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RESEARCH ARTICLE

Firmware Development Process for Food Refrigeration System

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Abstract The refrigeration system is essential for preserving food and processing frozen food. A system firmware is a common and important feature in refrigeration system. However, it is difficult to verify the software, optimize the energy efficiency, and solve the system fault without refrigeration hardware. A virtual environment was established to verify software. The firmware developed in the virtual refrigerator was ported into an actual refrigerator, and then energy optimization was performed by auto test system. Even after the firmware verification by the processes stated above, and required tests were executed under strict test condition, unexpected faults could be appeared when they are used by consumers in the field. As a solution, new method using Internet was adopted to gather data, and software defects were able to be reported in real time. This new development process can be applied in all refrigeration systems for food industry and other home appliances.

Keywords: refrigerator, firmware, virtualization, energy efficiency, remote monitoring

Introduction

Refrigeration plays an important role in all stages of the food chain from processing frozen foods, to distribution, retail and preservation at home. The refrigerator is one of the most important and the biggest energy-consuming home appliances. The study of system and component efficiency improvements were gone on field of cycling losses, insulation, defrost methods, charge optimization, fans, compressors, refrigeration cycle alternatives, the Lorenz-Meutzner cycle, dual-loop system, two-stage system, control valve system, ejector refrigerator, and tandem system (1).

Most modern refrigerators use a system firmware for refrigeration control. Designing a firmware system includes both hardware and software design. In addition, mechanical design often needs to be considered. The best ideal firmware development model called co-design has been proposed by Haikala and Märijärvi (2). However, in many cases, the system hardware is not supplied on time owing to various issues. This leads to a shortage of time for testing the software for the actual machine (3).

Thus, software debugging is typically not completed on time, and insufficient test time is prone to cause many errors. Therefore, it was necessary for developers to construct a virtual system that simulates an actual system (4). Defects in the software decreased, and the virtual development system enabled the product to be quickly launched to market (5). It is important to have good software design and a process in place so that stringent deadlines can be met, and redundant work is minimized (6).

Using a virtual machine, developers can ensure a pristine environment and access to diverse (virtual) platforms (7). Recently, an advanced development method using a web-based cloud system was studied without any hardware platform (8). The feasibility of software development using the virtual machine of a refrigerator was verified through a comparison study using the operation data from an actual refrigerator. The developed firmware in the virtual refrigerator was verified by: 1) virtualization of the heat transfer, 2) test cases using a test automation system, and 3) simulation of the input/output adapter (9).

After verifying and validating the logic of the firmware algorithm from the virtual refrigerator, further testing was

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required with an actual refrigerator to acquire operation data using all the combinations of controllable factors related to refrigerator operation. The main purpose of the test was to improve the electrical energy efficiency. Because there were many test cases to evaluate the electrical power consumption (EPC) of the refrigerator, an automatic testing platform was required to reduce the test time and human resources. Such an automatic testing platform enabled the fully automatic testing and validation of the complete electrical power design comprising component safe-operating-area validation, system protection, firmware, and software implementation as well as overall system performance optimization (10). The results of the EPC were recorded to data archives with the data related to the temperature and the operational state of the refrigerator. The optimized parameters were found using factorial design analysis.

In spite of these well-designed development processes, there could be a fault in a system in the field, and it is difficult to acquire the problem data from customers after the incident occurs. Even after the manufacturer acquires the data including errors from the data acquisition device such as black box mounted in refrigerators or refrigerators, the analysis time and effort are too great to solve these problems, as the quantity of the data acquired over a long period is massive.

Electronic devices may be controlled using PC software and an embedded system, sending and receiving remote data at distances over 1 km (11). In addition, a virtual platform has been developed for an internet-based remote application dedicated to condition monitoring and fault detection for AC electrical machines located globally (12,13). After adoption of this method to collect the data, it was able to save and analyze the data in real-time without the limitations of time and region. The data were transmitted to the local host server from remote refrigerators using the Internet. Prior to customer recognition of a refrigerator problem, a pre-service solution was able to be supported without the need to physically access the remote location (14).

We have proposed a new firmware development process of refrigerators that facilitate more stable storage of food by applying diverse ways studied in the above-mentioned fields.

Materials and Methods

Virtual refrigerator A virtual refrigerator was simulated from a designed model system as shown in Fig. 1. The thermal conductivity (k) of the insulation material in the refrigerator, the heat transfer area, the speed of the fan, the volume, and the inside and outside convective heat transfer coefficients (h_i and h_o, respectively) can be adjusted using the graphical user interface (GUI) of the developed simulator program. The virtualization was verified from an actual system, FD-170-SF refrigerator (Unique Daesung Co., Ltd., Gyeonggi, Korea) (15).

