Cloudfridge: A Cloud-Based Control System for Commercial Refrigeration Systems

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ABSTRACT

In California, commercial refrigeration accounts for 14% of electric energy usage, corresponding to 9,014 GWh per year and affecting more than 110,000 commercial establishments. A single walk-in freezer uses more energy than 5 single-family houses. Despite more stringent standards and utility programs promoting hardware improvements, controls systems used for commercial refrigerators are still primitive. In fact, in traditional refrigerators, the vapor-compression cycle is controlled with a simple hysteresis controller to keep the air cabinet temperature within a specific range. The controller does not account for system dynamics, energy consumption, utility prices or recurrent events such as food loading schedules and business opening hours. Also, demand response is precluded with these unsophisticated controls. With the help advanced control theory and efficient optimization algorithms, computer-based real-time optimization is now feasible and applicable in commercial refrigeration systems, but its practical use to date has been limited to industrial systems requiring expensive on-premise equipment and complex operations. This paper presents a novel hardware and software architecture that allows advanced control algorithms for commercial refrigerators to be developed, tested and deployed inexpensively. The aim of this new control framework is to optimize energy consumption as a software task, utilizing the benefits of lower cost computational resources inherent to cloud computing, minimizing on net overall energy usage of the refrigeration system. A prototype of the proposed system has been developed and tested under a California Energy Commission grant[1].

Introduction

There are more than 12 million commercial refrigerators installed in the US (Table 1). The vast majority of them, in particular walk-in coolers and freezers, food preparation equipment and reach-in refrigerators still use primitive controls. Cludfridge targets primarily this large base of unsophisticated systems.

In a traditional refrigerator, a thermostat controls the vapor-compression cycle with a simple hysteresis scheme to keep the air cabinet temperature or in some cases the evaporator temperature, within a specific range. The thermostat functioning parameters are set at the time of fabrication and assembly, energy used is not measured and no factors relevant to energy consumption dynamics are taken into consideration. With the help of advanced control theory and efficient optimization algorithms, computer-based real-time optimization is now feasible and applicable in commercial refrigeration systems, but its practical use to date has been limited to industrial systems requiring expensive on-premise equipment and complex operations.

This project demonstrates a new way of operating commercial refrigerators, reducing in a cost effective way their energy consumption while increasing their operational efficiency. The

[1] Visible Energy, Inc. (2014) Cloud Based Refrigeration Control System, Final Report. California Energy Commission EISG Program, Grant #: 57509A/1211. http://www.cloudfridge.io/

method is deployed as an automated energy optimization service based on the unique characteristics of each refrigerator and business. Additionally, this approach allows for insights to be drawn across a wide range of installations.

Network latency and security have always been challenges in the implementation of cloud-based control systems. Cloudfridge has been developed to provide secure and almost real-time communication between the device and the remote control algorithm.

Table 1. Total installed base of refrigerators in the US in 2008 (DOE 2009a)

Commercial Sector Technical Potential by equipment type	**Installed Base**	**Total Primary Energy Consumption**	
	[Units]	**[TWh / yr]**	**[TBtu / yr]**
(Supermarket)			
Display Cases	2,100,000	214	730
Compressor Racks	140,000	373	1,273
Condensers	140,000	50	171
Walk-ins	245,000	51	174
(Non-Supermarket)			
Walk-in Coolers and Freezers	755,000	148	505
Food Preparation and Service Equipment	1,516,000	55	188
Reach-in Refrigerators and Freezers	2,712,000	106	362
Beverage Merchandisers	920,000	45	154
Ice Machines	1,491,000	84	287
Refrigerated Vending Machines	3,816,000	100	341
Total		**1,226**	**4,183**

