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A Steward Robot to Help Daily Activities in a Smart House Environment [⋆]

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Abstract: Independence of the people in need in their activities of daily living becomes a matter of vital importance to any society in the years to come. As an approach to achieve independence, this paper addresses the problem of controlling assistive home environment emphasizing human-friendly human-machine interaction. To provide inhabitants with easily accessible, convenient, and cost-effective environment for independent living, we introduce a new service robot categorized into a steward robot as an intermediate agent between inhabitants and complex smart house environment. The learning capability and emotional interaction of the robot can enhance human-friendliness in various tasks. A learning system enables the robot to provide customized services by accumulating knowledge of the user's behavior patterns in daily activities. An emotional interaction system generates facial expressions to communicate with the user in a human-friendly manner. We have developed two types of steward robots: a software type to use everywhere by personal computing devices such as a PDA and a cellular phone, and a hardware type to provide tangible services with physical interaction by two robotic arms and a mobile base.

1. INTRODUCTION

The focus of advanced researches in designing automation systems has significantly shifted over the past decade from production and manufacturing areas to service sectors (Bien et al. [2005b]). Introducing various home automation systems, most of simple and repetitive tasks are executed by computers or microprocessors. We change the channel or volume of a television (TV) by simple click operation of a remote controller, while the early TV was manually operated by a human. These kinds of changes have been realized in almost all the electronic devices and home appliances. We can control home temperature by a telephone far from home and use several automated kitchen devices such as a coffee maker and a toaster. As modern technology comes into our living environment more closely, our desire to lead a more convenient and safe life is increasing. In some cases, we may wish to control home appliances in a simple and natural way or just by thinking.

The initial design of home automation has been recently expanded to a "smart house" concept, which incorporates advanced sensors and various automation facilities to make the existing house more comfort, convenient, and safe (Stefanov et al. [2004]). One of the very important user groups of a smart house in the future is believed to be the elderly and/or people with disabilities because the smart house is supposed to provide them with independence in mobility, manipulation, and human-machine communication as well as health and living conditions (Bien et al. [2005a]). It is instructive to note that the world is now acutely paying attention to the tendency of increasing percentage of the aged population and of non-decreasing statistics of people with disabilities, when projected into the years to come. Therefore, the shortage of care-givers for nursing the elderly is expected, which will be a serious problem in the near future. As a means of care-giving aids, a smart house can be an alternative to assist the elderly and people with disabilities improving their quality of life and doing a certain work instead of them in activities of daily living, since they have some limitations in doing the work with their own effort.

The effect of a smart house toward its inhabitants strongly depends on the list of automatic systems and the functionalities of devices that build the home environment. However, the increase of the number and the complexity of subsystems, to enhance available services in a smart house,

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can lead to the decrease of convenience, accessibility and cost-effectiveness, since it is difficult to control all the devices/systems using a lot of corresponding human-machine interfaces. The user should learn complicated procedures and commands of all the machines, and take cognitive load during the operation. For example, for a going-out task in our smart house (Intelligent Sweet Home) (Bien et al. [2004], Park and Bien [2003], Park et al. [2007]), the user initiates the task by using a voice and/or a hand gesture. An intelligent bed assists and supports the user in changing body posture on the bed. A robotic hoist moves to the bed and lifts up the user. An intelligent wheelchair also moves to take a docking with the robotic hoist, and then the robotic hoist lowers the user onto the wheelchair. Finally the wheelchair navigates to go out of the house. In this task, the user should command each step and remember the whole sequence of the commands.

As an alternative, we propose the concept of a "steward robot" which can help the inhabitant to operate all the subsystems easily in the smart house environment. Literally, a steward means someone employed in a large household or estate to manage domestic concerns such as supervision of servants, collection of rents, and keeping of accounts. We apply the same concept to a robotic agent in the smart house to perform a set of specific tasks for the inhabitant, i.e., the steward robot can be an intermediate agent between complex home environment and the end-user to enhance usability and convenience (Lee et al. [2005]).

In this paper, we introduce two types of steward robots. A software-type robot is represented by a virtual 3D avatar and can be accessed everywhere using personal computing devices such as a PDA and a cellular phone when a wired/wireless communication network is available. A hardware-type robot has been developed to provide active services such as delivering a meal, bringing an object, etc. with physical interaction by using two robotic arms and a mobile platform. Both types of robots have an intelligent processing module with learning and emotional interaction capability. Learning capability enables the robot to provide customized and proactive services depending on the preference and living behavior patterns of the user. The learning system collects environmental sensory information and the command history of the user to the target subsystems. Then, it reveals the empirical patterns from an incrementally drawn set of behaviors and appropriately controls the target devices based on the obtained knowledge (Lee et al. [2005]). In addition, if the user assigns a task name for a complicated sequence of commands or behaviors, the steward robot can be commanded later by the given name of a task such as "going-out." For more human-friendly interaction, the robots generate and express their own emotional state to the user.

