



(43) International Publication Date
14 September 2017 (14.09.2017)

- (51) **International Patent Classification:**
F24F 7/00 (2006.01) *G06F 17/11* (2006.01)
F04D 25/16 (2006.01)
- (21) **International Application Number:**
PCT/SG2017/050119
- (22) **International Filing Date:**
10 March 2017 (10.03.2017)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
62/307,223 11 March 2016 (11.03.2016) US
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(81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) **Title:** METHOD OF CONTROLLING A PLURALITY OF FANS DISPOSED IN AN AREA TO PROVIDE THERMAL COMFORT CONTROL, AND DEVICE THEREOF

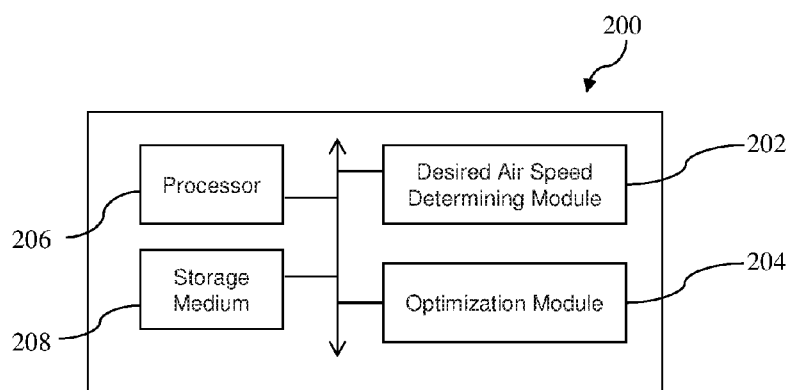


FIG. 2

(57) **Abstract:** There is provided a computer-implemented method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area. Each of the plurality of fans configured to generate air movement at an elevated air speed based on an operating parameter. The method includes determining desired air speeds at the plurality of target positions, respectively, and optimizing the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions in the area. There is also provided a corresponding device for controlling a plurality of fans.



Published:

— *with international search report (Art. 21(3))*

**METHOD OF CONTROLLING A PLURALITY OF FANS DISPOSED IN AN
AREA TO PROVIDE THERMAL COMFORT CONTROL, AND DEVICE
THEREOF**

5 **[0001]** This application claims the benefit of priority of United States Provisional Patent Application No. 62/307,223, filed 11 March 2016, the contents of which being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

10 **[0002]** The present invention generally relates to a computer-implemented method of controlling a plurality of fans disposed in an area, and a device thereof, to provide thermal comfort control for a plurality of target positions in the area.

BACKGROUND

15 **[0003]** Momentous percentages of global energy consumption are attributed to buildings and studies have found that energy consumption attributed to buildings accounts for about 37% of total energy consumption in the EU, about 39% of total energy consumption in the UK, about 40% of total energy consumption in the US, and about 51% of total electricity usage in Singapore. For end use, the heating, ventilation and air
20 conditioning (HVAC) system has been found to contribute to the largest building energy consumption, namely, about 47% in the US. In the tropics such as Singapore, 50% of building electricity usage is consumed by air conditioning. Raising cooling setpoint of air conditioning system in buildings can both bring financial benefits and reduce negative
25 impact on the environment, but doing so runs the risk of sacrificing the level of thermal comfort felt by occupants, which may directly influence their health, well-being and productivity.

[0004] Elevated air speed generated by fans (electric fans) is an effective and energy-efficient method of cooling people in moderately warm indoor and outdoor environments. Electric fans do not actually lower air temperature or air humidity to cool people as air
30 conditioners do. They cool people only by increasing the air movement around people to make human body release heat faster. This cooling approach can be used either in indoor

environments to assist air conditioning system with higher cooling set-point or in public outdoor environments such as bazaars and hawker centers (open-air food centers), where air conditioning is not applicable. Academic peer-reviewed research has demonstrated that personally controlled air movement using fans can maintain human thermal comfort in warm environments and strongly reduce energy usage.

[0005] Several types of fan speed control approaches have been disclosed in the past, and a number of the conventional approaches are briefly mentioned below.

[0006] U.S. Pat. No. 4,734,012 to Dob et al. describes a speed controlling circuit for reliable and cost effective fan or blower speed control in proportion to ambient temperature.

[0007] U.S. Pat. No. 5,197,858 to Cheng describes a thermal control variable speed DC brushless fan which may change speed in accordance with the temperature sensed. The change in the fan's rotation speed relation to the temperature is almost linear under normal conditions.

[0008] U.S. Pat. No. 5,449,275 to Gluszek et al. describes a fan speed controller which is able to maintain a constant level of thermal comfort by varying a fan speed in response to dry bulb air temperature, relative air humidity, thermal radiation and distance between a human body and a fan.

[0009] U.S. Pat. No. 5,627,527 to Menta describes an apparatus and a method for thermostatically controlling the operation of a multiple speed fan and light assembly by inputting a desired temperature range and airflow direction for each fan speed and by inputting a single number for controlling the on time and duration of the light assembly.

[0010] U.S. Pat. No. 6,415,984 to Parker et al. describes a ceiling fan operation control for turning the fan on and off based on a passive infrared sensor, combined with a temperature sensor to regulate the speed of the fan.

[0011] However, there are various problems/limitations associated with conventional approaches or technologies.

[0012] For example, none of the above-mentioned disclosures is applicable to a system of fans. For a system of fans, each fan usually operates individually. Thus, there is a lack of coordination among them, resulting in wasted energy and suboptimal thermal comfort.

[0013] Furthermore, a single fan or a system of fans may provide a significantly non-uniform air speed field. Thus, people sitting at different positions may experience different air flow, and therefore, may experience different sensation of thermal comfort. The configuration of the fans (e.g., number of fans and their placements) and their operation are also not optimized. As a result, some occupants may experience very weak or very strong airflow.

[0014] A need therefore exists to provide a method of controlling a plurality of fans disposed in an area, and a device thereof, to provide thermal comfort control in the area, that seek to overcome, or at least ameliorate, one or more of the deficiencies of conventional methods/approaches of providing thermal comfort control in an area. It is against this background that the present invention has been developed.

SUMMARY

[0015] According to a first aspect of the present invention, there is provided a computer-implemented method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area, each of the plurality of fans configured to generate air movement at an elevated air speed based on an operating parameter, the method comprising:

determining desired air speeds at the plurality of target positions, respectively;

and

optimizing the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions in the area.

[0016] In various embodiments, the operating parameters for the plurality of fans are optimized based on differences between the desired air speeds and measured air speeds at the plurality of target positions, respectively.

[0017] In various embodiments, the method further comprises generating gain information based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans.

[0018] In various embodiments, optimizing the operating parameters comprises minimizing a largest difference in said differences based on the gain information and the desired air speeds at the plurality of target positions.

[0019] In various embodiments, optimizing the operating parameters comprises determining changes in the operating parameters for the plurality of fans to obtain the optimized operating parameters based on the gain information and the desired air speeds at the plurality of target positions, wherein the gain information comprises a plurality of gain values, each gain value derived based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan.

[0020] In various embodiments, the changes in the operating parameters are determined based on the equation:

$$\begin{aligned} & \text{Minimize } ||K \cdot \Delta P - \Delta V_d||_{\infty} \\ & \text{subject to } -\hat{P} < \Delta P < P_{max} - \hat{P} \end{aligned}$$

where K denotes the gain matrix, ΔP denotes said changes in the operating parameters $\hat{P}$, and $\Delta V_d = V_d - V(\hat{P})$, where V_d denotes the desired air speeds at the plurality of target positions, and $V(\hat{P})$ denotes the measured air speeds at the plurality of target positions from the plurality of fans generating air movement based on the operating parameters $\hat{P}$.

[0021] In various embodiments, one or more of the desired air speeds are determined based on a thermal comfort model and a temperature measured at the area as an input to the thermal comfort model.

[0022] In various other embodiments, one or more of the desired air speeds are determined based on feedback received from one or more occupants at the corresponding one or more target positions.

[0023] In various embodiments, the feedback comprises one or more of a first type of input indicating a desire to increase the air speed at the corresponding target position and/or one or more of a second type of input indicating a desire to decrease the air speed at the corresponding target position collected over a time period.

[0024] In various embodiments, the operating parameter is a power parameter or a speed parameter for controlling the elevated air speed generated by the fan.

[0025] According to a second aspect of the present invention, there is provided a device for controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area, each of the plurality of fans being configured to generate air movement at an elevated air speed under the control of a fan control module based on an operating parameter, the device comprising:

a desired air speed determining module configured to determine desired air speeds at the plurality of target positions, respectively; and

an optimization module configured to optimize the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions in the area.

[0026] In various embodiments, the optimization module is configured to optimize the operating parameters for the plurality of fans based on differences between the desired air speeds and measured air speeds at the plurality of target positions, respectively.

[0027] In various embodiments, the device further comprises a gain information generating module configured to generate gain information based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans.

[0028] In various embodiments, optimizing the operating parameters comprises minimizing a largest difference in said differences based on the gain information and the desired air speeds at the plurality of target positions.

[0029] In various embodiments, optimizing the operating parameters comprises determining changes in the operating parameters for the plurality of fans to obtain the optimized operating parameters based on the gain information and the desired air speeds at the plurality of target positions, wherein the gain information comprises a plurality of gain values, each gain value derived based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan.

[0030] In various embodiments, the changes in the operating parameters are determined based on the equation:

$$\text{Minimize } ||K \cdot \Delta P - \Delta V_d||_{\infty}$$

subject to $-\hat{P} < \Delta P < P_{max} - \hat{P}$

where K denotes the gain matrix, ΔP denotes said changes in the operating parameters $\hat{P}$, and $\Delta V_d = V_d - V(\hat{P})$, where V_d denotes the desired air speeds at the plurality of target positions, and $V(\hat{P})$ denotes the measured air speeds at the plurality of target positions from the plurality of fans generating air movement based on the operating parameters $\hat{P}$.

[0031] In various embodiments, the desired air speed determining module is configured to determine one or more of the desired air speeds based on a thermal comfort model and a temperature measured at the area as an input to the thermal comfort model.

[0032] In various other embodiments, the desired air speed determining module is configured to determine one or more of the desired air speeds based on feedback received from one or more occupants at the corresponding one or more target positions.

[0033] In various embodiments, the feedback comprises one or more of a first type of input indicating a desire to increase the air speed at the corresponding target position and/or one or more of a second type of input indicating a desire to decrease the air speed at the corresponding target position collected over a time period.

[0034] In various embodiments, the operating parameter is a power parameter or a speed parameter for controlling the elevated air speed generated by the fan.

[0035] According to a third aspect of the present invention, there is provided a computer program product, embodied in one or more computer-readable storage mediums, comprising instructions executable by one or more computer processors to perform the method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area according to the first aspect of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 depicts a flow diagram of a method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area according to various embodiments of the present invention;

FIG. 2 depicts a schematic drawing of a device for controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area according to various embodiments of the present invention;

FIG. 3 depicts a schematic block diagram of a system for providing thermal comfort control for a plurality of target positions in an area according to various example embodiments of the present invention;

FIGs. 4A and 4B depict a picture of a meeting room (FIG. 4A) and the corresponding room layout (FIG. 4B), respectively, in which experiments were conducted according to various example embodiments of the present invention;

FIG. 5 depicts a picture showing an air distribution measuring system used for sensing the room temperature and measuring air speed at the target positions in the experiments conducted according to various example embodiments of the present invention;

FIGs. 6A and 6B depict the relationship between air speed and fan power with respect to the linear function (FIG. 6A) and the natural logarithm function (FIG. 6B), respectively, obtained in experiments conducted;

FIGs. 7A and 7B depict the relationship between air speed and fan speed setting with respect to the linear function (FIG. 7A) and the natural logarithm function (FIG. 7B), respectively, obtained in experiments conducted;

FIGs. 8A to 8C depict boxplots of air speed before and after optimization for operative temperatures at $t_o=26^{\circ}\text{C}/79^{\circ}\text{F}$ (FIG. 8A), $t_o=27.5^{\circ}\text{C}/82^{\circ}\text{F}$ (FIG. 8B), and $t_o=29^{\circ}\text{C}/84^{\circ}\text{F}$ (FIG. 8C), respectively, obtained in experiments conducted;

FIG. 9 depicts boxplots of the median values of measured air speeds before and after optimization obtained in experiments conducted;

FIG. 10 depicts boxplots of PMV deviation from target (i.e., actual PMV values minus target PMV values) before and after optimization obtained in experiments conducted;

FIG. 11 depicts a schematic block diagram of a system for providing thermal comfort control for a plurality of target positions in an area according to various example embodiments of the present invention;

FIG. 12 depicts a schematic drawing showing an illustrative framework for a SMS-based remote fan control system according to various example embodiments of the present invention;

FIGs. 13A and 13B depict a lecture room layout (FIG. 13A) and a picture of the lecture room (FIG. 13B), respectively, in which experiments were conducted according to various example embodiments of the present invention;

FIG. 13C depicts a timeline of an experiment conducted in the lecture room shown in FIGs. 13A and 13B;

FIGs. 14A and 14B depict the temperature (FIG. 14A) and the relative humidity (FIG. 14B), respectively, measured by four HOBO temperature/relative humidity data loggers arranged in the lecture room as shown in FIG. 13A during the experiment;

FIG. 15 depicts a survey questionnaire used in the experiment for collecting occupants' feedback;

FIGs. 16A and 16B show the overall thermal acceptability for two tested conditions in the experiment, in boxplots and in bar charts (dichotomous), respectively;

FIG. 17 shows the overall thermal sensation for the two tested conditions in the experiment in boxplots;

FIGs. 18A and 18B show the overall acceptance of air movement for the two tested conditions in the experiment, in boxplots and in bar charts (dichotomous), respectively;

FIGs. 19A and 19B show the fan speed setting adjustments recorded in the experiment for fans 1 to 5 (FIG. 19A) and fans 6 to 10 (FIG. 19B) shown in FIG. 13A, respectively; and

FIG. 20 depicts a schematic drawing showing a device capable of being communicatively coupled to a control system configured to control a plurality of fans based on operating parameters.

DETAILED DESCRIPTION

[0037] Various embodiments of the present invention provide a method of controlling a plurality of fans (or interchangeably referred to as a system of fans herein) disposed in an area, and a device thereof, to provide thermal comfort control in the area, that seek to overcome, or at least ameliorate, one or more of the deficiencies associated with conventional methods/approaches of providing thermal comfort control in an area, such as those as described in the background. It will be appreciated by a person skilled in the art that a fan described herein may be any device or apparatus configured to produce air movement for providing a cooling effect on one or more subjects, including but not limited to, a fan with rotatable blades or a centrifugal fan, such as a blower, that produces a current of air.

[0038] Elevated air speed generated by fans is an effective and energy-efficient method of cooling people in moderately warm indoor and outdoor environments. However, fans are not commonly incorporated into the building automation system (BAS) to save energy (e.g., by allowing the air conditioning system to operate at a higher setpoint) and improve comfort. In this regard, such as to facilitate the incorporation of fans into the BAS, various embodiments of the present invention provide a method of controlling a system of fans disposed in an area to provide thermal comfort control in the area, such as to control a system of fans cooperatively (collectively) to generate elevated air speed (uniform or non-uniform) according to a thermal comfort model by using a linear programming algorithm/technique. For example and without limitations, the method may be applied in either air conditioned spaces (area) such as office cubicles, theaters and classrooms, or non-air conditioned spaces such as hawker centers (open-air food centers) where fans may conventionally be provided in such spaces to operate at a particular speed setting.

[0039] In various embodiments, the method/device may automatically determine the optimal fan speed settings (or fan power) based on the temperature(s) measured at the area. The device may also advantageously be provided as a separate component to an existing BAS, but may be coupled or incorporated to the BAS to control the plurality of fans disposed in the area so as to provide thermal comfort control. Accordingly, for example, the method and device may be applied after the installation of the fans in the

area. Accordingly, the method/device may advantageously enable low implementation costs (thus low investment required), thereby allowing ease of commercialization. Various embodiments of the present invention may also facilitate in determining the configuration of the fans (e.g., the number of fans and their placements in an area). As will be described later below, experimental results for an indoor application have demonstrated that method/device according to various embodiments of the present invention is capable of controlling a system of fans effectively and maintain or enhance thermal comfort while the air conditioner thermostat was set to a higher setpoint, thus advantageously saving energy.

[0040] FIG. 1 depicts a flow diagram of a method (computer-implemented method) 100 of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area according to various embodiments of the present invention. In this regard, each of the plurality of fans is configured to generate air movement at an elevated air speed based on (e.g., under the control of) an operating parameter. The method 100 comprising a step 102 of determining desired air speeds at the plurality of target positions, respectively, and a step 104 of optimizing the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions (e.g., target occupancy positions) in the area. Accordingly, with the optimized operating parameters, the elevated air speed generated by each of the plurality of fans may be optimized with respect to the plurality of target positions to provide improved thermal comfort control for the plurality of target positions.

[0041] In various embodiments, the operating parameter may be a power parameter or a speed parameter (e.g., fan speed setting) for controlling the elevated air speed generated by the fan.

[0042] Accordingly, by optimizing the operating parameters for controlling the plurality of fans in an area collectively based on desired air speeds at a plurality of target positions in area, the plurality of fans in the area are controlled (or coordinated) collectively (or cooperatively) to improve human thermal comfort particularly at the plurality of target positions in the area, such as at positions occupied by people. Therefore, the method is capable of controlling a plurality of fans in an area effectively to

provide the desired air speeds at the target positions as best as possible to provide the occupants at such target positions with a satisfactory or pleasant level of thermal comfort. For example, the method may advantageously be adaptable to occupancy variation in the area such that the air speeds generated by the plurality of fans are specifically optimized at the target occupancy positions. Furthermore, when implemented at an area with air conditioning, the method may further enable the air conditioning temperature setpoint to be adjusted higher, thus saving energy and reducing power usage costs.

[0043] In various embodiments, the operating parameters for the plurality of fans are optimized based on differences between the desired air speeds at the plurality of target positions and measured air speeds at the plurality of target positions, respectively. In various embodiments, optimizing the operating parameters comprises minimizing a largest difference in such differences based on gain information and the desired air speeds at the plurality of target positions. This will be described in further details later below according to various example embodiments of the present invention.

[0044] In various embodiments, the gain information (e.g., a gain matrix) may be generated based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans. For example, the gain information may be used to determine the air speeds at the plurality of target positions to the operating parameters (e.g., fans speed setting) for the plurality of fans such that the operating parameters may be optimized to minimize differences/deviations between the desired air speeds and the measured/actual air speed at the plurality of target positions (e.g., to minimize a largest difference in such differences).

[0045] In various embodiments, one or more of the desired air speeds are determined based on a thermal comfort model and a temperature measured at the area as an input to the thermal comfort model. For example and without limitation, the thermal comfort model may be a Predicted Mean Vote-Standard Effective Temperature (PMV-SET) model. However, it will be appreciated that the present invention is not limited to applying the PMV-SET model for determining the desired air speeds at various target positions in the area based on a temperature measured at the area, and other models known in the art may be applied for determining the desired air speeds and are within the scope of the present invention.

[0046] In various other embodiments, one or more of the desired air speeds are determined based on feedback received from one or more occupants at the corresponding one or more target positions. For example, the feedback may comprise one or more of a first type of input (e.g., “+” symbol) indicating a desire to increase the air speed at the
5 corresponding target position and/or one or more of a second type of input (e.g., “-” symbol) indicating a desire to decrease the air speed at the corresponding target position collected over a time period (e.g., a regular optimization time period, such as every 2 minutes).

[0047] FIG. 2 depicts a schematic drawing of a device 200 (e.g., corresponding to the
10 method 100 as described hereinbefore with reference to FIG. 1) for controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area. In this regard, each of the plurality of fans is configured to generate air movement at an elevated air speed based on (e.g., under the control of) an operating parameter. The device 200 comprises a desired air speed determining module/circuit 202
15 configured to determine desired air speeds at the plurality of target positions, respectively, and an optimization module/circuit 204 configured to optimize the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively by the optimizing module based on the desired air speeds at the plurality of target positions in the area. As shown, the device 200 may
20 further comprise a computer processor 206 capable of executing computer-executable instructions (e.g., the desired air speed determining module 202 and the optimization module 204) to perform one or more functions or methods (e.g., to optimize the operating parameter for each of the plurality of fans), and a computer-readable storage medium 208 communicatively coupled to the processor 206 having stored therein one or more sets of
25 computer-executable instructions (e.g., the desired air speed determining module 202 and the optimization module 204).