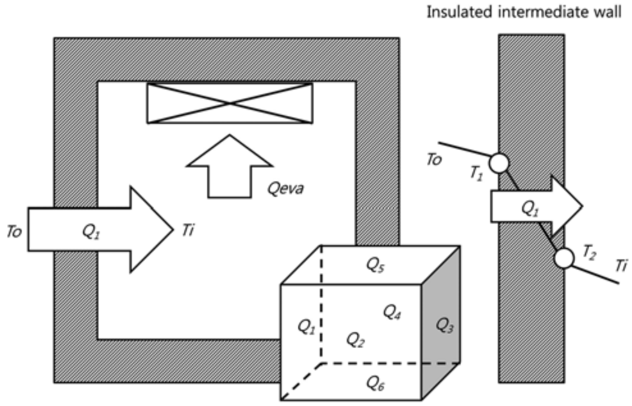

Fig. 1. The various energy flows inside the refrigerator. α, diffusivity; T_n, nodal temperature; Δx, nodal space

The flow of heat in the refrigerator was modeled (Fig. 1). The refrigerator cabinet heat transfer conductance allows the heat transfer through the cabinet walls ($Q_{cabinet}$) to be calculated using Eq. 1-3.

$$Q_{cabinet}=Q_1+Q_2+Q_3+Q_4+Q_5+Q_6 \quad (1)$$

$$Q_{cabinet}=UA(T_o-T_i)=h_oA(T_o-T_1)=k\frac{A}{x}(T_1-T_2)=h_iA(T_2-T_i) \quad (2)$$

$$U=\frac{1}{\frac{1}{h_o}+\frac{x}{k}+\frac{1}{h_i}} \quad (3)$$

where Q with numerical subscripts is the transfer rate (W) through each faces of the cabinet, A is heat transfer area (m^2), U is overall heat transfer coefficient [W/(m^2·°C)], T_1 is outside surface temperature (°C), T_2 is temperature at inner wall of the cabinet (°C), x is the thickness of the cabinet (m) and the subscript o and i indicate outside and inside, respectively.

Eq. 4-6 represent the heat removed by evaporator. Instead of using a refrigerant side energy balance, the sum of all heat transfer and power entering the refrigerator cabinet is used.

$$Q_{eva}=Q_{\max}\times\varepsilon \quad (4)$$

$$Q_{\max}=(\dot{m}\,c_p)_{air}\times(T_{air,in}-T_{eva}) \quad (5)$$

$$\varepsilon=1-e^{-NTU}=\frac{Q_{eva}}{Q_{\max}} \quad (6)$$

where Q_{eva} is the heat removed by evaporator (W), ε is effectiveness, $\dot{m}$ is mass flow rate (kg/s), c_p is specific heat

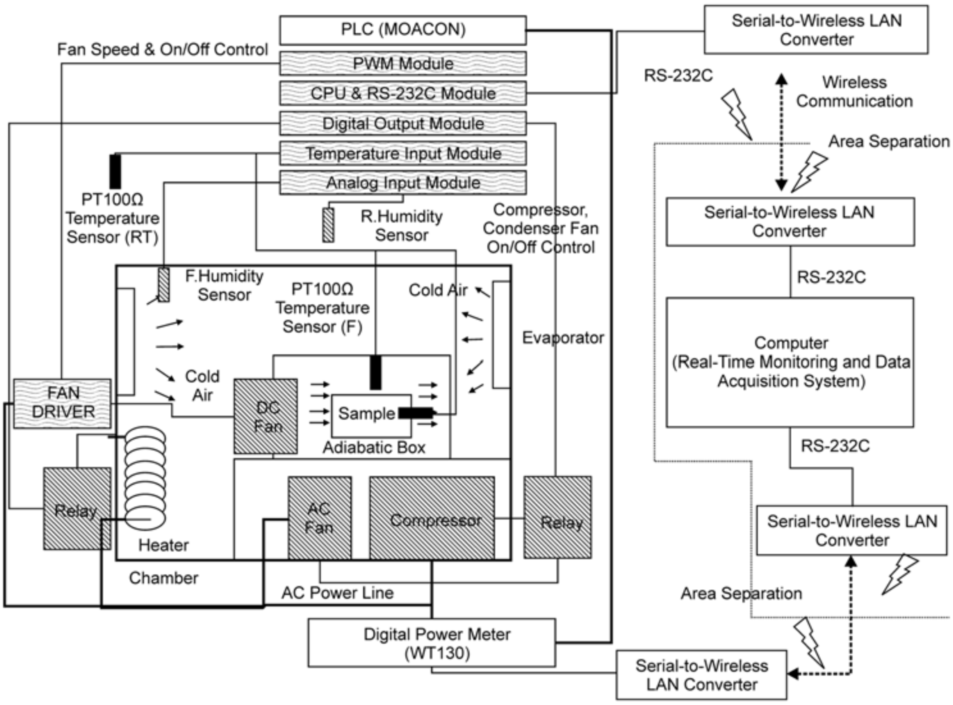

Fig. 2. Actual refrigerator system used to verify the virtual simulation.