This paper is organized as follows. In Section II, design philosophy is briefly described, and the structure and functions of the software-type robot are explained in Section III. Realization of a hardware-type robot is presented in Section IV, and conclusions follow in Section V.

2. DESIGN PHILOSOPHY

From the functional point of view, a smart house can be considered as a large-scale system including various assistive subsystems playing their inherent roles to provide the inhabitant with comfortable living conditions, independence and happiness (Bien et al. [2005a]). Therefore, the way of interaction between the inhabitant and the home-installed systems is a significant aspect in the design of a smart house especially for the elderly and people with disabilities.

The steward robot has been designed based on Leifer's design laws for service robots (Leifer et al. [1995]) and the idea that the technology and solutions for the service robot should be as human-friendly as possible, i.e. the robot should possess high level of intelligence in their control, actions and interaction with the users, offering them high level of comfort and functionality. When the user commands a predefined task in the smart house, the steward robot generates a sequence of subtasks, distributes subtasks to subsystems, and supervises actions of each subsystem to synchronize subtasks. This can reduce the cognitive load of the user and increase human-friendliness.

It is usually difficult to model and handle interaction between human beings and machines due to the variability of the user's status and uncertainty of the environment (Bien et al. [2005b]). Therefore, the acquired information in interaction, which includes physical, emotional, mental status and intention of the user, should be incorporated into the system to enhance human-friendliness. The steward robot should be able to provide personalized services autonomously in advance to the user's command with learning capability, and reflect the user's satisfaction degree on the knowledge database of living behavior patterns. It has also to be a more human-friendly interactive agent with its own emotional expression.

3. SOFTWARE-TYPE STEWARD ROBOT

3.1 Structure

Figure 1 shows a block diagram of the software-type robot and Intelligent Sweet Home. All home-installed systems are linked via a network for common control and information exchange. The user can directly control subsystems in the smart house using various human-machine interfaces, as well as command the steward robot to control subsystems indirectly using a voice command. The steward robot collects the user's commands to the subsystems and status information from health monitoring and environmental sensing devices, which are used in the learning module to recognize living behavior patterns and provide proactive services. Facial expression of a 3D avatar is generated in the emotional interaction module according to the service of the robot and the context of interaction.

3.2 Learning Module

During the last decade, a number of application platforms of smart houses have been developed to deal with a learning problem of living behavior patterns. Adaptive House developed at University of Colorado is based on an optimal

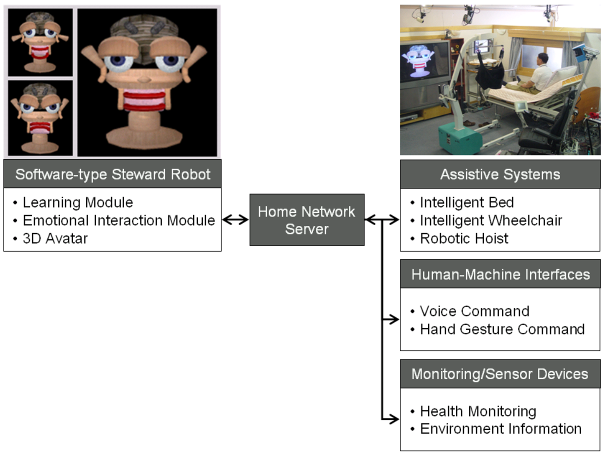

Fig. 1. Block diagram of the software-type steward robot and Intelligent Sweet Home

heating/lighting control scheme to minimize energy and discomfort cost using environmental sensory information and an artificial neural network (ANN) (Mozer [1998]). iDorm at University of Essex has been intended to control various home appliances automatically based on the inhabitant's life style using a fuzzy rule-based learning technique (Hagras et al. [2002], Duman et al. [2003]).

