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Control of Human Thermal Comfort Using Digit Feedback Set Point Reset

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Abstract— **This paper presents a definition of human thermal comfort that can be used for control purposes. A control strategy and architecture based on a Proportional Integral Derivative (PID) controller format is developed. Simulation results using a human thermal model are used to demonstrate the practicality of the comfort definition.**

I. Introduction

In 1964, following the first American space walk, NASA adopted the Liquid Cooling Garment (LCG) as the primary means of removing heat from an astronaut. The literature indicates that it can remove up to 80% of an astronaut's metabolic heat depending on his work rate [2]. The temperature of the water flowing into the LCG, and hence its heat absorption or rejection rate, is manually controlled by the astronauts' manipulation of a chest-mounted dial, which can be problematic.

Research has shown that humans are poor estimators of their own thermal states [1]. This often results in over compensation when manual adjustments of the thermal environment are available. For the astronaut performing an extravehicular activity (EVA), this translates to a manual control effort costly in both time and resources as an astronaut hunts for thermal comfort. The increased number and duration of EVA missions in conjunction with satellite deployment, repair, retrieval, space station construction, and the proposed Mars missions would greatly benefit from automatic control of astronaut thermal comfort. Astronauts would be able to focus their attention on the tasks of the EVA. Additionally, automatic control of human thermal comfort has other applications. These applications include, fighter jet pilots, fire fighters, deep-sea divers, soldiers, hazardous waste workers, and any other occupations that require individuals perform stressful duties in enclosed suits and extreme environments.

The reported research focuses on the development of a control system for the Portable Life Support System (PLSS). For that reason, we present the details using figure 1 as the focus, and discussing each component of figure 1. Overall, the paper briefly discusses human thermoregulation, concepts of thermal comfort, hypotheses regarding thermal comfort, and known problems. It also presents results of simulations to test hypotheses, and develops a controller.

II. Human Thermoregulation

Human beings reject excess heat to the environment through tissues normally in contact with the air: the skin and air passages. Heat not removed via conduction, convection, radiation, and evaporation will contribute to heat storage in the body and its accompanying rise in core temperature. The heat load (metabolic rate minus mechanical work done), transferred from the body core and muscles to the skin, must equal the heat transfer from the skin to the environment in order for thermal equilibrium to exist.

It is reported that in order to maintain thermal equilibrium, autonomic mechanisms are called forth when internal and skin temperatures are changed from one steady-state level to another [7]. The primary control center for this thermoregulation is in the hypothalamus [17]. The autonomic mechanisms at the disposal of the hypothalamus are vasodilation, vasoconstriction, shivering, and sweating. In vasodilation the blood vessels in the skin of the peripheral areas of the body are dilated. This increases blood flow, which increases the heat rejection by the blood to the skin. Conversely, the body constricts these vessels to decrease heat flow. This is vasoconstriction. Shivering is the simultaneous asynchronous contraction of the muscles to produce heat [16]. Sweating is the secretion of fluid from the pores of the skin to allow cooling by evaporation. Human thermoregulatory actions follow the predictable sequence of vasomotor actions first, followed by sweating or shivering as required. There are combinations of metabolic rate and environmental conditions that will result in spontaneous sweating or