Background

Recent scientific literature on advanced control strategies applied to refrigeration or HVAC shows the potential for substantial energy savings. A well-designed optimal control scheme, continuously maintaining a commercial refrigeration system at its optimum operation condition, despite changing environmental conditions, will achieve an important performance improvement, both on energy efficiency and food quality reliability (Cai et al, 2008a). Several alternative methods for establishing a control strategy that minimizes the overall energy consumption in the refrigeration system have been described in the literature. For instance Jakobsen and colleagues (2001) showed how to optimize set points for operating theoretical refrigeration systems under certain constrains. Larsen and Thybo (2002) show significant energy saving using flexible set points. In another paper, Larsen and colleagues created an indirect method for optimization of the energy consumption (Larsen et al, 2005) and then they applied it to a refrigerator model, resulting in energy usage reduction up to 20%. In (Stoustrup and Rasmussen, 2008) food quality together with energy, are used as parameters to determine an optimal time between defrost cycles. Based on this, a new defrost-on-demand method is proposed. The method uses a feedback loop consisting of an on-line model updating and estimation by an Extended Kalman Filter (EKF), as well as a model-based optimization. In (Cai et al, 2008b) a new defrost, on-demand control scheme is described resulting in 25% energy saving from performing the defrost cycles at the estimated energy optimal points. Cai also discusses how a well-designed optimal control scheme, continuously maintaining a commercial refrigeration system at its optimum operation condition, can achieve an important performance improvement in energy efficiency and without compromising food quality. Earlier studies proposed fuzzy logic (Becker et al, 1994)) or neural networks (Choi et al, 1998) but they have not been studied yet with the objective of reducing overall energy consumption. A computer-based energy management system has been installed in the world's largest integrated nylon plant to optimize the refrigeration systems, and it proved a substantial energy cost reduction (Cho and Norden, 1982). Up to date this research has found little implementation in the refrigeration market, with a few exceptions in large refrigeration systems. Cloudfridge provides the architecture to develop these new control methods inexpensively in any type of refrigerator.

Technology Developed

Under a California Energy Commission grant, Visible Energy, Inc. developed a cloud infrastructure and related applications able to remotely manage, control and monitor commercial refrigerators[2]. The goals of the project were to prove the feasibility and develop the infrastructure as well the hardware and software tools of a cloud-based control for commercial refrigerators.

Its practical use will allow a larger number of research institutions and companies, even without large R&D budgets, to experiment and test novel ideas for control methods that reduce energy consumption or improve other aspects of their products using real systems and not only mathematical models.

System Diagram

Figure 1 depicts Cloudfridge system diagram. The refrigerators on the left side are each equipped with a purpose-made control and communication board, which connect to the Internet over local Wi-Fi via a facility switch to reach the Internet and the control software residing in the cloud. Given an available Wi-Fi network, the control and communication board is the only new piece of equipment needed for a retrofit. The system does not need a full computer on the premises. The board is installed outside the refrigerator.

The major innovation of this system is the collection of a large amount of data, including energy consumption, and using it in the control method, implemented as software in a cloud environment. Each refrigerator could potentially implement a different method, customized on its technical and environmental conditions.

Hardware

The control and communication board developed allows both data acquisition from sensors, including power consumption, and remote control of a refrigerator's main components, i.e. the compressor, the evaporator fan, and the defrost element, if present. The refrigerator's original thermostat is bypassed and the control loop is performed purely by the software running remotely. The infrastructure allows near real-time access to the control board in the refrigerator. A contract manufacturer has estimated the bill of materials for the control board to be about $50 per unit (at scale[3]). Additional sensors can be installed to measure food temperature, door

[2] Open-source software components will be released under AGPL license (www.gnu.org/licenses/agpl-3.0.html).
[3] Bill on materials for 10,000 pieces

opening and ambient temperature. In case of lost connection the controller switches back to a traditional fixed set-points operation.

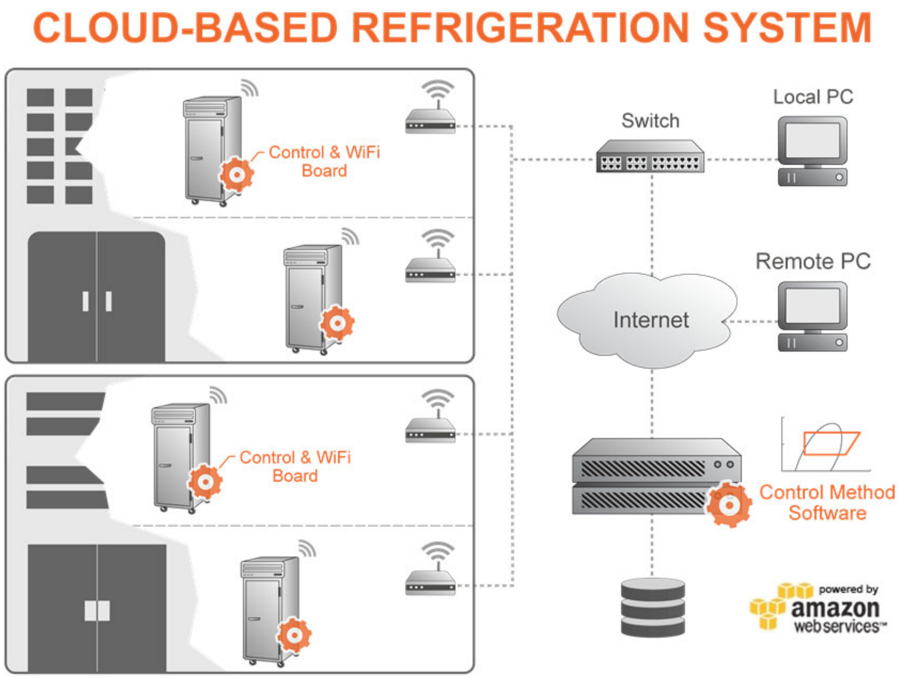

Figure 1. CloudFridge system diagram.