In this paper, we are focusing on the understandable representation of knowledge for behavior patterns to combine the obtained knowledge with the linguistic expression of the user's preference. In this sense, the fuzzy logic-based approach of iDorm is more relevant to our system, since an ANN expresses the accumulated knowledge by numerical weights between neurons while fuzzy logic generates knowledge-base in the way how human thinks with fuzzy terms and association rules from uncertain data. However, the learning system in iDorm requires predefined fuzzy partition of input space, and this can lead to lack of autonomy. Moreover, the improperly divided input space usually degenerates the performance of the system, and we have no guideline to divide the input space.

To relieve this limitation and construct efficient fuzzy partitions, we propose an algorithm called Iterative Fuzzy Clustering with Supervision (IFCS). Meaningful fuzzy partitions with a corresponding rule base are gradually obtained through an iterative process of selective fuzzy clustering with supervisory guidance based on cluster-pureness and class-separability. To describe the IFCS algorithm in more detail, we first define cluster-pureness and class-separability.

Let x_{jk} be the kth data with a class label $j, 1 \leq j \leq K$, and n_j be the number of data with the class label j. The cluster-pureness index P_i^α of the cluster i is defined by

$$P_i^\alpha = \frac{\max_{j\in\{1,2,\cdots,K\}} \sum_{k=1}^{n_j} \mu_{ijk} f\left(\mu_{ijk}-\alpha\right)}{\sum_{j=1}^{K}\sum_{k=1}^{n_j} \mu_{ijk} f\left(\mu_{ijk}-\alpha\right)}.$$

where μ_{ijk} is the membership value of x_{jk} for the cluster i and $f(\cdot)$ is a function satisfying

$$f(z) = \begin{cases} 1 & , z \geq 0 \\ 0 & , z < 0. \end{cases}$$

Table 1. Classification result for lamp control

Algorithm Algorithm	Number of Rules	Success Rate (%)
Conventional FCM using v_{XB}	21	98.2
Wang and Mendel's Method with 8-Grid Partitioning	923	94.2
Proposed IFCS ($\alpha = 0.4, S_{min} = 0.3, \epsilon_P = 0.001$)	2	98.2

Let $m_i^\alpha(j)$ and $\Sigma_i^\alpha(j)$ be the mean vector and the covariance matrix, respectively, of data satisfying $\mu_{ijk} \geq \alpha, k = 1, 2, \cdots, n_j$. Then, the class-separability S_i^α of the cluster i is defined by

$$S_i^\alpha = \max_{a \neq b} Sep_i^\alpha(a,b) N_i^\alpha(a) N_i^\alpha(b)$$

where

$$N_i^\alpha(j) = f\left(\sum_{k=1}^{n_j} f\left(\mu_{ijk}-\alpha\right) - 2\right)$$

$$Sep_i^\alpha(a,b) = \frac{1}{1+e^{-4.4\left(\lambda_i^\alpha(a,b)-0.5\right)}}$$

$$\lambda_i^\alpha(a,b) = \frac{1}{8}\left(m_i^\alpha(a) - m_i^\alpha(b)\right)^T \left[\frac{\Sigma_i^\alpha(a)+\Sigma_i^\alpha(b)}{2}\right]^{-1} \times \left(m_i^\alpha(a) - m_i^\alpha(b)\right) + \frac{1}{2}\ln\frac{\left|\frac{\Sigma_i^\alpha(a)+\Sigma_i^\alpha(b)}{2}\right|^2}{\sqrt{\left|\Sigma_i^\alpha(a)\right|\left|\Sigma_i^\alpha(b)\right|}}.$$

The learning algorithm is as follows.

1) We first perform initial clustering using the fuzzy c-means (FCM) algorithm with the cluster validity v_{XB} proposed by Xie and Beni (Xie and Beni [1991]), and find the first local minimum to get the number of clusters c with high reliability and high calculation speed.

2) We calculate the cluster-pureness P_i^α for each cluster i, and find i^* which corresponds to the smallest value of P_i^α and indicates the most mixed cluster containing data with different class labels.

3) For the cluster i^*, we calculate the class-separability $S_{i^*}^\alpha$.

4) If $S_{i^*}^\alpha$ is larger than a threshold value S_{min}, we perform re-clustering process using the FCM with the cluster validity v_{XB} for the data in the cluster i^*.

5) Using the newly obtained clusters, we generate a fuzzy rule base and get the recognition rate as a performance measure. If the recognition rate is not increased by a given value ϵ_P, the procedure is terminated. Otherwise, the procedure is repeated from 2).