[J/(kg·°C)], and *NTU* is number of transfer unit=$\frac{UA}{(\dot{m}C_p)_{air}}$ and, $U=27.2\times V_{air}^{0.56}$ (empirical formula about fin tube evaporators).

The heat energy associated with the air (Q_{air}) and food (Q_{food}) in the refrigerator was calculated by the value of the eliminated energy from the evaporator (Q_{eva}) minus the sum of the incoming heat through the insulation material ($Q_{insulation}$) and the food respiration heat ($Q_{respiration}$) using the energy balance equation (16-21).

To calculate this heat flow, we assume the following. One dimensional steady-state heat transfer was assumed for a quick calculation. The thermal properties, heat transfer coefficients, and outdoor temperature were constant, and the radiant heat was ignored. In addition, the temperature of the contents inside the refrigerator, including the refrigerator air, constantly increased. The internal barometric pressure was 1 atm, and the food and corner space were ignored. The incoming heat transfer in all aspects of the refrigerator was the same (21,22).

Actual refrigerator The virtual model created by software was verified by the system shown in the Fig. 2. An external cabinet part and the refrigeration cycle part of the FD-170-SF refrigerator (Unique Daesung) were used, but the control part was redesigned.

Software architecture of virtual model The virtual refrigerator system was comprised of an environment simulator and a PLC (or MICOM) emulator. Once the refrigerator logic program in the PLC emulator was executed, the environment simulator calculated the in-cabinet temperatures by using the output states of the compressor and the fans of the refrigerator. By changing these outputs, the values of the temperature sensors were changed as well. To express these values correctly, the simulator continuously calculated the compressor operation ratio (*F*) related to the heat transfer of the refrigerator using Eq. 7.

$$F=Q_{cabinet}/Q_{eva} \quad (7)$$

This virtualization was programmed using the MFC library based on Windows OS. The GUI was developed using Microsoft Visual C++. The refrigerator program section was written in the standard C language. The program section was ported to the PLC, and it operated well in the actual system as well as in the virtual system.

Test case design Five factors, which were Notch, Differential, Compressor_Delay time, Fan_Speed, and Fan_Delay time, were selected as controllable changeable parameters to test the EPC of the actual refrigerator. The first test was designed to test each factor level within 2 or 3 steps [i.e., 3 (Notch) steps×3 (Differential) steps×3 (Compressor_Delay time) steps×3 (Fan_Speed) steps×2 (Fan_Delay time) steps=162 test cases]. The creation of a test case followed the full factorial design law. The design of the test case was customized through the parameter