[0048] In various embodiments, the device 200 may be provided as a separate unit to a control system e.g., building automation system (BAS)) configured to control the plurality of fans (e.g., to generate air movement at an elevated air speed based on the
30 operating parameters). In this regard, the device 200 may be configured to be capable of being communicatively coupled (e.g., according to any wireless or wired protocol known

in the art) to the control system for transmitting the optimized operating parameters thereto for the control system to control the plurality of fans based on the optimized operating parameters. In various other embodiments, the device 200 may be integrated in the control system such that the control system may comprise the desired air speed
5 determining module 202 and the optimization module 204 executable by one or more computer processors of the control system to perform one or more functions or methods as described herein. In this regard, the control system may thus constitute the device 200 for controlling a plurality of fans disposed in an area to provide thermal comfort control. In further other embodiments, the device 200 may be configured to be capable of being
10 communicatively coupled (e.g., according to any wireless or wired protocol known in the art) to each of the plurality of fans so as to control the plurality of fans (e.g., directly) based on the operating parameters (e.g., optimized operating parameters) communicated thereto.

[0049] A computing system, a controller, a microcontroller or any other system
15 providing a processing capability may be presented according to various embodiments in the present disclosure. Such a system may be taken to include one or more processors and one or more computer-readable storage mediums. For example, as mentioned above, the device/system 200 described herein includes a processor (or controller) 206 and a computer-readable storage medium (or memory) 208 which are for example used in
20 various processing carried out therein as described herein. A memory or computer-readable storage medium used in various embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate
25 memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[0050] In various embodiments, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing
30 software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g. a microprocessor (e.g. a Complex

Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g. any kind of computer program, e.g. a computer program using a virtual machine code, e.g. Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a “circuit” in accordance with various alternative embodiments. Similarly, a “module” may be a portion of a system according to various embodiments in the present invention and may encompass a “circuit” as above, or may be understood to be any kind of a logic-implementing entity therefrom.

[0051] Some portions of the present disclosure are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

[0052] Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as “optimizing”, “computing”, “determining”, “applying”, “generating”, “minimizing” or the like, refer to the actions and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

[0053] The present specification also discloses a system or an apparatus for performing the operations/functions of the methods described herein. Such a system or apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose

machines may be used with computer programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform the required method steps may be appropriate.

[0054] In addition, the present specification also at least implicitly discloses a computer program or software/functional module, in that it would be apparent to the person skilled in the art that the individual steps of the methods described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the invention. It will be appreciated by a person skilled in the art that various modules described herein (e.g., the desired air speed determining module 202 and the optimization module 204) may be software module(s) realized by computer program(s) or set(s) of instructions executable by a computer processor to perform the required functions, or may be hardware module(s) being functional hardware unit(s) designed to perform the required functions. It will also be appreciated that a combination of hardware and software modules may be implemented.

[0055] Furthermore, one or more of the steps of the computer program/module or method may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the methods described herein.

[0056] In various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium), comprising instructions (e.g., the desired air speed determining module 202 and the optimization module 204) executable by one or more computer processors to perform a method 100 of controlling a plurality of fans disposed

in an area to provide thermal comfort control as described hereinbefore with reference to FIG. 1 or other method(s) described herein. Accordingly, various computer programs or modules described herein may be stored in a computer program product receivable by a computer system or electronic device (e.g., device 200) therein for execution by a processor of the computer system or electronic device to perform the respective functions.

[0057] The software or functional modules described herein may also be implemented as hardware modules. More particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the software or functional module(s) described herein can also be implemented as a combination of hardware and software modules.

[0058] It will be appreciated by a person skilled in the art that the terminology used herein is for the purpose of describing various embodiments only and is not intended to be limiting of the present invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0059] In order that the present invention may be readily understood and put into practical effect, various example embodiments of the present invention will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present invention may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art.

[0060] Various example embodiments of the present invention provide a method for generating elevated air speed (uniform or non-uniform) at target occupancy positions to improve human thermal comfort in indoor and outdoor environments, by cooperatively scheduling a system of fans. In various example embodiments, the operating parameters for the system of fans are optimized collectively based on desired air speeds at the target occupancy positions, whereby such desired air speeds are determined based on a thermal comfort model (e.g., the integrated PMV-SET model or other appropriate thermal comfort model) and using linear programming algorithm/technique.

[0061] Various example embodiments of the present invention may provide calibration of the system of fans in the actual environment. In this regard, the air speed field generated by fans depends on various parameters (e.g. air temperature, furniture layout, interaction between fans, and so on). Therefore, the process of calibration is a significant advantage because the air flow field generated by the fan may not be predicted in the design phase in a cost-efficient manner.

[0062] Various example embodiments of the present invention may provide optimization of the operation of fans in the actual environment with or without knowing the occupancy information. For example, if positions of occupants can be detected, only the occupied positions may be considered in optimizing the operating parameters for the plurality of fans. Otherwise, all the calibrated target positions may be considered.

[0063] In various example embodiments, the optimal operation of the fans depends on the measured temperature at the area being subjected to thermal comfort control, which can be either the dry-bulb air temperature or the operative temperature. In this regard, an optimization technique is used to obtain the most desirable air flow for the comfort of occupants. This is achieved according to various example embodiments by minimizing the worst-case deviation of the measured air speeds from the desired air speeds at the plurality of target occupancy positions in the area, respectively. Thermal comfort may be assessed with the PMV-SET model, but as mentioned hereinbefore, other thermal comfort models may also be used.

[0064] In various example embodiments, quantification of the effect of operating parameters (e.g., fans speed settings) on the thermal sensation through the thermal

comfort model (e.g., the PMV-SET model) for positions of the occupants in the space is provided.

[0065] In the case of the system of fans being movable/relocatable, various example embodiments of the present invention may also determine the configuration of fans (e.g., number of fans and their placements) for facilitating the method of controlling the plurality of fans described herein to achieve the desired air speeds (e.g., as close as possible) at the plurality of target positions in the area.

[0066] In the case of the occupancy information being available, various example embodiments of the present invention may provide automatic re-optimization of the operation of the fans (i.e., their operating parameters such as fan power or fan speed setting) to handle or adapt to occupancy variation. For example, at a predetermined time interval, the occupancy information (e.g., locations/positions of occupants) at the area may be detected, and the operating parameters for the plurality of fans may be re-optimized collectively based on desired air speeds at such locations/positions of occupants detected.

[0067] FIG. 3 depicts a schematic block diagram of a system 350 for providing thermal comfort control for a plurality of target positions in an area according to various example embodiments of the present invention. The system 350 comprises a plurality of fans 320 disposed in the area and a device 300 for controlling the plurality of fans 320 to provide thermal comfort control for the plurality of target positions in the area. Each of the plurality of fans 320 being configured to generate air movement at an elevated air speed based on an operating parameter. In the device 300, the desired air speeds at the plurality of target positions are determined based on a thermal comfort model and a temperature measured at the area as input to the thermal comfort model. As an illustrative example, a PMV-SET model is applied in the device 300 for determining the desired air speeds. As shown in FIG. 3, the device 300 is configured to receive a temperature (e.g., sensed/measured temperature) as an input (e.g., the only input to the device 300), which can be either the dry-bulb air temperature or the operative temperature, and is configured to output optimized operating parameters (e.g., optimized fans speed settings) to the plurality of fans 320. The plurality of fans 320 may thus generate optimal air speeds after

the optimal fans speed settings are applied. Various components of the system 350 will now be described further below.

[0068] A gain information generating module 306 (shown as “Calibration Process” in FIG. 3) is provided in the device 300 for generating gain information (e.g., a gain matrix) based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans. For example, the gain information generating module 306 may be configured to determine the gains of the air speeds to the operating parameters (fans speed settings) at different/various positions in the area where the occupants are or expected to be located (i.e., target occupancy positions). Accordingly, calibration of the system of fans in the actual environment is performed.

[0069] A desired air speed determining module 302 (shown as “PMV-SET Model” in FIG. 3) is provided in the device 300 for determining the desired air speeds at the plurality of target positions, respectively. For example, as shown in FIG. 3, the desired air speed determining module 302 may be configured to determine the desired air speeds at a given temperature (temperature measured/sensed) using an integrated PMV-SET model.

[0070] An optimization module 304 (shown as “Linear Programming Optimizer” in FIG. 3) is provided in the device 300 for optimizing the operating parameters for the plurality of fans collectively based on the desired air speeds from the desired air speed determining module 302 and the gain information from the gain information generating module 306. Therefore, the optimization module 304 may be configured to consider/assess the differences/deviations of the measured/actual air speeds from the desired air speeds for all target positions (e.g., for all the occupants), and then cooperatively/collectively controls/manipulates the system of fans 320 to minimize the worst-case difference/deviation (i.e., minimize the largest difference/deviation).

[0071] As shown in FIG. 3, the optimized operating parameters (P_{opt}) may then be sent to the system of fans 320 for controlling the system of fans 320 so as to optimize their elevated air speeds (V_{opt}) with respect to the target positions to provide improved thermal comfort control for the target positions.

[0072] For a better understanding, the PMV-Model thermal control model (or elevated air speed comfort zone) according to various example embodiments of the present invention will now be described below.

Fanger's PMV Model

[0073] Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. The most common approach used nowadays to predict thermal comfort for the purpose of building design is to correlate the results of psychological experiments to thermal analysis variables.

[0074] Among the experiments on the human perception of thermal comfort, the experiments performed by Fanger (e.g., see Fanger, P. O., "Thermal comfort. Analysis and applications in environmental engineering", 1970, *Copenhagen: Danish Technical Press*) are commonly cited. During the experiments, human subjects wearing standardized clothing and performing standardized activities were exposed to different environmental conditions such as different air temperatures and surface temperatures, different humidities, and different air speeds and patterns. The subjects were then asked to record how hot or cold they felt, using the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) thermal sensation scale given in Table 1 below.

Table 1 – ASHRAE thermal sensation scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

[0075] From these laboratory and climate chamber studies, a model describing whole body thermal comfort, known as Predicted Mean Vote (PMV) model, was developed by Fanger on the basis of thermoregulation and heat balance theories. Although thermal comfort is largely a state of mind, separate from equations for heat balance, the

perception of comfort is expected to be influenced by the variables that affect the heat transfer in the heat balance model.

[0076] According to the heat balance theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat loss from the body (e.g., see Charles K. E, “Fanger’s Thermal Comfort and Draught Models”, 2003, *Institute for Research in Construction National Research Council of Canada, Ottawa*, K1A 0R6, Canada IRC Research Report RR-162, October 10, 2003).

[0077] Fanger investigated in these physiological processes (e.g., see Fanger, P. O., “Calculation of Thermal Comfort, Introduction of a Basic Comfort Equation”, *ASHRAE transactions*, 73(2), III-4, 1967) and indicated that the heat balance was most significantly influenced by mean skin temperature and sweat rate which depend on activity level. Combining these two factors with the heat balance equation, the PMV can be calculated as in ISO Standard 7730 (2005) by using the following equations:

$$\begin{aligned} \text{PMV} = & (0.303e^{-0.036M} + 0.028)\{(M - W) \\ & - 3.05 \cdot 10^{-3}[5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0014M(34 - t_a) \\ & - 1.7 \cdot 10^{-5}M(5867 - p_a) - 3.96 \cdot 10^{-8}f_{cl}[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\} \end{aligned}$$

(Equation 1)

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96 \cdot 10^{-8}f_{cl}[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl}h_c(t_{cl} - t_a)\}$$

(Equation 2)

$$h_c = \max \{2.38|t_{cl} - t_a|^{0.25}, 12.1\sqrt{V}\}$$

(Equation3)

$$f_{cl} = \begin{cases} 1.00 + 1.290I_{cl} & I_{cl} \leq 0.078 \text{ m}^2 \cdot \text{K/W} \\ 1.05 + 0.645I_{cl} & I_{cl} > 0.078 \text{ m}^2 \cdot \text{K/W} \end{cases}$$

(Equation 4)

where:

M: the metabolic rate, in watts per square metre (W/M^2);

W: the effective mechanical power, in watts per square metre (W/M^2);

t_a : the air temperature, in degrees Celsius ($^{\circ}\text{C}$);

p_a : the water vapour partial pressure, in pascals (Pa);

f_{cl} : the clothing surface area factor;

t_{cl} : the clothing surface temperature, in degrees Celsius ($^{\circ}\text{C}$);

$\bar{t}_r$: the mean radiant temperature, in degrees Celsius ($^{\circ}\text{C}$);

5 h_c : the convective heat transfer coefficient, in watts per square metre kelvin [$\text{W}/(\text{M}^2 \cdot \text{K})$];

I_{cl} : the clothing insulation, in square metres kelvin per watt ($\text{m}^2 \cdot \text{K}/\text{W}$);

V : the relative air speed, in metres per second (m/s).

10 **[0078]** The PMV value represents the average thermal sensation response (corresponding to ASHRAE thermal sensation scale) from a large group of people in a space. There are six primary variables affecting the PMV value, including four environmental variables: dry-bulb air temperature, mean radiant temperature, relative humidity, air speed and two personal variables: metabolic rate and clothing insulation. The comfort zone may be defined by recommended limits of PMV values being from
15 -0.5 to 0.5 where 80% occupants will be satisfied. Within the comfort zone, the higher satisfaction rate is expected when the PMV value is zero representing thermal neutrality, the PMV value being positive means slightly warm and being negative means slightly cold. Beyond the comfort zone, the thermal sensation may be regarded to be not acceptable.

20 **[0079]** Conventionally, the PMV model has been the standard method of predicting thermal comfort for occupants adopted by many organizations for standardization such as ASHRAE Standard 55 (ANSI/ASHRAE 2013), EN Standard 15251 (CEN 2007) and ISO Standard 7730 (ISO 2005).

25 *Thermal Comfort Prediction: Integrated PMV-SET Model*

[0080] Air movement has a significant cooling effect, which increases the acceptable range of indoor temperatures. Since the PMV human heat balance model underestimates the influence of air movement, ASHRAE Standard 55-2013 adopts the *Standard Effective Temperature* (SET) index based on Gagge's two-node model of human temperature
30 regulation to set a comfort zone for air movement at elevated air speed (see Gagge, A. P., "An effective temperature scale based on a simple model of human physiological

regulatory response”, *ASHRAE Trans.*, 77, 247-262, 1971). In the two-node model, the body is modeled as two concentric cylinders, the inner representing the body core and the outer representing the thin skin shell.

[0081] SET is defined as the equivalent air temperature of an isothermal environment at 50% relative humidity in which a subject, wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature) and thermoregulatory strain (skin wettedness) as in the actual environment. Isothermal environment refers to the environment at sea level, in which air temperature is equal to mean radiant temperature and the air is still. The SET model reduces any combination of real environmental and personal variables into the temperature of the imaginary standard environment.

[0082] The above leads to the PMV-SET model (or Elevated Air Speed model) (see Schiavon, S. et al., “Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55”, In *Building Simulation*, Tsinghua University Press, Vol. 7, No. 4, pp. 321-334, August 2014), a two-step procedure comprising first using the PMV model to determine the comfort zone at the still-air region ($V \leq 0.2$ m/s) and then utilizing the SET index to extend the comfort zone to the elevated air speed region ($V > 0.2$ m/s). The PMV-SET model is based on the idea that equal heat balance and skin wettedness for different air speeds can be plotted in terms of SET contours. Each contour is a curve over a range of dry-bulb temperature, mean radiant temperature and air speed such that every point on this curve produces the same SET value. Dry bulb temperature refers to the ambient air temperature. It may be referred to as “dry bulb” because the temperature is measured by a thermometer freely exposed to the air but shielded from radiation and moisture. If one starts with the underlying PMV comfort zone, these SET contours form the boundaries of an air-movement comfort zone (e.g., see Arens E. A. et al., “Moving air for comfort”, *ASHRAE Journal*, 51(5): 18–29, 2009).

[0083] Consider functions, PMV and SET, with the six parameters. Let t_a be the average air temperature, $\bar{t}_r$ be the mean radiant temperature, and V_{elev} be the elevated average air speed which should be larger than the average speed in still air, $V_{\text{still}} = 0.2$ m/s. The cooling effect, CE, due to the elevated air speed may be obtained by iteratively solving the following equation:

$$\text{SET}(t_a, \bar{t}_r, V_{\text{elev}}, *) = \text{SET}(t_a - \text{CE}, \bar{t}_r - \text{CE}, V_{\text{still}}, *) \quad (\text{Equation 5})$$

where * denotes the invariant parameters which should be the same for the both cases. Equation (5) means that the adjusted average air temperature, $(t_a - \text{CE})$, and adjusted mean radiant temperature, $(\bar{t}_r - \text{CE})$, at still air yields the same SET value as the actual average air temperature and actual mean radiant temperature do at elevated air speed. Equation (5) can be solved by using the secant and bisection iterative algorithm. Once the CE is obtained, then the adjusted PMV value in the still-air zone is given by

$$\text{PMV}_{\text{adj}} = \text{PMV}(t_a - \text{CE}, \bar{t}_r - \text{CE}, V_{\text{still}}, *) \quad (\text{Equation 6})$$

[0084] It should be noted that, according to ASHRAE Standard 55, the analytical comfort zone generated by the PMV-SET model is applicable when the occupants have activity levels that result in average metabolic rates between 1.0 and 2.0 met. Likewise, the air speed should be adjustable continuously or in maximum steps of 0.25 m/s in the range from still air, 0.2 m/s to 1.2 m/s, which is suitable for sedentary occupants.

[0085] When the desired air speed is to be determined, relative humidity, metabolic rate and clothing insulation are set to be constant, and PMV value at every target occupancy position is set to be different values for different room temperatures. For the purpose of keeping occupants comfortable in a warm environment, the value of PMV may be limited within the range of 0 to 0.5 to avoid overcooling people. For relatively lower temperature, the PMV value at each position can be set as zero. However, for higher temperature, it is very difficult for PMV to be zero since large air speed which may cause the discomfort felt by occupants is needed in this case. In this regard, according to various example embodiments of the present invention, the PMV may be set to be 0 at 26°C or below, 0.3 at 29°C, 0.5 above 29°C and intermediate values for temperatures between 26°C and 29°C. However, it will be appreciated that the present invention is not limited to such PMV settings, and other PMV settings may be applied as desired or as appropriate.

Optimization of Fans Operation

[0086] In order to make occupants feel comfortable by utilizing elevated air movement, given the target position and the desired air speed, optimal operating

parameters (e.g., fans speed setting) are derived for a system of fans according to various embodiments of the present invention. For clarity and illustration purposes, the operating parameter may be described hereinafter as being the fans speed setting. However, it will be appreciated by a person skilled in the art that the operating parameter is not limited to fans speed setting and may be any parameter(s) controlling the air movement (in particular, elevated air speed) generated by the fan, such as the power parameter. According to various example embodiments of the present invention, the optimal operating parameters for the system of fans are determined by minimizing the errors (differences or discrepancies) between desired air speeds and actual/measured air speeds at the target positions. According to various example embodiments of the present invention, a minimax-error method/technique is applied, which minimizes the infinity-norm of the errors, that is, the largest absolute value of the errors.

[0087] For example and without limitation, in practice, there may be more people in an area than the fans, and thus not everyone is able to have their desired air speed. To address this problem, various example embodiments of the present invention seek to minimize the worst case of the errors to keep the maximum error within an acceptable range. As a result, since the operating parameters for the system of fans are determined (optimized) such that the maximum error of the errors is minimized (e.g., to the minimum possible), unnecessarily large discrepancy/error at one or more target positions is advantageously avoided, which would otherwise have caused undesirable thermal dissatisfaction at such target positions which grow exponentially when a deviation from the comfort condition increases. By way of an example only, if the initial deviations from the desired air speeds for 3 occupants are 0.1 m/s, 0.2 m/s and 0.3 m/s, and then the worst case is 0.3 m/s.

[0088] In various example embodiments, the problem is formulated as to find the optimal fans speed setting, P_{opt} , that minimizes the largest absolute error between the desired air speeds, V_d , and the actual/measured air speeds, $V(P)$, as follows:

$$\text{Minimize } ||V(P) - V_d||_{\infty} \quad (\text{Equation 7})$$

where V_d can be obtained from the PMV-SET model and P is the speed setting applied to the fans. In the example embodiments, a linear relationship between P and $V(P)$ is assumed for substantial reduction in derivation complexity.

[0089] For a better understanding, an example of one fan with speed setting, p , and two occupants located at different locations with desired air speeds, v_{d1} and v_{d2} , respectively, will be described below before the general case is described. Let the air speeds (v_1, v_2) at the two locations due to the fan be given by:

$$v_1 = k_1 p \quad (\text{Equation 8})$$

$$v_2 = k_2 p \quad (\text{Equation 9})$$

where k_1 and k_2 are gains of v_1 and v_2 to p , respectively.

