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Development of an Embedded RTU FDD System using Open-Source Monitoring and Control Platform

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ABSTRACT

Previous research on automated fault detection and diagnostics (FDD) for HVAC systems has shown promising benefits like earlier detection and more accurate isolation of common faults. While most researchers, equipment manufacturers, and policymakers agree that HVAC system FDD is important and has the potential to reduce significant energy waste due to faulty system operation, widespread adoption of these tools has been slow. An automated fault detection and diagnosis system has been developed for packaged (rooftop) air conditioners based on the VOLTTRON™ monitoring and controls framework developed by the Department of Energy. The system implements a virtual-sensor-based FDD methodology capable of isolating common rooftop unit faults such as improper refrigerant charge level, heat exchanger fouling, liquid-line restrictions, and compressor valve leakage. A fault impact evaluation component has also been implemented in order to determine the relative impact that faults have on system performance. This is accomplished using virtual sensor outputs and manufacturers' performance map reference models for performance indices such as cooling capacity and COP. This system has been implemented using low-cost electronics components and was tested using a 5-ton RTU in a laboratory environment.

In this work, a high-level overview of the automated rooftop unit (RTU) FDD system structure will be presented detailing how individual software agents interact along with a description of the computational and network requirements of the system. Alternative system architectures will also be discussed in comparison to the hybrid system presented. A review of the FDD algorithms is also presented that details the virtual sensor implementations along with the methodology to detect, diagnose, and evaluate different faults. Finally, the performance of the FDD system will be demonstrated using laboratory test data collected for a 5-ton RTU that utilizes a micro-channel condenser. The goal of this research is to produce a field ready FDD tool for RTUs that can be used to show the benefits of FDD in real systems. Ultimately, the software implementation (using Python) and hardware designs of all the systems components will be released under an open source license in an effort to reduce the engineering effort required by equipment manufacturers interested in a complete AFDD solution.

1. INTRODUCTION

1.1 RTU AFDD Background

Studies have shown that packaged commercial air conditioning equipment (commonly called rooftop units, RTUs) tend to be poorly maintained and significant energy may be wasted due to unnoticed or unrepaired equipment faults. One often cited review of FDD technologies for building systems estimates between 10-30% additional annual energy may be caused by repairable faults (Katipamula and Brambley 2005). While uncertainty about the prevalence of different faults still exists, previous field studies have shown that RTUs may benefit from automated FDD in particular (Jacobs 2003; Cowan 2004). Moreover, statistical analyses by Li and Braun (2007c) and Yuill (2014) estimate that FDD can provide positive value by reducing operating costs and improving in-field equipment diagnostics. These results have led to continued academic and institutional research interest in the area of equipment and building system FDD.

Manufacturers have been slow to translate FDD research and technologies into new equipment for a few reasons:

- FDD systems must be low-cost and easy to install,

- uncertainty with respect to economic benefit/savings potential still exists, especially in regards to prevalence of different faults,
- and there has been a lack of integration and interoperability with other building technologies.

In order to address these issues, a complete automated FDD system has been designed that implements a previously developed automated FDD approach using virtual sensors (Li and Braun 2007, 2009). The system is able to monitor operation of an RTU continuously and detect and diagnose multiple faults, even when multiple faults affect system operation simultaneously. In addition, a methodology to estimate the total impact on equipment performance has been implemented using the virtual sensors and reference models for normal system performance.

What follows is a technical description of the FDD system that has been developed for RTUs. The remainder of this section gives a high level overview of the system architecture and the open-source monitoring and control platform utilized to implement the system in software. In Section 2, a high level description of the automated FDD algorithms as well as a description of the low-cost system hardware is presented, along with references to the original work for more details. In Section 3, results collected from applying the AFDD system to a RTU in a laboratory setting are presented. Finally, in Section 4, the completed work is summarized and possible future work is proposed.

1.2 Overview of AFDD Architecture

Two hurdles that limit the adoption of FDD as a retrofit for existing RTUs and for integration in new RTUs are the lack of sensors and peripheral communications installed in equipment. It is difficult to detect problems with the typical data that is typically available. Additionally, it is difficult to alert building owners and facility managers about problems in a timely and effective manner. With this in mind, a dedicated FDD module has been developed that can be integrated within or in parallel with existing RTU controllers. The system addresses the need for sensors by adding low-cost measurement electronics and enables external communications by adding standard internet connectivity hardware. A schematic outline of the system architecture in relation to a typical RTU controller is shown in Figure 1.

