences.

**Requirement 1**: Equipments are required to hand over or pick up anything such as book in the shelf.

**Requirement 2**: Equipments are required to support and assist their body to even a little bit movement on the bed.

III. SYSTEM DESCRIPTION

Most previous researches have a focus on the system which can monitors the patient’s posture and motion on bed. In this paper, we will propose the robotic system which can actively help the patient using robotic manipulator. While there exists the patient on the bed, the pressure sensors monitor his posture and motions. When he moves on the bed, the robotic manipulator can support his body.
Before we design an intelligent bed robot system, we conducted a survey of patients’ opinion on IBRS at a rehabilitation center and hospitals in Korea. At the survey, we made a questionnaire focused on activities in bed, the functionality of IBRS, and difficulties in doing something without assistant. The survey said that people with motor difficulties in their legs need assistant in doing body movement for posture change or taking a ride on a wheel-chair. They also answered a robot system supporting the stability of body posture during movement would be helpful.

A. Pressure Sensors Distribution Bed

In order to realize unrestraint estimation of gross and slight movements, we distributed pressure sensors over a bed surface. Vertical motions against the bed surface can be estimated by measured pressure and horizontal motions can be estimated by the positions of the pressure sensors.

Force Sensing Resistor is applied as a pressure sensor. The FSR is a thin film sensor which is made from piezoresistive polymer. The resister value of the FSR decreases in proportion to applied force on the active surface. Measurement range of force is up to 10kg/cm². The size of pressure sensor pad is 1900×800×12mm. A spatial interval is 70mm to vertical direction and 50mm to horizontal direction. This sensor pad is divided into three modules in order to correspond to reclining beds.

A pressure sensor control box can select one of the pressure sensors and read the selected pressure sensor’s value. There are so many pressure sensors to get pressure values at one time, so the pressure sensor control box scans pressure sensors one by one by using the multiplexers, reads one of pressure sensors’ value and transmits this sensor’s value to the computer. Pressure distribution is measured as a pressure distribution image. Sampling frequency of the images is 10Hz. Its resolution is 1 dimension in these application is usually small. But, the pressure distribution image in our system has a high dimensional property. The pressure distribution image has 336 features (equal to the number of FSR sensors).

Due to the high redundancy present in the pressure distribution image vector, principal component analysis (PCA) was used to reduce the dimensionality of data. PCA is a multivariate statistical technique that can be used to calculate the principal directions of variability in data and to transform the original set of correlated variables into a smaller set of uncorrelated variables. The new uncorrelated variables are linear combinations of the original variables. These principal components represent the most important directions of variability in a dataset.

PCA is an optimal representation criterion in the sense of mean square error, however, it does not consider the classification aspect. To improve the classification performance, one should combine PCA with some classification criterion, such as RBF classifier.

IV. POSTURE AND MOTION ESTIMATION

The mass of the body and the force produced by the muscle generate the pressure on the FSR sensors attached on the mattress.

Normally, RBF neural networks are widely used for function approximation and pattern recognition wherein the pattern dimension in these application is usually small. But, the pressure distribution image in our system has a high dimensional property. The pressure distribution image has 336 features (equal to the number of FSR sensors).

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A. Principal Component Analysis (PCA)

Let a pressure distribution image \( Z_i \) be a two-dimensional \( m \times n \) array of intensity values. An image may also be considered as a vector of dimension \( m(=m_w \times m_h) \). Denote the training set of \( n \) pressure distribution images by \( Z = (Z_1,Z_2,\ldots,Z_n) \subset \mathbb{R}^{m \times n} \), and we assume that each image belongs to one of \( c \) classes. Define the covariance matrix as
follows:
\[
\Gamma = \frac{1}{n} \sum_{i=1}^{n} (Z_i - \bar{Z})(Z_i - \bar{Z})^T
\]
\[
= \Phi \Phi^T
\]
(1)
where \( \Phi = (\Phi_1, \Phi_2, \ldots, \Phi_n) \subset R^{m \times n} \) and \( \bar{Z} = (1/n) \sum_{i=1}^{n} Z_i \). Then, the eigenvalues and eigenvectors of the covariance matrix \( \Gamma \) are calculated. Let \( U = (U_1, U_2, \ldots, U_r) \subset R^{m \times r} (r < n) \) be the \( r \) eigenvectors corresponding to the \( r \) largest eigenvalues. Thus, for a set of original of pressure distribution images \( Z \subset R^{m \times n} \), their corresponding eigenimage-based feature \( X \subset R^{r \times n} \) can be obtained by projecting \( Z \) into the eigenimage space as follows:
\[
X = U^T Z.
\]
(2)

B. RBF Neural Network

An RBF neural network can be considered as a nonlinear mapping: \( R^r \rightarrow R^r \).