[0090] Let the absolute value of all errors between the desired air speeds and actual/measure air speeds be less than or equal to the maximum error (minimax-error), ε , which is to be minimized. In other words, the maximum error, ε , is minimized if the absolute value of all the errors in air-speed is less than or equal to ε , i.e.,

$$|v_{d1} - v_1| \leq \varepsilon \quad (\text{Equation 10})$$

$$|v_{d2} - v_2| \leq \varepsilon \quad (\text{Equation 11})$$

and then minimize ε . Removing the modulus sign in inequalities (10) and (11) gives:

$$v_1 - v_{d1} \leq \varepsilon \quad (\text{Equation 12})$$

$$v_2 - v_{d2} \leq \varepsilon \quad (\text{Equation 13})$$

$$v_{d1} - v_1 \leq \varepsilon \quad (\text{Equation 14})$$

$$v_{d2} - v_2 \leq \varepsilon \quad (\text{Equation 15})$$

[0091] Substituting Equations (8) and (9) into inequalities (12) to (15) and then rearranging gives:

$$\begin{bmatrix} k_1 & -1 \\ k_2 & -1 \\ -k_1 & -1 \\ -k_2 & -1 \end{bmatrix} \begin{bmatrix} p \\ \varepsilon \end{bmatrix} \leq \begin{bmatrix} v_{d1} \\ v_{d2} \\ -v_{d1} \\ -v_{d2} \end{bmatrix} \quad (\text{Equation 16})$$

[0092] The optimal speed setting, p_{opt} , that minimizes the maximum error, ε , may then be obtained by solving the following linear programming problem (e.g., see Norman, S. A., "Optimization of wafer temperature uniformity in rapid thermal processing systems", *IEEE Transactions on Electron Devices*, 1-46, 1991):

$$\begin{aligned} & \text{Minimize } [0 \quad 1] \begin{bmatrix} P \\ \varepsilon \end{bmatrix} \\ & \text{subject to constraint (16)} \end{aligned} \quad (\text{Equation 17})$$

[0093] For the general case of n fans and m positions, the air speeds, $V(P)$, generated by fans under speed setting, P , may be given by

$$K \cdot P = V(P) \quad (\text{Equation 18})$$

where K is an $m \times n$ gain matrix, P is an $n \times 1$ column vector and V is an $m \times 1$ column vector. The system in Equation (18) is overdetermined if $m > n$ (more people than fans).

10 In general, it will be appreciated that no exact value of P will exactly satisfy Equation (18).

[0094] Substituting Equation (18) into (7), the problem may be summarized as:

$$\begin{aligned} & \text{Minimize } \|K \cdot P - V_d\|_{\infty} \\ & \quad (\text{Equation 19}) \end{aligned}$$

15 [0095] The minimax-error solution P_{opt} to the problem given in Equation (19) may be obtained by solving an equivalent linear programming problem given as:

$$\begin{aligned} & \text{Minimize } [0 \quad \dots \quad 0 \quad 1] \begin{bmatrix} P \\ \varepsilon \end{bmatrix} \\ & \text{subject to } \begin{bmatrix} K & -1_I \\ -K & 1_I \end{bmatrix} \begin{bmatrix} P \\ \varepsilon \end{bmatrix} \leq \begin{bmatrix} V_d \\ -V_d \end{bmatrix} \end{aligned} \quad (\text{Equation 20})$$

20 where 1_I is a $m \times 1$ column vector with all entries equal to one, ε is a scalar, and where for vectors a and b , $a \leq b$ indicates every entry of a is no more than the corresponding entry of b . In various example embodiments, the above linear programming problem may be expressed as to find a minimum ε^* that satisfies $\|K \cdot P - V_d\|_{\infty} = \varepsilon^*$, which is equivalent to the minimax-error problem stated in Equation (19).

25 [0096] In various example embodiments, optimizing the operating parameters (e.g., fans speed settings) comprises determining changes in the operating parameters for the plurality of fans to obtain the optimized operating parameters based on the gain information and the desired air speeds at the plurality of target positions. In this regard, the gain information comprises a plurality of gain values, each gain value derived based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan.

30 [0097] By way of an example according to various example embodiments, let $\hat{P}$ be the initial fans speed settings, the first-order approximation for $V(P)$ around $\hat{P}$ gives:

$$V(P) \approx V(\hat{P}) + K \cdot \Delta P \quad (\text{Equation 21})$$

where $\Delta P = P - \hat{P}$. The closer $V(\hat{P})$ (measured air speeds at the plurality of target positions from the plurality of fans generating air movement based on the operating parameters $\hat{P}$) is to V_d , the more accurate the approximation Equation (21) will be.

[0098] The gain matrix K can be determined by measuring $V(\hat{P}^{(1)})$ through $V(\hat{P}^{(j)})$, where each $\hat{P}^{(j)}$ is $\hat{P}$ slightly perturbed by Δp_j as follows

$$\hat{P}^{(1)} = \hat{P} + \begin{bmatrix} \Delta p_1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \hat{P}^{(2)} = \hat{P} + \begin{bmatrix} 0 \\ \Delta p_2 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \dots, \hat{P}^{(n)} = \hat{P} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \Delta p_n \end{bmatrix} \quad (\text{Equation 22})$$

and K can be obtained by

$$K = [k_1 \quad k_2 \quad \dots \quad k_n] \quad (\text{Equation 23})$$

where $k_j = \frac{V(\hat{P}^{(j)}) - V(\hat{P})}{\Delta p_j}$ is the j^{th} column of K and $j = 1, 2, \dots, n$.

[0099] Substituting Equation (21) into (7), the optimization problem may then be formulated as:

$$\begin{aligned} &\text{Minimize } \|K \cdot \Delta P - \Delta V_d\|_{\infty} \\ &\text{subject to } -\hat{P} < \Delta P < P_{\max} - \hat{P} \end{aligned} \quad (\text{Equation 24})$$

where $\Delta V_d = V_d - V(\hat{P})$ is the desired air speed change. The optimal fans speed settings adjustment ΔP_{opt} can be obtained by solving the following equivalent linear programming problem:

$$\begin{aligned} &\text{Minimize } [0 \quad \dots \quad 0 \quad 1] \begin{bmatrix} \Delta P \\ \varepsilon \end{bmatrix} \\ &\text{subject to } \begin{bmatrix} K & -1_I \\ -K & 1_I \end{bmatrix} \begin{bmatrix} \Delta P \\ \varepsilon \end{bmatrix} \leq \begin{bmatrix} \Delta V_d \\ -\Delta V_d \end{bmatrix} \end{aligned} \quad (\text{Equation 25})$$

and the optimal fans speed settings can be obtained as $P_{\text{opt}} = \hat{P} + \Delta P_{\text{opt}}$

[00100] In the above-described problem formulation, K refers to the gain matrix (e.g., pre-calibrated gain matrix) comprising gain values, each gain value derived based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan. For example, each gain value may be a ratio of change in air speed measured at the corresponding target position to

adjustment in fan speed setting of the corresponding fan, for various different target positions. ΔV_d refers to the desired air speeds change obtained based on the PMV-SET model (or occupant feedback described hereinbefore and will be described further later below), and ΔP_{opt} refers to changes in operating parameters, e.g., optimal fans speed settings adjustment that optimizes thermal comfort for occupants, obtained by solving (25).

[00101] In order to demonstrate the effectiveness of the method of or device for controlling a plurality of fans disposed in an area to provide improved thermal comfort control for a plurality of target positions in the area, experiments conducted according to various example embodiments of the present invention will now be described below.

Experimental Setup

[00102] The experiments were conducted in a meeting room at Nanyang Technological University. The meeting room has a volume of $6.4 \text{ m} \times 5.0 \text{ m} \times 2.7 \text{ m} \approx 86.4 \text{ m}^3$ as shown in FIG. 4A, and four standing electric fans were employed to provide thermal comfort control of up to 12 occupants (up to 12 target occupancy positions) as shown in FIG. 4B. The fan employed is a three-phase brushless direct current (DC) fan (Model FSAW98RI-A, Airmate, China), which provides 32-level speed settings. The fan power ranges from 3.8 W to 32.5 W (see Table 2 below). An air distribution measuring system (AirDistSys5000, Sensor Electronics, Poland) as shown in FIG. 5 was used for sensing the room temperature and measuring air speed at the target positions. The measurement range of temperature is between -10°C and $+50^\circ\text{C}$ with an accuracy of 0.2°C . The measurement range of air speed is between 0.05 m/s and 5 m/s with an accuracy of $\pm 0.02 \text{ m/s} \pm 1.5\%$ of readings. At a sampling interval of 2 seconds, each measurement takes 90 samples over 3 minutes in all the experiments conducted. The axis of the fan blades and motor, and the sensors were placed at a height of 1.1m above the ground which is equal to the head height of a seated person according to thermal comfort standards. In this regard, it has been found that the head region is the dominant body part affecting overall comfort in warm environments.

Linearity Verification

[00103] An experiment was conducted to verify the linearity between air speed and fan power, fan speed setting. The measuring sensor was situated at one of eight positions with a certain distance away from the fan: from 0.5 to 4.0 m with a distance grid of 0.5 m. At each position, the air speed generated by the electrical fan was measured accordingly when the fan speed was set from 1 to 32 with a grid of 1. For each speed setting, 90 samples of air speed were taken and the average value was used to fit a curve at this distance by means of the least-squares algorithm. The relationship between air speed and fan power, fan speed setting was investigated, respectively. In this regard, Table 2 below provides the single fan speed setting, its corresponding fan power and average air speed at each distance for the fans used in the experiment conducted. The fan power was measured using a power meter (Energy monitoring socket, Efergy, UK) with an accuracy of $\pm 2\%$ of readings.

Table 2 - Fan speed setting, fan power and corresponding air speed at tested distance

Speed setting	Power (W)	Average air speed (m/s)							
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m	4.0 m
1	3.8	0.96	0.77	0.67	0.58	0.46	0.39	0.32	0.31
2	4.4	1.13	0.93	0.81	0.69	0.54	0.46	0.38	0.37
3	4.7	1.30	1.07	0.94	0.79	0.65	0.57	0.46	0.44
4	5.2	1.51	1.20	1.03	0.85	0.72	0.66	0.54	0.51
5	5.7	1.67	1.29	1.12	0.92	0.79	0.72	0.57	0.55
6	6.4	1.79	1.38	1.18	0.96	0.84	0.76	0.59	0.58
7	6.8	1.87	1.44	1.24	1.01	0.85	0.76	0.60	0.59
8	7.9	2.06	1.53	1.32	1.06	0.94	0.84	0.68	0.64
9	8.6	2.21	1.64	1.42	1.17	0.98	0.90	0.73	0.69
10	9.1	2.21	1.66	1.45	1.21	1.00	0.91	0.75	0.71
11	9.6	2.33	1.73	1.50	1.24	1.02	0.92	0.75	0.69
12	10.9	2.44	1.81	1.59	1.31	1.04	0.95	0.80	0.73
13	11.8	2.56	1.87	1.63	1.35	1.13	1.03	0.84	0.78
14	13.0	2.57	1.85	1.63	1.38	1.14	1.02	0.83	0.77
15	14.2	2.82	2.00	1.76	1.45	1.16	1.04	0.89	0.80
16	15.4	2.90	2.05	1.80	1.48	1.28	1.13	0.95	0.85
17	16.4	3.02	2.11	1.88	1.59	1.33	1.19	1.02	0.92
18	17.6	2.98	2.11	1.89	1.58	1.30	1.16	1.00	0.90

19	18.4	2.98	2.05	1.85	1.58	1.32	1.17	0.99	0.85
20	19.3	3.04	2.15	1.93	1.63	1.37	1.22	1.06	0.93
21	19.9	3.30	2.28	2.05	1.69	1.22	1.09	0.93	0.81
22	20.6	3.35	2.29	2.07	1.73	1.35	1.21	1.03	0.92
23	21.2	3.22	2.14	1.96	1.68	1.35	1.22	1.01	0.87
24	22.4	3.55	2.36	2.12	1.77	1.27	1.12	0.96	0.84
25	23.2	3.40	2.30	2.05	1.74	1.34	1.19	1.01	0.88
26	24.1	3.58	2.39	2.16	1.83	1.45	1.29	1.08	0.96
27	25.2	3.69	2.49	2.24	1.86	1.38	1.25	1.08	0.95
28	26.0	3.78	2.52	2.26	1.87	1.47	1.33	1.12	0.99
29	27.3	3.82	2.58	2.29	1.90	1.45	1.30	1.11	1.00
30	29.2	3.98	2.60	2.32	1.96	1.57	1.41	1.18	1.04
31	30.9	4.10	2.69	2.39	1.96	1.54	1.39	1.21	1.03
32	32.5	4.20	2.78	2.46	2.01	1.37	1.25	1.00	0.98

[00104] It has been reported that the air speed is a natural logarithm function of the fan power (e.g., see Yang B. et al., “Cooling efficiency of a brushless direct current stand fan”, *Building and Environment*, 85, 196-204, 2015). This observation is adopted here as a comparison to the linear function. The least-squares algorithm was used to fit the curve between air speed and fan power, and the curves between air speed and fan speed setting, respectively. The obtained curve parameters of the linear function ($y = k \cdot x + b$), the natural logarithm function ($y = k \cdot \ln(x) + b$) by least-squares for fan power and fan speed setting are summarized in Tables 3 and 4 below, respectively, for reference.

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Table 3 - Least-squares fitted parameters in FIGs. 6A (linear function) and 6B (natural logarithm function)

Distance (m)	Linear function		Natural logarithm function	
	k	b	k	b
0.5	0.102	1.127	1.402	-0.884
1.0	0.059	0.990	0.826	-0.208
1.5	0.055	0.842	0.763	-0.264
2.0	0.046	0.700	0.638	-0.225
2.5	0.032	0.640	0.454	-0.034
3.0	0.029	0.571	0.411	-0.040
3.5	0.025	0.453	0.365	-0.090
4.0	0.021	0.447	0.297	0.006

Table 4 - Least-squares fitted parameters in FIGs. 7A (linear function) and 7B (natural logarithm function)

Distance (m)	Linear function		Natural logarithm function	
	k	b	k	b
0.5	0.095	1.192	1.007	0.193
1.0	0.056	1.023	0.603	0.403
1.5	0.051	0.873	0.553	0.308
2.0	0.043	0.725	0.460	0.258
2.5	0.030	0.653	0.336	0.287
3.0	0.027	0.582	0.306	0.246
3.5	0.024	0.463	0.270	0.171
4.0	0.020	0.456	0.222	0.213

[00105] FIGs. 6A and 6B illustrate the relationship between air speed and fan power with respect to the linear function (FIG. 6A) and the natural logarithm function (FIG. 6B). In particular, the average measured air speeds and fitted curves between air speed and fan power at different distances are plotted in FIGs. 6A and 6B. It can be seen in FIGs. 6A and 6B that the natural logarithm curves fit the measured data slightly better than the linear curves. The mean absolute error (e_{ma}) and root mean square (RMS) error (e_{rms}) between measured data and fitted curves in fan power are summarized in Table 5 below.

Table 5 – Errors between measured data and fitted curves in fan power

Distance (m)		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Linear curves	e_{ma} (m/s)	0.15	0.11	0.10	0.08	0.09	0.08	0.07	0.06
	e_{rms} (m/s)	0.19	0.14	0.13	0.10	0.12	0.11	0.10	0.08
Logarithmic curves	e_{ma} (m/s)	0.08	0.05	0.04	0.02	0.05	0.05	0.04	0.03
	e_{rms} (m/s)	0.10	0.07	0.05	0.03	0.06	0.06	0.05	0.04

[00106] As shown in Table 5, both mean absolute and RMS errors of the natural logarithm curves are within 0.1 m/s, which are smaller than those of the linear curves at all distances. These experimental results are consistent with the observations in the above-mentioned reference, Yang B. et al (2015). In this case, the air speed can be regarded as a linear function of the natural logarithm of fan power. Therefore, the concept still stands.

[00107] However, when desk fans or standing fans, like in the above example, are used, it may be difficult to control the fan power directly. In particular, additional transformers may be needed for power control, which may not be convenient to use in

practice and may occupy extra space. Therefore, for most of the commercial electrical fans currently available in the market, the fan speed setting as the operating parameter may be preferred than fan power for air speed control according to various example embodiments of the present invention.

5 [00108] FIGs. 7A and 7B illustrate the relationship between air speed and fan speed setting with respect to the linear function (FIG. 7A) and the natural logarithm function (FIG. 7B). In particular, the average measured air speed and fitted curves between air speed and fan speed setting at different distances are plotted in FIGs. 7A and 7B. From FIG. 7B, at farther positions, it can be observed that the natural logarithm curves still fit the measured data very well. But at nearer positions within 2 m, both the mean absolute and RMS errors can be over 0.2 m/s as shown in Table 6 below. Table 6 provides the errors between the measured data and fitted curves in fan speed settings for mean absolute and RMS errors. On the contrary, the linear curves fit the measured data better than the logarithmic curves at nearer positions. Even though the errors are bigger beyond 15 the distance of 2.5 m than those of natural logarithm curves, it can be observed that the errors are within 0.1 m/s, which are still accepted. Therefore, it can be concluded that the linearity between air speed generated by electric fans and fan speed setting is tenable.

Table 6 - Errors between measured data and fitted curves in fan speed setting

Distance (m)		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Linear curves	e_{ma} (m/s)	0.11	0.09	0.07	0.06	0.08	0.07	0.06	0.05
	e_{rms} (m/s)	0.13	0.11	0.09	0.07	0.10	0.09	0.08	0.07
Logarithmic curves	e_{ma} (m/s)	0.21	0.10	0.10	0.08	0.06	0.05	0.05	0.04
	e_{rms} (m/s)	0.26	0.13	0.12	0.10	0.07	0.06	0.06	0.04

20 Calibrated Thermal Comfort Control

[00109] In this experiment, the thermal comfort at target positions was controlled to be maintained at a targeted level. The fans were set to be in oscillation mode during the experiments. In this regard, it has been found that oscillating air movement does not 25 affect the thermal comfort or thermal sensation, but improves the air quality perception (e.g., see Pasut W. et al., "Enabling energy-efficient approaches to thermal comfort using room air motion", *Building and Environment*, 79, 13-19, 2014)

[00110] Firstly, the calibration process (e.g., by the gain information generating module 306) was conducted at all the 12 positions in the test environment shown in FIGs. 4A and 4B by using Equation (23), and the gain matrix, K, was obtained as:

$$K = [k_1 \quad k_2 \quad k_3 \quad k_4] = \begin{bmatrix} 0.0151 & 0.0035 & 0.0053 & 0.0150 \\ 0.0132 & 0.0003 & 0.0034 & 0.0082 \\ 0.0110 & 0.0062 & 0.0080 & 0.0066 \\ 0.0053 & 0.0055 & 0.0032 & 0.0028 \\ 0.0046 & 0.0072 & 0.0042 & 0.0006 \\ 0.0029 & 0.0101 & 0.0066 & 0.0005 \\ 0.0022 & 0.0138 & 0.0100 & 0.0005 \\ 0.0001 & 0.0114 & 0.0154 & 0.0008 \\ 0.0017 & 0.0105 & 0.0107 & 0.0028 \\ 0.0053 & 0.0108 & 0.0096 & 0.0066 \\ 0.0098 & 0.0075 & 0.0061 & 0.0132 \\ 0.0070 & 0.0020 & 0.0002 & 0.0141 \end{bmatrix}$$

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where K is a 12×4 matrix referring to four fans being utilized to provide thermal comfort control for 12 occupants at target positions. It can be understood that the gains at certain positions are only used when these positions are occupied. In order to show the flexibility of the method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions (e.g., selected target positions), 8 out of 12 occupancy positions as labeled in FIG. 4B are selected/treated as occupied.

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[00111] Next, the desired air speed was determined by using the integrated PMV-SET model (e.g., by the desired air speed determining module 202/302). Since the air conditioning system is usually set at around 23°C in tropical climate, higher temperature setpoints were tested in the experiments to save energy. In particular, three operative temperature categories, $t_o = 26^\circ\text{C}$, 27.5°C and 29°C (79°F , 82°F and 84°F) were considered assuming that the average air temperature (t_a) and the mean radiant temperature ($\bar{t}_r$) were the same. In a typical office environment where room temperature is above 29°C , it may be challenging to be thermally comfortable even with high air speed.

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[00112] The typical value of business clothing insulation in the tropics is 0.7 clo (short sleeve button or polo shirt, long trousers, socks, business shoes plus chair insulation) and in more informal settings (e.g. at home) or outdoor (e.g. open-air food centers), people are expected to wear less clothes. With higher temperature setpoints, the clothing insulation is reduced as people are expected to dress according to the indoor climate. It

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will be appreciated by a person skilled in the art that such an assumption may be changed as appropriate to reflect the clothing actually worn by the occupants.

- [00113] Relative humidity, rh , is assumed to be 50%. Metabolic rate, M , being 1.2 met (1 met=58.2 W/m²) refers to seating and filing in a typical office environment. The desired air speeds calculated and other parameters based on the integrated PMV-SET model for the three categories are summarized in Table 7 below.

Table 7 - Desired air speed and other parameters for PMV-SET model ($rh=50\%$, $M=1.2$)

Operative temperature t_o (°C/°F)	Clothing insulation	Target PMV	Desired air speed V_d (m/s)
26/79	0.7	0.00	0.55
27.5/82	0.6	0.15	0.64
29/84	0.5	0.30	0.78

- [00114] Finally, the optimal fans speed settings for three categories were calculated by using the linear programming algorithm (e.g., by the optimization module 204/304) and the results are shown in Table 8 below. The speed setting of each fan was initially set to 2.