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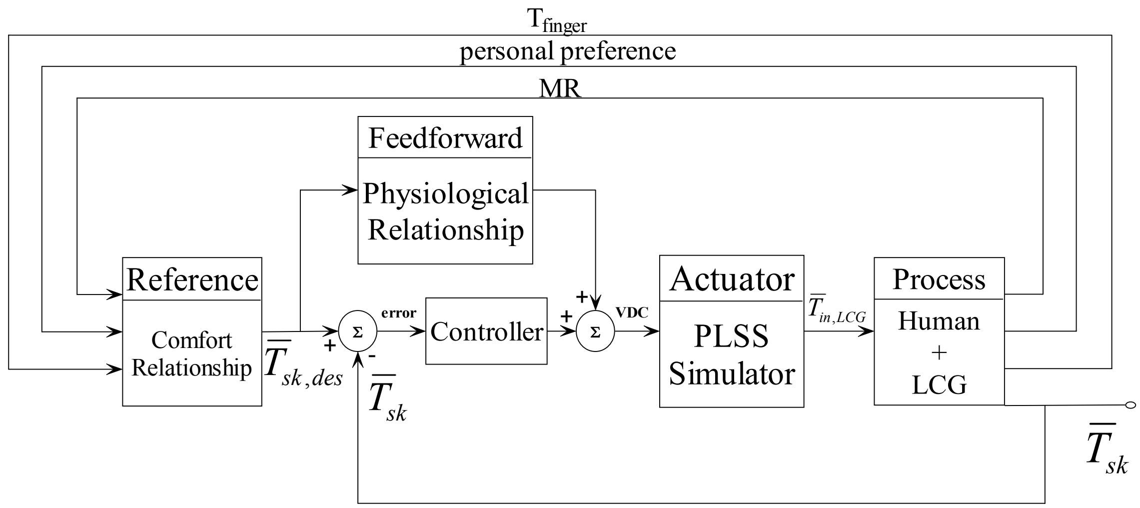

Fig. 1. Control System Block Diagram

shivering, but these are uncommon conditions.

The autonomic mechanisms previously discussed are not the only means by which the body accomplishes thermoregulation. The body also engages in behavioral thermoregulation which is a more powerful system than the autonomic system. Behavioral thermoregulation affects the metabolic rate and environmental conditions. It involves behavioral acts such as the removal of clothing, a change in posture, or the initiation of activity to cause heat generation in the muscles. An astronaut's manual adjustment of the space suit's chest mounted dial would be a behavioral change that establishes the temperature at which the skin rejects or absorbs heat via conduction. Both behavioral and autonomic systems continually interact to ensure thermal safety and comfort [17].

As mentioned previously, autonomic responses activating heat production and heat dissipation are called forth in order to maintain thermal equilibrium when internal and skin temperatures are changed from one steady-state level to another [7]. This indicates that the brain center for autonomic thermoregulation, the hypothalamus, has the intention of maintaining thermal equilibrium. Cabanac [14] reports that thermal comfort is a conscious perception and indicates dissociation between consciousness and the portion of the hypothalamus that controls the autonomic system. These important observations allow the distinction between two separate, but compatible thermoregulatory goals within the nervous system: thermal equilibrium and thermal comfort. This becomes important when defining human thermal comfort.

A. *Pertinent Past Human Thermal Comfort Results*

1) *Body Heat Storage Comfort Relation*

The present steady state thermal comfort definition used by NASA [11,6] consists of a linear relationship between metabolic rate and body heat storage for human thermal comfort. The relationship line:

$$Q_{nom,ss} = (\dot{M} - 278)/13.2 \qquad (1)$$

where $\dot{M}$ is the metabolic rate in BTU/hr and heat storage is in BTUs, defines the middle of a ± 65 BTU comfort band. Accurate measurement of body heat storage requires invasive measurement of one or more interior body temperatures, as well as accurate estimates of the specific heats of various body components.

2) *Mean Skin Temperature Comfort Relation*

Gonzalez et al. [15] report a linear relationship between the fraction of maximum oxygen consumption and mean skin temperature for thermal comfort. The upper bound of validity for the relationship is 40 $\%\dot{V}_{O_2}$ max, and the relationship is depicted in Eqn. 2.

$$\overline{T}_{sk,des} = 33.966 - 4.58\frac{\dot{V}_{O_2}}{\dot{V}_{O_2,max}} \qquad (2)$$

where $\overline{T}_{sk,des}$ is defined as the desired average skin temperature for comfort.

Average skin temperature is much more readily measured than body heat storage. With twelve temperature sensors positioned at specified locations on the body [10], average skin temperature can be measured with a standard error of 0.07 ºC and a correlation coefficient (R^2) of 1.00. Fewer sensors may be used and still have acceptable accuracy [10].

