Research on Wearable Sensing for Constructing Human Comfortable Environments

毛，昊珉

(Degree)
博士（工学）
(Date of Degree)
2023-09-25
(Date of Publication)
2024-09-01
(Resource Type)
doctoral thesis
(Report Number)
甲第8741号
(URL)
https://hdl.handle.net/20.500.14094/0100485925

(別紙様式3)

論文内容の要旨

氏　名　毛　昊珉

専　攻　電気電子工学

論文題目（外国語の場合は，その和訳を併記すること。）

Research on Wearable Sensing for Constructing Human Comfortable Environments

（人が快適と感じる環境構築のためのウェアラブルセンシングに関する研究）

指導教員　寺田 努　教授

There is an interactive relationship between humans and the environment, which means humans and the environment affect each other. Generally, people look forward to living in a comfortable environment. Constructing a comfortable environment for humans requires proper evaluation of current environmental conditions or accurate quantification of people's subjective feelings. Only the environmental conditions cannot reflect the comfortable levels of people in the current environment, but quantifying people's feelings is not easy. Thus, we considered that some metrics from humans, which illustrate environmental conditions' effects and people's subjective feelings, can be used as references for constructing comfortable environments. In this thesis, we adopted physiological indicators of the human body and comfort indices as the metrics because physiological indicators of the human body directly reflect the whole or a part of the state of a person, and comfort indices directly reflect the comfortable levels of people on a specific characteristic of the current environment.

On the other hand, with the development of wearable sensing technology, wearable sensors have become more miniaturized, portable, and flexible, which are easier to measure human biometric data. Although wearable sensors can measure most physiological indicators of the human body, some indicators are inconvenient to be measured directly because of depending on large or expensive instruments. Thus, this thesis focused on constructing comfortable environments by estimating human physiological indicators for inconveniently measured ones.

The comfort indices can reflect not only the comfortable levels of people affected by the environments but also the changes in the state of the human body caused by external conditions. However, the comfort indices cannot be directly measured after all. Human comfort can be divided into many types with people's physical and spiritual sensations, such as visual, acoustic, thermal, air, behavioral, emotional, and psychological. Most of these comfort indices are quantified into a particular scale based on people's subjective feelings. According to the definition of indices and the approaches to creating the indices, some comfort indices are determined by some elements from humans and the environment, and sensors can measure these elements directly. Therefore, this thesis focused on estimating comfort indices based on wearable sensing technology to construct comfortable environments.

This thesis aimed to build a baseline for constructing comfortable environments with indirectly estimated physiological indicators and comfort indices based on wearable sensing technology. We built the baseline following constructing a comfortable environment with an indirectly estimated human physiological indicator based on wearable sensing technology, constructing a comfortable environment with an indirectly estimated comfort index based on wearable sensing technology, and improving the comfortable environment by optimizing the accuracy of the evaluation of the comfort index and the procedure of obtaining the comfort index based on wearable sensing technology. We combined four topics to elaborate on estimation methods for a physiological indicator and a comfort index, and optimization of the estimation results and acquisition procedure of the comfort index under some conditions.

The first topic focused on constructing a comfortable hat environment using scalp moisture content as a physiological indicator. The most critical factors affecting scalp health are surface temperature, environmental humidity, and scalp moisture content. If the three factors could be kept in a proper range, scalp health would be guaranteed. Scalp temperature and environmental humidity can be measured directly by sensors. The instruments for measuring the scalp moisture content are heavy and expensive, which are not easy to be carried on and be purchased by individuals. Therefore, we developed a hat-shaped device equipped with wearable sensors that can continuously collect scalp data in daily life for estimating scalp moisture with machine learning. We estimated the scalp moisture of fifteen experimental participants through four machine-learning models based on scalp surface temperature, core body temperature, internal hat temperature and humidity, external hat temperature and humidity, and heartbeat obtained from the hat-shaped device. The support vector machine (SVM) had the smallest mean absolute error (MAE) in the inter-subject evaluation, and the random forest (RF) had the smallest average MAE in the intra-subject evaluation. Also, we developed a cloud-service-based system for deploying the scalp moisture estimation results as an online service. When constructing a comfortable hat environment, people could refer to the fed-back estimated scalp moisture value of the system.

