A Design Methodology for Controlling Local Airflow Delivery in Data Centers Using Air Dampers

Ghazal Mohsenian, Sadegh Khalili, Bahgat Sammakia
Departments of Mechanical Engineering, Binghamton University-SUNY
Binghamton, NY, USA, 13902
Email:gmohsen1@binghamton.edu

ABSTRACT

Optimizing data centers for energy efficiency plays a key role in the successful operation of modern data centers. One important factor is the proper management of airflow. In most air-cooled data centers, the required airflow for cooling of IT equipment is supplied from a raised floor to server racks through perforated tiles. In recent years, different approaches have been implemented to increase the efficiency of air delivery through tiles such as the use of directional tiles, adding understructure scoops or using air dampers [1].

Because the IT load of each rack in the data center is constantly changing due to the processing demands of the IT hardware at a given time, simultaneous manual tuning of the airflow at the panel level is impossible or at least impractical. The amount of airflow delivered to the Cold Aisle Containment (CAC) can be adjusted using Variable Airflow Panels (Dampers) that can be controlled remotely. In this study, we design and optimize a fuzzy control system to control the open area ratio of air dampers in order to adjust the local airflow rate in the ES2 data center.

KEYWORDS: Airflow Management, Air Damper, CRAH, Active Control, Fuzzy Controller, Dynamic IT Workload

NOMENCLATURE

CAC	Cold Aisle Containment
CPU	Central Processing Unit
CRAH	Computer Room Air Handler
CRAC	Computer Room Air Conditioning
DC	Data Center
FR	Flow Rate
IT	Information Technology
OAR	Open Area Ratio
PUE	Power Usage Effectiveness
SNMP	Simple Network Management Protocol
ΔP	Differential Pressure

Introduction

Today, data center thermal management challenges for achieving efficient energy consumption is driving considerable research [2]. About a third to half of a data center's total power goes to the cooling system [3,4]. Hence, a cost-effective cooling strategy is a great approach for energy and cost saving in the DC. Most data centers use air-cooled systems for the heat removal due to its lower maintenance cost and high reliability [5]. Information technology equipment use devices such as heat sinks and server fans to keep components cool. The fans are arranged in a way so that cool air is pulled into servers from adjacent cold aisles and pushed out from the back of servers. To achieve the desired server inlet temperature, minimizing the mixing of supplied cold air with the hot air exiting from the rack is required. Containment is an important energy-saving solution in high-density data centers. Air containment systems help isolate the warm air from the cold air and provides a physical separation between the cold supply air and the hot return air. A separation of cold and hot air provides the opportunity to closely match supply cooling airflow to IT equipment airflow. It helps to provide a more uniform cabinet inlet temperature profile. It allows increasing the cold air supply temperature (within the ASHRAE recommended design range [6]) which in turn results in higher return temperature to the cooling units without risk of hot spots [7-13]. Different load balancing algorithm like HEROS in heterogeneous data centers cause significant energy savings in comparison with load balancers that are not aware of heterogeneity in homogeneous data centers[14]. Heterogeneous data centers usually utilize a common raised floor to supply sufficient amount of cooled air to server racks. For optimal provisioning of a cold aisle containment, first there must be enough cold air available and, second, this cold air delivered by the floor tiles must be drawn in by the server fans at the location of the servers [15]. Due to a transient workload in data centers active approach for managing and balancing airflow is required. Bash et al. [16] utilized a distributed sensor network at the face of the rack. And designed a PID control system to manipulate supply air temperature and flow rate of each cooling resources in an air-cooled environment to ensure thermal management in data centers. Winston et al. [17] presented a different configuration of linear quadratic regulators based on regulating the outlet temperature and volumetric airflow of the computer room air handler (CRAH) units. One of the other approaches for airflow management is using the active tiles having integrated fans to supply extra air through the tiles. Arghode et al. [18] showed that in the contained aisle using active fan tiles can increase temperature uniformity. However, in the open aisle, we notice hot air entrainment in presence of active tiles. Impact of active fan tiles by increasing the flow rate of tiles locally is demonstrated by Athavale et al. [15]. However, installing fans and the associated batteries under the tiles occupy a large portion of perforated area and reduces the tile flow rate when the fans are not operated. Also, tiles' fans consume power which increase the cost of operation in a data center. In the present work, airflow management for a contained cold aisle using remotely controllable air dampers is studied. A fuzzy control system is designed and developed based on differential pressure between a hot aisle and a cold aisle to adjust the open area ratio of damper. To the best of the authors' knowledge, in all the previous studies on the cooling control system for airflow management in data centers inlet or outlet temperature of servers, CRAH output temperature or temperature of returned air to the CRAH is considered as a manipulated variable for the control system. In this work, differential pressure between the cold and hot aisles is the control parameter. The performance of the controller is evaluated and optimized at the rack level. In addition, implementation of the developed control system is demonstrated at an aisle level.