Prior efforts to maintain comfort by utilizing the relationship between metabolic rate and average skin temperature lacked physiological feedback in the controller, so the approach did not work for all subjects but could be customized for each. The lack of physiological feedback means that customization of the relationship for an individual could not accommodate intra-subject variations such as an increase in physical fitness.

III. Reference Component

A. Current Steady State Definition of Human Thermal Comfort

Thermal equilibrium can be maintained in an envelope of combinations of work rates and environmental conditions. If the body should see a combination outside this envelope, damage will occur and eventual death. Within this envelope, the maintenance of thermal equilibrium does not imply thermal comfort but does indicate relative thermal safety.

Since human thermoregulatory actions follow the predictable sequence of vasomotor actions first, followed by sweating or shivering as required, three overlapping envelopes can be inferred: 1. The first envelope consists of the combinations of work rates and environmental conditions at which the brain can maintain thermal equilibrium; 2. Within the first envelope exists the second envelope, which is a range of the combinations of work rates and environmental conditions where thermal equilibrium can be obtained primarily, if not solely, through the brain's use of vasomotor actions; 3. Within the second envelope exists the third envelope, which is a range of combinations of work rates and environmental conditions where primarily, if not solely, vasomotor actions are used to maintain a state of thermal equilibrium that will elicit no dissatisfaction from the conscious perception of the subject. The third envelope defines the present steady state thermal comfort definition. It is thus stated, *for a person to be in steady state thermal comfort their body must be in a thermal equilibrium maintained primarily if not solely by vasomotor actions and there must be a lack of dissatisfaction with this thermal equilibrium.*

This definition is defined only for relatively low metabolic rates, which for the present research constitutes work rates below 40 $\% \dot{V}_{O_2}$ max. A more general definition that can be applied across the complete range of metabolic rates is stated as thus; *comfort is the conscious subjective recognition and approval of a state of minimum thermoregulatory effort for the current metabolic rate* [13].

B. Proposed Control Architecture

The development of a steady state human thermal comfort controller begins with the recognition that the hypothalamus is the expert in human thermoregulation, giving physiological clues that indicate the body's thermal state and what its own thermoregulatory intentions are. An automatic control strategy should consist of an indicator of the body's thermal state and the hypothalamus's thermoregulatory intentions and assist the hypothalamus in achieving its intended goal. As mentioned previously, the hypothalamus's thermoregulatory goal is to maintain thermal equilibrium. This implies that a control strategy should consist of an indicator of the body's thermal state and the thermal equilibrium desired by the hypothalamus and assist the hypothalamus in achieving this thermal equilibrium.

As discussed earlier, human thermoregulatory actions follow the predictable sequence of vasomotor actions first, followed by sweating or shivering as required. This indicates that vasomotor actions in the fingers and toes can be used as clues of the body's thermal state and the thermal equilibrium desired by the hypothalamus. This is supported by Koscheyev et al. [9] who report that temperatures of the digits are good candidates for use in control of human thermal comfort because finger and toe temperatures telegraph the hypothalamus's intention to conserve heat or increase the heat rejection rate.

The practical requirements guiding the development of the comfort control hypothesis are that measurement of parameters and variables must be noninvasive to the human and that the controller should adapt to individual physiologies and personal preferences, thus being usable by anyone. Skin temperature measurement fulfills the requirement for noninvasive measurement and feedback of digit temperatures will allow the control strategy to adapt to intrasubject and intersubject variations in physiology. The use of permanent preferential biases will allow the control strategy to be adaptable to personal preferences.

It is thus hypothesized that comfort control at relatively low metabolic rates consists of using the LCG to maintain the body in a state of thermal equilibrium that can be achieved primarily, if not solely, by vasomotor actions. In addition, the changes in the finger temperature will indicate whether or not the body is in this state and what is needed to get the body to this state. It is further hypothesized that a preferential bias will be needed to insure that this state is a state that will elicit no dissatisfaction.