Software

The Cloudfridge software infrastructure is composed of a back-end for 2-way device secure communication, the sMAP Archiver and database, a highly efficient time series database developed by UC Berkeley (Dawson-Haggerty et al. 2010), the software for control methods execution (Workers Cluster), and an application server (Stardome), which provides the user interface for the whole system. Cloudfridge is a distributed software system structured in four main components, each of a certain complexity, but all capable of being distributed on a number of servers. Figure 2 represent a map of Cloudfridge software architecture. It depicts the computing resources, data flows and management underlying the cloud-resident control method capabilities.

Cometa[4] is the "secure switchboard" edge service[5] used for data vetting and assured data coherence across the Internet trust boundary. Cometa allows secure real-time HTTP communication between an application server and the Amazon Redshift[6] endpoints devices connected to the refrigerators. Black arrows stand for internal data transfers separate from Cometa. Colored arrows show specific types of data flows mediated by Cometa, most

[4] Cloud infrastructure for embedded systems developed by Visible Energy Inc. http://www.cometa.io/

[5] Computer for running middleware or applications that is close to the edge of the network, where the digital world meets the real world. Edge servers are put in warehouses, distribution centers and factories, as opposed to corporate headquarters.

[6] Amazon data warehouse service

prominently on the left side of the graphic, the red arrows representing data traffic from the control and communication boards (Redshfit) to the sMAP Archiver and its data base(s). The Workers Cluster runs the actual control method, using query data from the sMAP Archiver. Blue and yellow arrows represent the command-response messages flowing between the Workers Cluster and the endpoints. The modularity represented allows broader server distribution and ultimately better scaling capacity.

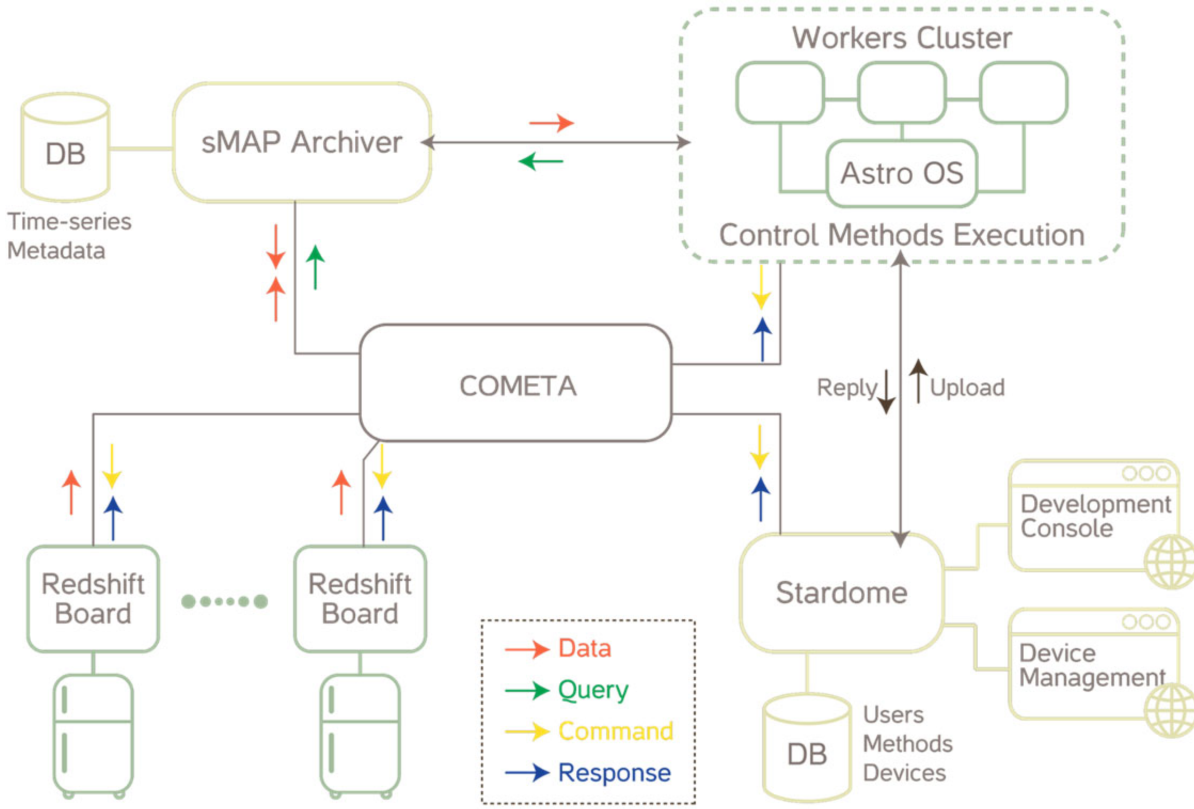

Figure 2. CloudFridge software components.