Variable Airflow Panel (Air Damper)

Increased use of cloud computing and changing processing demands of the IT hardware at a given time, driving up load variability in each rack in data centers. So, supplying a constant airflow to a contained aisle with a dynamic IT workload profile is inefficient. Variable airflow panels (Dampers) are utilized to ensure enough air is supplied to an aisle at different airflow demands due to variation in IT load. Air dampers reduce bypass air which can lead to significant saving in energy and improve power usage effectiveness (PUE). The air damper that is used in this paper can adjust airflow delivery to four separate zones independently which allows for efficient air delivery in different IT loads at different rack heights and partially deployed racks. In this study, dampers are operated in single-zone mode in which, all four zones (1-4) are paired together. Remotely controllable air dampers are installed below directional tiles and regulate the required airflow by controlling the open area ratio (OAR) of the dampers.

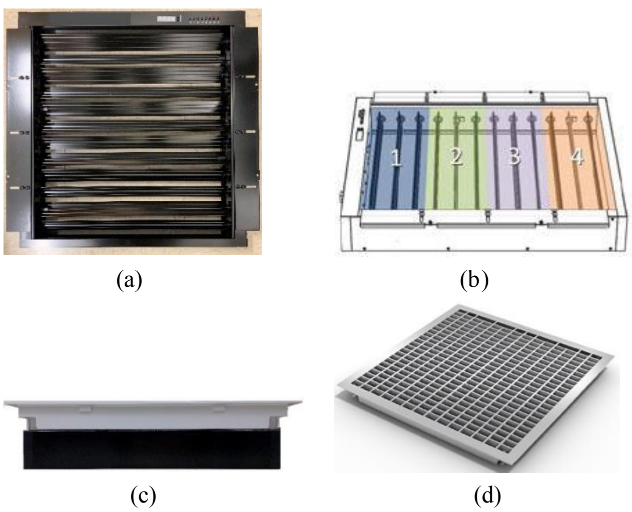


Fig. 1: Air damper: a) Top view of the damper, b) individual zones for airflow control, c) side view of the damper mounted under a perforated floor tile. d) directional floor tile.

Experimental Setup

The layout of ES2-Data Center Laboratory at Binghamton University is shown in Fig. 2. The lab area is a 215 m^2 (2,315 ft^2) and the plenum depth is 0.91 m (3 ft). There are two chilled water-based CRAH units with the nominal maximum airflow rates of 16,500 CFM (CRAH1) and 17,500 CFM (CRAH 2). A 47-RU rack in the aisle E is populated with 22 servers (Dell PowerEdge 2950 2-RU). The Air damper is in the single-zone mode and is installed below a directional tile adjacent to the rack. A Bapi ZPT-LR pressure sensor with a measurement range of 0 to 1″ wc (248.84 Pa) and accuracy of ±0.25% of the range (0.625 Pa) is installed at the middle height of the rack. The dimensions of the local cold aisle containment (CAC) are 99″ H × 32″ D × 32″ W. BAPI pressure sensor measures the differential pressure (ΔP) between the CAC and the room. All of the IPMI data from the servers is gathered by the Linux core temp module which provides individual CPU temperatures. In addition, servers' fan speeds and IPMI inlet temperatures are collected through OpenIPMI libraries [11,19].

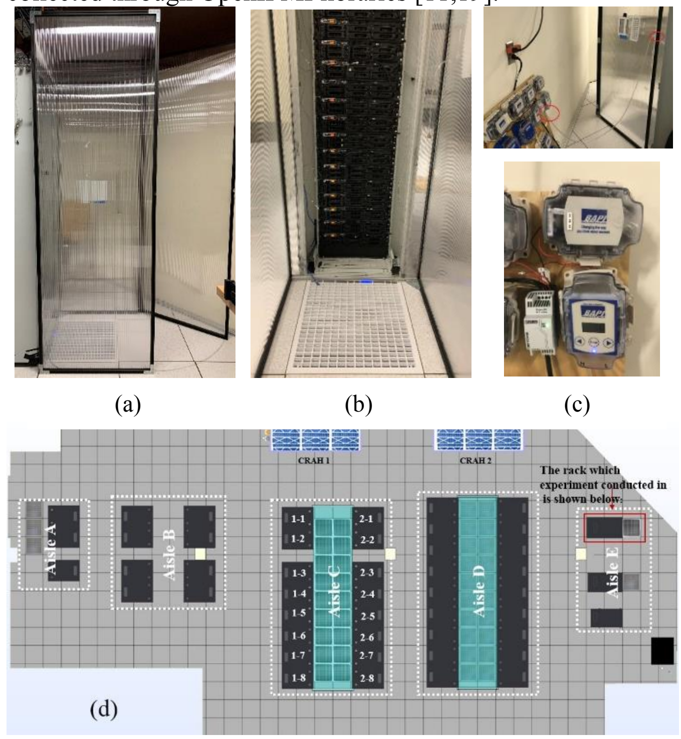


Fig. 2: Experimental setup and instruments: a) local CAC (door is open), b) installed damper under the directional tile in the rack, c)BAPI ZPT-LR pressure sensor d) layout of the ES2 data center lab at Binghamton University