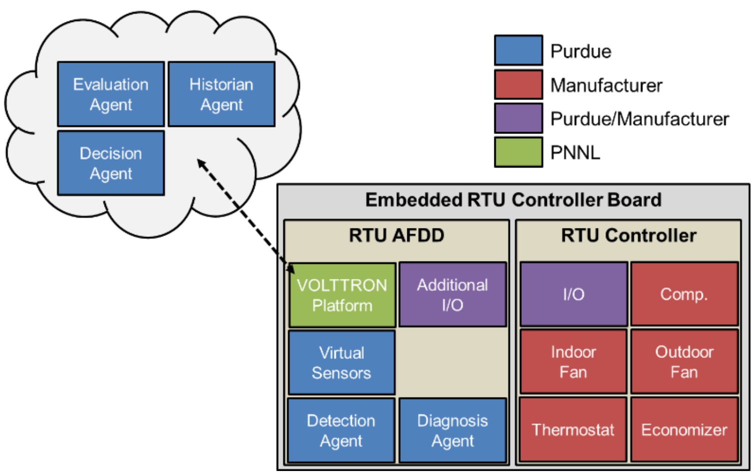

Figure 1. Overall architecture of VOLTTRON^{TM} enabled RTU AFDD system as an additional module of current RTU control units.

It should be noted that integrating a dedicated FDD module in existing RTU controllers is not the only possible solution for detecting and diagnosing equipment faults. An alternative solution, commonly called in-field FDD, uses devices that can be temporarily installed on equipment to aid field technicians in determining problems. A significant advantage of these diagnostics tools is that the cost can be distributed to many different RTUs since they can be generally applied. However, designing a tool that can be generally applied to many different RTUs while still having sufficient fault detection sensitivity and false alarm rejection is challenging (Yuill and Braun 2013). In addition, in-field FDD requires inspection of actual RTUs in order to detect and diagnose faults but previous studies have concluded that RTU inspection may be infrequent (Jacobs 2003; Cowan 2004; NMR Group 2015). Finally, the cost of sending service technicians into the field is significant in comparison with monitoring the health of equipment using electronics.

From its conception, the automated FDD (AFDD) system has been developed with the potential for existing as a passive, standalone system within the RTU controller. This means it was essential to incorporate all basic components of an AFDD product: a sensor measurement and data acquisition (DAQ) module, a fault detection module, and a fault diagnosis module. This involved both hardware design and extensive software development to implement the AFDD methods and algorithms. Rather than using propriety tools and code, the RTU AFDD system leverages open-source software exclusively, most importantly the VOLTTRON^{TM} monitoring and control platform (Somasundaram et al 2014, Akyol et al 2015). The VOLTTRON^{TM} platform, developed by the US Department of Energy, facilitates communication between software agents and other physical devices and resources with a primary focus on building systems and technologies. The role VOLTTRON^{TM} plays in the RTU AFDD system is to act as a message broker between AFDD services so that development, operation, and management may be organized hierarchically. This modularity offers the flexibility to modify, add, or completely swap out individual subcomponents depending on system requirements and RTU configuration.

2. IMPLEMENTATION DETAILS

2.1 Description of FDD Methodology and Software Implementation

Many automated FDD approaches have been previously proposed for RTUs (Rossi and Braun 1996; Armstrong et al 2006; Li and Braun 2007a; Najafi et al 2012; Katipamula et al 2015; Hjortland and Braun 2016a). The system described in this work implements a virtual sensor based methodology originally described by Li and Braun (2007a; 2007b). A virtual sensor uses low-cost sensor measurements with a mathematical model to estimate quantities that are difficult or expensive to measure directly. Several virtual sensors developed previously were implemented that can be used to detect and diagnose common faults, including:

- improper refrigerant charge levels,
- reduction in evaporator airflow caused by fouled evaporator coils,
- reduction in condenser airflow cause by fouled condenser coils,
- loss of compressor volumetric efficiency caused by compressor valve leakage,
- and liquid-line restrictions.

One major advantage of the virtual sensor approach is the ability to diagnose faults in the presence of multiple simultaneous faults. This is important since many faults may cause system performance to degrade over time if regular maintenance is not performed. In addition to detecting and diagnosing common faults, the cooling capacity, electrical power input, and COP of the system can be estimated using virtual sensors when the system operates.

One differentiating quality of the method implemented in this work is that faults are diagnosed using virtual sensors that are sensitive only to certain faults. This approach is what enables the diagnosis of multiple faults that occur simultaneously, which other methodologies were unable to do (Rossi and Braun, 1996). The virtual sensors implemented include:

- a virtual refrigerant charge sensor originally proposed by Li and Braun (2007b) and improved by Kim and Braun (2013) based on an empirical relationship between refrigerant charge level and suction superheat, liquid-line subcooling, and evaporator inlet thermodynamic quality,
- a virtual evaporator airflow rate sensor based on an evaporator coil energy balance using entering and leaving refrigerant-side and air-side sensor measurements (Li and Braun 2007b),
- a virtual condenser airflow rate sensor based on a condenser coil energy balance using entering and leaving refrigerant side and air-side sensor measurements (Li and Braun 2007b),
- and several virtual refrigerant mass flow rate sensors that can be used to diagnose compressor valve leakage and liquid-line restrictions (Li and Braun 2007b; Kim and Braun 2016).

Using other virtual sensors along with direct sensor measurements at different system state points, virtual cooling capacity, electrical input power, and COP sensors were implemented. These sensors can be used along with empirical models developed to estimate the normal performance of the system at different ambient conditions in order to determine the overall impact of faults. Using these impact estimates, more sensible maintenance and service decisions can be made by considering the cost to performe service and the additional utility cost to operate the system.