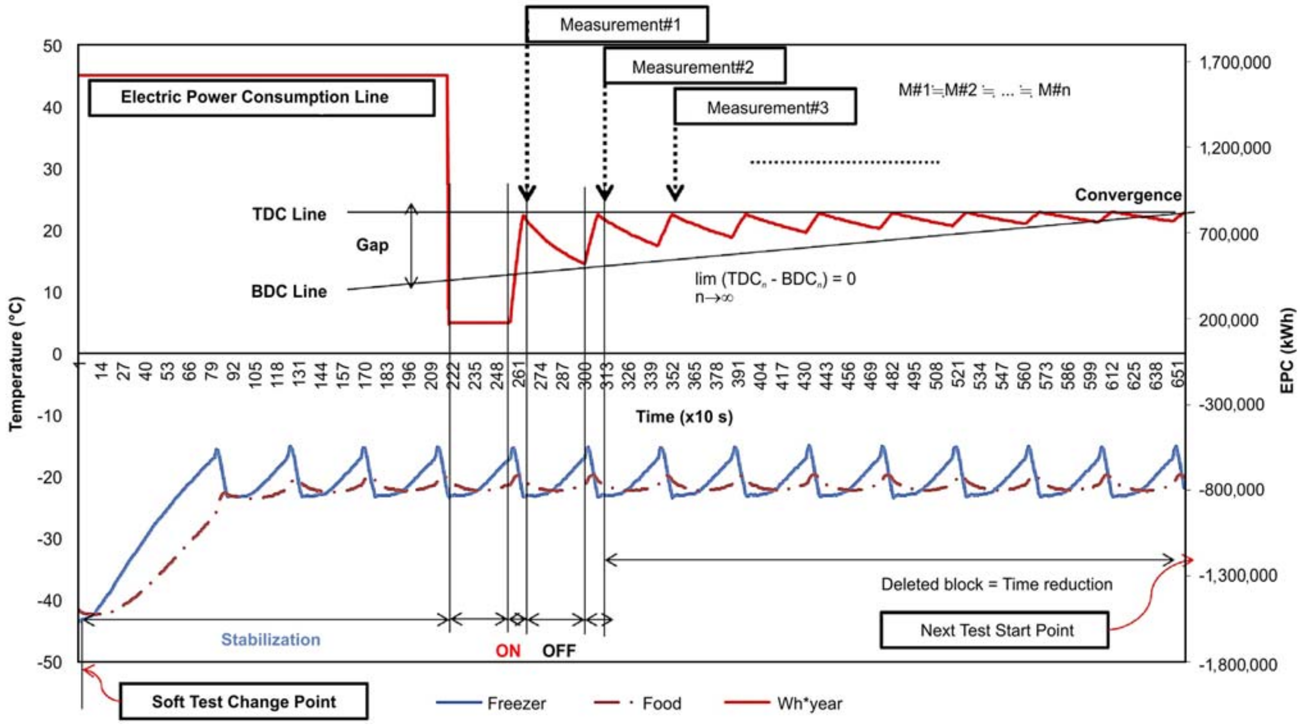

Fig. 3. Optimal method for reducing the measurement time.

settings from the GUI program. If a more detailed test was required, it could be easily redesigned by changing each of the parameters.

Test flow The test may be customized by inserting the highest value, the lowest value, the increment step of each level (20, 30, and 40ºC) of the 5 factors, and the iteration test number of the refrigeration cycle.

Test time reduction The temperature stabilization process of the refrigerator was executed by a method that includes repeating the on/off of cycle until the insulating material of the refrigerator approached the set stabilization temperature before the annual EPC was measured in the following cycles, as shown in Fig. 3. The end point of the compressor on time was the top dead center, TDC, and the end point of the compressor off time was the bottom dead center, BDC. For a long test time, the cycle at which TDC and BDC converged to the same point was predicted using Eq. 8.

$$\lim_{n\to\infty}(\mathrm{TDC}_n - \mathrm{BDC}_n) = 0 \quad (8)$$

Because the slope of the TDC line was close to zero as shown in Fig. 3, the first measured point of the TDC was simply used as the annual EPC data.

Derived accelerated test method In the International Organization for Standardization (ISO) standards, the test period shall be at least 24 h long. It shall also comprise a whole number of control cycles for appliances without automatic defrosting, or a whole number of defrost cycles for appliances with automatic defrosting, respectively (23). When the accelerated test method found in Fig. 3, which had four stabilization cycles and one measurement cycle, was applied to the test program, as seen in Fig. 4, the test period was able to be reduced by approximately 83% by this method, because 6 test cases compared to ISO standards were executed a day.

Hardware composition To design this remote monitoring system, a domestic French-door refrigerator (GRL218ASL; LG electronics, Seoul, Korea) was used. The mounted firmware gathered various data including the temperature and door switch state from the refrigerator. The temperature was measured at the refrigerator compartment, the refrigerator compartment, the left hinge of the top door, and the evaporator. A damper, a compressor, a heater for defrosting the evaporator, a condenser fan for cooling the condenser and compressor, and an evaporator fan for circulating cold air were controlled by the firmware.

Communication method To connect the RS-232C signal level to the LAN, a serial-to-wireless LAN converter (CSW-H80; Sollae Systems, Incheon, Korea) was used. This unit has many functions for network solutions, and it