Table 8 - Optimal fans speed settings

Fan #	1	2	3	4
Initial case	2	2	2	2
26°C/79°F category	25	18	12	11
27.5°C/82°F category	32	26	16	9
29°C/84°F category	32	31	22	14

- [00115] After applying the optimal results to the fans, the air speed at each target position was measured for theory verification and the corresponding PMV value was calculated to check the thermal comfort improvement compared to the initial cases without optimization.

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Results and Discussion

- [00116] The air speed measurements before and after optimization for the three operative temperature categories is shown as boxplots in FIGs. 8A to 8C, respectively. In particular, FIGs. 8A to 8C depict boxplots of air speed before (lower row of boxplots) and after (higher row of boxplots) optimization for operative temperatures at

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$t_o=26^{\circ}\text{C}/79^{\circ}\text{F}$ (FIG. 8A), $t_o=27.5^{\circ}\text{C}/82^{\circ}\text{F}$ (FIG. 8B), and $t_o=29^{\circ}\text{C}/84^{\circ}\text{F}$ (FIG. 8C), respectively.

[00117] In FIGs. 8A to 8C, each box-and-whisker plot contains 90 measured samples that were taken at one position for 3 minutes using a 2-second sampling rate. The line inside the box, the bottom line, and the top line shows the median, 25th percentile and 75th percentile of the samples, respectively. The end of each whisker line represents the lowest/highest datum that is within 1.5 interquartile range (IQR) of the lower/upper quartile. Measurements beyond the end of a whisker are plotted as dots.

[00118] The distribution of all the air speed measurements was tested for normality using the Shapiro-Wilk normality test. The air speed measurements do not exhibit a normal distribution ($W = 0.92$, $p < 0.001$). The median values (1st quartiles, 3rd quartiles) of all the measured data at each position are summarized in Table 9 below. Compared to the initial cases without optimization of fans operation, the present approach is shown to be capable of increasing air movement towards target values thereby improving thermal comfort at higher temperatures. The improvement in air speed is statistically significant ($p < 0.001$) by using Wilcoxon signed rank test for non-normally distributed data.

Table 9 - The medians (1st quartiles, 3rd quartiles) of measured air speed at each position

Test positions	26°C/79°F category(m/s)		27.5°C/82°F category (m/s)		29°C/84°F category (m/s)	
	Initial	Optimized	Initial	Optimized	Initial	Optimized
1	0.23(0.19,0.29)	0.57(0.50,0.64)	0.21(0.18,0.24)	0.62(0.55,0.66)	0.20(0.16,0.23)	0.63(0.58,0.68)
2	0.17(0.11,0.24)	0.40(0.33,0.46)	0.15(0.11,0.18)	0.42(0.38,0.47)	0.13(0.10,0.18)	0.45(0.39,0.49)
3	0.18(0.13,0.21)	0.42(0.36,0.47)	0.14(0.11,0.18)	0.40(0.32,0.47)	0.15(0.13,0.19)	0.44(0.39,0.49)
4	0.22(0.20,0.26)	0.51(0.46,0.56)	0.20(0.18,0.22)	0.54(0.51,0.60)	0.22(0.19,0.25)	0.61(0.56,0.67)
5	0.23(0.21,0.30)	0.64(0.52,0.88)	0.21(0.17,0.28)	0.78(0.62,0.96)	0.23(0.20,0.27)	0.84(0.67,1.05)
6	0.21(0.16,0.24)	0.53(0.47,0.64)	0.16(0.12,0.23)	0.64(0.49,0.78)	0.21(0.15,0.25)	0.69(0.54,0.86)
7	0.21(0.18,0.25)	0.55(0.48,0.62)	0.15(0.12,0.17)	0.63(0.58,0.67)	0.13(0.11,0.15)	0.70(0.62,0.76)
8	0.19(0.14,0.23)	0.51(0.42,0.65)	0.14(0.13,0.17)	0.59(0.50,0.67)	0.14(0.10,0.19)	0.66(0.56,0.72)

[00119] FIG. 9 shows the boxplots of the median values of measured air speeds before (left) and after (right) optimization. Each box-and-whisker plot corresponds to a column in Table 9 above, including all the 8 test positions information. The air speeds at test positions are closer to the desired values after being optimized. These data can be further converted into PMV deviation from the target PMV values (i.e., actual PMV values minus target PMV values) shown in FIG. 10. Despite the initial deviations being far from

zero, it can be observed that the present method implemented in the experiments conducted is able to improve the thermal environment by keeping PMV deviations around zero under 26°C/79°F, 27.5°C/82°F and 29°C/84°F. This verifies/demonstrates that the present method implemented in the experiments conducted is advantageously able to generate the desired air speed at various target positions for thermal comfort under different room temperatures by using a system of fans.

[00120] As described hereinbefore, FIG. 3 depicts a system 350 for providing thermal comfort control for a plurality of target positions in an area according to various example embodiments of the present invention for the case where the desired air speed is determined by a thermal comfort model, such as a PMV-SET model. However, the present invention is not limited to the desired air speed at a target position being determined by a thermal comfort model, and other appropriate techniques for determining the desired air speed are also within the scope of the present invention. For example as also described hereinbefore according to various example embodiments, the desired air speeds may be determined based on feedback received from one or more occupants at the corresponding one or more target positions. In such example embodiments, the method may thus optimally and cooperatively manipulate/control a system of fans based on occupant feedback. For example, the optimal operating parameters (e.g., optimal fan speed setting) is determined according to occupants' preference by optimization technique and hence is able to provide individual thermal comfort.

[00121] Therefore, various example embodiments of the present invention provide a method of generating elevated air speed (uniform or non-uniform) at target occupancy positions to improve human thermal comfort in indoor and outdoor environments by cooperatively/collectively controlling a system of electric fans based on occupant feedback. In various embodiments, the operating parameters for the system of fans are optimized collectively based on desired air speeds at the target occupancy positions, whereby such desired air speeds are determined based on occupant feedback and using linear programming algorithm/technique.

[00122] Various example embodiments of the present invention may provide interpretation of occupants' desire to have more or less air movement as air movement increment or decrement.

[00123] In various example embodiments, the optimal operation of fans depends on the occupant feedback which may include both the occupants' position and their desire to have more or less air movement. In this regard, an optimization technique is used to obtain the most desirable air flow for the comfort of occupants. This is achieved according to various example embodiments by minimizing the worst-case deviation of the measured air speeds from the desired air speed at the plurality of target occupancy positions in the area, respectively. The feedback from the occupants may be collected via any form of data communication between devices/systems known in the art, such as but not limited to, short message service (SMS).

[00124] In various example embodiments, automatic re-optimization of the operation of fans may occur when there is new feedback to achieve consensus and to adapt to occupancy variation.

[00125] FIG. 11 depicts a schematic block diagram of a system 1150 for providing thermal comfort control for a plurality of target positions in an area according to various example embodiments of the present invention. The system 1150 comprises a plurality of fans 320 disposed in the area and a device 1100 for controlling the plurality of fans 320 to provide thermal comfort control for the plurality of target positions in the area. Each of the plurality of fans 320 is configured to generate air movement at an elevated air speed based on an operating parameter. In the device 1100, the desired air speeds at the plurality of target positions are determined based on occupant feedback by the occupant feedback module 1102. As shown in FIG. 11, the device 1100 is configured to receive occupant feedback as an input (e.g., the only input to the device 1100), which may include the occupant position and the respective indication of their desire to have more or less air movement, and is configured to output optimized operating parameters (e.g., optimized fans speed settings) to the plurality of fans 320. The plurality of fans 320 may thus generate optimal air speeds after the optimal fans speed settings are applied. Various components of the system 1150 will now be described further below.

[00126] A gain information generating module 306 (shown as "Calibration Process" in FIG. 11) is provided in the device 1100 for generating gain information (e.g., a gain matrix) based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans. For example, the gain information

generating module 306 may be configured to determine the gains of the air speeds to the operating parameters (fans speed settings) at different/various positions in the area where the occupants are or expected to be located (i.e., target occupancy positions).

5 [00127] A desired air speed determining module 1102 (shown as “Occupant Feedback” in FIG. 11) is provided in the device 1100 for determining the desired air speeds at the plurality of target positions, respectively. For example, as shown in FIG. 11, the desired air speed determining module 1102 may be configured to determine the desired air speeds by interpreting occupants’ desire to have more or less air movement as air speed increment or decrement.

10 [00128] An optimization module 304 (shown as “Linear Programming Optimizer” in FIG. 11) is provided in the device 1100 for optimizing the operating parameters for the plurality of fans 320 collectively based on the desired air speeds from the desired air speed determining module 1102 and the gain information from the gain information generating module 306. Therefore, the optimization module 304 may be configured to
15 consider/assess the differences/deviations of the measured/actual air speeds from the desired air speeds for all target positions (e.g., for all the occupants), and then cooperatively/collectively controls/manipulates the system of fans 320 to minimize the worst-case difference/deviation (i.e., minimize the largest difference/deviation).

[00129] As shown in FIG. 11, the optimized operating parameters (P_{opt}) may then be
20 sent from the optimization module 304 to the system of fans 320 for controlling the system of fans 320 so as to optimize their elevated air speeds (V_{opt}) with respect to the target positions to provide improved thermal comfort control for the target positions.

[00130] Thermal comfort may be defined as the condition of mind that expresses satisfaction with the thermal environment and may be assessed by subjective evaluation.
25 The environmental conditions for human thermal comfort have been studied extensively and several published standards, such as ASHRAE 55, EN15251 and ISO 7730, are available for reference. These standards focus on specifying the ranges of indoor thermal environmental factors (air temperature, mean radiant temperature, humidity and air speed) and personal factors (activity and clothing) that are acceptable to a majority of
30 occupants. ASHRAE 55 recommends thermal conditions that are acceptable to at least 80% occupants.

[00131] In various example embodiments, a system of DC fans that can collect users' feedback through Short Message Service (SMS) was implemented. FIG. 12 depicts a schematic drawing showing an illustrative framework for the SMS-based remote fan control system. However, it will be understood by a person skilled in the art that the system is not limited in its application to the particular arrangement/configuration as shown in FIG. 12 and that system may be modified according to various other embodiments or implemented in various other ways as appropriate without deviating from the scope of the present invention. The system as shown in FIG. 12 is to demonstrate the effective creation of the desired air movement to satisfy the occupants by cooperatively manipulating the fans based on occupant feedback. Nevertheless, for the sake of clarity and illustration purposes, the data communication for transmitting the occupant feedback may be described hereinafter as being based on SMS. However, it will be appreciated by a person skilled in the art that the occupant feedback may be collected via any other form of data communication between devices/systems known in the art, e.g., smartphone APP or Internet GUI (Graphical User Interface).

[00132] In order to demonstrate the effectiveness of the method of or device for controlling a plurality of fans disposed in an area to provide improved thermal comfort control for a plurality of target positions in the area based on occupant feedback, experiments conducted according to various example embodiments of the present invention will now be described below.

Experiment Setup

[00133] The system of fans was installed and calibrated in a lecture room at National University of Singapore. The room has a dimension of about 10.5 m × 9.5 m × 2.5 m (volume ≈ 249.4 m³) and is fitted with 80 chairs as shown in FIGs. 13A and 13B. In particular, FIG. 13A shows the lecture room layout, and FIG. 13B shows a photo of the lecture room with students occupying various seats. FIG. 13C illustrates a timeline of the experiment conducted. FIGs. 14A and 14B depict graphs showing air temperature (FIG. 14A) and relative humidity (FIG. 14B), respectively, measured by the four HOBO temperature/relative humidity data loggers arranged in the lecture room as shown in FIG. 13A during the experiment.

[00134] Ten three-phase brushless direct current (DC) fans (Model FSAW98RI-A, Airmate, China) were placed on both sides of the room with at the height of 2 meters (the axis of the fan blades and motor). The speed settings were all initially set to “2” to avoid causing any discomfort and the fans were made to oscillate. The fan has a maximum
5 power of 32.5 W and their 32 speed settings can be adjusted wirelessly.

[00135] Before the experiment, an air distribution measuring system (AirDistSys 5000, Sensor-Electronic, Poland) of omnidirectional air speed sensors (SensoAnemo 5100SF) were used to measure the air speed at an accuracy of 0.02 m/s and a range of 0.05 to 5 m/s. Measurements were made to characterize the gain ratios at each chair at the
10 height of 1.1 m.

[00136] During the experiment, air temperature and relative humidity (RH) were recorded at one-minute sampling rate by HOBO temperature/RH data logger (Model U12-013, Onset, USA), with $\pm 0.35^{\circ}\text{C}$ uncertainty for temperature, and $\pm 2.5\%$ uncertainty for RH. Four HOBO data loggers were attached to the back of the seats with thermally
15 isolated material placed in the middle. Their locations in the experiment are as shown in FIG. 13A, together with the occupancy distribution.

[00137] Forty undergraduate students (27 males, 13 females) participated in the experiment and were randomly seated in the room when having a class (FIG. 13B). No restrictions were imposed on their clothing. However, most of them came with typical
20 summer dresses (about 0.5 clo). Before attending the formal experiment, all students have already attended one training experiment to become familiar with the experimental room, the experimental procedure, SMS-based fan control and survey questionnaires. To avoid bias in the results, all the measurements of environment variables were made not known to the students.

[00138] During the experiment, an occupant can provide feedback comprising one or more of a first type of input indicating a desire to increase the air speed at the corresponding target position and/or one or more of a second type of input indicating a desire to decrease the air speed at the corresponding target position collected over a time period. By way of an example and without limitation, an occupant may send a message
30 through the short message service on his phone giving his seat number and a ‘+’ (“first type of input”) or a ‘-’ (“second type of input”) to indicate increasing or decreasing air-

speed respectively. The device (i.e., the desired air speed determining module 202/1102) may then quantify the occupants' desire to have more or less air movement into levels by counting how many '+' or '-' each individual has sent in one optimization cycle. Within a cycle, the maximum level of one same symbol accumulated for each occupant is limited to three to prevent a sudden change in air speed. These levels are then multiplied by a coefficient, α (e.g., may be set to 0.05 m/s), to determine the desired air speed change ΔV_d in Equation (24). Therefore, the change of at most $0.05 \times 3 = 0.15$ m/s in air speed can be experienced by an occupant within one optimization cycle. Subsequently, the device (i.e., the optimization module 204/304) optimizes the fan speed setting based on the desired air speed determined and the gain matrix K to obtain an optimal fan speed setting that minimizes the maximum deviation of the actual/measured air speed from the desired air speed. By way of an example only and without limitation, the optimization module 204/304 may be configured to execute the following optimization algorithm to obtain the optimized fan speed settings.

Optimization Algorithm - Pseudo code for optimized air movement control

Parameters: α
Input: Feedback.symbol, Feedback.position and K in (Equation 23)

Output: ΔP_{opt}
Function Optimization(Run every 2 minutes)

 n = Number of occupants

 for $i = 1 : n$

 $\Delta v_i = 0$

 end

 m = Number of feedback items in one optimization cycle

 for $j = 1 : m$

 k = Feedback(j).position

 if Feedback(j).symbol = '+'

 $\Delta v_k = \Delta v_k + 1$

 elseif Feedback(j).symbol = '-'

 $\Delta v_k = \Delta v_k - 1$

 end

 if $\Delta v_k > 3$ or $\Delta v_k < -3$

 $\Delta v_k = 3 * \text{sign}(\Delta v_k)$

 end

 end

 $\Delta V_d = \alpha * [\Delta v_1, \Delta v_2, \dots, \Delta v_n]^T$

 $\Delta P_{opt} = \text{LinearProgramming}(K, \Delta V_d)$ in (Equation 25)

 return ΔP_{opt}
end

[00139] In various example embodiments, the optimization process and fan speed setting adjustment may be repeated at a predetermined time interval, such as every 2 minutes. Furthermore, the gain matrix K may be pre-calibrated by the gain information generating module 206/306 in the manner as described hereinbefore. As an example only, the gain matrix K generated in the experiment is provided below.

Table 10 – Example Gain Matrix K generated in the experiment

0.0140	0.0010	0	0	0	0	0	0	0	0
0.0123	0.0010	0	0	0	0	0	0	0	0
0.0100	0.0020	0	0	0	0.0020	0	0	0	0
0.0090	0.0020	0	0	0	0.0030	0	0	0	0
0.0060	0.0010	0	0	0	0.0040	0	0	0	0
0.0040	0	0	0	0	0.0060	0.0010	0	0	0
0.0030	0	0	0	0	0.0090	0.0020	0	0	0
0.0020	0	0	0	0	0.0100	0.0020	0	0	0
0	0	0	0	0	0.0123	0.0010	0	0	0
0	0	0	0	0	0.0140	0.0010	0	0	0
0.0165	0.0084	0	0	0	0	0	0	0	0
0.0157	0.0064	0	0	0	0	0	0	0	0
0.0145	0.0064	0	0	0	0.0020	0	0	0	0
0.0131	0.0062	0.0013	0	0	0.0050	0	0	0	0
0.0111	0.0043	0.0013	0	0	0.0080	0.0020	0	0	0
0.0080	0.0020	0	0	0	0.0111	0.0043	0.0013	0	0
0.0050	0	0	0	0	0.0131	0.0062	0.0013	0	0
0.0020	0	0	0	0	0.0145	0.0084	0	0	0
0	0	0	0	0	0.0157	0.0084	0	0	0
0	0	0	0	0	0.0165	0.0104	0	0	0
0.0165	0.0140	0.0070	0	0	0	0	0	0	0
0.0158	0.0127	0.0080	0	0	0	0	0	0	0
0.0139	0.0105	0.0060	0	0	0	0.0020	0	0	0
0.0136	0.0090	0.0050	0.0010	0	0.0010	0.0030	0	0	0
0.0105	0.0070	0.0030	0.0010	0	0.0050	0.0050	0.0020	0	0
0.0050	0.0050	0.0010	0	0	0.0105	0.0070	0.0040	0.0010	0
0.0010	0.0030	0	0	0	0.0136	0.0090	0.0060	0.0010	0
0	0.0020	0	0	0	0.0139	0.0105	0.0060	0	0
0	0	0	0	0	0.0158	0.0107	0.0070	0	0
0	0	0	0	0	0.0165	0.0100	0.0070	0	0
0.0120	0.0160	0.0153	0.0080	0.0007	0	0	0	0	0
0.0102	0.0142	0.0138	0.0080	0.0012	0	0	0	0	0
0.0083	0.0130	0.0119	0.0069	0.0013	0	0.0010	0.0020	0	0
0.0060	0.0101	0.0100	0.0050	0.0016	0	0.0030	0.0040	0.0010	0
0.0044	0.0090	0.0080	0.0041	0.0012	0.0020	0.0050	0.0060	0.0030	0.0010
0.0020	0.0070	0.0060	0.0020	0.0010	0.0044	0.0070	0.0080	0.0041	0.0012
0	0.0050	0.0040	0.0010	0	0.0060	0.0081	0.0100	0.0050	0.0016
0	0.0020	0.0020	0	0	0.0083	0.0100	0.0119	0.0069	0.0013
0	0	0	0	0	0.0082	0.0122	0.0138	0.0070	0.0012
0	0	0	0	0	0.0100	0.0140	0.0153	0.0060	0.0007

0.0080	0.0140	0.0160	0.0140	0.0080	0	0	0	0	0
0.0067	0.0133	0.0145	0.0134	0.0080	0	0	0	0	0
0.0044	0.0111	0.0134	0.0126	0.0069	0	0	0.0020	0.0010	0
0.0030	0.0101	0.0104	0.0106	0.0050	0	0.0020	0.0040	0.0030	0.0010
0.0023	0.0080	0.0080	0.0090	0.0041	0.0013	0.0050	0.0060	0.0070	0.0030
0.0013	0.0050	0.0060	0.0070	0.0030	0.0023	0.0080	0.0080	0.0090	0.0041
0	0.0020	0.0040	0.0030	0.0010	0.0030	0.0101	0.0104	0.0106	0.0050
0	0	0.0020	0.0010	0	0.0034	0.0101	0.0134	0.0126	0.0069
0	0	0	0	0	0.0047	0.0133	0.0145	0.0134	0.0080
0	0	0	0	0	0.0030	0.0100	0.0160	0.0140	0.0080
0.0010	0.0070	0.0130	0.0160	0.0140	0	0	0	0	0
0.0010	0.0080	0.0117	0.0149	0.0134	0	0	0	0	0
0.0010	0.0080	0.0100	0.0134	0.0126	0	0	0	0.0040	0.0010
0.0010	0.0070	0.0080	0.0122	0.0106	0	0	0.0020	0.0060	0.0030
0	0.0050	0.0060	0.0100	0.0090	0	0.0030	0.0040	0.0080	0.0070
0	0.0030	0.0040	0.0080	0.0070	0	0.0080	0.0060	0.0100	0.0090
0	0	0.0020	0.0060	0.0030	0	0.0080	0.0090	0.0122	0.0106
0	0	0	0.0040	0.0010	0	0.0070	0.0110	0.0134	0.0126
0	0	0	0	0	0	0.0060	0.0127	0.0149	0.0134
0	0	0	0	0	0	0.0040	0.0110	0.0160	0.0140
0	0	0.0080	0.0140	0.0160	0	0	0	0	0
0	0	0.0070	0.0131	0.0149	0	0	0	0	0
0	0	0.0070	0.0115	0.0134	0	0	0	0	0.0040
0	0.0013	0.0064	0.0094	0.0122	0	0	0.0010	0.0020	0.0060
0	0.0017	0.0056	0.0073	0.0100	0	0	0.0030	0.0040	0.0080
0	0	0.0030	0.0040	0.0080	0	0.0017	0.0056	0.0083	0.0100
0	0	0.0010	0.0020	0.0060	0	0.0013	0.0064	0.0104	0.0122
0	0	0	0	0.0040	0	0	0.0070	0.0115	0.0134
0	0	0	0	0	0	0	0.0050	0.0131	0.0149
0	0	0	0	0	0	0	0.0030	0.0140	0.0160
0	0	0.0010	0.0040	0.0140	0	0	0	0	0
0	0	0.0012	0.0070	0.0131	0	0	0	0	0
0	0	0.0024	0.0080	0.0115	0	0	0	0	0
0	0	0.0021	0.0061	0.0104	0	0	0	0	0.0020
0	0	0.0022	0.0040	0.0083	0	0	0.0010	0.0010	0.0040
0	0	0.0010	0.0010	0.0040	0	0	0.0022	0.0020	0.0083
0	0	0	0	0.0020	0	0	0.0021	0.0041	0.0104
0	0	0	0	0	0	0	0.0014	0.0080	0.0115
0	0	0	0	0	0	0	0.0012	0.0070	0.0131
0	0	0	0	0	0	0	0.0010	0.0030	0.0140

[00140] The timeline of the experiment conducted is shown in FIG. 13C. The lecture started at 14:00 and for the first 40-minute session, the optimization of fans operation through the feedback was not provided to the students. For the next 10 minutes from 14:40 to 14:50, there was a break. During the second 40-minute session from 14:50 to 15:30, the students could send their feedback towards preferred air movement whenever they wanted to. The operation of the fans system was then optimized based on the feedback. The students were required to complete a survey questionnaire regarding 1)

thermal acceptability, 2) thermal sensation, and 3) acceptance of air movement at the end of each session, i.e., at 14:40 and 15:30 respectively. The survey questionnaire used is shown in FIG. 15. For statistical analysis, Shapiro-Wilk test was used to test the normality of the data distribution. Paired-sample *t*-test was used for normally distributed data. Wilcoxon signed rank test was used for non-normally distributed data. Statistical significance was obtained when $p < 0.05$.