The empirical and mathematical models for the different virtual sensors were implemented using several open-source numerical computing libraries in the Python programming language (Hjortland 2016b). These models were incorporated into VOLTTRON[TM] compatible agents within a low-cost computing device. This software also included data acquisition functionality to interface with sensors required to monitor system operation.

2.2 Hardware Design and Initial Prototype Details

Due to the limited availability of sensors installed on existing RTUs in production and the relatively modest computing resources available, additional electronics hardware has been designed for implementing the aforementioned AFDD algorithms. The system designed can be considered standalone – these electronics can be installed on a typical RTU and with the proper initial configuration, an effective AFDD system can be utilized by building operators without any other sensor requirements or hardware. While this system could seemingly be applied as a retrofit, it was primarily designed from the standpoint of being embedded by equipment manufacturers during the production process.

In order to implement the virtual-sensor-based AFDD algorithms, several refrigerant-side and air-side temperature measurements (shown in Table 1) are required. To measure these temperatures, a low-cost buffered analog-to-digital thermistor circuit was designed (the hardware designs can be found with the source code, Hjortland 2016b). The thermistors selected for the application can be easily surface-mounted to the RTU refrigerant circuit in the locations required. In comparison to other types of temperature sensors (thermocouples, RTDs, etc.) thermistors offer a good combination of accuracy, reliability, and cost. When using thermistors, the highly nonlinear relationship between temperature and internal resistance must be considered during the design process. While there are different ways to address this problem, each with their own tradeoffs, a more expensive (yet still relatively inexpensive) analog-to-digital converter (ADC) with a higher resolution was selected for this application.

Table 1. Description of required refrigerant-side temperature sensors used for RTU AFDD methods.

Symbol	Type	Description
T_{eri}	10 kΩ Thermistor[1]	Evaporator Refrigerant Inlet Temperature
T_{suc}	10 kΩ Thermistor	Compressor Refrigerant Suction Temperature
T_{dis}	10 kΩ Thermistor	Compressor Refrigerant Discharge Temperature
T_{crs}	10 kΩ Thermistor[2]	Condenser Refrigerant Saturation Temperature
T_{cro}	10 kΩ Thermistor	Condenser Refrigerant Outlet Temperature
T_{cai}	10 kΩ Thermistor	Condenser Air Inlet Temperature
T_{cao}	10 kΩ Thermistor	Condenser Air Outlet Temperature
T_{eai}	Temp/RH Chip	Evaporator Air Inlet Temperature
φ_{eai}	Temp/RH Chip	Evaporator Air Inlet Relative Humidity
T_{eao}	Temp/RH Chip	Evaporator Air Outlet Temperature
φ_{eao}	Temp/RH Chip	Evaporator Air Outlet Relative Humidity

[1] In some applications, a compressor suction pressure measurement is available. When this is the case, the T_{eri} sensor is not required since the evaporating temperature can be calculated using two-phase property relations.

[2] In some applications, a compressor discharge pressure measurement is available. When this is the case, the T_{crs} sensor is not required since the condensing temperature can be calculated using two-phase property relations.

It should also be noted that pressure measurements can be used to calculate the evaporator refrigerant inlet temperature and condenser refrigerant saturation temperature since the refrigerant at these points is a two-phase fluid. Systems that already have these pressure sensors installed for control purposes do not need to install additional temperature sensors which reduces the additional instrumentation costs for AFDD. It is also worth noting that pressure sensors may be required for systems with micro-channel condensers. On these systems, locating a consistent and reliable saturation temperature point over the expected equipment operating range is not trivial task.

The RTU AFDD methodology requires a calculation of the enthalpy of the entering and leaving evaporator air in order to determine if the evaporator coil is fouled or airflow has been reduced. Measuring enthalpy directly is not possible, so the temperature and relative humidity at these points is measured instead (described in Table 1). In the initial design, two solid-state sensors that measured both the dry-bulb temperature and relative humidity were used. Unlike the analog thermistor circuits described previously, these sensors provide a digital output using the I^2C communications protocol. Besides using these sensors for the virtual evaporator airflow (VEAF) sensor, the entering evaporator air drybulb temperature and wetbulb temperature are used as inputs in reference models of normal performance also used by the AFDD algorithms.

An overall schematic view of the temperature, pressure, and relative humidity sensors used by the RTU AFDD system is shown in Figure 2. In comparison with the sensors typically found on RTUs, significantly more sensors are required. The additional sensor sensors enable the ability to diagnosis simultaneous faults and estimate impacts of faults on cooling capacity and COP.