In achieving this, the average skin temperature comfort relation, as developed by Gonzalez et al. [15], is used to determine a baseline comfort skin temperature. The finger temperature is then used as a feedback signal indicating whether this baseline skin temperature set point is correct and if not, the amount of adjustment needed. This will require unknown relationships between finger temperatures, average skin temperature,

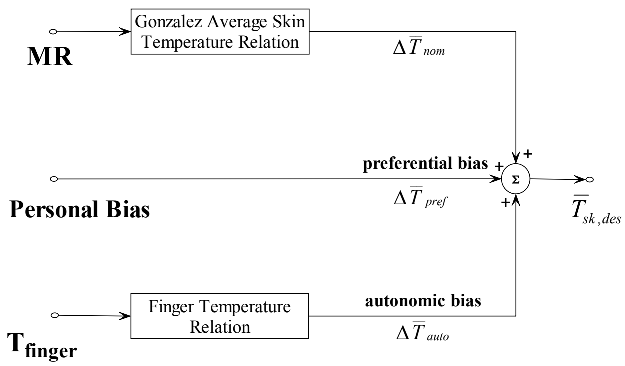

Fig. 2. Physiological Relation Block Diagram

desired average skin temperature, and perhaps rates of change of those variables.

Shown in figure 2, finger temperature feedback and preferential bias feedback provide fine adjustment of the baseline comfort skin temperature. These adjustments are referred to as autonomic bias adjustment and preferential bias adjustment respectively. The final adjusted temperature is the desired average skin temperature for comfort. This constitutes the comfort relationship of the reference component as shown in figure 1.

IV. FEEDFORWARD COMPONENT

It is known that in thermal equilibrium the body must dissipate its entire heat load via skin tissues through conduction, convection, radiation, and evaporation. If the heat transfer by all of these modes is constant as well as the heat load of the body during a steady state thermal equilibrium period, it is expected that the skin temperatures will stabilize to approximately the same values each time the exact conditions are encountered. (Factors controlling these approximate values include but aren't limited to body conditioning variations and body content variations; the variations will be inter- and intra- subject.) In verifying this, it is important that the body see an adequately long steady state period at these constant conditions so that the brain can dissipate or absorb access heat to compensate for any possible heat credits or deficits previously incurred.

Knowing that the environmental conditions around the subject are constant ensures that the rates of heat transfer by convection, radiation, and evaporation are constant. Placing subjects into the LCG and establishing a constant inlet temperature then insures a constant rate of heat transfer by conduction. Using this, experiments with the LCG will be performed to determine a relationship between LCG inlet temperature and mean skin temperature. This relationship will be used in the feedforward path of figure 1.

V. CONTROLLER

Figure 1 shows the placement of the controller. It illustrates the controller's role of indirectly modulating the LCG inlet temperature in order to influence the average skin temperature towards the desired average skin temperature set point. In the initial stages of experimentation a PID controller was used.

A. Using A PID Contoller

A PID (Proportional, Integral, Derivative) controller uses the error between the input set point and actual output. Its control signal is proportional to the weighted sum of this error, the rate of change of this error, and integral sum of this error. The following equation summarizes the output of a PID controller:

$$u(t) = K(e(t) + \frac{1}{T_I} \int e(t)dt + T_D \dot{e}(t)) \qquad (3)$$

where K is the proportional gain, $\frac{K}{T_I}$ represents the integral gain, KT_D represents the derivative gain, and e is the error. There are empirical strategies for determining the best values of each gain. These strategies are very time-consuming when applied to a complete control system that includes a process with a large time constant, as the human has. In this study, an empirical strategy was applied in a human thermal model and the gains roughly determined. They were then fine-tuned using experiments.

The empirical strategy used is known as the Ziegler-Nichols tuning method. It first determined the gain at which the closed loop human and LCG system with only a proportional gain would become marginally stable. It then calculated the proportional gain, reset time, and derivative time values using that gain and the period of the continuous oscillations. It ultimately produced controller gains that obtained a good closed loop response from the modeled human and LCG system.