Cooling-Control System

A control system for provisioning the cold aisle containment depends on CAC parameters such as pressure, temperature, workload and etc. Since we have a closed containment the temperature is uniform, but pressure is a key parameter to be considered inside the CAC. To supply sufficient air for cooling the servers, we need to measure the required air flow rate. The amount of airflow rate through a tile can be adjusted using the corresponding damper. We can remotely communicate and control the damper with the help of simple network management protocol (SNMP). SNMP opens up a window to allow you to remotely look inside the device and change parameters.

A fuzzy feedback control system can use the pressure differential between the CAC and room (Hot Aisle) to determine the provisioning level of the system in the rack. Based on this assessment, the control system sends a proper signal to the damper to adjust its openness which varies the supplied airflow rate. A feedback controller can evaluate the provisioning level and take further action if required. The fuzzy control system is designed from a set of if-then rules and based on the definition of the fuzzy algorithm, the fuzzy controller is suitable for controlling the complex system performance which mathematical techniques are incapable[20].

In the beginning, based on the difference between measured pressure and ideal value (error signal), the controller changes the openness of the damper with a fix small step. In this method, we avoid the overshoot but when the differential pressure between the cold aisle and hot aisle is near zero, we observe fluctuations in the pressure. In order to save some time and solve the instabilities near zero pressure difference, we change the constant rate of openness to dynamic rate of opening. The logic for the controller would be measuring the response of error signal by making an arbitrary change in the OAR of the damper at the initial state. Afterward, with the help of linear extrapolation based on the latest response of CAC pressure to the OAR, control system can approximate the next opening for reaching to the provisioning. In this study, 1 Pa over-provisioning of the CAC is allowed.

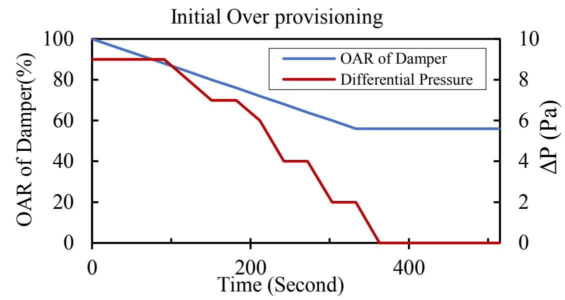
Results for the Rack Level

Constant rate of change in openness of a damper for extreme cases: In this case, performance of the control system with the constant rate of change in openness of damper is tested in over and under-provisioning of the rack. Based on the pressure inside the CAC, controller adjusts the OAR of damper. Fuzzy control system sleeps 30 seconds after each change in the OAR of damper to allow sufficient time for the system to reach to the steady state before evaluating the pressure conditions again. As we can see in Fig. 3 damper is fully open and the differential pressure between the CAC and room is 9 Pa. This over- provisioning can lead to a significant energy loss due to cooled air bypass and leakage. The fuzzy control system, after approximately 8.5 minutes adjusts opening of damper to 52% to respond to the positive CAC pressure. The Dell PowerEdge 2950 has 4 fans for cooling the internal components. As it is shown in figure 3.b. average fan speed of one of the servers over the time stays constant.

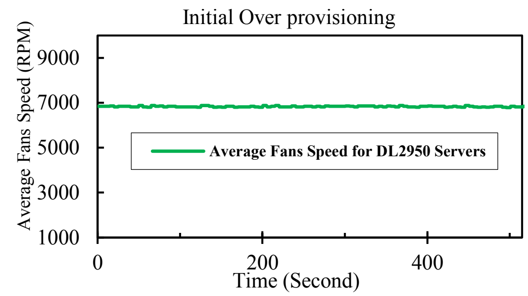
Fig. 4 shows the variation of the OAR of damper and pressure in an initially under-provisioned CAC. In the early stages, we set openness of damper to 0% manually. Lack of cooled air for the servers inside the CAC is cause of initial elevated fans RPM and -44 Pa CAC's pressure. As a result, we need to increase the flow rate inside the cold aisle and increase the OAR of damper till the neutrally provisioned CAC. For this case, time to reach to the desired opening is longer and equals to 21.2 minutes. Response time of the system is also a function of servers' fan speed. As we can see in the Figure 4.b. server fans speed are in their maximum speed due to insufficient air inside the cold aisle initially but after running the control system and provisioning the CAC and allow sufficient time for the system the fans speed reduce and reach to the normal velocity.