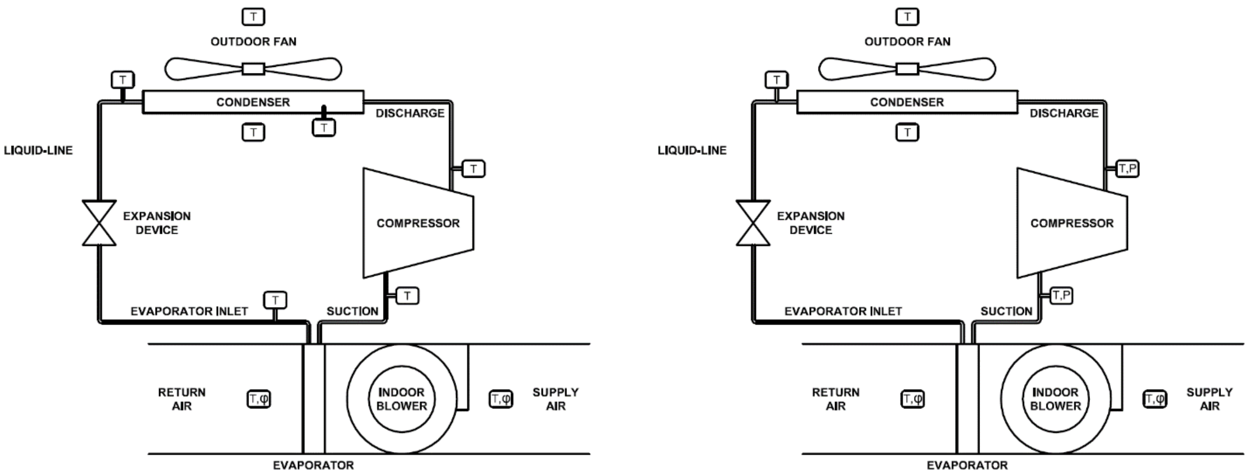

Figure 2. Locations of temperature (T), pressure (P), and relative humidity (φ) sensors used by RTU AFDD system. System using only refrigerant-side temperature measurements is shown on left; system using refrigerant-side pressure measurements is shown on right.

Besides sensors and signal conditioning circuitry, the RTU AFDD data acquisition system requires a computational engine that is able to monitor the sensor outputs and perform the required mathematical transformations to the data and communicate the results with the VOLTTRON^{TM} message bus. Typically, in HVAC applications, a low cost microcontroller is used for data acquisition purposes. Most microcontrollers by themselves do not have the type of communications abilities that are required by the VOLTTRON^{TM} communication protocol. While with enough time and effort, this could be implemented in some microcontrollers, an alternative type of device was selected to perform the required data analysis and communications.

The BeagleBone Black is a low-cost, open-source, community supported development platform with a TI Sitara^{TM} ARM$^{®}$ Cortex A8 microprocessor that is capable of running the Linux operating system. In other words, the BeagleBone Black is a computer with all essential components (microprocessor, RAM, hard drive, etc.) on a single circuit board. The first role of the BeagleBone Black in this application is to provide analog and digital interfaces between the data acquisition software and the required sensors installed on the RTU. Compared to other microcontrollers and microprocessors, application development using the BeagleBone Black is easier since many of these low-level hardware and software interfaces are provided out of the box. The second role of the BeagleBone Black is to support a run-time environment for the central VOLTTRON^{TM} application as well as the embedded RTU AFDD software agents. The BeagleBone Black is not the only system capable of this; other development platforms are available with similar functionality. Development using the BeagleBone Black was selected since the TI Sitara^{TM} microprocessor is widely available. Because of this, any work done with the prototype platform is almost directly translatable to any future (potentially lower cost) platform using a similar chipset.

The RTU AFDD electronics system designed was implemented using actual components, shown in Figure 3. The hardware selected for the prototype is considered to be typical and widely available. The system implemented is relatively low-cost when compared to similar data acquisition applications within the HVAC market – the final system could be built for approximately $120 USD. With consideration for economies of scale and optimized manufacturing process, significant cost reduction should be possible. While the through-hole prototyping system shown in Figure 3 can be readily manufactured, a printed circuit board design was also developed.

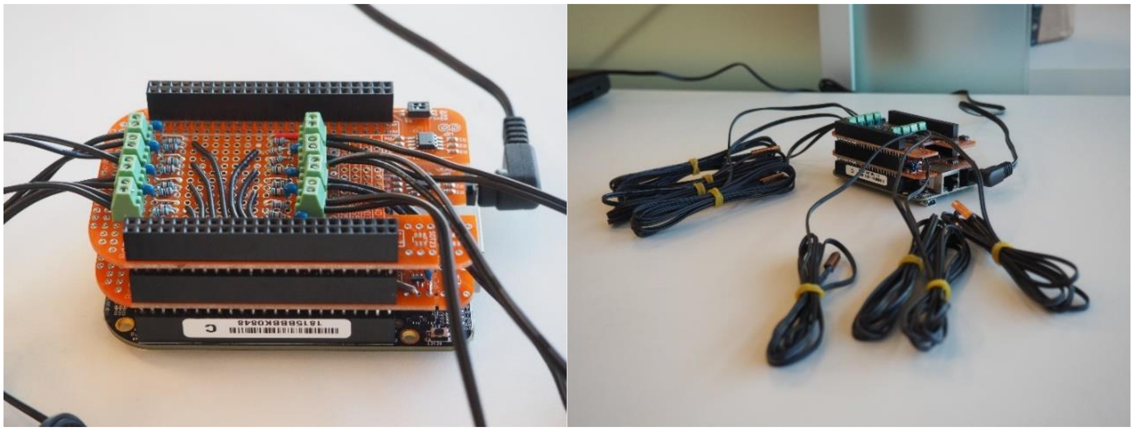

Figure 3. RTU AFDD system through-hole prototype implementation using pre-fabricated prototyping electronics boards.