Results and Discussion

[00141] Thermal acceptability votes (from -3 = clearly unacceptable to 3 = clearly acceptable) for the two tested conditions are shown in FIG. 16A (boxplots). Thermal acceptability is non-normally distributed ($W = 0.95$, $p = 0.01$). The median value for Survey 1 without optimization of fans operation is 0.3 (1st quartile = -0.68, 3rd quartile = 1.45) while the median value for Survey 2 with optimization of fans operation is 1.14 (1st quartile = 0.41, 3rd quartile = 2.00). The improvement in thermal acceptability is statistically significant ($p < 0.001$). By looking at the data in a dichotomous way (acceptable and unacceptable) as shown in FIG. 16B (bar charts (dichotomous)), the percentage of students who express satisfaction with the thermal environment are 62% and 94% in Survey 1 and 2, respectively. In accordance with ASHRAE 55 and ISO 7730, 80% or more of the occupants should express satisfaction with the thermal environment. Therefore, it is clear that the thermal environment does not meet the requirements when the optimization of fans operation through the feedback is not provided (Survey 1).

[00142] Thermal sensation using the ASHRAE 7-point scale votes (from -3 = cold to +3 = hot) for the two tested conditions are shown in FIG. 17. Thermal sensation is barely normally distributed ($W = 0.96$, $p = 0.05$). The median thermal sensation for Survey 1 without optimization of fans operation is 0.73 (1st quartile = 0, 3rd quartile = 1.63) and most occupants recorded their thermal sensation in the range from neutral to warm in this case. After fans operation was kept being optimized through feedback for 40 minutes, the median thermal sensation for Survey 2 decreased to -0.04 (1st quartile = -0.62, 3rd quartile = 0.13) and most occupants reported that their thermal sensation was in the range from neutral to slightly cool. The difference is significant ($p < 0.001$) since the operation of the

fans was optimized based on that the occupants could request higher air speed in Session 2.

[00143] Acceptance of air movement votes (from -3 = clearly unacceptable to +3 = clearly acceptable) for the two tested conditions are shown in FIG. 18A (boxplots).

5 Acceptance of air movement is normally distributed ($W = 0.97$, $p = 0.18$). The median value of air movement acceptability is 0.27 (1st quartile = -0.55, 3rd quartile = 0.64) before optimization was provided and 1.09 (1st quartile = 0.45, 3rd quartile = 2.00) after optimization through SMS ($p < 0.001$). The percentages of students who express satisfaction with the air movement are 68% and 94% in Survey 1 and 2, respectively, as
10 shown in Figure 18B (bar charts (dichotomous)). For each occupant, the score of Survey 1 is subtracted from Survey 2 and 80% of the occupants have increased their vote regarding acceptance of air movement as well as thermal acceptability.

[00144] The fan speed setting adjustments are recorded and shown in FIG. 19A (fan 1 to 5 on the left side of FIG. 13A) and FIG. 19B (fan 6 to 10 on the right side of FIG.
15 13A), respectively.

[00145] As mentioned hereinbefore, the device 200/300/1100 described herein according to various embodiments of the present invention may be provided as a separate component/unit to a control system (e.g., BAS or Building Management System (BMS)) configured to control the plurality of fans to generate air movement at an elevated air
20 speed based on the operating parameters. In this regard, the device may be configured to be capable of being communicatively coupled (e.g., according to any wireless or wired protocol known in the art) to the control system for transmitting the optimized operating parameters thereto for the control system to control the plurality of fans based on the optimized operating parameters.

25 **[00146]** By way of an example illustration only, FIG. 20 depicts a schematic drawing showing such a device 2000/2001 capable of being communicatively coupled to a control system (computer system) 2010 configured to control a plurality of fans based on operating parameters. For example, the device 2000/2001 may be communicatively coupled to the control system 2010 via a LAN cable (e.g., Ethernet cable) 2020 shown in
30 FIG. 20. However, it will be appreciated that the device 2000/2001 may be communicatively coupled to the control system 2010 according to any other forms of

wireless or wired protocol known in the art, such as Wi-Fi, Bluetooth, or USB cable. As shown in FIG. 20, the device 2000 may comprise a feedback acquisition and processing module 2002 (e.g., corresponding to the desired air speed determining module 202 or the occupant feedback module 1102 as described hereinbefore) configured to determine
5 desired air speeds at a plurality of target positions, respectively, a gain matrix module 2006 (e.g., corresponding to the gain information generating module or calibration process module 306 as described hereinbefore) configured to generate gain information, a linear programming module 2004 (e.g., corresponding to the optimization module 204 or linear programming optimizer 304 as described hereinbefore) configured to optimize the
10 operating parameters for the plurality of fans collectively based on the desired air speeds determined, and a control signal generation module 2008 configured to generate a control signal including the optimized operating parameters for transmitting to the control system 2010 to control the plurality of fans based on the optimized operating parameters. FIG. 20 also illustrates another device 2001, which is the same or similar to the device 2000,
15 except that the desired air speeds at the plurality of target positions are determined using a thermal comfort model 2003, such as a PMV-SET model, as described hereinbefore with reference to FIG. 3. In particular, the desired air speeds at the plurality of target positions are determined based on the thermal comfort model 2003 and a temperature measured at the area as input to the thermal comfort model 2003.

20 **[00147]** Accordingly, various embodiments of the present invention provide a method of controlling a system of electric fans cooperatively to generate uniform or non-uniform elevated air speed for thermal comfort maintenance or enhancement. The method according to various embodiments may provide thermal comfort control or optimized air movement control based on a cooperative scheduling approach of multiple electric fans
25 which takes all the occupants into consideration and aims to make every occupant feel as comfortable as possible.

[00148] In various embodiments, the method may interpret multiple occupant feedbacks as fan control signal.

30 **[00149]** In various embodiments, the method may be applied to various types of electric fans such as ceiling fans, standing fans or wall fans.

[00150] In various embodiments, the method may be applied indoors and outdoors. For example, the method may be applied in either air-conditioned spaces such as office cubicles, theaters and classrooms, or non-air-conditioned spaces such as open-air food centers where fans conventionally operate at a predetermined speed setting.

5 [00151] In various embodiments, a method of calibrating the system of fans in the actual environment is provided. The air speed field generated by fans may depend on various parameters (e.g. air temperature, furniture layout, interaction between fans, and so on). The process of calibration may provide a significant advantage because the air flow field generated by the fan cannot be predicted in the design phase in a cost-efficient
10 manner.

[00152] In various embodiments, the calibration process of the method may assume a linear relationship between air speed generated by electric fans and the fan speed setting (or natural logarithm of fan input power). The input power may be within the physical range of the fan.

15 [00153] In various embodiments, the calibration process of the method may be a one-time work. Once the calibration is done, the relative positions between the fans and occupancy locations are fixed. Otherwise, the system can be recalibrated.

[00154] In various embodiments, a method of optimization of the fans operation (fan speed setting or fan input power) is provided to generate desired air speed in the actual
20 environment depending on the measured temperature. For fans operation optimization, the method may automatically determine the optimal fans speed settings (or fan input power) to generate desired air speeds under different temperatures.

[00155] In various embodiments, a method of quantification of the occupants' desire to have more or less air movement is provided as air movement increment or decrement.

25 [00156] In various other embodiments, the method may include a desired air speed determination method which quantifies the occupants' desire to have more or less air movement into levels by counting how many '+' or '-' each individual has sent in one optimization cycle. These levels are multiplied by a coefficient, α , to determine the desired air speed change for each individual. For example, the gain α may be set to 0.05
30 m/s by default, but other values may also be used as appropriate or desired. Accordingly, a method of optimization of the fans operation (fan speed setting or fan input power) to

generate desired air speed in the actual environment according to occupant feedback is provided.

[00157] The method may be a minimax-error solution which aims at minimizing the worst-case deviation from the desired air speed to obtain the most desirable air flow for the comfort of occupants.

[00158] In various embodiments, the method may include an optimization technique to minimize the worst-case deviation from desired air speed based on linear programming algorithm. For example, this can help address the case whereby the positions near to the fan need less air flow or the positions far from the fan need more air flow.

[00159] In various embodiments, the method may include the input of a measured temperature (e.g., to the thermal comfort control model for determining the desired air speeds), which can be either the dry-bulb air temperature or the operative temperature.

[00160] In various embodiments, the method may include a desired air speed determination and thermal comfort assessing method, that is, the PMV-SET model.

Besides the measured temperature and desired air speed, other model parameters such as relative humidity, metabolic rate and clothing insulation may be predetermined. The user may change the default/initial setting as desired or appropriate. For example, the PMV value may be set to be in the range of (0, 0.5) since overcooling may be unexpected. In addition to the PMV-SET model, other thermal comfort models may also be used.

[00161] In various embodiments, the method may be able to generate either the uniform air flow if the PMV values at all target positions are set to be the same or the non-uniform air flow if the PMV values at target positions are different due to the customization for different preferences of occupants.

[00162] In various embodiments, the method of fans operation optimization may be applied with or without knowing occupancy information. If positions of occupants can be detected, only the occupied positions may be considered. Otherwise, all the calibrated target positions may be considered.

[00163] In various embodiments, a method of quantification of the effect of fans speed settings (or fan input power) on the thermal sensation through the PMV-SET model for positions of the occupants in the space is provided.

[00164] In various embodiments whereby the desired air speeds at target positions are determined based on occupants' feedback, the method may include the input of occupant feedback which can be done by any means of communication between human and the present device/system.

5 [00165] In various embodiments, the method may be able to generate different air flow for different occupants at different positions, according to different preferences of the occupants.

[00166] In various embodiments, the method may be applied to the occupied positions. For unoccupied positions, minimum air flow can be designated to save energy. For
10 example, this may help to control only some fans to switch on while others to shut down to advantageously save energy without compromising thermal comfort.

[00167] In various embodiments, the method may include a re-optimization scheme that repeats the optimization process every few minutes, according to latest feedbacks. This can advantageously help to achieve consensus and address occupancy variation.

15 [00168] In various embodiments, a method of determining the number of fans and their placements for moveable fans is provided in the design phase. By way of an example and without limitation, during the calibration process, the air speed at a plurality of target positions is measured. If the measured air speed at certain positions is too small or too large and violates the requirement of thermal comfort, the number of fans could be
20 decreased or increased accordingly or the placements of the fans could be adjusted to offset the impact.

[00169] In various embodiments, the method may be configured to obtain the best or optimal relative positions between fans and occupancy locations to provide acceptable thermal sensation. For example, by trying different relative positions, the actual air
25 speeds at target locations can be adjusted to the same as desired ones.

[00170] In various embodiments, a method of automatic re-optimization of fans operation to deal with occupancy variation is provided if occupancy information is available. For example, the method of automatic re-optimization of fans operation may consider the occupants at present, regardless of the predetermined occupancy layout. For
30 example, this may help to control only some fans to switch on while others to shut down to advantageously save energy without compromising thermal comfort.

[00171] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

- 5 The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

What is claimed is:

- 5 1. A computer-implemented method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area, each of the plurality of fans configured to generate air movement at an elevated air speed based on an operating parameter, the method comprising:
 - 10 determining desired air speeds at the plurality of target positions, respectively; and
 - optimizing the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions in the area.
- 15 2. The method according to claim 1, wherein the operating parameters for the plurality of fans are optimized based on differences between the desired air speeds and measured air speeds at the plurality of target positions, respectively.
- 20 3. The method according to claim 2, further comprising generating gain information based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans.
- 25 4. The method according to claim 3, wherein optimizing the operating parameters comprises minimizing a largest difference in said differences based on the gain information and the desired air speeds at the plurality of target positions.
- 30 5. The method according to claim 3 or 4, wherein optimizing the operating parameters comprises determining changes in the operating parameters for the plurality of fans to obtain the optimized operating parameters based on the gain information and the desired air speeds at the plurality of target positions, wherein the gain information comprises a plurality of gain values, each gain value derived

based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan.

6. The method according to claim 5, wherein said changes in the operating parameters are determined based on the equation:

$$\begin{aligned} &\text{Minimize } ||K \cdot \Delta P - \Delta V_d||_{\infty} \\ &\text{subject to } -\hat{P} < \Delta P < P_{max} - \hat{P} \end{aligned}$$

where K denotes the gain matrix, ΔP denotes said changes in the operating parameters $\hat{P}$, and $\Delta V_d = V_d - V(\hat{P})$, where V_d denotes the desired air speeds at the plurality of target positions, and $V(\hat{P})$ denotes the measured air speeds at the plurality of target positions from the plurality of fans generating air movement based on the operating parameters $\hat{P}$.

7. The method according to any one of claims 1 to 6, wherein one or more of the desired air speeds are determined based on a thermal comfort model and a temperature measured at the area as an input to the thermal comfort model.

8. The method according to any one of claims 1 to 6, wherein one or more of the desired air speeds are determined based on feedback received from one or more occupants at the corresponding one or more target positions.

9. The method according to claim 8, wherein the feedback comprises one or more of a first type of input indicating a desire to increase the air speed at the corresponding target position and/or one or more of a second type of input indicating a desire to decrease the air speed at the corresponding target position collected over a time period.

10. The method according to any one of claims 1 to 9, wherein the operating parameter is a power parameter or a speed parameter for controlling the elevated air speed generated by the fan.

11. A device for controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area, each of the plurality of fans being configured to generate air movement at an elevated air speed under the control of a fan control module based on an operating parameter, the device comprising:
- 5 a desired air speed determining module configured to determine desired air speeds at the plurality of target positions, respectively; and
- an optimization module configured to optimize the operating parameter for each of the plurality of fans, the operating parameters for the plurality of fans being optimized collectively based on the desired air speeds at the plurality of target positions in the area.
- 10 12. The device according to claim 11, wherein the optimization module is configured to optimize the operating parameters for the plurality of fans based on differences between the desired air speeds and measured air speeds at the plurality of target positions, respectively.
- 15 13. The device according to claim 12, further comprising a gain information generating module configured to generate gain information based on the measured air speeds at the plurality of target positions and the operating parameters for the plurality of fans.
- 20 14. The device according to claim 13, wherein optimizing the operating parameters comprises minimizing a largest difference in said differences based on the gain information and the desired air speeds at the plurality of target positions.
- 25 15. The device according to claim 13 or 14, wherein optimizing the operating parameters comprises determining changes in the operating parameters for the plurality of fans to obtain the optimized operating parameters based on the gain information and the desired air speeds at the plurality of target positions, wherein the gain information comprises a plurality of gain values, each gain value derived
- 30

based on a ratio of a change in the measured air speed at the corresponding target position to a change in the operating parameter of the corresponding fan.

16. The device according to claim 15, wherein said changes in the operating parameters are determined based on the equation:

$$\begin{aligned} &\text{Minimize } ||K \cdot \Delta P - \Delta V_d||_{\infty} \\ &\text{subject to } -\hat{P} < \Delta P < P_{max} - \hat{P} \end{aligned}$$

where K denotes the gain matrix, ΔP denotes said changes in the operating parameters $\hat{P}$, and $\Delta V_d = V_d - V(\hat{P})$, where V_d denotes the desired air speeds at the plurality of target positions, and $V(\hat{P})$ denotes the measured air speeds at the plurality of target positions from the plurality of fans generating air movement based on the operating parameters $\hat{P}$.

17. The device according to any one of claims 11 to 16, wherein the desired air speed determining module is configured to determine one or more of the desired air speeds based on a thermal comfort model and a temperature measured at the area as an input to the thermal comfort model.

18. The device according to any one of claims 11 to 16, wherein the desired air speed determining module is configured to determine one or more of the desired air speeds based on feedback received from one or more occupants at the corresponding one or more target positions.

19. The device according to claim 18, wherein the feedback comprises one or more of a first type of input indicating a desire to increase the air speed at the corresponding target position and/or one or more of a second type of input indicating a desire to decrease the air speed at the corresponding target position collected over a time period.

20. The device according to any one of claims 11 to 19, wherein the operating parameter is a power parameter or a speed parameter for controlling the elevated air speed generated by the fan.

5 21. A computer program product, embodied in one or more computer-readable storage mediums, comprising instructions executable by one or more computer processors to perform a method of controlling a plurality of fans disposed in an area to provide thermal comfort control for a plurality of target positions in the area according to any one of claims 1 to 10.