To show the effectiveness of the proposed algorithm, we compared the recognition rates with conventional methods such as a fuzzy c-means algorithm and Wang and Mendel's method (Wang and Mendel [1992]) applying the algorithms to the on/off control patterns of a lamp in a house and using 7 features including internal/external temperature, illumination and time. Table 1 shows that the proposed IFCS algorithm obtains the comparatively high success rate with small number of rules.

Table 2. Emotion words of the steward robot

Emotion Word	Description of Expression	Event
Neutral	Default	
Like /Dislike	Sentiment relation between the user and the robot	The user calls the robot or the robot recognizes other individuals
Pride /Shame	Self-evaluation of praiseworthiness	A service task is initiated by the user of the learning module
Hope /Fear	Expectation for the user's evaluation	The service task is completed
Joy /Distress	Response to the user's evaluation for the service task	The user responds to the service task

3.3 Emotional Interaction Module

The emotional interaction module of the steward robot is based on the OCC emotion model (Ortony et al. [1988]) which handles interaction-related emotion words assigned from observation of human interaction. The upper part of Fig. 2 describes the structure of the OCC emotion model. The tree-structured model makes branches according to three main dimensions: consequences of events, actions of the robot, and aspects of the user. Using this model, Ortony addressed 22 emotion words related to real interaction (Ortony et al. [1988], Norman et al. [2003]), and we selected four pairs of two opposite emotion words: like/dislike, pride/shame, hope/fear, and joy/distress, considering services and interaction between the steward robot and the user in the smart house.

Each emotion word is assigned to the event in executing service tasks as shown in Table 2. When the robot is called by the user or recognizes other individuals, it generates 'like' or 'dislike' emotion according to the sentiment relation between the user and the robot. When the user commands or the learning module initiates a service task, the robot expresses 'pride' or 'shame' emotion based on the self-evaluation of praiseworthiness for the execution of the service. If the service task is completed successfully, the robot shows 'hope' emotion, and otherwise it expresses 'fear' emotion. The robot also generates 'joy' or 'distress' emotion according to the user's response or feedback. These emotion words are expressed as facial expressions of a 3D avatar as shown in Fig. 1.

To describe the sentiment relation in human-robot interaction, we adopt Heider's balance theory (Cartwright and Harrary [1956], Khanafiah and Situngkir [2004]), which discusses the relation among individuals based on sentiment. The sentiment relations are balanced between two people when they like or dislike each other, and if one has different sentiment, the relations become imbalance. In case of multiple individuals, the sentiment relations are balanced if the algebraic multiplication of signs in the relations has a positive value as shown in Fig. 3. Based on the predefined interpersonal relation of the user, the steward robot chooses an emotional word, 'like' or 'dislike', to make balance (Kim et al. [2005]).