Let \( P \in R^r \) be the input vector and \( C_i \in R^r (1 \leq i \leq u) \) be the prototype of the input vectors. Usually, the Gaussian function is preferred among all possible radial basis functions due to the fact that it is factorizable. The output of each RBF unit is as follows:
\[
R_i(P) = \exp \left[ -\frac{||P - C_i||^2}{\sigma_i^2} \right] \quad i = 1, \ldots, u
\]
(3)
where \( || \cdot || \) indicates the Euclidean norm on the input space, and \( \sigma_i \) is the width of the \( i \)th RBF unit. The \( j \)th output \( y_j(P) \) of an RBF neural network is
\[
y_j(P) = \sum_{i=0}^{u} R_i(P) \times w(j,i)
\]
(4)
where \( R_0 = 1 \), \( w(j,i) \) is the weight or strength of the \( i \)th receptive field to the \( j \)th output and \( w(j,0) \) is the bias of the \( j \)th output.

C. Hybrid Learning

Hybrid learning is used for the adjustment of RBF parameters. The adjustment of RBF parameters is a nonlinear process while the identification of weight \( w(i,j) \) is a linear one. A hybrid learning algorithm combines the gradient paradigm and the linear least square (LLS) paradigm to adjust the parameters.

1) Weight Adjustment: Let \( r \) and \( s \) be the number of inputs and outputs respectively, and suppose that \( u \) RBF units are generated. For any input \( P_i \), the \( j \)th output \( y_i \) of the system is
\[
Y = WR
\]
(5)
Given \( R \in R^{u \times n} \) and \( T = (T_1, T_2, \ldots, T_n)^T \in R^{s \times n} \), where \( n \) is the total number of sample patterns, \( T \) is the target matrix with exactly one “1” per column that identifies the processing unit to which a given exemplar belongs. Then, find an optimal coefficient matrix \( W^* \in R^{s \times u} \) such that the error energy \( \bar{E}^T \bar{E} = (T - Y)^T (T - Y) \) is minimized. This problem can be solved by the LLS method.
\[
W^* = T(R^T R)^{-1} R^T
\]
(6)
where \( R^T \) is the transpose of \( R \), and \( R^* = (R^T R)^{-1} R^T \) is the pseudoinverse of \( R \).

2) RBF Parameters Modification: Here, the parameters (centers and widths) of the prototypes are adjusted by taking the negative gradient of the error function \( E_c \)
\[
E_c = \frac{1}{2} \sum_{c=1}^{n} (t_{ik}^c - y_{ik}^c)^2 \quad c = 1, 2, \ldots, n
\]
(7)
where \( y_{ik}^c \) and \( t_{ik}^c \) represent the \( k \)th actual output of RBF classifier and the target output at the \( c \)th pattern, respectively.

By the chain rule, the error rate with respect to center \( C \) and width \( \sigma \) can be derived from (7) as follows:
\[
\Delta C^c(i,j) = -\xi_1 \frac{\partial E_c}{\partial C^c(i,j)}
\]
\[
= -\xi_1 \frac{\partial E_c}{\partial y_{ik}^c} \frac{\partial y_{ik}^c}{\partial C^c(i,j)} R_j^c \quad i = 1, 2, \ldots, r, \quad j = 1, 2, \ldots, u
\]
\[
= 2 \xi_1 \sum_{k=1}^{u} (t_{ik}^c - y_{ik}^c) \cdot w^c(k,j) \cdot R_j^c
\]
\[
\Delta \sigma_j^c = -\xi_2 \frac{\partial E_c}{\partial \sigma_j^c}
\]
\[
= -\xi_2 \frac{\partial E_c}{\partial y_{ik}^c} \frac{\partial R_j^c}{\partial \sigma_j^c}
\]
\[
= 2 \xi_2 \sum_{k=1}^{u} (t_{ik}^c - y_{ik}^c) \cdot w^c(k,j) \cdot R_j^c
\]
(8)
where \( \Delta C^c(i,j) \) is the central error rate of the \( i \)th input variable of the \( j \)th prototype at the \( c \)th training pattern, \( \Delta \sigma_j^c \) is the width error rate of the \( j \)th prototype at the \( c \)th pattern, \( P(i,l) \) is the \( i \)th input variable at the \( l \)th training pattern and \( \xi \) is the learning rate.

V. EXPERIMENTAL RESULTS

Figure 6 shows the developed system, which has pressure sensor distributed bed and two robotic arm.

Mainly four kinds of postures on the bed (supine, right lateral, left lateral, and sitting posture) are considered in this paper. These postures were used for body posture estimation process. In our system, discrimination that the current patient’s posture belongs to the posture class is more important than the fact such as opening degree of legs. The patient’s motion and intension are estimated from changes between the posture classes. The proposed algorithm was applied to estimate pose and motion.

Figure 7 shows the postures to be estimated. In our research, 93.6% success rate for pose estimation was obtained.
Fig. 6. Intelligent Bed Robot System.

(a) supine (b) right lateral

(c) left lateral (d) sitting

Fig. 7. Postures to be estimated.

VI. CONCLUSION

In this paper, the unrestraint human pose and motion estimation system using the pressure sensor distribution bed was described. This system is thought to be used for analyzing the body pose and motion, assisting the patient with robotic manipulator. Furthermore, it can be used for a health monitoring and evaluation of rehabilitation progress and so on.

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REFERENCES