3. LABORATORY TESTING RESULTS

In order to test the performance of the fault detection and diagnostics system, a RTU with 5-ton rated capacity was installed in psychrometric chambers at Ray W. Herrick Laboratories. The system was installed with a two-stage scroll compressor, a finned-tube evaporator, a finned-tube condenser, and used R410A as the working fluid. The system is shown in Figure 4 installed in the psychrometric chambers.

Figure 3. 5-ton RTU used to test automated fault detection and diagnostics system installed in psychrometric chambers.

In order to test the performance of the AFDD system, the RTU was operated under a range of operating conditions, described in Table 2. This included both wet coil and dry coil tests under outdoor ambient conditions ranging from 20.56 °C (69 °F) to 42.22 °C (108 °F). In order to test the performance of the AFDD system at diagnosing refrigerant charge faults, the system charge level was adjusted to values ranging from 60% (40% undercharge) to 120% (20 overcharge). The ability to diagnose reductions in evaporator and condenser airflow (simulating fouling) was tested by adjusting the indoor blower and outdoor fan control inputs to prescribed levels. Two levels of airflow were tested for each fan: normal and reduced. Finally, combinations of all three faults were tested simultaneously at the different ambient conditions.

Table 2. Test conditions for RTU with finned-tube condenser and fixed orifice expansion device for low stage cooling operation in psychrometric test chambers.

Test Variable		Test Values	
Compressor Stage	[-]	LOW	HIGH
Indoor Dry Bulb	[°C]	26.67	26.67
Indoor Wet Bulb	[°C]	13.89, 20.56	13.89, 20.56
Outdoor Dry Bulb	[°C]	20.56, 27.78, 35.00, 41.22	20.56, 27.78, 35.00, 41.22
Charge Level[1]	[%]	60, 70, 80, 90, 100, 110, 120	60, 70, 80, 90, 100, 110, 120
Indoor Fan Torque[2]	[%]	30, 60	50, 90
Outdoor Fan Speed[3]	[%]	40, 70	70, 100

[1] Charge is measured relative to the recommended charge according to the manufacturer's nameplate data.
[2] Indoor fan torque is set according to a nominal flow rate of 1350 CFM for low stage operation; 2000 CFM for high stage operation.
[3] Outdoor fan speed is set using the manufacturer's default value for low and high stage operation.

The accuracy of the VRC model for each stage of operation is shown in Figure 4 over the range of ambient conditions and fault scenarios tested. The virtual refrigerant charge sensor required empirical data to tune the model parameters. These parameters were tuned using an automated training algorithm without the use of psychrometric chambers (Patil et al. 2016). In both stages of operation, the prediction accuracy was mostly within 10% of the measured charge levels. Moreover, the root-mean-square error (RMSE) was approximately 6.20% for both stages operation. It should also be noted that the relative accuracy remains approximately unchanged over the range of refrigerant charge levels tested and minimal bias exists as a function of outdoor ambient temperature.