The second topic focused on constructing a thermally comfortable environment using human thermal comfort as a comfort index. Human thermal comfort is a human's psychological satisfaction with the current thermal environment, which could be qualified by the predicted mean vote (PMV) model in an indoor environment. Generally, human thermal comfort could be obtained by asking a questionnaire or calculating the PMV formula. We proposed a method to estimate thermal comfort using a small number of wearable and environmental sensors by machine learning. Wearable and environmental sensors measured biometric and environmental data shown in the PMV model, such as skin surface temperature, clothes surface temperature, heartbeat, environmental radiation temperature, wind speed, environmental temperature, and relative environmental humidity. The correct labels of human thermal comfort were obtained in a specially designed space with environmental control equipment. We estimated the human subjective and objective thermal comfort through three machine learning models. The RF had the best accuracy for estimating subjective thermal comfort for using all sensors, and the neural network had the best for estimating objective thermal comfort. Because the estimation error was relatively large when only one sensor was used, we confirmed that two sensors should be used to estimate the thermal comfort within an acceptable range of errors. Also, we developed a cloud-service-based system for deploying the human thermal comfort results estimated by a small number of sensors as an online service. When constructing a thermally comfortable environment, people could refer to the fed-back estimated thermal comfort value of the system.

The third topic verified whether sensor data could optimize the accuracy of estimation results of thermal comfort under various learning conditions by adding sensor data to the learning data based on estimating thermal comfort using image data with convolutional neural network (CNN) models. We trained 36 types of CNN models corresponding to 36 learning patterns and confirmed that sensor data could improve the estimation accuracy of thermal comfort in some cases. To construct a thermally comfortable environment using cameras, we could set up cameras in an indoor environment to identify the thermal comfort of people entering the room and combine image data and wearable sensor data to estimate the thermal comfort of people willing to wear wearable sensors.

Estimating human thermal comfort with CNN models requires lots of image data. Because acquiring image data with the assigned correct labels of human thermal comfort by asking people to answer a questionnaire is time-consuming, the fourth topic proposed a semi-supervised learning method for thermal comfort estimation by assigning estimated wearable sensor data labels to unlabeled image data with the same timestamp to optimize the procedure of label acquisition. We verified that the estimation accuracy of the proposed method was higher than that of the conventional self-training method, a representative semi-supervised learning method. The proposed method reduced the difficulty of the acquisition procedure of thermal comfort for constructing a thermally comfortable environment.

As mentioned above, this thesis claimed the approaches to constructing comfortable environments by feeding back indirectly estimated physiological indicators and comfort indices to the environment through online cloud services. We hope this thesis becomes a baseline for constructing comfortable environments with physiological indicators and comfort indices.

（別紙１）　　　　　　　　　　　論文審査の結果の要旨

氏名	毛　昊珉		
論文題目	Research on Wearable Sensing for Constructing Human Comfortable Environments （人が快適と感じる環境構築のためのウェアラブルセンシングに関する研究）		
審査委員	区　分	職　名	氏　　　名
	主　査	教　授	寺田 努
	副　査	教　授	塚本 昌彦
	副　査	教　授	沼 昌宏
	副　査	教　授	中村 匡秀
	副　査		

要　　　旨

There is an interactive relationship between humans and the environment, which means humans and the environment affect each other. Generally, people look forward to living in a comfortable environment. Constructing a comfortable environment for humans requires proper evaluation of current environmental conditions or accurate quantification of people's subjective feelings. Only the environmental conditions cannot reflect the comfortable levels of people in the current environment, but quantifying people's feelings is not easy. This thesis considered that some metrics from humans, which illustrate environmental conditions' effects and people's subjective feelings, can be used as references for constructing comfortable environments. This thesis adopted physiological indicators of the human body and comfort indices as the metrics because physiological indicators of the human body directly reflect the whole or a part of the state of a person, and comfort indices directly reflect the comfortable levels of people on a specific characteristic of the current environment.

On the other hand, with the development of wearable sensing technology, wearable sensors have become more miniaturized, portable, and flexible, which are easier to measure human biometric data. Although wearable sensors can measure most physiological indicators of the human body, some indicators are inconvenient to be measured directly because of depending on large or expensive instruments. Thus, this thesis focused on constructing comfortable environments by estimating human physiological indicators for inconveniently measured ones.

The comfort indices can reflect not only the comfortable levels of people affected by the environments but also the changes in the state of the human body caused by external conditions. However, the comfort indices cannot be directly measured. Human comfort can be divided into many types with people's physical and spiritual sensations, such as visual, acoustic, thermal, air, behavioral, emotional, and psychological. Most of these comfort indices are quantified into a particular scale based on people's subjective feelings. According to the definition of indices and the approaches to creating the indices, some comfort indices are determined by some elements from humans and the environment, and sensors can measure these elements directly. Therefore, this thesis focused on estimating comfort indices based on wearable sensing technology to construct comfortable environments.