VI. PLSS SIMULATOR (ACTUATOR)

The space suit configuration worn during EVA missions includes a Portable Life Support System or PLSS. As part of this system's functions, it provides conditioned water to the LCG. In experimentally testing the hypothesis an analogous system was needed. The apparatus developed at the University of Missouri for this purpose was termed the PLSS simulator. Its purpose in the control system, shown in figure 1, is to produce a controlled inlet LCG temperature, given an input signal from the controller.

VII. CONTROL SYSTEM

The block diagram in figure 1 is a schematic representing the complete closed loop control system. The components of this system have been previously discussed in detail and include: the human and LCG system, a relation determining the feedforward input, a relation determining the desired or reference input, a controller strategy, and the PLSS simulator or actuator. The control system incorporates these components in a feedback configuration with a total of four feedback variables.

The controlled output variable of the human and LCG system is the mean skin temperature. This is the only feedback variable used in the classical sense, to calculate an error for use by the controller. The remaining three feedback variables are used in the comfort relation to determine the desired mean skin temperature. The desired mean skin temperature is taken for feedforward to obtain a course adjustment of the control signal. It is also passed through a comparator with actual mean skin temperature prior to reaching the controller. The controller then performs fine adjustment of the control signal and the control signal is input to the actuator. The output of the actuator is the control input to the Human + LCG system, the LCG inlet temperature.

In the block diagram, $T_{sk,des}$ is the desired average skin temperature; T_{sk} is the actual average skin temperature; MR is metabolic rate; T_{finger} is finger temperature; VDC is the DC voltage and $T_{in,lcg}$ is the inlet water temperature to the LCG.

VIII. COMPUTER SIMULATIONS

This research used the 41-Node Man human thermal computer model to validate comfort relationships and tune the controller.

A. *Validation of Comfort Relationship*

The first simulations demonstrated that if a comfortable body heat storage existed as described by Waligora [11], the average skin temperatures for comfort described by Gonzalez et al. [15] existed, and vice versa. Therefore, a comfortable average skin temperature should indicate the existence of comfort conditions meeting NASA's current definition based on body heat storage. Figure 3 shows the results of simulations using the 41-Node Man human thermal model in which the body heat storage was controlled to conform to its comfort relationship for four metabolic rates.

The results show that the average skin temperature of the 41-Node Man at each metabolic rate is close to those specified by Gonzalez et al. [15]. Figure 4 shows the opposite case: the mean skin temperature was controlled to conform to the comfort relation developed

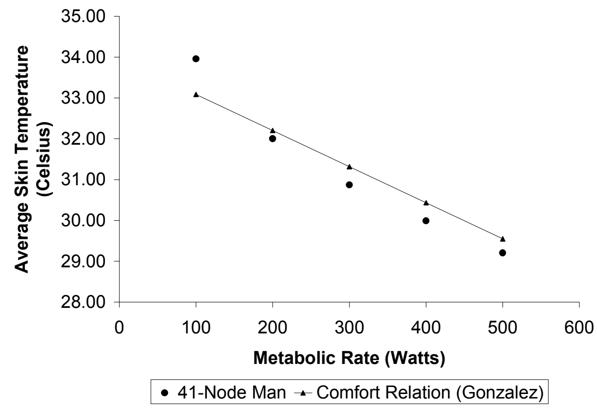

Fig. 3. Results of simulations in which the body heat storage of the human thermal model was controlled to conform to the body heat storage specified by Waligora for comfort [11,6]. The corresponding average skin temperature of the model is compared to the average skin temperature for comfort specified by Gonzalez et al. [15].