Dynamic rate of change in openness of a damper for extreme cases: The goal of this scenario is to test the developed fuzzy control system in the rack level with the dynamic rate of change in OAR. For the over-provisioning level with the openness of 100% and 8 Pa differential pressure between a CAC and a room. It takes 3.3 minutes for control system to reduce the openness of damper through SNMP and provide neutral pressure inside the CAC (Fig. 5). As we can see we have significant amount of saved time compare to the similar scenario with constant rate of change in openness of damper.

For under-provisioned scenario when the damper is completely closed, after around 30 minutes waiting, the BAPI pressure sensor shows -47 Pa. As a result, controller increased the flow rate inside the CAC and opened the damper till 56% neutral provisioning state. In this case, respond time of the system is 5.4 minutes and the time-saving compared to the exact case with fixed rate of openness would be around 6 minutes.



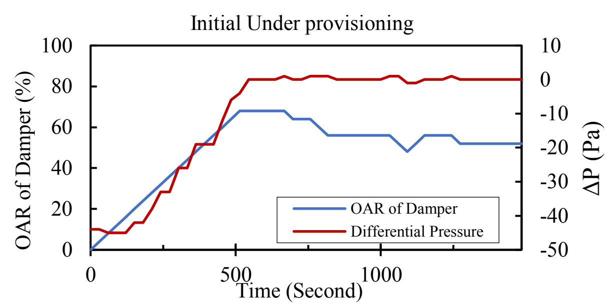
(a)



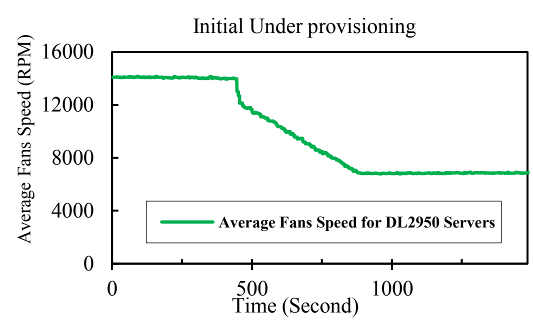
(b)

Initial State: Openness 100%, P = 9 Pa
Final State: Openness 52%, P = 0 Pa
Transient Time = 8.55 min

Fig. 3: Over-Provision case a) variation of the pressure and OAR, b) averaged fans speed for DL2950 servers



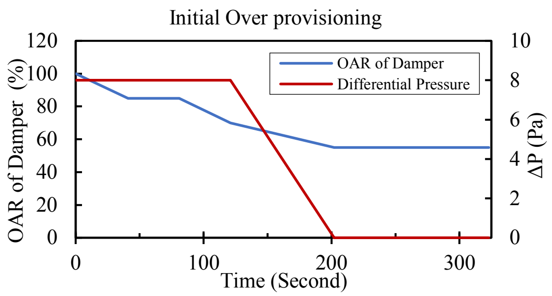
(a)



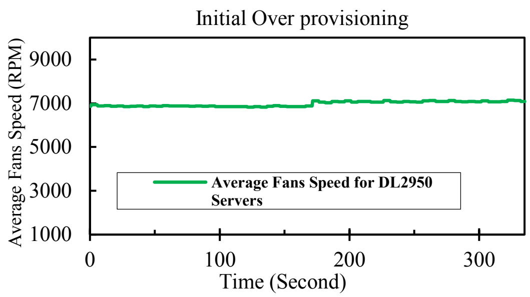
(b)

Initial State: Openness 0%, P = -44 Pa
Final State: Openness 52%, P = 0 Pa
Transient Time = 21.22 min

Fig. 4: Under-Provision case a) variation of the pressure and OAR, b) averaged fans speed for DL2950 servers



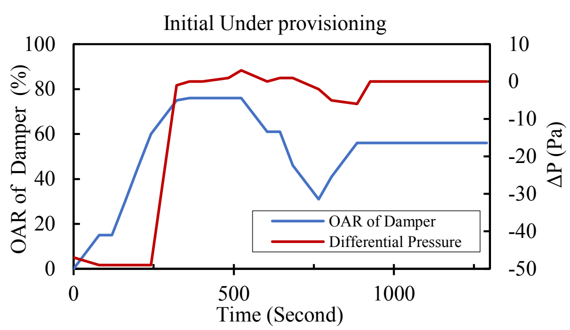
(a)



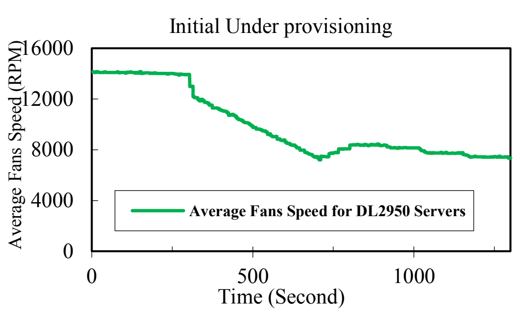
(b)