This thesis aimed to build a baseline for constructing comfortable environments with indirectly estimated physiological indicators and comfort indices based on wearable sensing technology. The baseline was created by constructing comfortable environments with an indirectly estimated human physiological indicator and an indirectly estimated comfort index and improving the comfortable environment by optimizing the accuracy of the evaluation of the comfort index and the procedure of obtaining the comfort index based on wearable sensing technology. This thesis combined four topics to elaborate on estimation methods for a physiological indicator and a comfort index, and optimization of the estimation results and acquisition procedure of the comfort index under some conditions.

This thesis consists of 6 chapters. The content of each chapter is as follows. Chapter 1 is the introduction illustrating the background and purpose of this thesis. Chapter 6 summarized this thesis.

Chapter 2 focused on constructing a comfortable hat environment using scalp moisture content as a physiological indicator. The most critical factors affecting scalp health are surface temperature, environmental humidity, and scalp moisture content. If the three factors could be kept in a proper range, scalp health would be guaranteed. Scalp temperature and environmental humidity can be

氏名	毛　昊珉

measured directly by sensors. The instruments for measuring the scalp moisture content are heavy and expensive, which are not easy to be carried on and be purchased by individuals. Therefore, this chapter developed a hat-shaped device equipped with wearable sensors that can continuously collect scalp data in daily life for estimating scalp moisture with machine learning. The scalp moisture was estimated from fifteen experimental participants through four machine-learning models based on scalp surface temperature, core body temperature, internal hat temperature and humidity, external hat temperature and humidity, and heartbeat obtained from the hat-shaped device. The support vector machine (SVM) had the smallest mean absolute error (MAE) in the inter-subject evaluation, and the random forest (RF) had the smallest average MAE in the intra-subject evaluation. Also, this chapter developed a cloud-service-based system for deploying the scalp moisture estimation results as an online service. When constructing a comfortable hat environment, people could refer to the fed-back estimated scalp moisture value of the system.

Chapter 3 focused on constructing a thermally comfortable environment using human thermal comfort as a comfort index. Human thermal comfort is a human's psychological satisfaction with the current thermal environment, which could be qualified by the predicted mean vote (PMV) model in an indoor environment. Generally, human thermal comfort could be obtained by asking a questionnaire or calculating the PMV formula. This chapter proposed a method to estimate thermal comfort using a small number of wearable and environmental sensors by machine learning. Wearable and environmental sensors measured biometric and environmental data shown in the PMV model, such as skin surface temperature, clothes surface temperature, heartbeat, environmental radiation temperature, wind speed, environmental temperature, and relative environmental humidity. The correct labels of human thermal comfort were obtained in a specially designed space with environmental control equipment. Human subjective and objective thermal comfort were estimated by three machine learning models. The RF had the best accuracy for estimating subjective thermal comfort for using all sensors, and the neural network had the best for estimating objective thermal comfort. Because the estimation error was relatively large when only one sensor was used, this chapter confirmed that two sensors should be used to estimate the thermal comfort within an acceptable range of errors. Also, this chapter developed a cloud-service-based system for deploying the human thermal comfort results estimated by a small number of sensors as an online service. When constructing a thermally comfortable environment, people could refer to the fed-back estimated thermal comfort value of the system.

Chapter 4 verified whether sensor data could optimize the accuracy of estimation results of thermal comfort under various learning conditions by adding sensor data to the learning data based on estimating thermal comfort using image data with convolutional neural network (CNN) models. CNN models corresponding to 36 learning patterns were trained. Estimation results of CNN models confirmed that sensor data could improve the estimation accuracy of thermal comfort in some cases.

Estimating human thermal comfort with CNN models requires lots of image data. Because acquiring image data with the assigned correct labels of human thermal comfort by asking people to answer a questionnaire is time-consuming, Chapter 5 proposed a semi-supervised learning method for thermal comfort estimation by assigning estimated wearable sensor data labels to unlabeled image data with the same timestamp to optimize the procedure of label acquisition. This chapter verified that the estimation accuracy of the proposed method was higher than that of the conventional self-training method, a representative semi-supervised learning method. The proposed method reduced the difficulty of the acquisition procedure of thermal comfort for constructing a thermally comfortable environment.

This thesis proposed approaches to constructing comfortable environments by feeding back indirectly estimated physiological indicators and comfort indices to the environment through online cloud services. These approaches contribute to building a baseline for constructing comfortable environments. The submitted thesis satisfied the engineering research dissertation evaluation criteria, and the degree applicant Mao Haomin is acknowledged to obtain a Ph.D. (Engineering) degree.