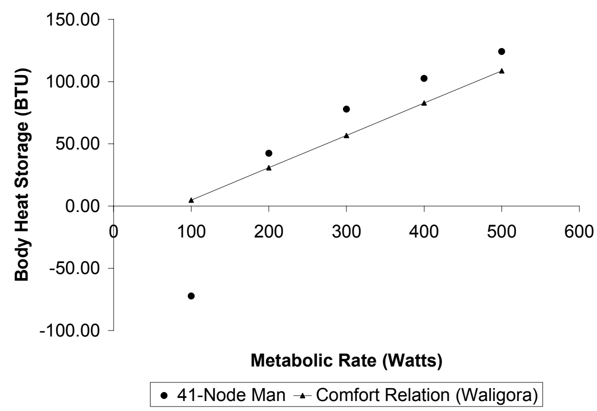

Fig. 4. Results of simulations in which the average skin temperature of the human thermal model was controlled to conform to the average skin temperature specified by Gonzalez et al. for comfort [15]. The corresponding body heat storage of the model is compared to the body heat storage for comfort specified by Waligora [11, 6].

by Gonzalez et al. and the body heat storage was discovered to be within the +/- 65 BTU band defining thermal comfort, according to the comfort relation developed by Waligora, for metabolic rates of 200, 300, 400, and 500 watts.

B. *Controller Tuning*

As discussed earlier, there are several empirical strategies for determining the PID controller gains. These strategies are very time-consuming in practice when applied to the human system. In this study, the Ziegler-Nichols tuning method was applied and MPLSS simulations were used to determine the PID gains for the subjects that will be used in the experiments. Simulations were started by setting integral = 0, derivative = 0 and proportional gain = 5 for a subject weighing 60 kg and 175 cm in height. The simulations were allowed to "warm-up" or reach a steady-state

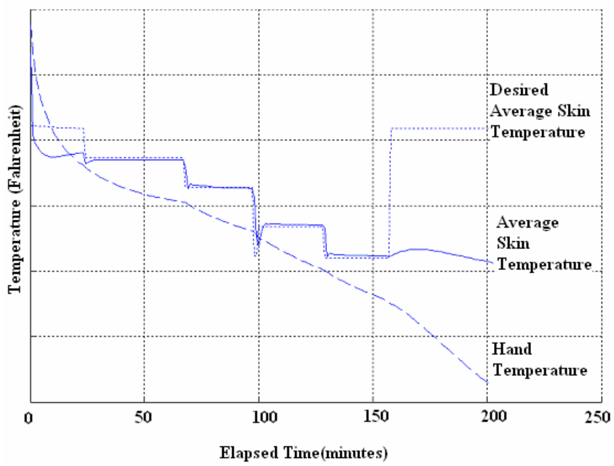

Fig. 5. PID controller performance

period. Then, the proportional gain was increased until continuous oscillations were observed, that is until the system became marginally stable. Ultimate Gain for this subject was 30 and the Ultimate Period was 363.64. Using these values, PID gains were calculated and these gains are as listed below: Proportional gain = 18; Integral gain = 181.82, and derivative gain = 45.45

The performance of the controller with these gains was verified by stepping down the average skin temperature set point as shown in Fig. 5. In the first twenty minutes (the first level) the model was allowed to reach steady state and controller performance was evaluated after the first step. The results show average skin temperature tracking its set point. However, small error is evident during both transient and steady state periods. The transient error during each step can be partially attributed to the human thermal response time delay. The set point was stepped instantaneously while the LCG inlet temperature and average skin temperature have first order dynamics. The steady state error can be attributed to a low integral gain. Controller performance can be improved with more tuning.

The large error during the last step is due to severe heat debt in the human. During the previous steps down in average skin temperature the resting human thermal model continually lost. This is shown by the decreasing trend in the hand temperature. The inlet LCG temperature was saturated during this time. A longer period would have seen a restoration of heat balance and thus skin temperatures to a normal level. This is representative of a series of simulations that have been run to investigate controller design.

IX. Conclusion

The hypotheses presented here regarding the automatic control of human thermal comfort are promising and have been successfully tested using simulations, but need real-world validation. Presently, the feedforward relationship and the finger temperature feedback relationship are being investigated. We are also beginning experiments with subjects using our human-thermal testing facility using Matlab/Simulink RTW interface for the experiments.

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