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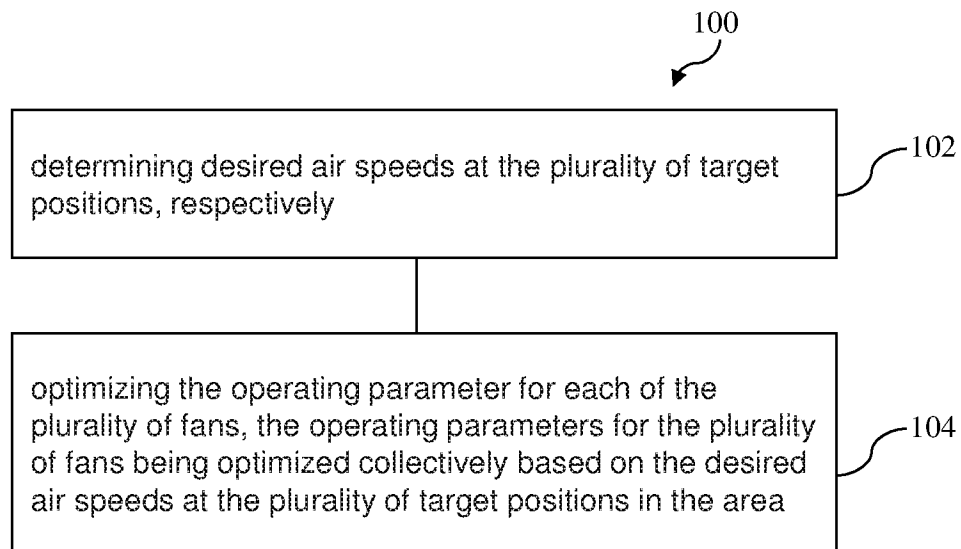


FIG. 1

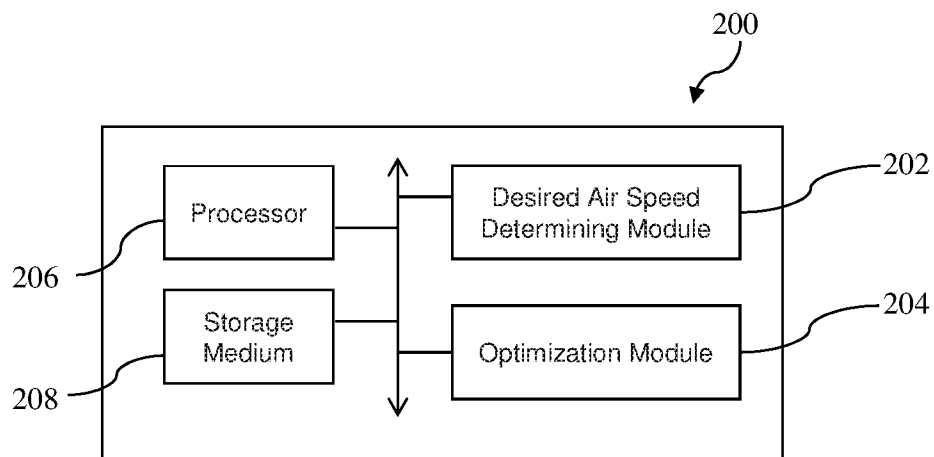


FIG. 2

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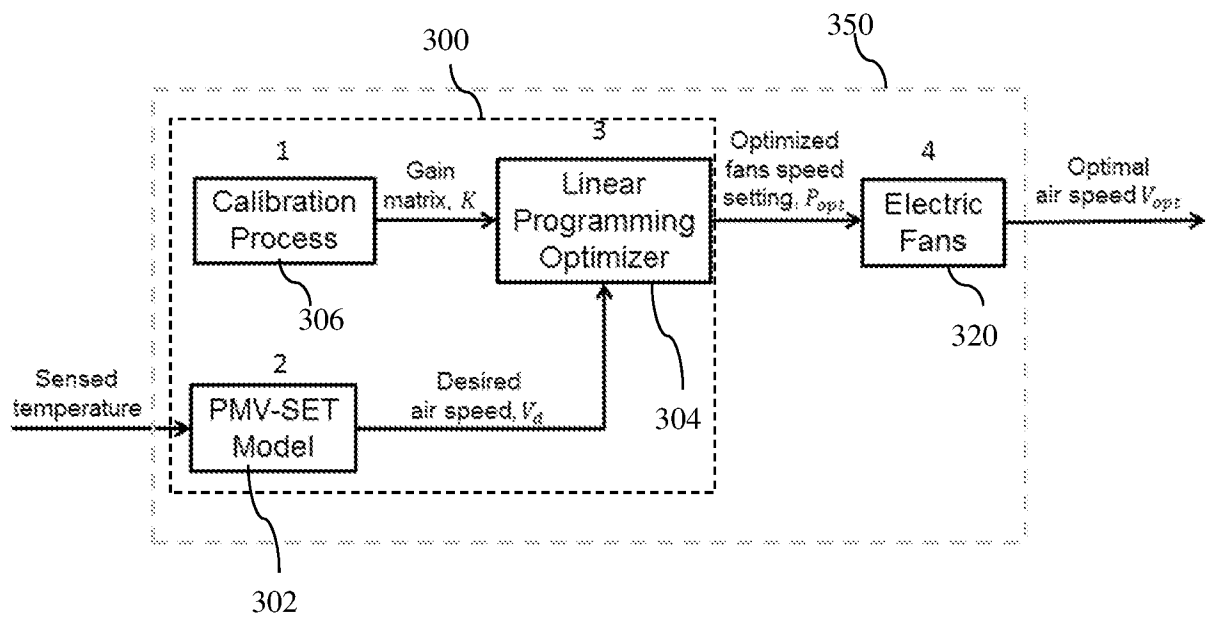


FIG. 3

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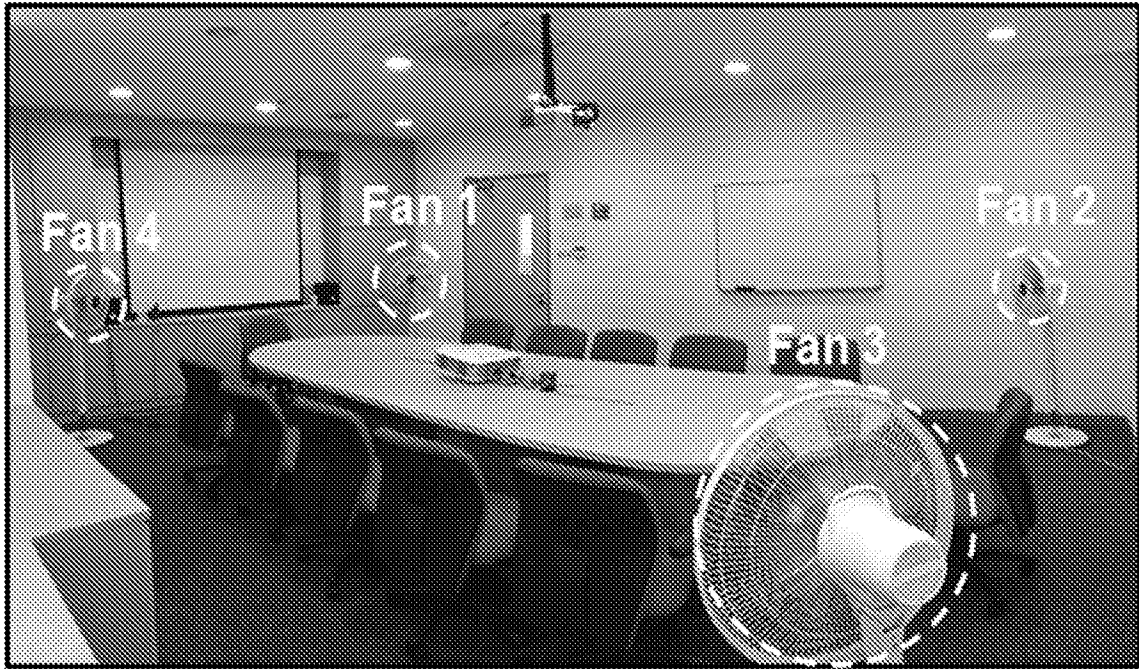


FIG. 4A

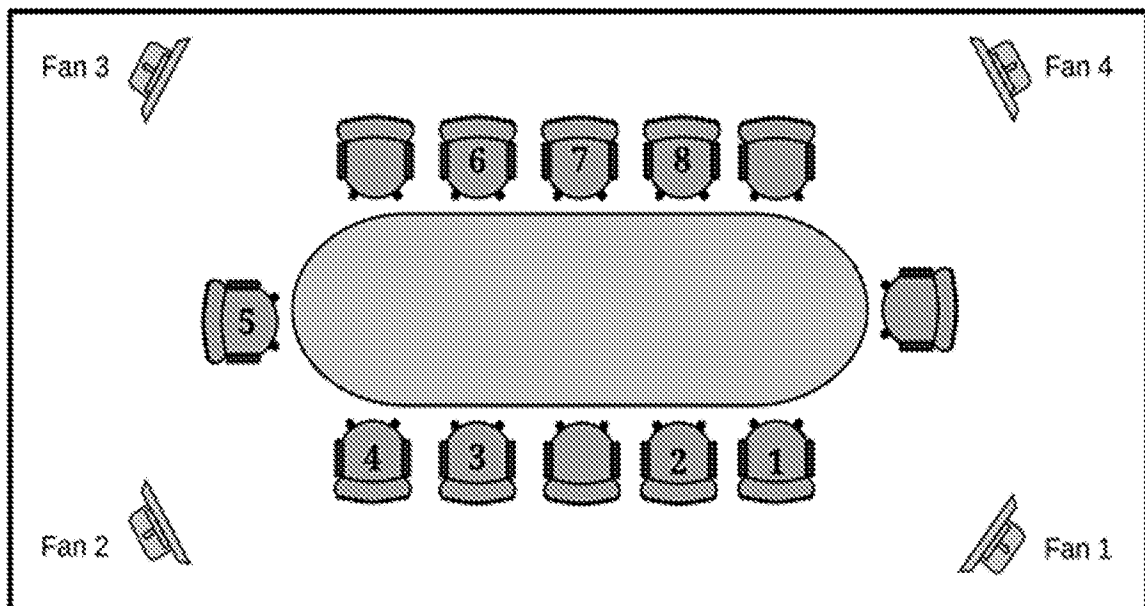


FIG. 4B

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FIG. 5

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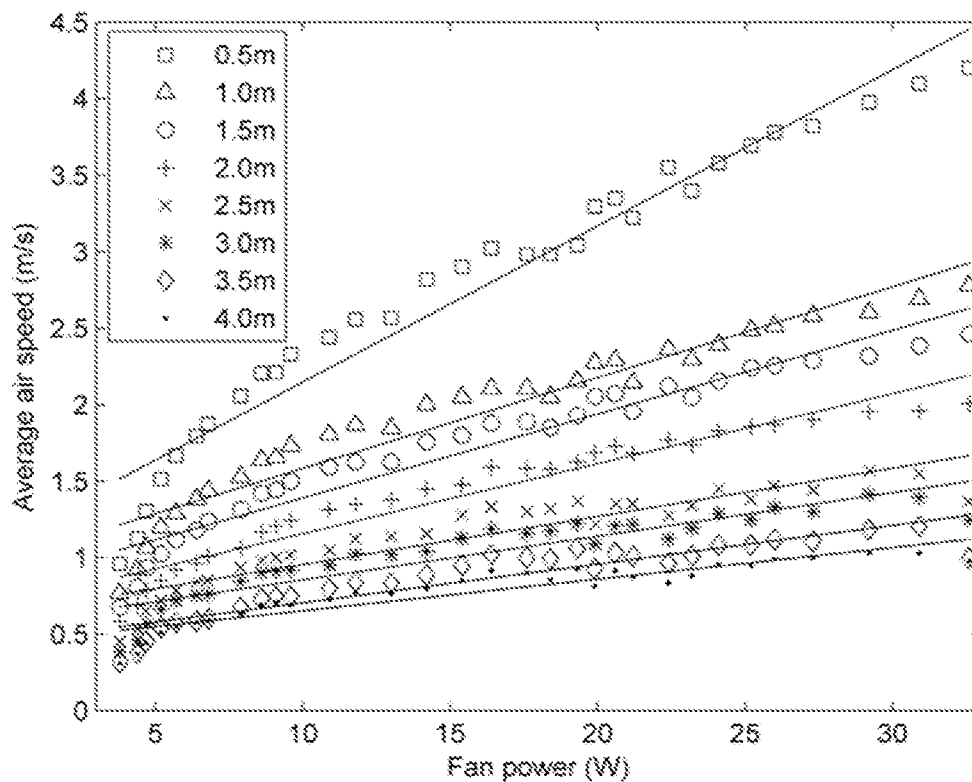


FIG. 6A

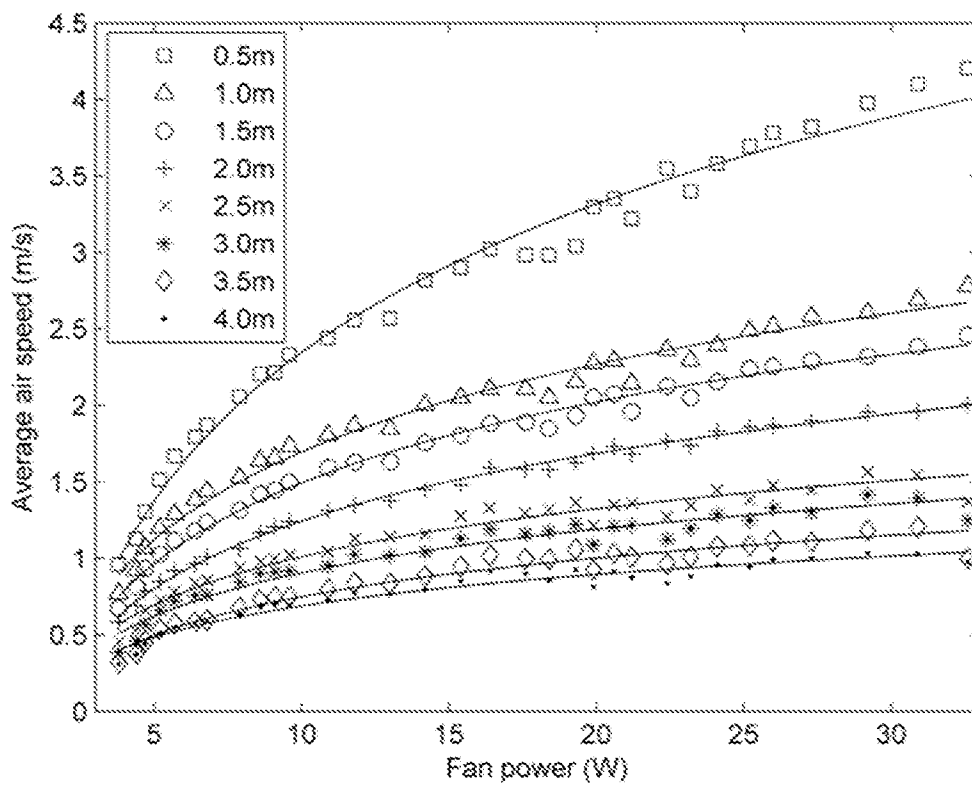


FIG. 6B

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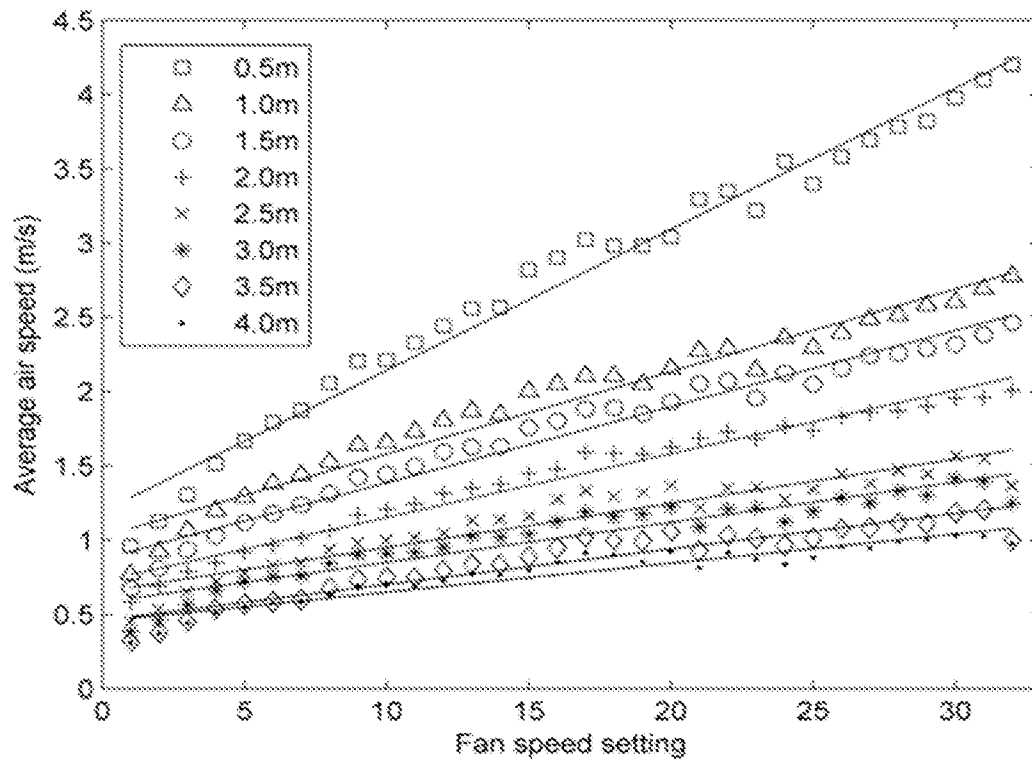