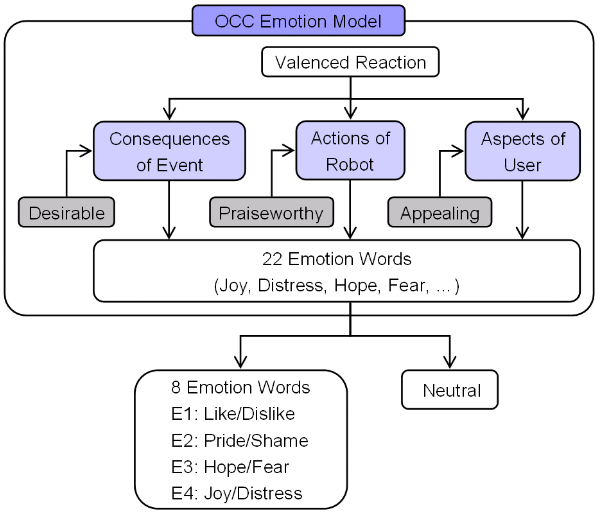

Fig. 2. Generation of 8 emotion words based on the OCC model

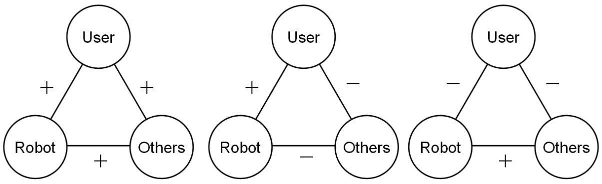

Fig. 3. Balanced sentiment relations in Heider's balance theory

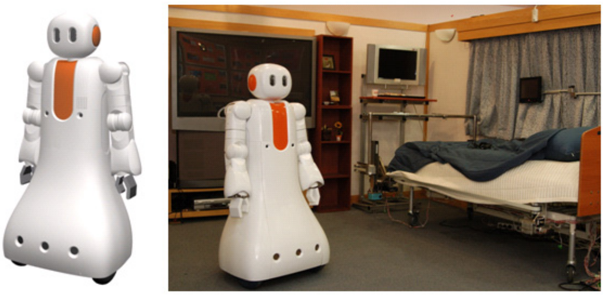

Fig. 4. Appearance design of hardware-type steward robot

4. HARDWARE-TYPE STEWARD ROBOT

4.1 Design

For a human-friendly appearance as shown in Fig. 4, we adopted sa-sang constitution theory which is a basis of Korean oriental medicine. In the theory, we categorize human into 4 groups (tae-yang-in, tae-eum-in, so-yang-in and so-eum-in) according to the appearance. Among these groups, we selected the so-eum-in since it is relevant to the steward due to the corresponding personality of so-eum-in (prudent, obedient, adorable and human-friendly). Finally, we selected orange color which represents joyful, lively and cheerful feeling.

4.2 System Specification

Figure 5 shows the structure of the hardware-type steward robot, which can provide active services using two robotic

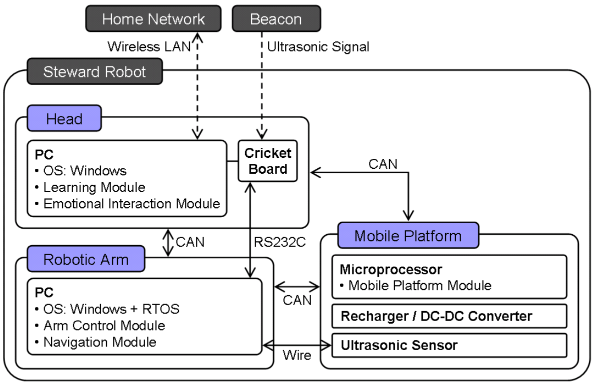

Fig. 5. Structure of the hardware-type steward robot

arms with grippers and a mobile base as well as control home appliances by accessing a home network server in the smart house. For the external communication with the home network server, a TCP/IP-based communication protocol has been defined. We also defined a CAN-based communication protocol with 8 bytes of data for the internal communication between each modules of the steward robot.

Hardware specification of the robot is as follows (Lee et al. [2005]).

- 2 DOFs for head motion
- 2 × (6 DOFs robotic arm + 1 DOF gripper)
- 2 wheel-driven mobile platform + 1 omni castor
- Ultrasonic sensor for obstacle detection
- Cricket board for localization
- DC-DC converting/recharging system
- $600mm \times 600mm \times 1100mm$
- 2 CPU + 1 microprocessor
- Wireless LAN for external communication
- CAN for internal communication

4.3 Description of Functions

Functions of the software-type robot, such as learning and emotional interaction capability, are implemented in the head part of the hardware-type robot. The learning module performs the management of tasks. For example, the steward robot controls subsystems in the smart house to support a meal and provide a going-out service. Based on the obtained fuzzy rule base from the user's behavior patterns, it controls home appliances such as an air conditioner, lamp, and television (TV), and also recommends the user's favorite TV channels. Emotional expressions are displayed using the animations of eyes and the predefined motions of the head and arms while performing service tasks as shown in Fig. 6. Localization of the mobile platform is achieved using selected three beacons among all beacons attached on the ceiling of the smart house for a global path generation. Ultrasonic sensors, attached on the body of the robot, are also used for online obstacle detection. For a power supply, a small DC-DC converter has been equipped in each subsystem, and a recharging system with an equalizer has been developed for efficient recharging of the battery.

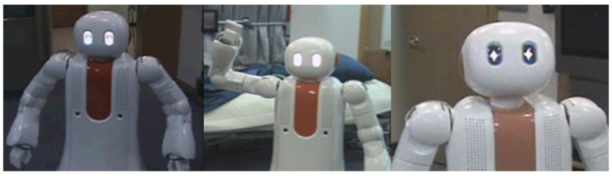

Fig. 6. Emotional interaction of the hardware-type steward robot

5. CONCLUSION

In this paper, we proposed a concept of a steward robot to appropriately provide the elderly and people with disabilities with various services in a smart house. To apply the concept to a robotic system, we studied the learning of the user's behavior patterns and the emotional interaction with the user, which are essential for the steward robot. To achieve the learning capability, we developed an algorithm called Iterative Fuzzy Clustering with Supervision (IFCS), and we adopted the OCC model and a Heider's balance theory for the emotional interaction. However, the investigations of subjective measures such as satisfaction degree from the end-users have to be carried out in further works.