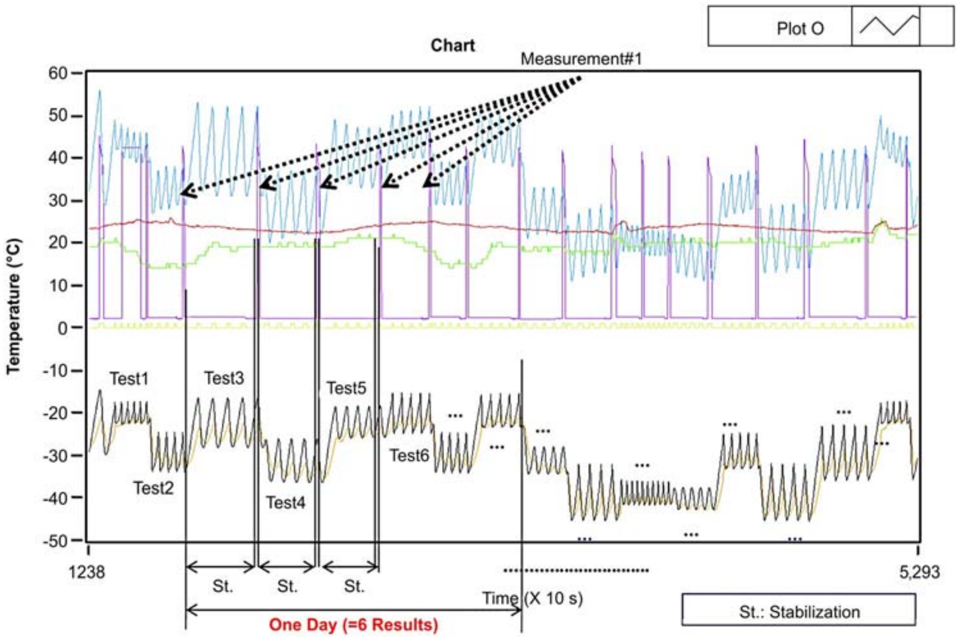

Fig. 4. Graphical results of the test automation software algorithm.

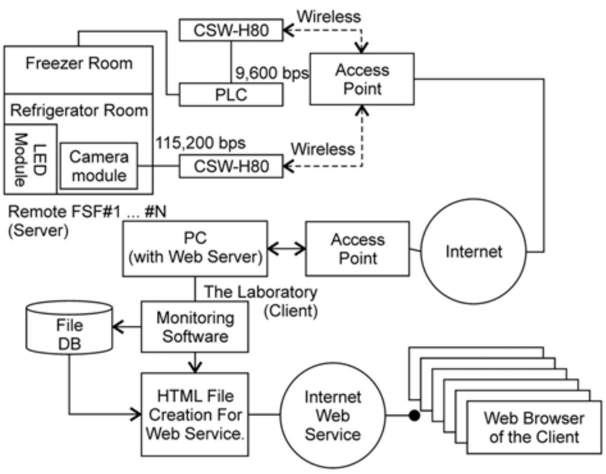

Fig. 5. Overall connectivity of the experimental network system.

was able to design a wireless LAN system very simply.

A wireless device using a commercial access point (N6004; EFM Networks) was connected to the wired LAN socket on the wall. Any access point could be used if it supported DDNS functionality. A C328 CCD module with an EV232 evaluation board (COMedia Ltd., Hong Kong, China) was used to send still images to the laboratory. Because the EV232 evaluation board supports RS-232C at a baud rate of 115,200, it was simply connected to the other CSW-H80 unit. The overall connectivity of the experimental network system is shown in Fig. 5.

Web service To support outside users who want to participate in our experiment, a web service was provided. An Apache web server (distributed by The Apache Software Foundation) was installed with a PHP interpreter (distributed by The PHP Group) language on the laboratory PC. The developed client software renewed HTML files every 2 s. The contents of the HTML file simply comprised of several sensor values, load states, and a still image.

Results and Discussion

Three process steps were applied for the firmware development process of refrigerators. Step 1: the virtualization that assisted the software was able to be programmed without the actual system. Step 2: the test automation was able to rapidly help find the optimum parameters without a huge investment of time and human resources. Step 3: remote monitoring was used as a method to verify the field tests and provided many advantages in finding bugs in the firmware program in real-time.

Virtual and actual systems The values for the notch and differential temperatures in the virtual refrigerator were set as –20°C and +/–3°C, respectively. The firmware developed and verified from this virtual refrigerator was ported to the PLC of the actual refrigerator, and the resulting data for both environments was compared. The developed firmware was promptly ported to the actual refrigerator without any revision because the actual refrigerator was simulated well by the virtual refrigerator.

The analysis results for various test cases are summarized

Table 1. Test results for the actual and virtual temperatures

Case No.	Notch (°C)	Differential (°C)	Actual average temperature (°C)	Virtual average temperature (°C)	Virtual/Actual (%)
1	-20.0	1.0	-22.55	-20.86	92.51
2	-20.0	1.0	-22.48	-20.86	92.78
3	-20.0	3.0	-22.78	-20.54	90.18
4	-20.0	3.0	-22.71	-20.54	90.46
5	-20.0	3.0	-22.67	-20.54	90.63
6	-20.0	5.0	-22.70	-20.43	90.02
7	-30.0	1.0	-31.36	-30.33	96.71
8	-30.0	3.0	-31.54	-30.44	96.50
9	-30.0	5.0	-31.59	-30.90	97.83
10	-30.0	5.0	-31.56	-30.90	97.90
11	-30.0	5.0	-31.49	-30.90	98.13
12	-30.0	5.0	-31.57	-30.90	97.89
13	-40.0	1.0	-40.33	-39.89	98.90
14	-40.0	1.0	-40.38	-39.89	98.78
15	-40.0	1.0	-40.22	-39.89	99.19
16	-40.0	3.0	-40.43	-40.97	101.32
17	-40.0	3.0	-40.37	-40.97	101.47
18	-40.0	3.0	-40.47	-40.97	101.23