Initial State: Openness 100%, P = 8 Pa
Final State: Openness 55%, P = 0 Pa
Transient Time = 3.36 min

Fig. 5: Over-Provision case a) variation of the pressure and OAR, b) averaged fans speed for DL2950 servers



(a)



(b)

Initial State: Openness 0%, P = -47 Pa
Final State: Openness 56%, P = 0 Pa
Transient Time = 15.43 min

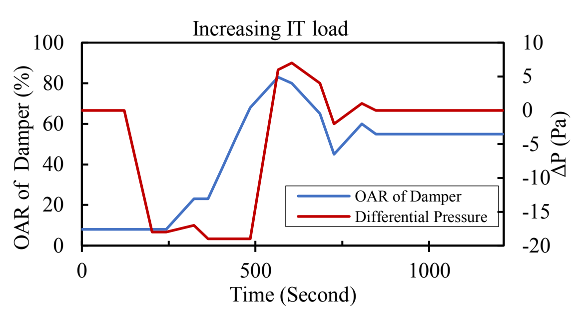
Fig. 6: Under-Provision case a) variation of the pressure and OAR, b) averaged fans speed for DL2950 servers

Dynamic rate of change in openness of damper for realistic cases. One of the big reasons in data centers waste is low server utilization. From a power perspective, low utilization is problematic because servers that are on, while idle, still utilize 60% or more of peak power[21]. In this study, the performance of the controller is tested in presence of IT variation. The idea is to shut down or enable sleeping state for some servers with very low utilization. Servers with the less workload can be centralized into a few servers with higher utilization at the time, without interruption of the business which leads to saving power and energy. During peak processing hours servers can be turned back on.

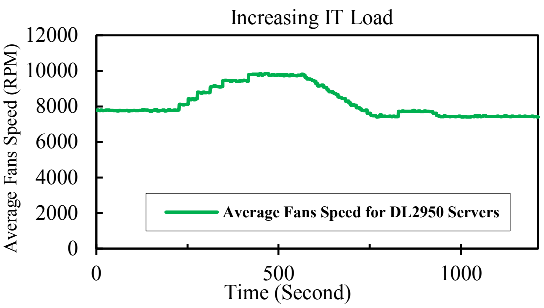
The developed fuzzy control system is tested in increasing and decreasing IT load cases in which some of the servers were powered on and off, respectively. Below, the impact of under-provisioning CAC is visited briefly. In the beginning, only 5 servers of the rack are on, with the openness of 8%, and we are in the provisioning level. But according to change in the workload, all the 22 servers turned back on. So the ΔP dropped to the -18 Pa in the CAC. As a result, we need to increase the open area ratio of the damper to provide more air in the cold aisle containment. So controller sends a signal to the damper with the help of SNMP and expands the openness. After 10.7 minutes with the openness of 55%, we reach the provisioning state. Initially, average servers' Fans rotate at the normal speed but after increasing IT load and pressure drop in the CAC, fans speed of servers increase. After reaching the provisioned state with a neutral differential pressure between CAC and room the fans slow down and reach the normal angular velocity again. Figure 7. shows the transient response of the controller to the pressure and also average fans speed of one of the servers.

A decrease in IT load is imitated by powering off the 17 out of 22 servers inside the cold aisle containment and transient response of the system is monitored.

Primitively, the openness of the damper is 53% for provisioning the whole CAC. But after turning off 17 servers, it will reach 8 Pa differential pressure between a cold aisle and a room. So, we are in the over-provisioning state. In order to avoid wasting energy and money, we need to decrease the open ratio of the damper to reach the steady-state and zero ΔP. It should be mentioned that no significant change in the fans speed of servers was observed in this scenario (Fig. 8).



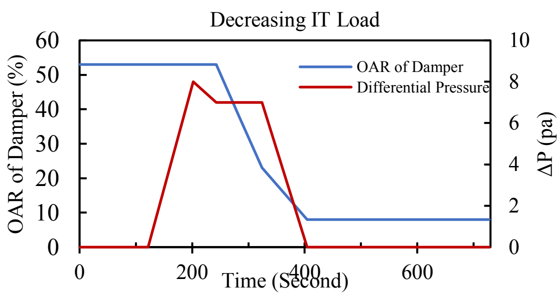
(a)



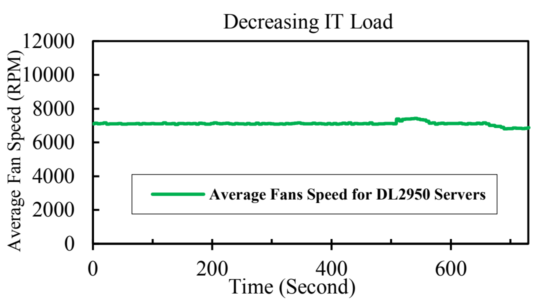
(b)