REFERENCES

Z. Zenn Bien, J.-W. Jung, K.-H. Park, and F. Wong. Human-friendly man-machine interaction in smart home. *International Journal of Human-friendly Welfare Robotic Systems*, 6(3):31–38, 2005a.

Z. Zenn Bien, K.-H. Park, J.-W. Jung, and J.-H. Do. Intention reading is essential in human-friendly interfaces for the elderly and the handicapped. *IEEE Transactions on Industrial Electronics*, 52(6):1500–1505, December 2005b.

Z. Zenn Bien, K.-H. Park, D.-J. Kim, and J.-W. Jung. Welfare-oriented service robotic systems: Intelligent Sweet Home & KARES II. *Advances in Rehabilitation Robotics: Human-friendly Technologies on Movement Assistance and Restoration for People with Disabilities, Lecture Notes in Control and Information Sciences*, 306: 57–94, September 2004.

D. Cartwright and F. Harrary. A generalization of Heider's theory. *Psychological Review*, 63:277–292, 1956.

H. Duman, V. Callaghan, H. Hagras, M. Colley, G. Clarke, Z. Bien, H. Lee, and Y. Kim. A multi-agent pervasive computing architecture for geographically dispersed care environments. In *Proceedings of the 10th International Fuzzy Systems Association World Congress (IFSA 2003)*, Istanbul, Turkey, 2003.

H. Hagras, V. Callaghan, G. Clarke, M. Colley, A. Pounds-Cornish, A. Holmes, and H. Duman. Incremental synchronous learning for embedded agents operating in ubiquitous computing environments. In *Soft Computing Agents*, pages 25–55. IOS Press, 2002.

D. Khanafiah and H. Situngkir. Social balance theory. Technical Report WPN2004BFI, Dept. of Computational Sociology, Bandung Fe Institute, 2004.

Y. Kim, H.-E. Lee, and Z. Bien. A study on a new emotion factor, affective relation, for emotional intelligence of a sociable robot in human-friendly interaction environment. In *Proceedings of the 2005 International Con-*

ference on Human-Computer Interaction (HCII 2005), 2005.

H.-E. Lee, Y.-M. Kim, K.-H. Park, and Z. Zenn Bien. Development of a steward robot for Intelligent Sweet Home. *International Journal of Human-friendly Welfare Robotic Systems*, 6(4):57–64, 2005.

L. Leifer, G. Toye, and M. Van der Loos. Teleservice-robot: Integrating the socio-technical framework of human service through the internet-world-wide-web. In *Proceedings of the International Workshop on Biorobotics: Human-Robot Symbiosis*, Tsukuba, Japan, 1995.

M. C. Mozer. The neural network house: An environment that adapts to its inhabitants. In *Proceedings of the American Association for Artificial Intelligence Spring Symposium on Intelligent Environments*, pages 110–114, Menlo Park, CA, USA, 1998.

D. A. Norman, A. Ortony, and D. M. Russell. Affect and machine design: Lessons for the development of autonomous machines. *IBM Systems Journal*, 42(1):38–44, 2003.

A. Ortony, G. L. Clore, and A. Collins. *The Cognitive Structure of Emotions.* Cambridge University Press, 1988.

K.-H. Park, Z. Bien, J.-J. Lee, B. K. Kim, J.-T. Lim, J.-O. Kim, H. Lee, D. H. Stefanov, D.-J. Kim, J.-W. Jung, J.-H. Do, K.-H. Seo, C. H. Kim, W.-G. Song, and W.-J. Lee. Robotic smart house to assist people with movement disabilities. *Autonomous Robots*, 22(2):183–198, 2007.

K.-H. Park and Z. Zenn Bien. Intelligent Sweet Home for assisting the elderly and the handicapped. In M. Mokhtari, editor, *Independent Living for Persons with Disabilities and Elderly People*, volume 12 of *Assistive Technology Research Series*, pages 151–158. IOS Press, Amsterdam, The Netherlands, 2003.

D. H. Stefanov, Z. Bien, and W.-C. Bang. The smart house for older persons and persons with physical disabilities: Structure, technology arrangements, and perspectives. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 12(2):228–250, 2004.

L. X. Wang and J. M. Mendel. Generating fuzzy rules by learning from examples. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(6):1414–1427, 1992.

X. L. Xie and G. Beni. A validity measure for fuzzy clustering. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 13(8):841–847, 1991.