in Table 1. In the –20°C temperature zone, the average temperature of the virtual refrigerator was controlled within the 90 to 92% level compared to the average temperature of an actual refrigerator. In the –30°C temperature zone, the virtual refrigerator was in accordance with the 96 to 98% level. In the –40°C temperature zone, the virtual refrigerator was controlled in accordance with 98 to 101% level, as summarized in Table 1. The virtual system was operated properly between the –30 and –40°C temperature zones if it was assumed that confidence level was higher than 95%.

When the software was properly developed in a simulated environment, even though a real environment cannot be modeled perfectly, it was found that verification and validation of the control algorithm was possible. The refrigerator firmware developed by this virtualization operated well in the actual hardware without additional efforts for debugging.

EPC optimization by test automation As shown in Fig. 6, the EPC results in same notch zone were diversely distributed. Therefore, the cause of the distribution was inferred from the other factors such as fan speed, fan off delay time, and the compressor on delay time. As compared to the default EPC, most of the EPC results of the tests showed less energy consumption. The default, maximum, minimum, and average EPC results are summarized in Table 2. Just by changing the software tuning level of the factors without hardware revision, the annual EPC was predicted with being reduced by more than 10%, as demonstrated by the Min/Max ratios. It was demonstrated that software tuning was sufficient enough to step up the refrigerator efficiency even without improving the hardware performance.

In the response optimization solution, the desirability was used to measure the overall satisfaction level among all response objectives. The desirability was divided into individual desirability (d) and synthesized desirability (D). In particular, the synthesized desirability range was from 0 to 1. The value of 1 represented the ideal case, while the value of 0 meant that more than one reaction was outside of the permissible limits. In addition, the synthesized desirability was the weighted geometric mean of the individual desirability.

When a target of 1,000,000 Wh for the annual EPC was desired, the optimum combination of factors was as follows:

(D, Notch Temperature, Differential Temperature, Compressor On Time Delay, Fan Speed, Fan Off Time Delay)=(0.99994, –23.64, 1.00, 423.03, 3000.00, 1.21), (0.99333, –28.13, 1.00, 420.00, 22128.03, 0.00), (0.99991, –27.63, 3.76, 720.00, 23000.00, 120.00).

In general, a lower storage temperature provided better frozen food quality. When the EPC was fixed, the operation parameters of the refrigerator for the maximum food quality were achieved with result combination 3, which was able to use the lowest notch temperature of –28.13°C. All of the above conditions assumed that the target annual EPC was 1,000,000 Wh. However, if a different EPC was required, it was able to be optimized by changing the target value.