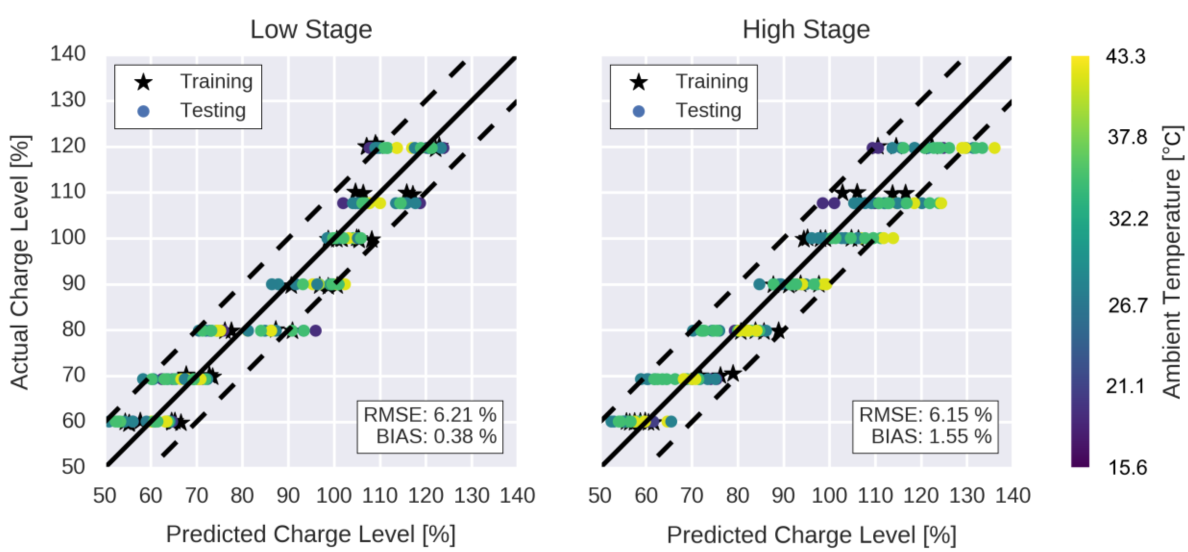

Figure 4. VRC sensor prediction accuracy for RTU with finned tube condenser and fixed orifice expansion device applied to both stages of operation under different ambient conditions.

Figure 5 shows the accuracy of the virtual charge sensor as well as the calculated fault probability for tests cases with normal airflow rate levels. Good agreement between the predicted charge level and the measured charge level was observed for these test cases. The charge fault probability was calculated using a statistical methodology originally described by Rossi and Braun (1997). Essentially, this assumes that two Gaussian distributions can be used to represent the expected and observed refrigerant charge levels. The degree that these two distributions overlap is analogous to the probability that the observed charge level is equal to the expected charge level. This probability is then calculated by integrating the area contained by both distributions. Also shown in Figure 5 is the calculated probability of a charge fault being present in each case. The results shown in Figure 5 show that the FDD system is able to identify refrigerant charge faults with probabilities greater than 95% when the actual charge level deviates ±15% from normal.

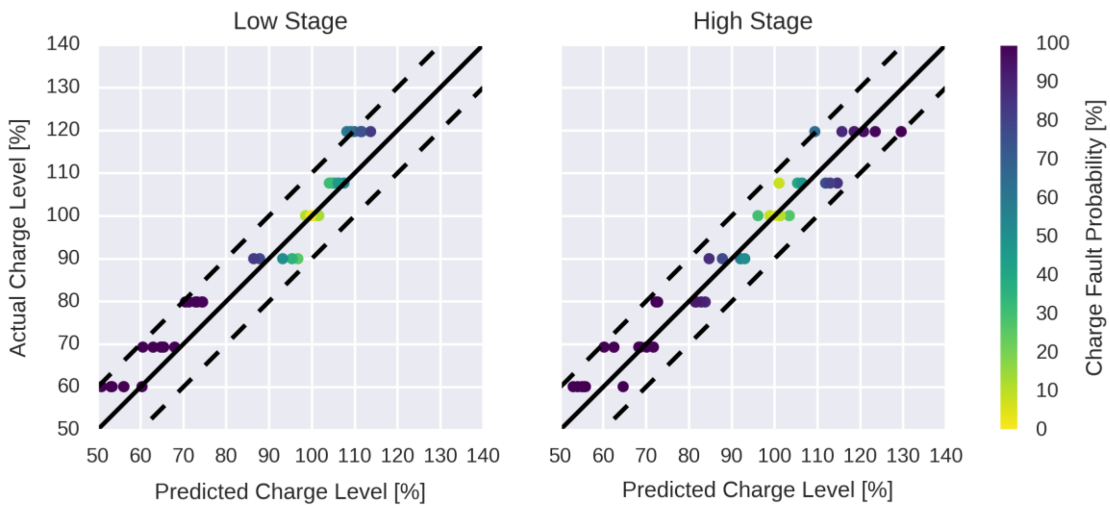

Figure 5. Prediction accuracy of VRC sensor applied to charge level vaults showing charge fault probability for each test case. The data show that the FDD system is able to identify faults with high confidence when actual charge is ±20% of the normal charge level.

It is important that the FDD system is able to accurately identify faults when there are multiple simultaneous faults affecting the system. Figure 6 shows the performance of the charge fault diagnostics for several combinations of improper refrigerant levels, indoor airflow levels, and outdoor airflow levels. In these results, tested under 27.78 °C (82 °F) outdoor temperature, refrigerant charge faults were correctly identified with probabilities greater than 95% in all cases where the charge level deviated by at least ±20%. It is also noteworthy that the VRC sensor tends to predict refrigerant charge faults with greater probability when the impact on system capacity of the faults increases. This indicates that when significant refrigerant charge faults affect the system, the FDD system is able to identify them.