The Stardome GUI interface includes:

1. Device Console for device creation and configuration (Figure 3)
2. Device Management, for receiving real-time data from devices, control method editing and deployment through the Monitoring Panel (Figure 4) and the Development Console.

In the control execution environment (Astro OS, inside the Workers Cluster) each refrigerator is associated with an independent thread of execution for its own control method written in the Ruby language. A control loop can also invoke an external process such as Matlab or Octave, to perform very sophisticated mathematical computations and use the results in evaluating the optimal cooling strategy.

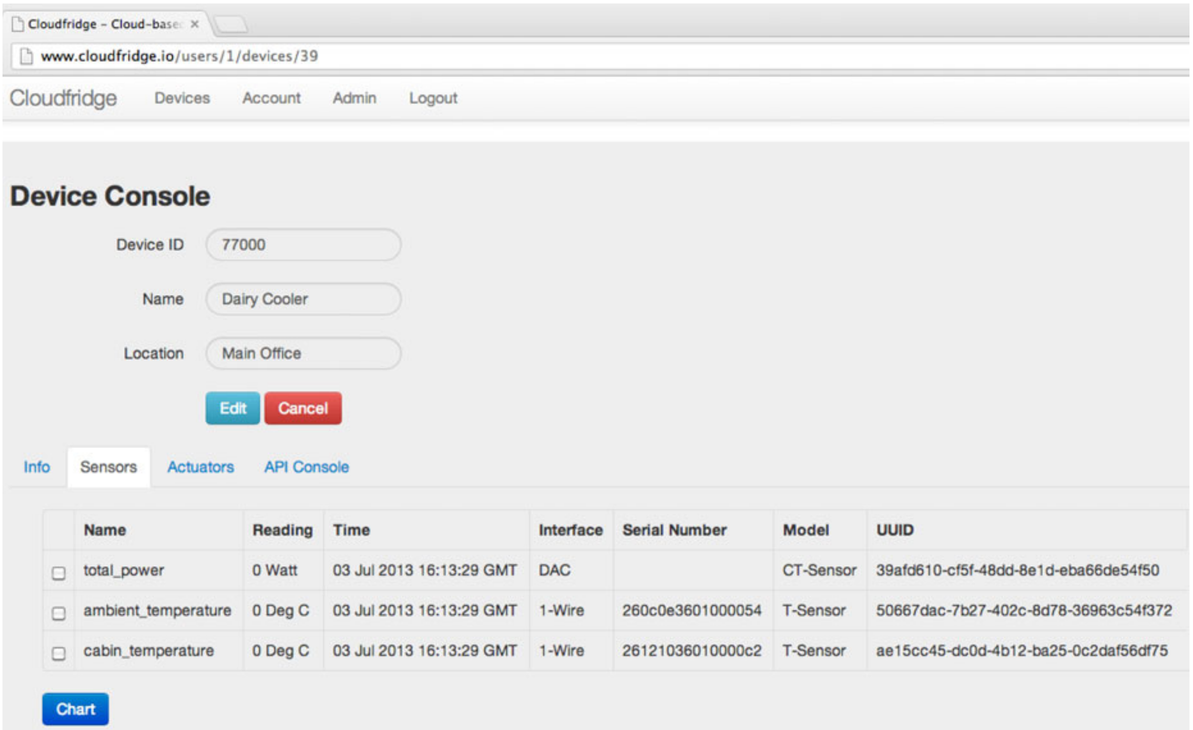

Figure 3. Device Console in the Stardome application.