FIG. 7A

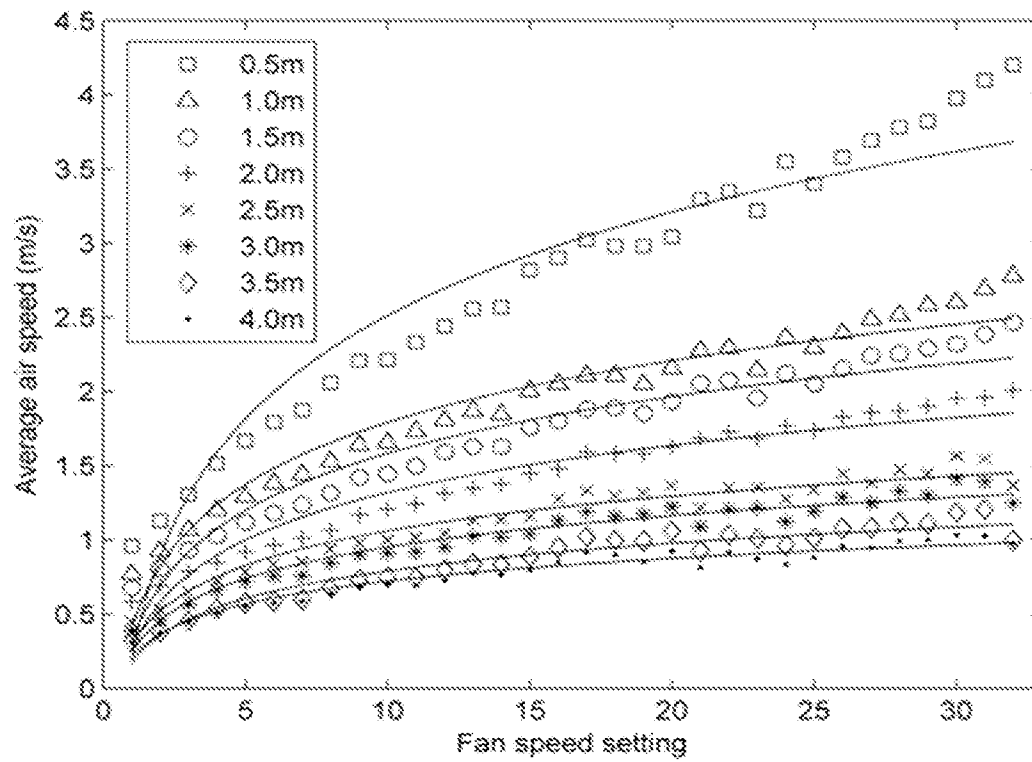


FIG. 7B

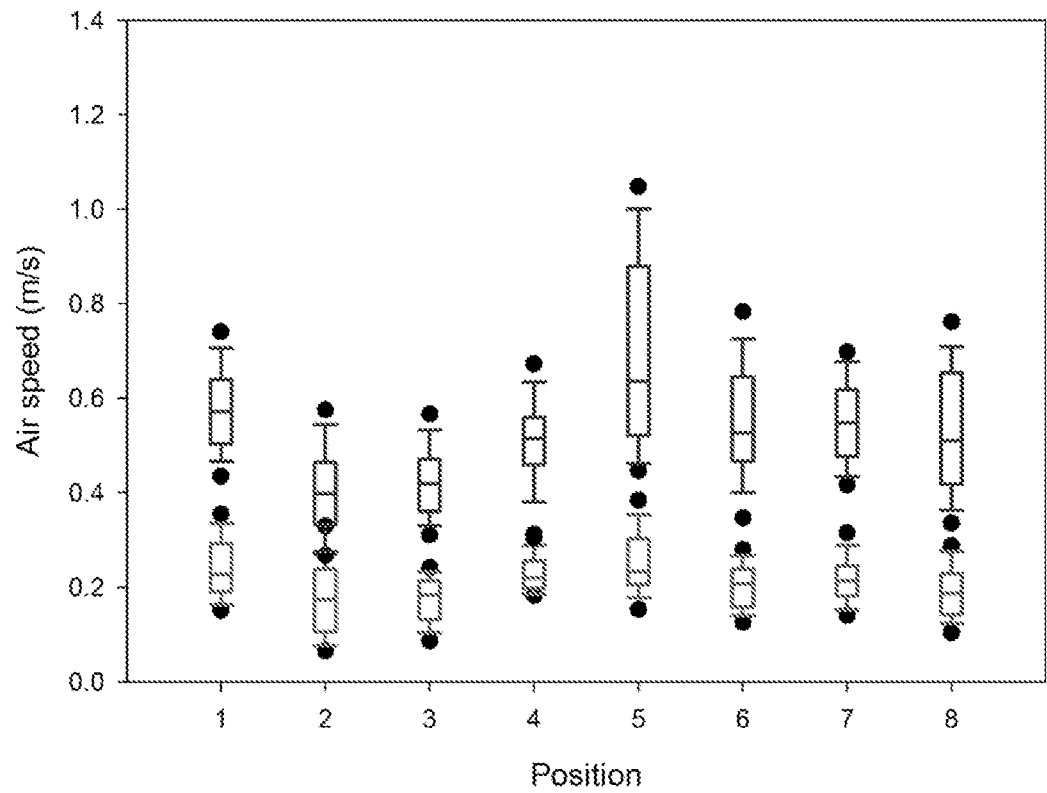


FIG. 8A

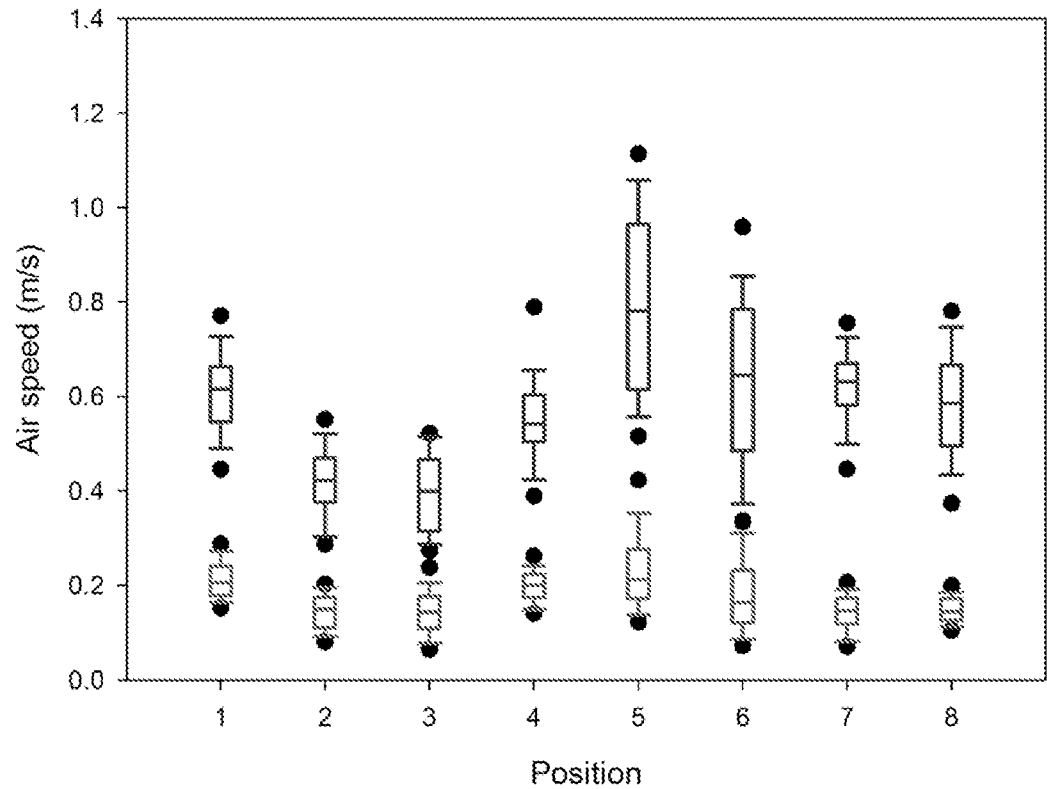


FIG. 8B

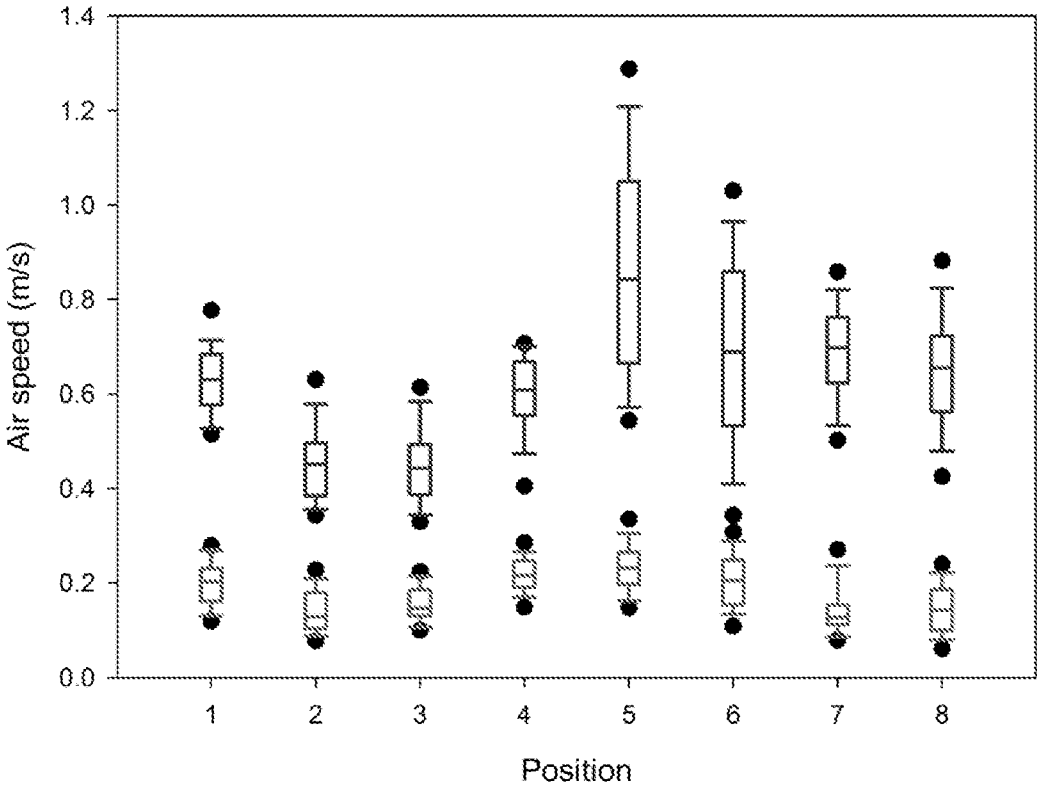


FIG. 8C

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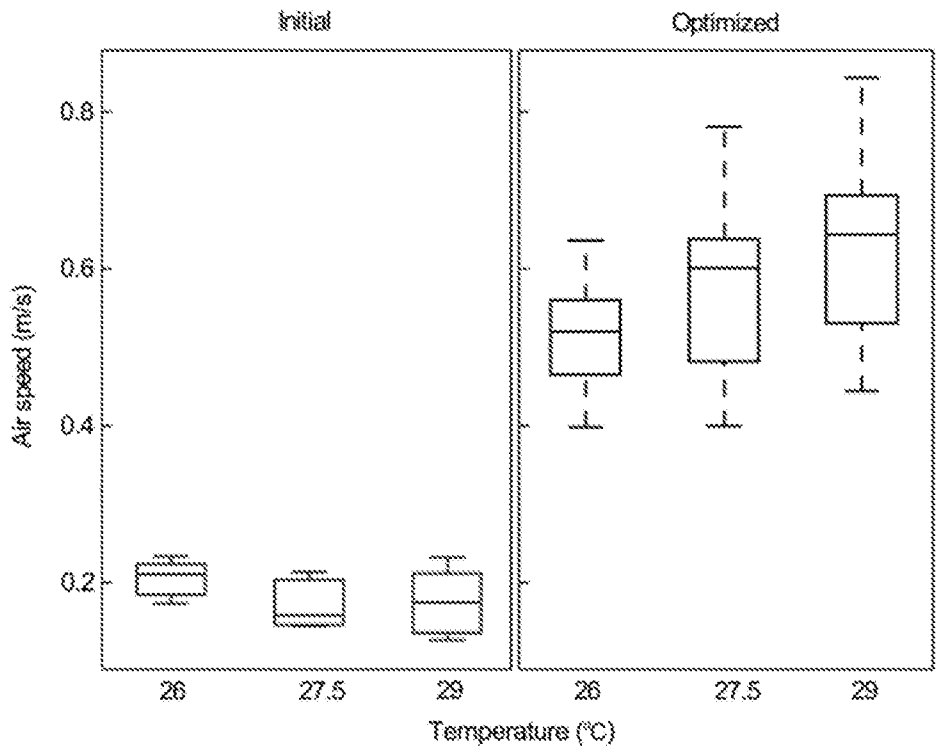


FIG. 9

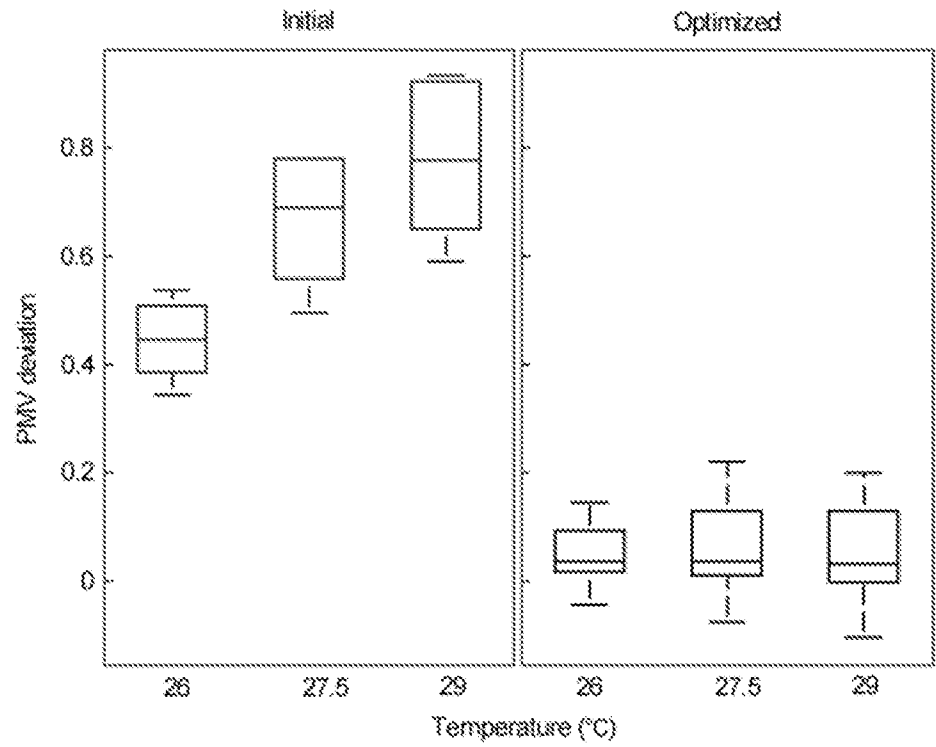


FIG. 10

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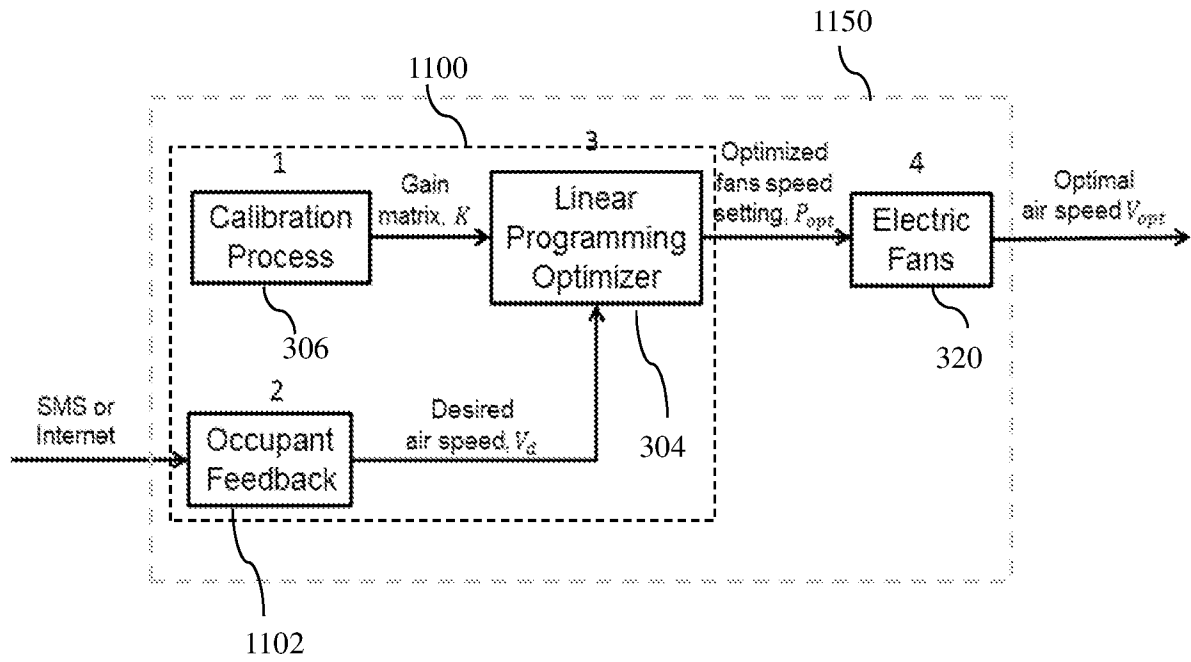


FIG. 11



FIG. 12

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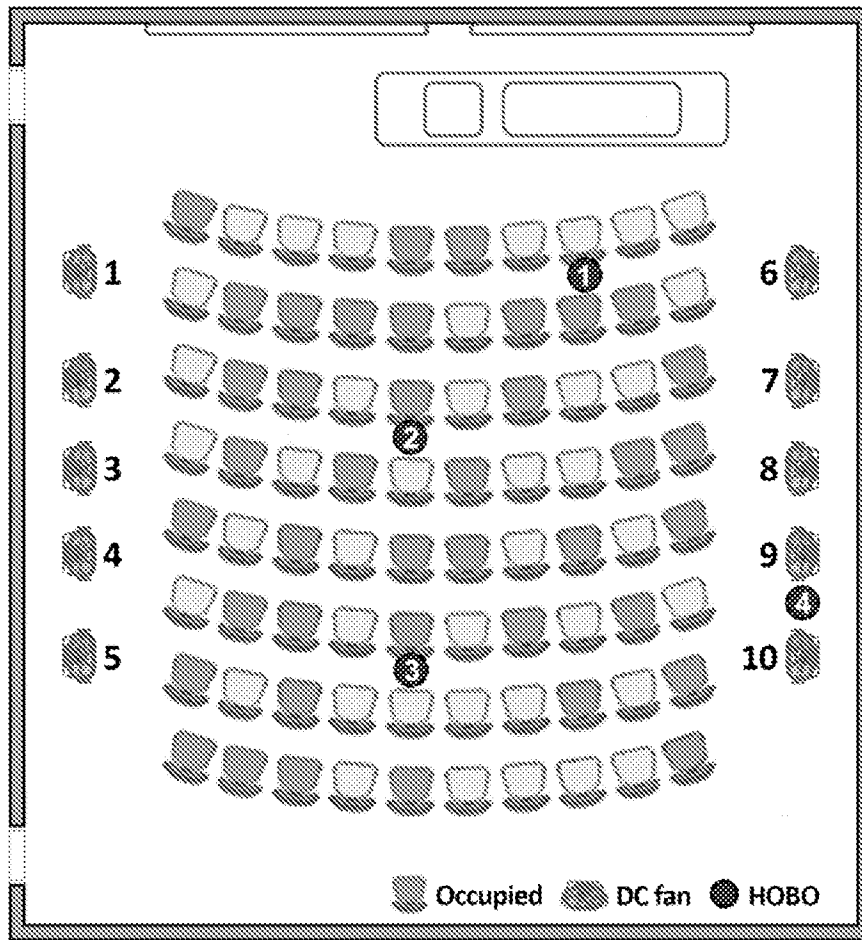


FIG. 13A



FIG. 13B

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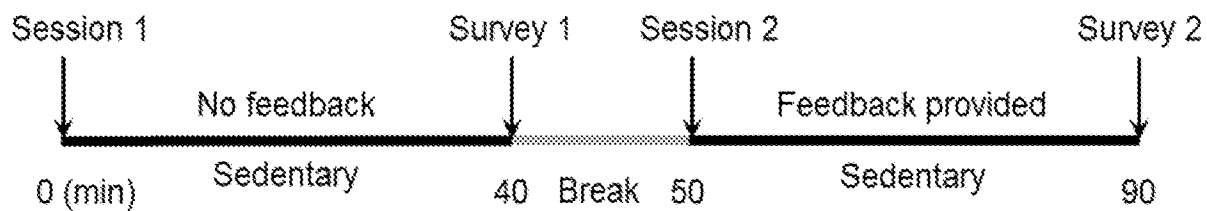