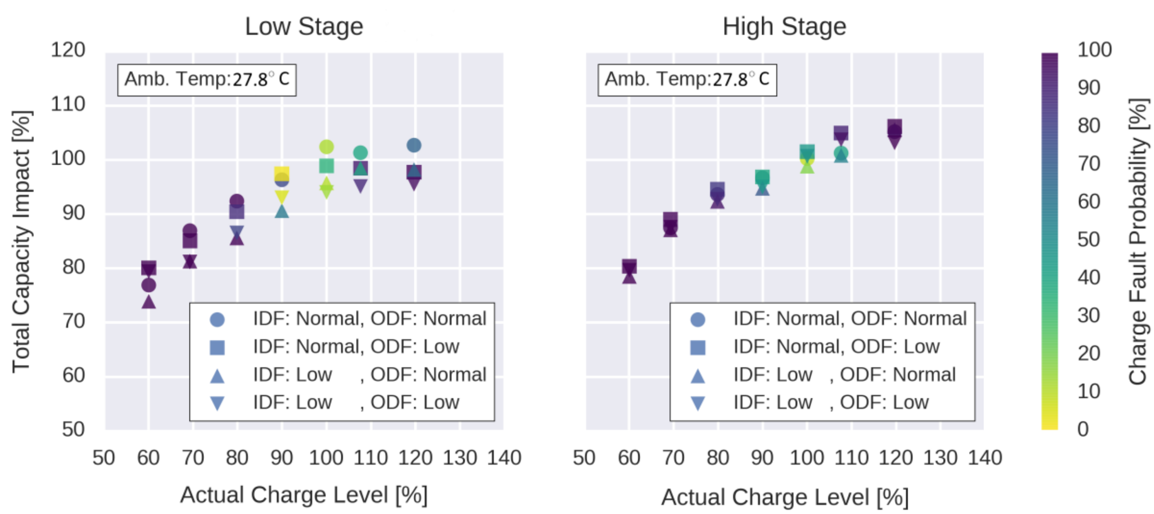

Figure 6. Total capacity impact of refrigerant charge faults at 27.78 °C (82 °F) outdoor ambient temperature. The points are colored based on the fault probability determined for each test case, indicating faults that have larger impacts are identified with greater probability. IDF indicates the indoor fan torque setting; ODF indicates the outdoor fan speed setting.

Similar results for test conditions at 35.00 °C (95 °F) and 41.22 °C (108 °F) outdoor temperature are shown in Figure 7 and Figure 8 respectively. In these results, refrigerant charge faults were correctly identified with high probabilities in test cases where the refrigerant charge deviated by ±10%. It should also be noted that refrigerant charge faults tended to have large impacts on the total capacity of the system at the higher outdoor temperatures.

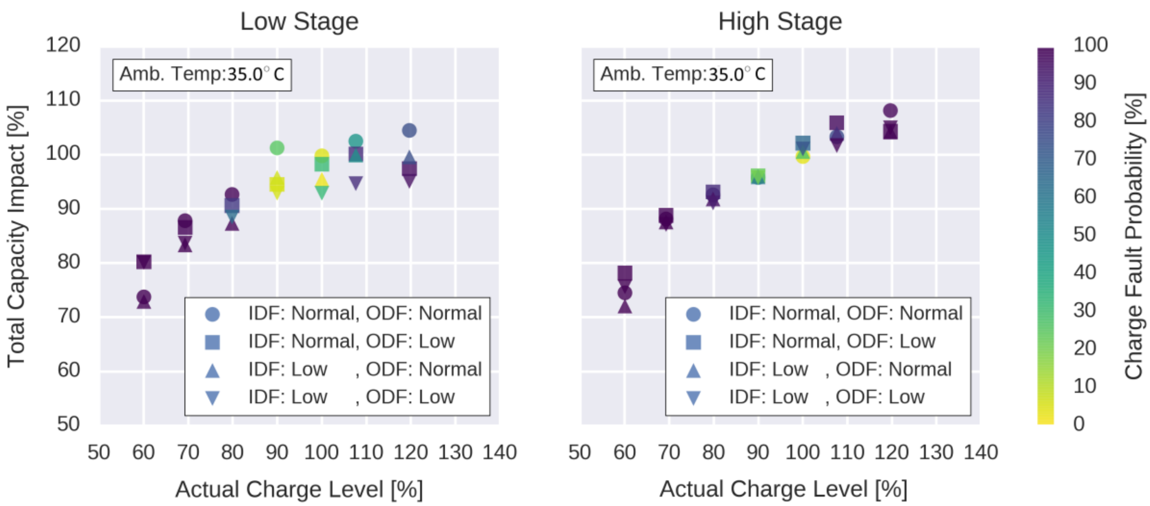

Figure 7. Total capacity impact of refrigerant charge faults at 35.00 °C (95 °F) outdoor ambient temperature. The points are colored based on the fault probability determined for each test case, indicating faults that have larger impacts are identified with greater probability. IDF indicates the indoor fan torque setting; ODF indicates the outdoor fan speed setting.