First State (Steady State): 5 servers On, Openness 8%, P = 0 Pa
Second State: 22 servers On, Openness 8%, P = -18 Pa
Final State: 22 servers On, Openness 55%, P = 0 Pa
Transient Time = 10.75 min

Fig. 7: Increasing IT load a) variation of the pressure and OAR, b) Averaged fans speed for DL2950 servers



(a)



(b)

First State (Steady State): 22 servers On, Openness 53%, P = 0 Pa
Second State: 5 servers On, Openness 53%, P = 8 Pa
Final State: Openness 8%, P = 0 Pa
Transient Time = 3.36 min

Fig. 8: Decreasing IT load a) Variation of the pressure and OAR b) Averaged fans speed for DL2950 servers

Results for the Aisle Level

Dynamic rate of change in openness damper for extreme cases. After assuring proper behavior and respond of the control system in the rack level, the optimized fuzzy controller is tested in an aisle level (larger scale). In the DC test cell, 16 racks are arranged in a hot aisle/cold aisle configuration and the cold aisles are contained. The racks in aisle C contain 272 2-RU servers from different vendors and generations. Number of servers in each rack differs from 14 to 20 servers (with a higher equipment density at the beginning of the aisle is higher). Three BAPI ZPT-LR pressure sensors with an accuracy of ±0.25% of the range (0.625 Pa) are installed at the top of the racks C1-1, C1-4, and C1-8 as shown in in Fig. 9. Dampers are installed below directional tiles in the aisle C and they operated in the single-zone mode.

(a) (b)

Fig. 9: a) Installed damper in aisle C, b) pressure sensor positioned in aisle C.

The performance of the controller was tested in presence of IT load variation in the aisle level. Based on differential pressure measurements, controller started to adjust the dampers open area ratio to respond to the negative or positive pressures in the CAC. In order to avoid an overshoot and potential instabilities, the fuzzy control system sleeps for 90 seconds before assessing any other change in the system again after adjusting the OAR of damper. This delay also allows some time for changes in fan speed of servers due pressure variation.

Figure. 10 demonstrates that the controller was able to manage airflow delivery to an initially over provisioned CAC successfully. In the beginning, the openness of dampers were set to 100% manually and the differential pressure between the CAC and room was 5 Pa across the aisle. After starting the test, the control system sends the proper signal to the dampers to adjust their openness. This varies the supplied airflow rate until reaching to a neutral provisioning level in the aisle.

The required time for provisioning the aisle decrease 9 minutes with a dynamic rate of change in the opening of dampers in comparison with similar scenario with the constant rate of change in OAR of damper. The results are shown in figure 10.

The test procedure for the under-provisioning situation is similar to the previous scenario. Except that pressure sensors showed -4 Pa in the CAC to mimic an under provisioned aisle. In this case, the flow rate and the OAR of the dampers should be increased until reaching to a neutral provisioning state for the CAC. The test showed that, the required time to reach this goal is 8.1 minutes if the rate of change in the OAR is fixed. The required time can be decrease to approximately 5 minutes by changing the OAR dynamically.

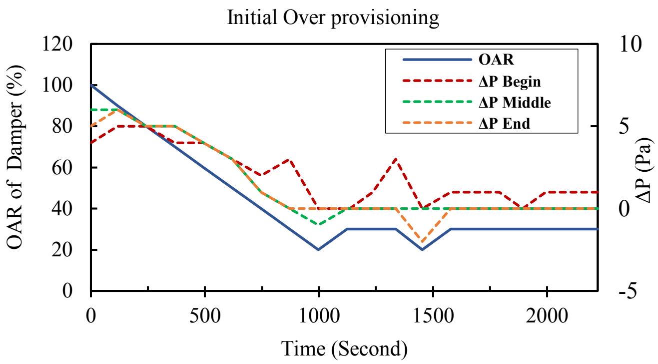
It is worth mentioning that pressure overshoots were observed in some of tests when the dynamic controller was used in under provisioned cases. In a future study, hybrid control system can be developed to change the OAR in constant steps for the small error signals. For large error signals, the controller can change the OAR with help of a linear extrapolation and dynamic rate of change of openness. By this, pressure fluctuations and overshoot may be avoided. The variation of dampers' open area ratio and pressures at the beginning, middle, and end of Aisle C is presented in figure 11.