The test time that originally required 60 days was able to

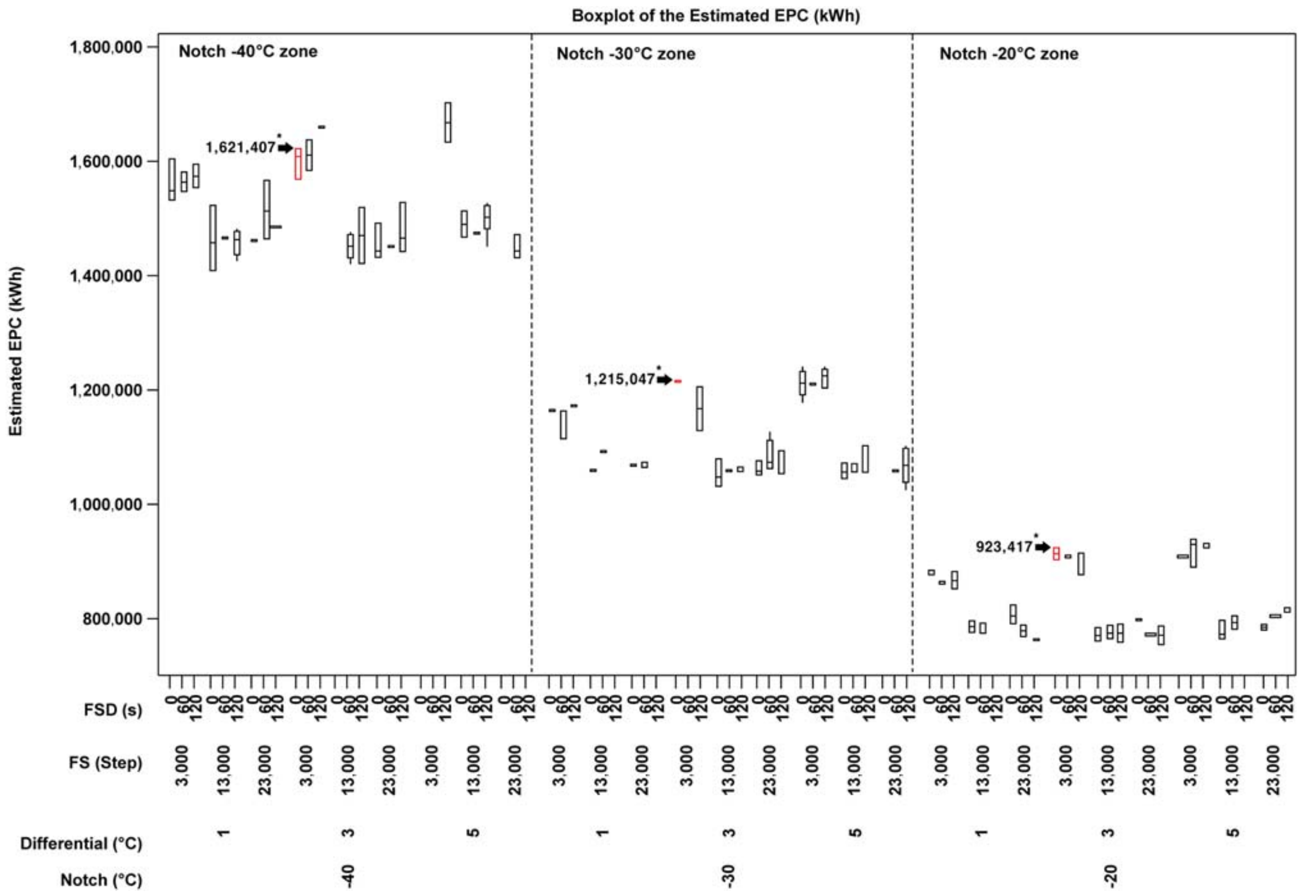

Fig. 6. Distribution chart of the EPC for each test case. *Default EPC of the original system

be reduced by approximately 50% by the test automation optimization method. In addition, the tester efforts were dramatically reduced, as the test was automatically progressed by the test software. The first test with 162 cases was completed and took about a month. After analyzing the results, the current refrigerator under development was able to be optimized for each target temperature.

Remote monitoring The refrigerators were in the second test facility of the remote unmanned system operating in the laboratory. Since this experiment was set up, it has functioned properly. The developed client data acquisition software is shown in Fig. 7A. The data from several refrigerators is currently being gathered over a period of 10 months.

Once new goods were loaded into the refrigerator, the compartment temperature in the refrigerator increased very rapidly, and then, the compartment temperature decreased very slowly, because of the high internal temperature of the goods and many input and output quantities of goods. Furthermore, the refrigerator door was open for a long time during the loading of goods (Fig. 7Bi).

In contrast, when goods were unloaded for meal preparation, the temperature of the compartments in the refrigerator increased slowly and then decreased rapidly because of the low internal temperature of the goods and a few input and output quantities. In addition, the door was open for a short time during the loading or unloading of

Table 2. EPC results of each notch and differential temperature

Notch (°C)	-20			-30			-40		
Differential (°C)	±5	±3	±1	±5	±3	±1	±5	±3	±1
Default system EPC (kWh)	-	923,417	-	-	1,215,047		-	1,621,407	-
Maximum EPC (kWh)	934,412	923,417	881,920	1,236,527	1,215,048	1,171,510	1,701,096	1,660,126	1,600,501
Minimum EPC (kWh)	760,568	756,175	761,361	1,029,990	1,028,190	1,056,434	1,432,057	1,416,057	1,406,442
Average EPC (kWh)	851,235	834,428	828,421	1,125,369	1,101,929	1,086,817	1,496,544	1,503,212	1,507,957
Mix/Max ratio (%)	81.40	81.89	86.33	83.30	84.62	90.18	84.18	85.30	87.88