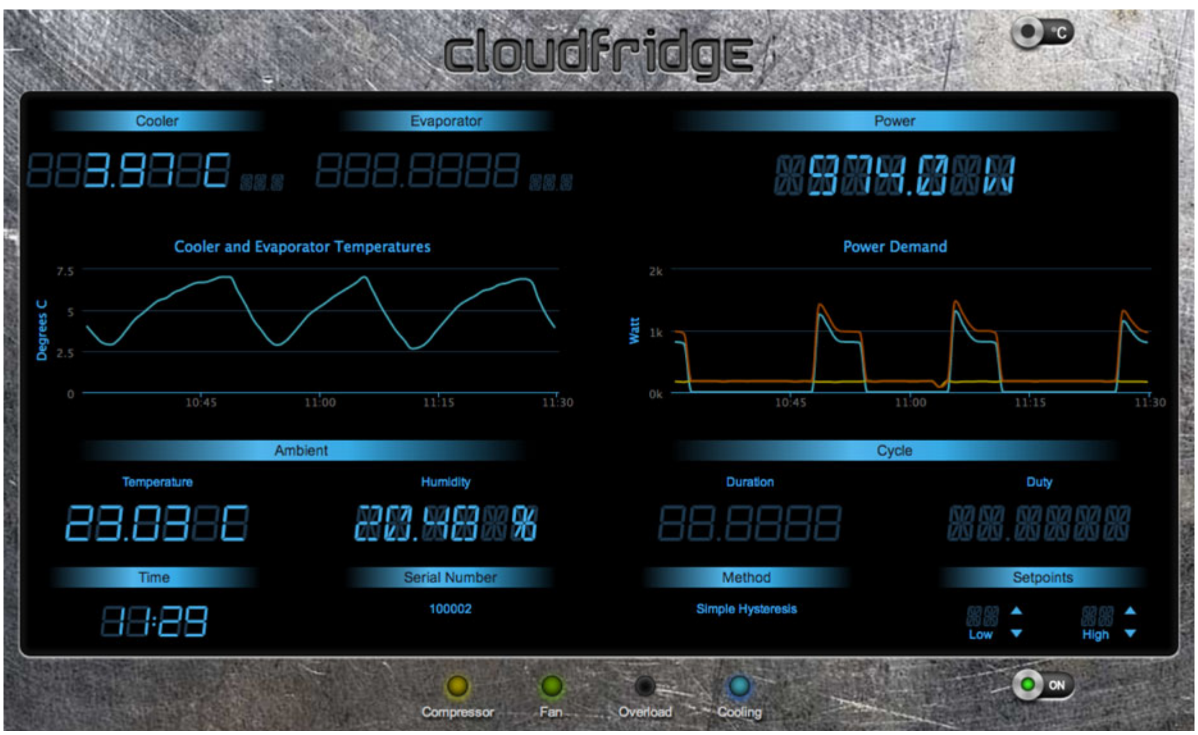

Figure 4. Monitoring Panel in Stardome application.

Discussion

While the new method used in the test optimization has been achieved by writing the software knowing the usage patterns and content, the optimization process can be easily replicated in a class of refrigerated appliances, including higher energy usage ones, such as walk-in boxes. The control software can be written directly in Ruby or can call external functions, for example using advanced control tools available in Matlab.

This technology enables customizing a control sequence for each refrigerator based on use patterns and type of application at very low cost. One can envision implementing demand response through thermal storage only in vending machines, ice machine or freezers, while saving energy in other refrigerators by optimizing defrost cycles. All these strategies can be implemented with the same inexpensive hardware. Regulating set-points based on electricity prices and anticipating compressor malfunction, thus preventing food losses, could achieve additional operational cost savings.

Conclusions

The technology developed in this research greatly lowers the cost of implementation and installation of state-of-the-art control methods in commercial refrigerated systems and self-contained appliances, thereby lowering major barriers to adoption, whether through retrofit, or by incorporation into newer refrigeration appliances and systems. Preliminary deployment test show savings in the order of 20-50%. The technology implemented and demonstrated in the project has a clear potential to disrupt standard practice in the commercial refrigeration industry. It provides substantial energy savings benefits, increased operational efficiency, demand-response capabilities, and fault detection and diagnostics at small marginal cost. Beyond the initial objective of feasibility, the project has delivered a smart controller reference design ready for production, and tools and functional software for deployment and commercialization of a refrigeration energy optimization service.

Recommendations and Future Work

A clear next step for this technology is to develop different advanced controls methods based on sensors data collected by the system. Using the online platform computation could be performed in real-time in the cloud, not constrained by limited hardware resources of a traditional refrigerator. One example of an energy optimized control strategy is called model predictive control (Rossiter, 2003; Wang, 2009; Boyd 2012), which continuously adjusts the refrigerator working parameters to optimize a function of energy, peak demand, cost, and food quality. Machine learning algorithms can be used during operation of the system to automatically detect usage patterns that can be incorporated in the advanced control method. While preliminary testing has been done in the lab and at one location in the field, large-scale testing and energy savings verification is essential to prove the technology for commercial adoption.

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