Constant Rate of Openness

Initial State: Openness100%, $P_{Begin} = 4$, $P_{Middle} = 6$, $P_{End} = 5$

Final State: Openness 30%, $P_{Begin} = 1$, $P_{Middle} = 0$, $P_{End} = 0$

Transient Time = 18.72 min



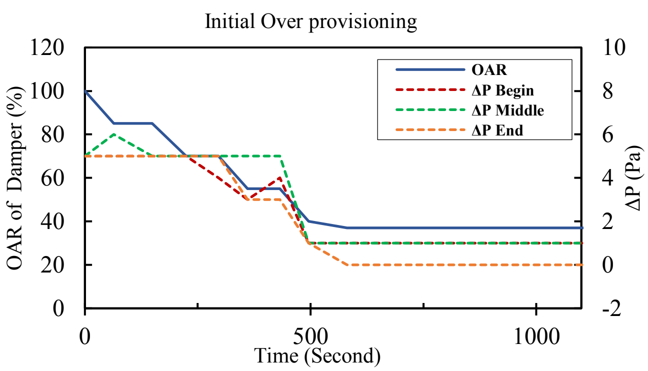
(a)

Dynamic Rate of Openness

Initial State: Openness100%, $P_{Begin} = 5$, $P_{Middle} = 5$, $P_{End} = 5$

Final State: Openness 37%, $P_{Begin} = 1$, $P_{Middle} = 1$, $P_{End} = 0$

Transient Time = 9.68 min



(b)

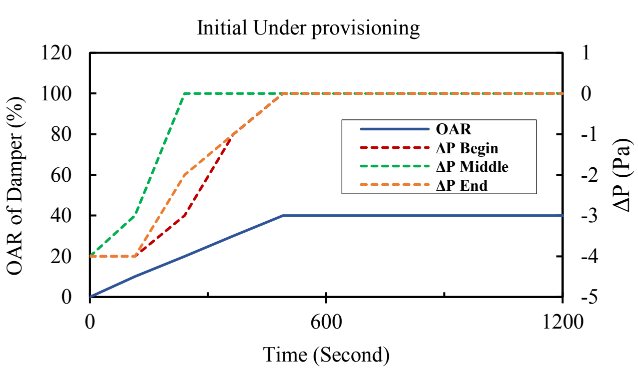
Fig. 10: Over-provisioning case a) constant OAR, b) dynamic OAR

Constant Rate of Openness

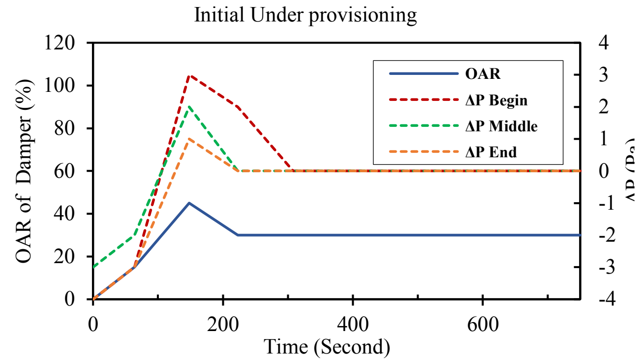
Initial State: Openness 0%, $P_{Begin} = -4$, $P_{Middle} = -4$, $P_{End} = -4$

Final State: Openness 40%, $P_{Begin} = 0$, $P_{Middle} = 0$, $P_{End} = 0$

Transient Time = 8.1 min



(a)



(b)

Dynamic Rate of Openness

Initial State: Openness0%, $P_{Begin} = -4$, $P_{Middle} = -3$, $P_{End} = -4$

Final State: Openness 30%, $P_{Begin} = 0$, $P_{Middle} = 0$, $P_{End} = 0$

Transient Time = 5.1 min

Fig. 11: Under-provisioning a) constant OAR, b) dynamic OAR

Conclusions and Next Steps

The IT workload in data centers varies over time. As a result, dynamic server provisioning has been proposed an attractive solution for data center power management. Delivering right amount of air to a CAC is one of the challenges that an energy efficient data center commonly encounters. Variable-air-volume dampers offer local control on airflow delivery in data centers. In this paper, an approach for adjusting air delivery through air panels via controlling pressure differential across IT equipment using remotely controllable dampers is studied. The performance of the control system is evaluated and optimized at a rack level to achieve a reasonable response time with minimum overshooting. Two different strategies for adjusting OAR of dampers are investigated and compared. The controller was able to successfully provision ITE in both decreasing and increasing IT load in the rack level. Also, the performance of the developed control system is demonstrated at an aisle level. It was observed that adjusting OAR dynamically can decrease the overall response time by 37% in the aisle level experiment.

In this paper, the controller is tested in an isolated cold aisle for two extreme cases, however, further tests can be done for more practical cases with the various IT workload at the aisle or even data center level. For example, IT load consolidation can be implemented to shut down or hibernate servers with very low utilization to save power further. In addition, resulting energy savings in the cooling system can be evaluated.

Acknowledgments

We would like to thank Russ Tipton and Arash Golafshan from Vertive and also Mark Seymour and Kourosh Nemati from Future Facilities for their advice and support. This work is supported by NSF IUCRC Award No. IIP-1738793 and MRI Award No. CNS1040666.