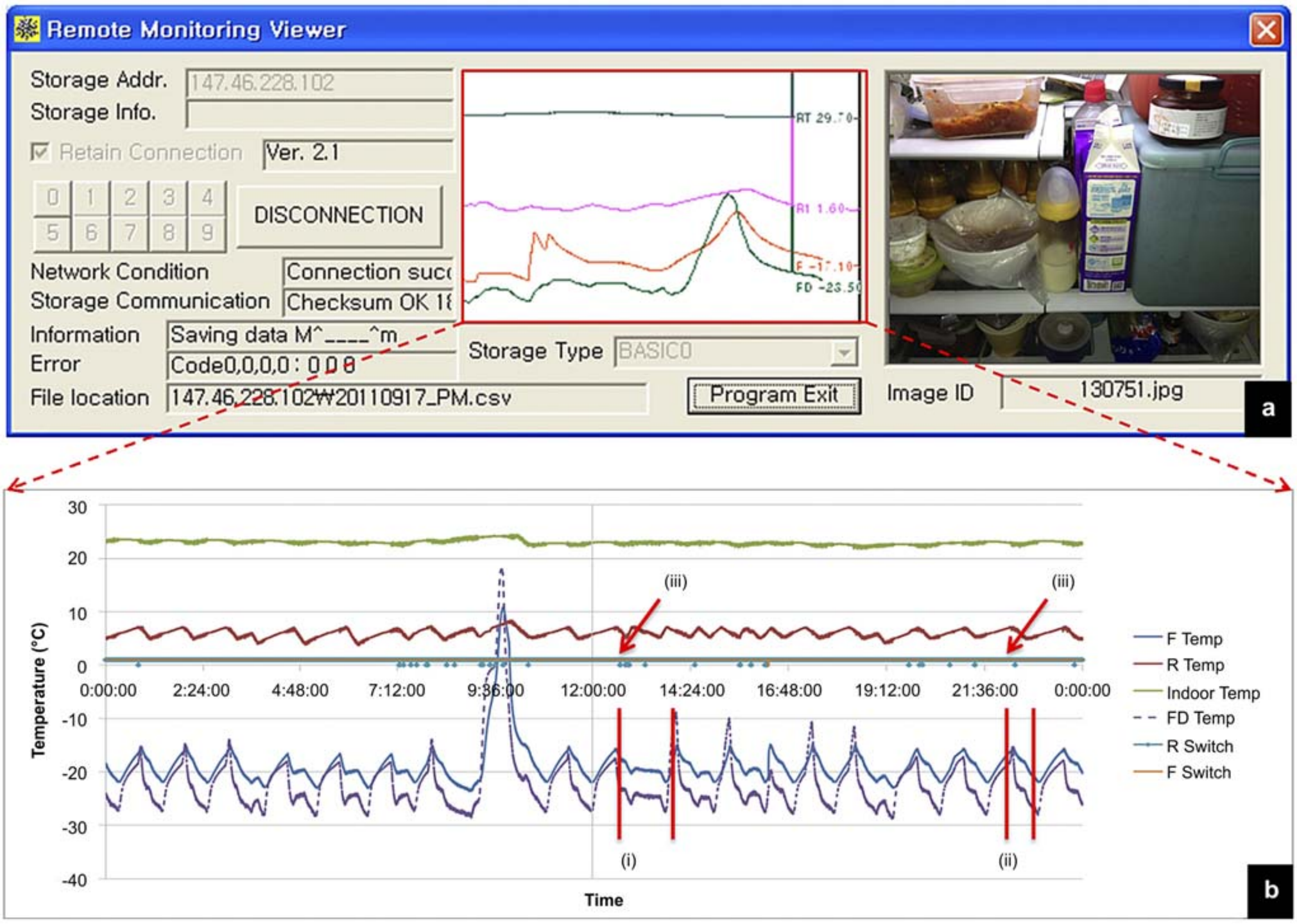

Fig. 7. (A) Client software that gathers the remote condition and image data. (B) Chart of the received data and the usage pattern between (i) and (ii). (i), long-time pattern; (ii), short-time pattern, (iii), dots indicating door-open signals

goods (Fig. 7Bii).

By applying a remote monitoring system, the field data of refrigerators were able to be monitored in real-time. Even though no errors occurred during the field test period, data regarding customer usage patterns were collected in a database. The data were analyzed in detail in this experiment. Even with a few samples, meaningful results were acquired regarding refrigerator usage patterns.

Further study of the remote monitoring system will be extended to a powerful pattern analyzer for the food industry and even other industries. For example, a real-time fault diagnosis system will be possible in near future by using this real-time remote monitoring and control method. Furthermore, manufacturers could immediately provide after-sales services including automatic firmware upgrades and automatic home visitation services. These data will be useful for providing better user experiences to industries for all refrigeration systems.

Disclosure The authors declare no conflict of interest.

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