FIG. 13C

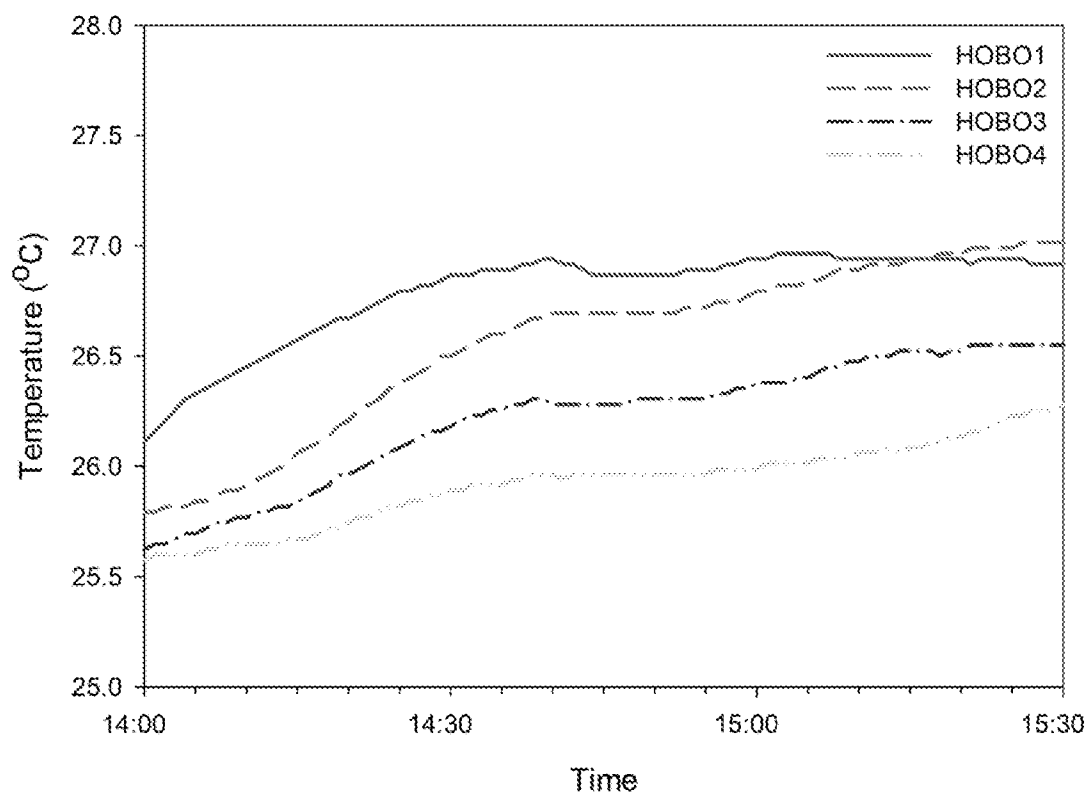


FIG. 14A

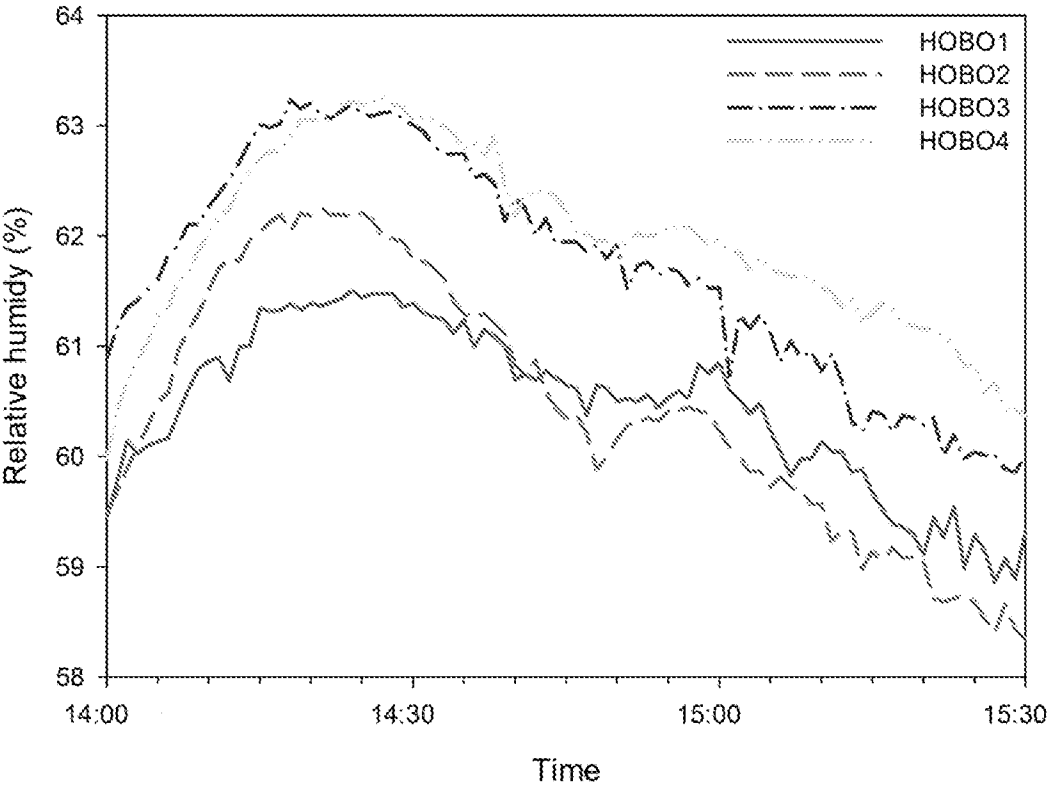


FIG. 14B

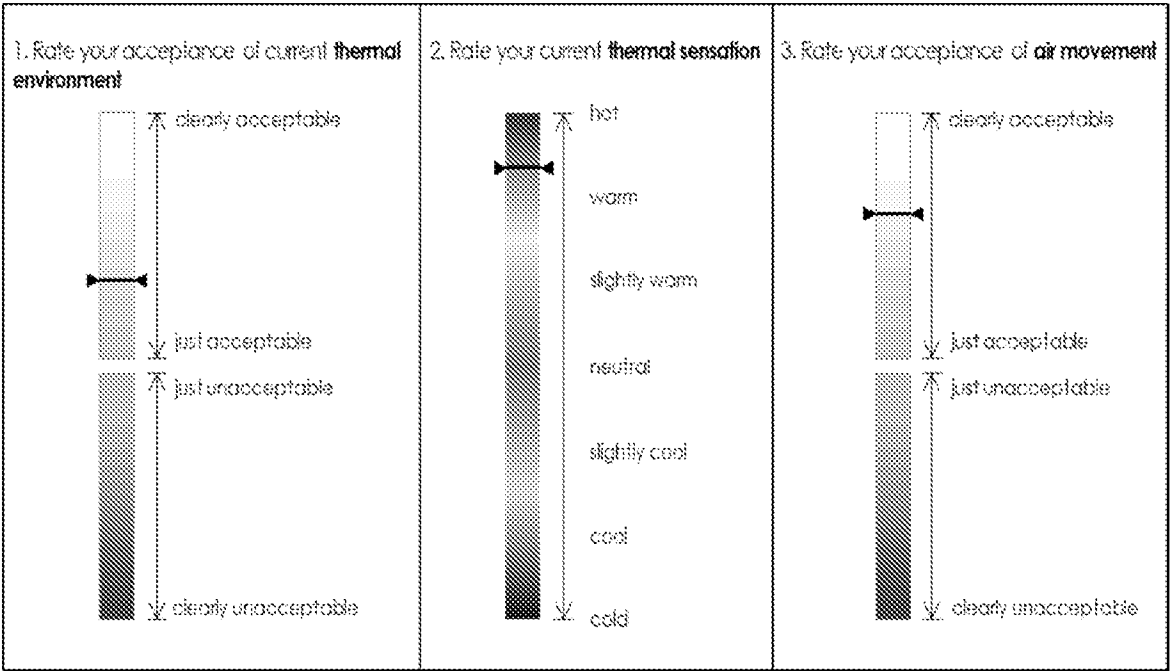
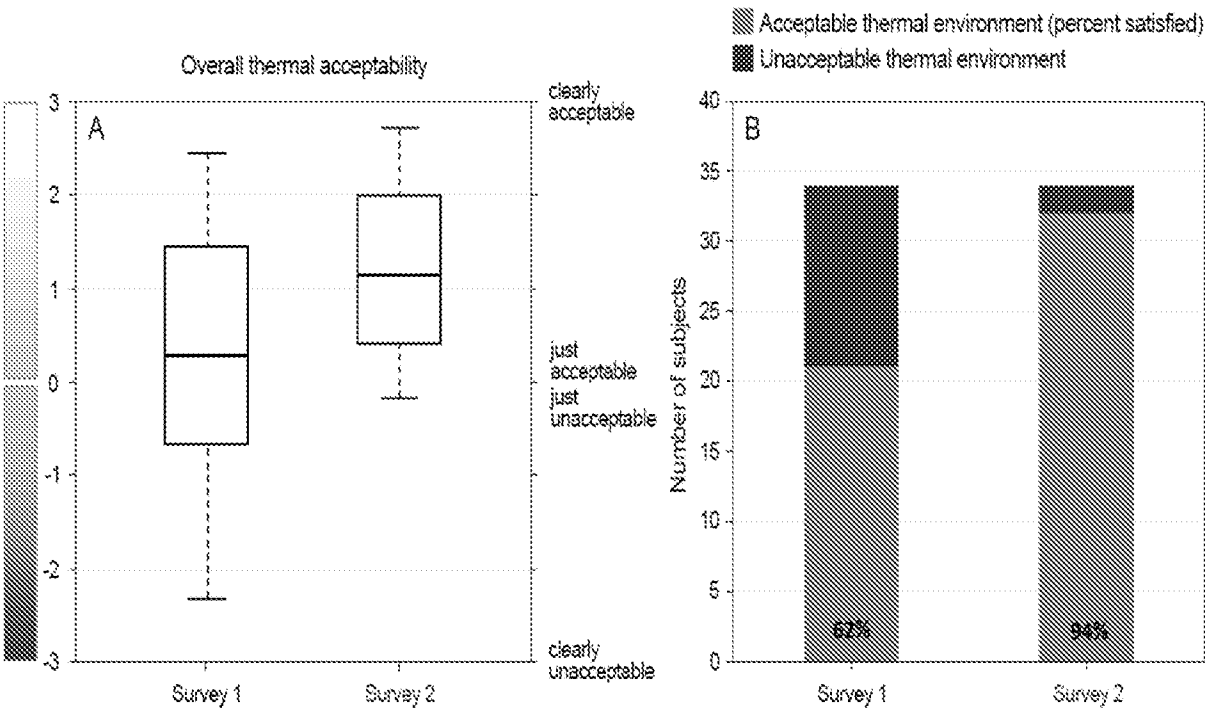


FIG. 15



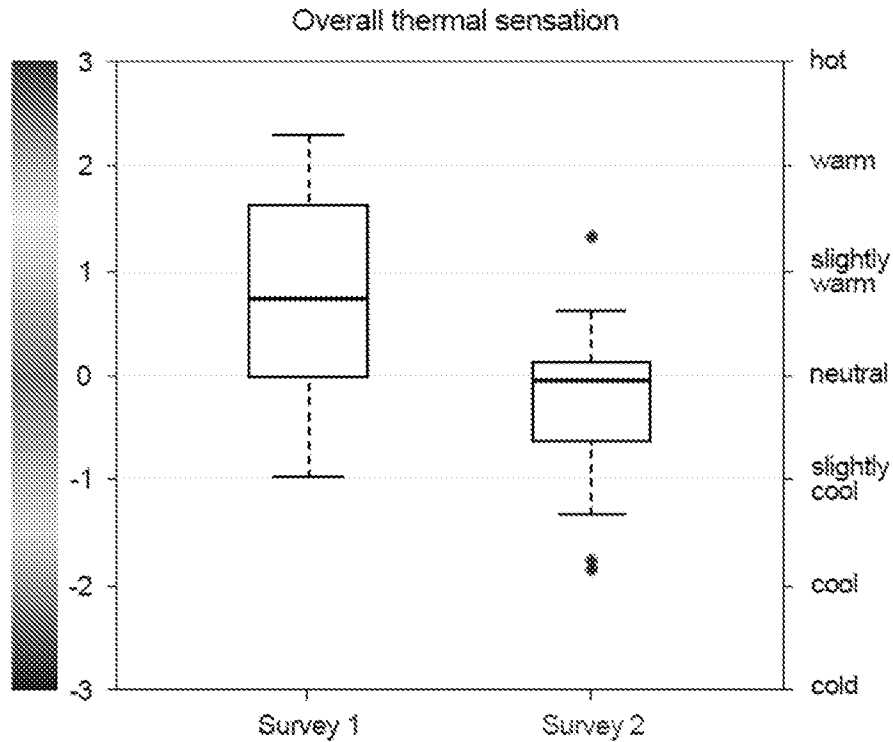


FIG. 17

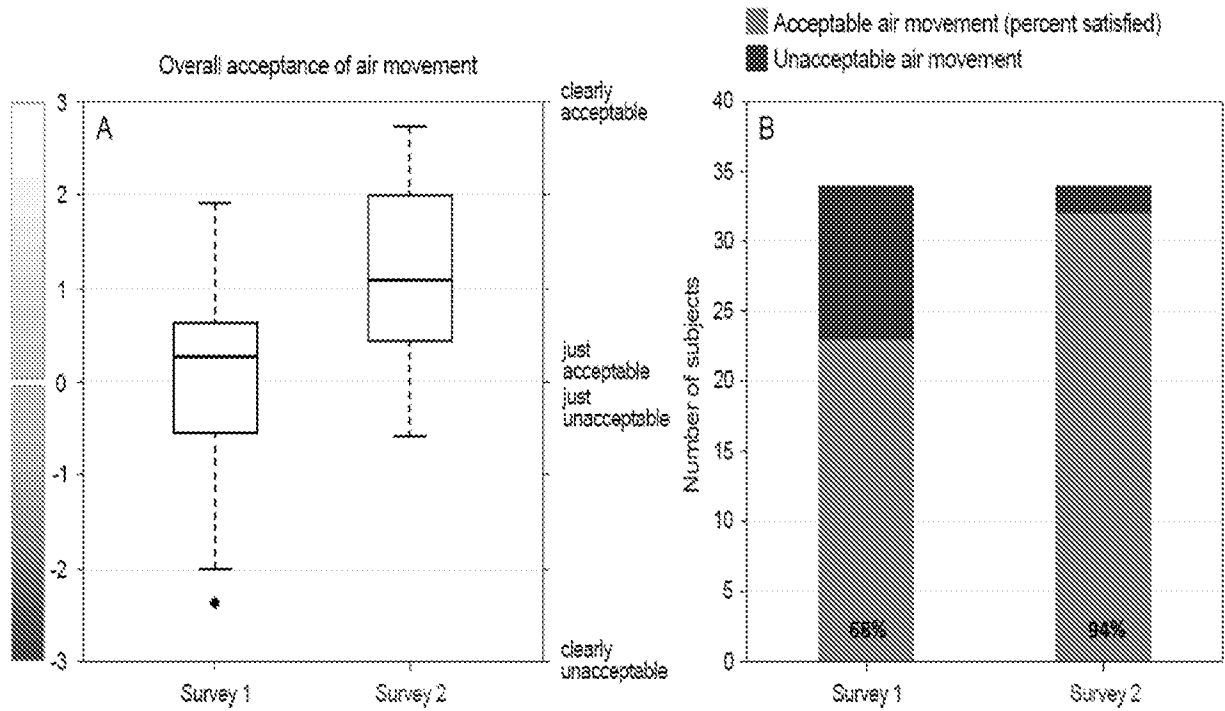


FIG. 18A

FIG. 18B

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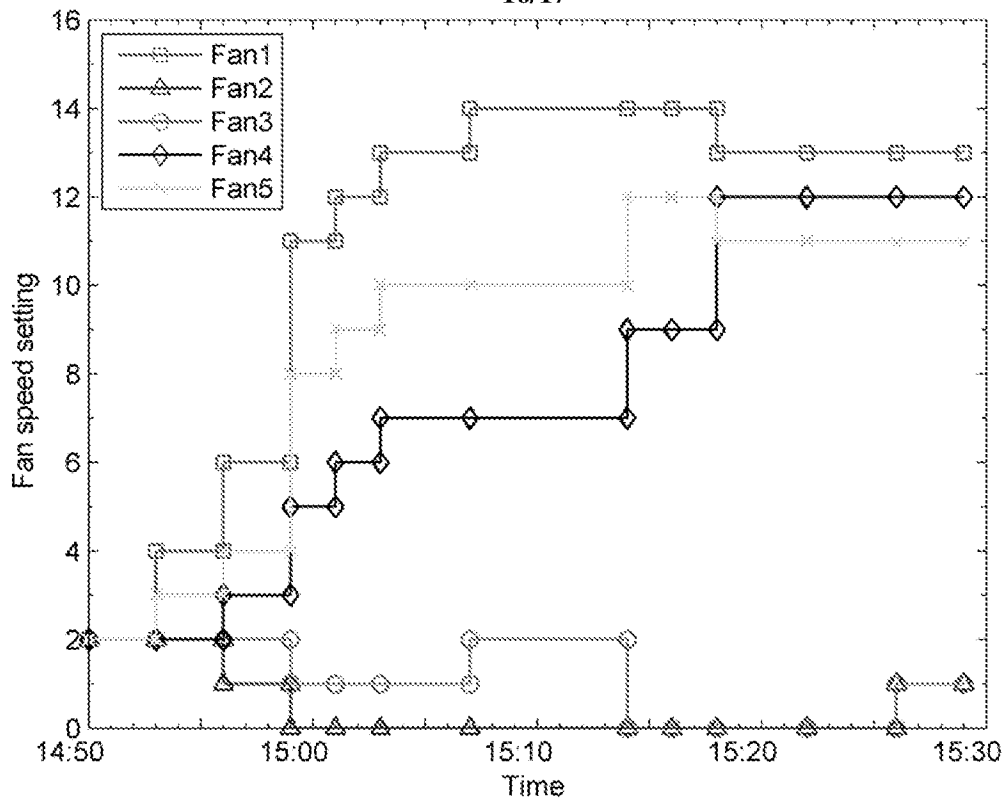


FIG. 19A

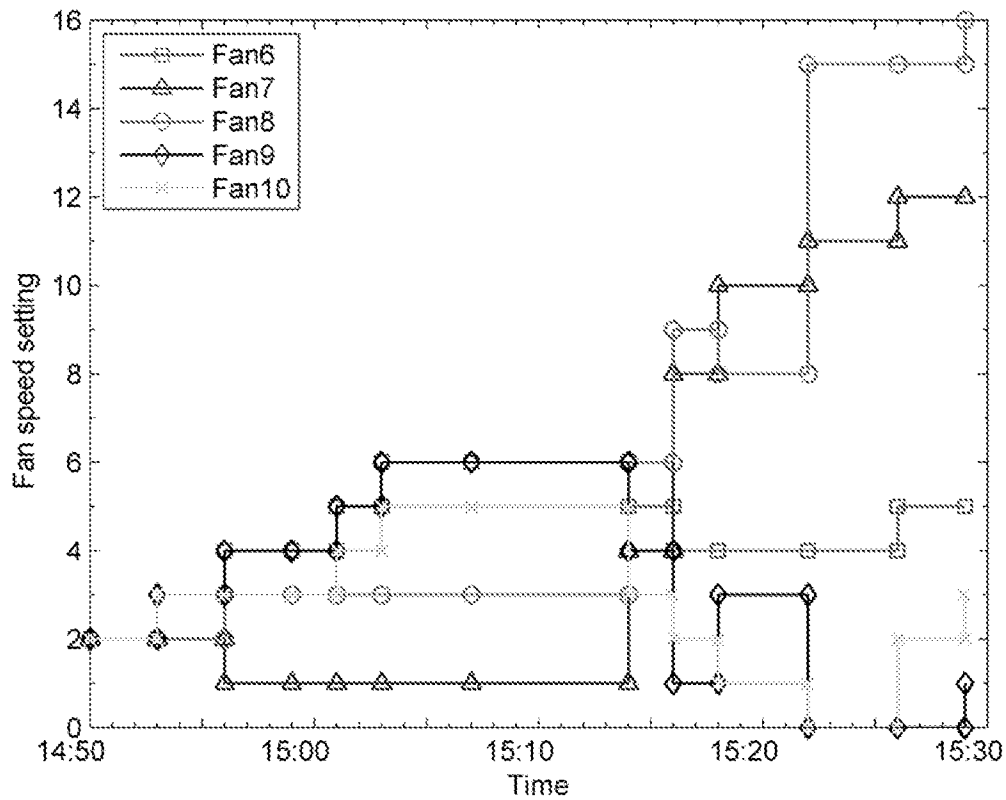


FIG. 19B

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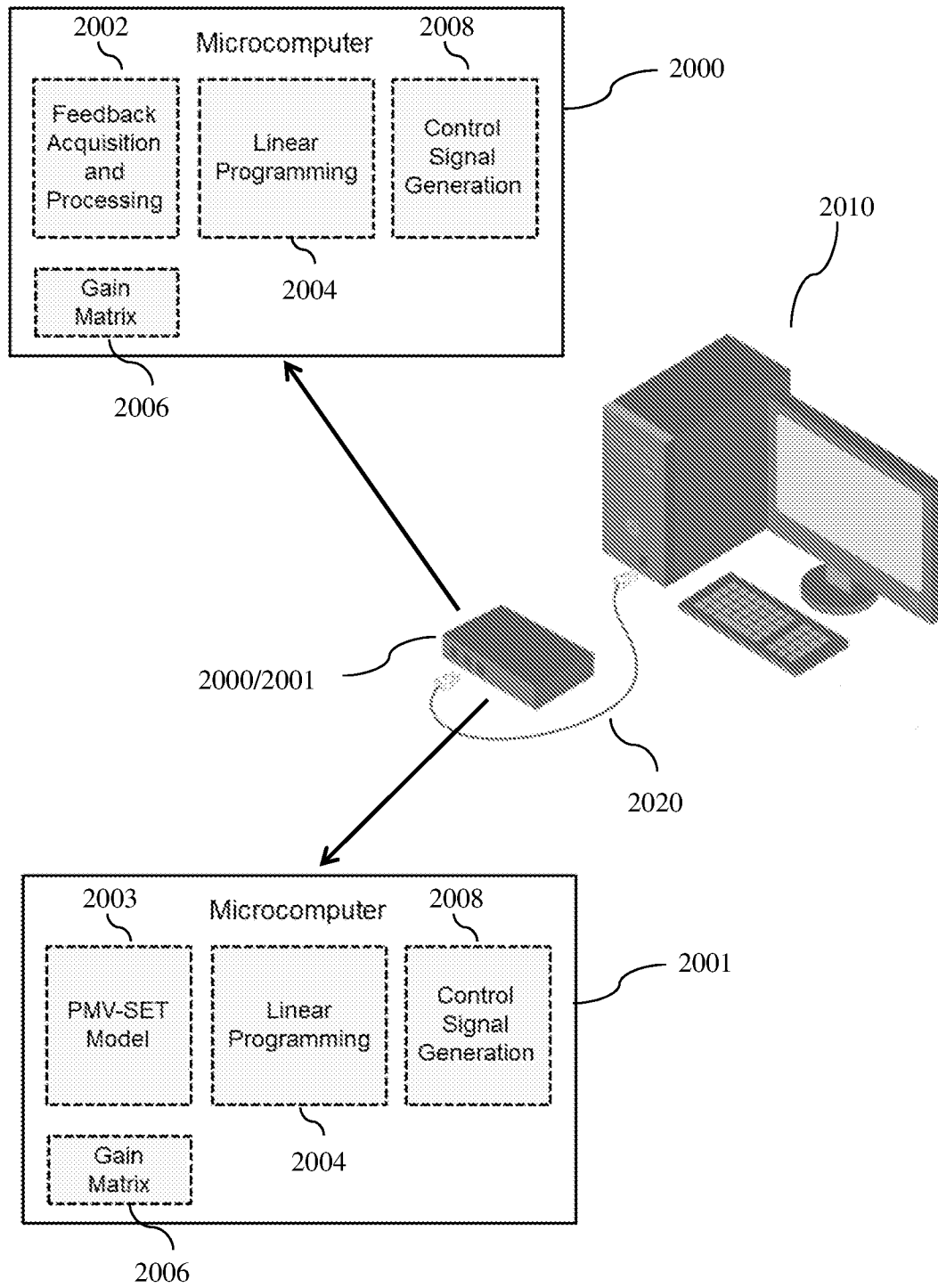


FIG. 20

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2017/050119

A. CLASSIFICATION OF SUBJECT MATTER

F24F 7/00 (2006.01) F04D 25/16 (2006.01) G06F 17/11 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F04D, F24D, F24F, G05B, G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC/WPI/FAMPAT: fans, ventilation, air circulation, 风扇, manage, control, optimize, 改, 调, 控, 管理, collective, coordinate, plurality, 集, 合, 群, operating, speed, 操, 功, 速, temperature, thermal, target, desire, spatial, distribution and related terms

IEEE: fans, collective, coordinate, power, speed, parameter and related terms

Google Scholar: inventors search

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2005/0232753 A1 (HOPKINS L.G.) 20 October 2005 Par. [0039] and [0044]-[0049]	1-4, 7-14, 17-21 5-6, 15-16
X A	US 2010/0163633 A1 (BARRETT J. & LINGEMANN R.) 1 July 2010 Par. [0074], [0078], [0079], [0081]-[0084], [0106], [0109], [0135], [0162], [0169], [0170] and [0178]	1-4, 7-14, 17-21 5-6, 15-16
A	US 4732318 A (OSHEROFF G.W.) 22 March 1988 Column 6 Lines 18-44; Figure 6	-

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

24/04/2017

(day/month/year)

Date of mailing of the international search report

07/05/2017

(day/month/year)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2017/050119

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

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US 2005/0232753	20/10/2005	CN 1795334 B CN 102200137 B EP 1604116 B1 EP 2014923 A3 JP 4008007 B2 KR 100736944 B1 US 7137775 B2 US 7527468 B2 US 7597534 B2 US 7914252 B2	01/06/2011 25/09/2013 22/12/2010 03/03/2010 14/11/2007 09/07/2007 21/11/2006 05/05/2009 06/10/2009 29/03/2011
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US 4732318 A	22/03/1988	NONE	