References

[1] S. Khalili, M. I. Tradat, K. Nemati, M. Seymour, and B. Sammakia, "Impact of Tile Design on the Thermal Performance of Open and Enclosed Aisles," *J. Electron. Packag.*, vol. 140, no. 1, pp. 10907–10912, Mar. 2018.

[2] Z. Song, B. T. Murray, and B. Sammakia, "A dynamic

compact thermal model for data center analysis and control using the zonal method and artificial neural networks," *Appl. Therm. Eng.*, vol. 62, no. 1, pp. 48–57, 2014.

[3] C. D. Patel, C. E. Bash, R. Sharma, M. Beitelmal, and R. Friedrich, "Smart Cooling of Data Centers," no. 36908b. pp. 129–137, 2003.

[4] R. Zhou *et al.*, "A holistic and optimal approach for data center cooling management," in *Proceedings of the 2011 American Control Conference*, 2011, pp. 1346–1351.

[5] A. Capozzoli and G. Primiceri, "Cooling Systems in Data Centers: State of Art and Emerging Technologies," *Energy Procedia*, vol. 83, pp. 484–493, 2015.

[6] ASHRAE Technical Committee 9.9, *Thermal Guidelines for Data Processing Environments*, 4th ed. Atlanta: W. Stephen Comstock, 2015.

[7] V. Sundaralingam, V. K. Arghode, Y. Joshi, and W. Phelps, "Experimental Characterization of Various Cold Aisle Containment Configurations for Data Centers," *J. Electron. Packag.*, vol. 137, no. 1, pp. 11007–11008, Oct. 2014.

[8] K. Nemati, H. A. Alissa, B. T. Murray, and B. Sammakia, "Steady-state and transient comparison of cold and hot aisle containment and chimney," in *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2016, pp. 1435–1443.

[9] B. Muralidharan, S. K. Shrivastava, M. Ibrahim, S. A. Alkharabsheh, and B. G. Sammakia, "Impact of Cold Aisle Containment on Thermal Performance of Data Center," no. 55768. p. V002T09A016, 2013.

[10] H. A. Alissa, K. Nemati, B. G. Sammakia, K. Schneebeli, R. R. Schmidt, and M. J. Seymour, "Chip to Facility Ramifications of Containment Solution on IT Airflow and Uptime," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 6, no. 1, pp. 67–78, 2016.

[11] S. Khalili, H. Alissa, A. Desu, B. Sammakia, and K. Ghose, "An Experimental Analysis of Hot Aisle Containment Systems," in *2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2018, pp. 748–760.

[12] S. K. Shrivastava and M. Ibrahim, "Benefit of Cold Aisle Containment During Cooling Failure," no. 55768. p. V002T09A021, 2013.

[13] M. K. Patterson, R. Weidmann, M. Leberecht, M. Mair, and R. M. Libby, "An Investigation Into Cooling System Control Strategies for Data Center Airflow Containment Architectures," no. 44625. pp. 479–488, 2011.

[14] M. Guzek, D. Kliazovich, and P. Bouvry, "HEROS: Energy-Efficient Load Balancing for Heterogeneous Data Centers," in *2015 IEEE 8th International Conference on Cloud Computing*, 2015, pp. 742–749.

[15] J. Athavale, Y. Joshi, M. Yoda, and W. Phelps, "Impact of active tiles on data center flow and temperature distribution," in *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2016, pp. 1162–1171.

[16] C. B. Bash, C. D. Patel, and R. K. Sharma, "Dynamic thermal management of air cooled data centers," in *Thermal and Thermomechanical Proceedings 10th Intersociety Conference on Phenomena in Electronics Systems, 2006. ITHERM 2006.*, 2006, p. 8 pp.-452.

[17] W. Garcia-Gabin, K. Mishchenko, and E. Berglund, "Cooling Control of Data Centers Using Linear Quadratic Regulators," in *2018 26th Mediterranean Conference on Control and Automation (MED)*, 2018, pp. 1–6.

[18] V. K. Arghode, V. Sundaralingam, and Y. Joshi, "Airflow Management in a Contained Cold Aisle Using Active Fan Tiles for Energy Efficient Data-Center Operation," *Heat Transf. Eng.*, vol. 37, no. 3–4, pp. 246–256, Mar. 2016.

[19] T. J. Stachecki and K. Ghose, "Short-Term Load Prediction and Energy-Aware Load Balancing for Data Centers Serving Online Requests," in *42nd International Symposium on Computer Architecture (ISCA), Portland, OR, June*, 2015, pp. 13–17.

[20] L. A. Zadeh, "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," *IEEE Trans. Syst. Man. Cybern.*, vol. SMC-3, no. 1, pp. 28–44, 1973.

[21] A. Gandhi, "Dynamic server provisioning for data center power management," *PhD diss., Intel*, 2013.