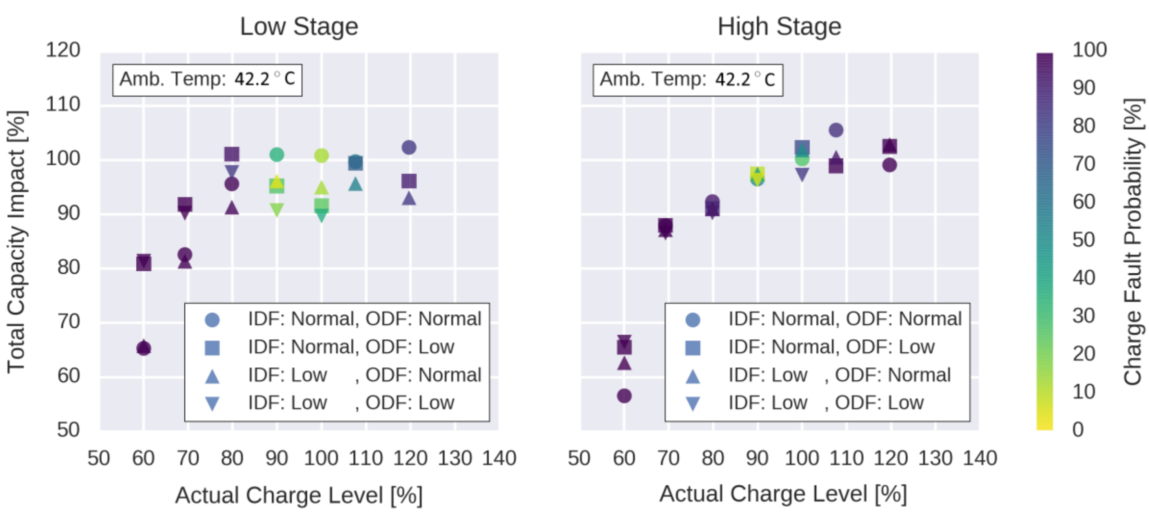

Figure 8. Total capacity impact of refrigerant charge faults at 41.22 °C (108 °F) outdoor ambient temperature. The points are colored based on the fault probability determined for each test case, indicating faults that have larger impacts are identified with greater probability. IDF indicates the indoor fan torque setting; ODF indicates the outdoor fan speed setting.

The probability of an evaporator airflow fault has been calculated for each test case in order to test the effectiveness of the FDD system at identifying evaporator fouling faults. This probability was calculated using the previously described method using the virtual evaporator airflow rate sensor. The results in Figure 9 compare test cases at 27.78 °C (82 °F) ambient conditions where evaporator airflow was normal and reduced to simulate a fouling fault. Fault cases that had reductions in evaporator airflow resulted in high fault probabilities, which can be used to identify faults. The results illustrate that evaporator fouling can be identified even in the presence of other faults, like low refrigerant charge.

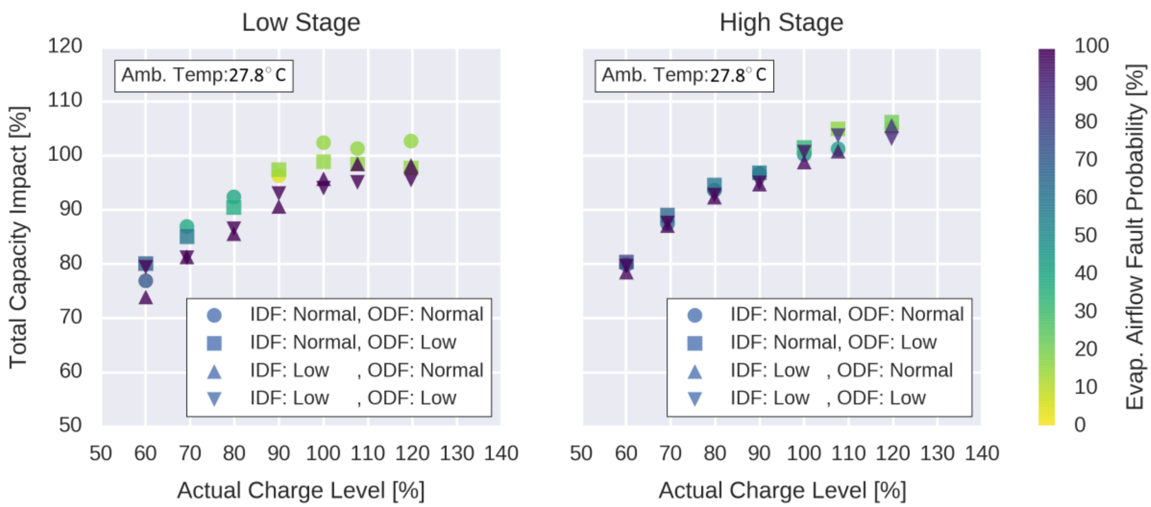

Figure 9. The FDD system is able to identify test cases with low evaporator airflow using the statistical fault detection and diagnostics method. Test cases without reductions in evaporator airflow were not identified with high fault probabilities. IDF indicates the indoor fan torque setting; ODF indicates the outdoor fan speed setting.

The probability of a condenser airflow fault has been calculated for each test case in order to test the effectiveness of the FDD system at identifying condenser fouling faults. This probability was calculated using the previously described method using the virtual condenser airflow rate sensor. The results in Figure 10 compare test cases at 27.78 °C (82 °F) ambient conditions where condenser airflow was normal and reduced to simulate a fouling fault. Fault cases that had reductions in condenser airflow resulted in high fault probabilities, which can be used to identify faults. The results illustrate that condenser fouling can be identified even in the presence of other faults, like low refrigerant charge.

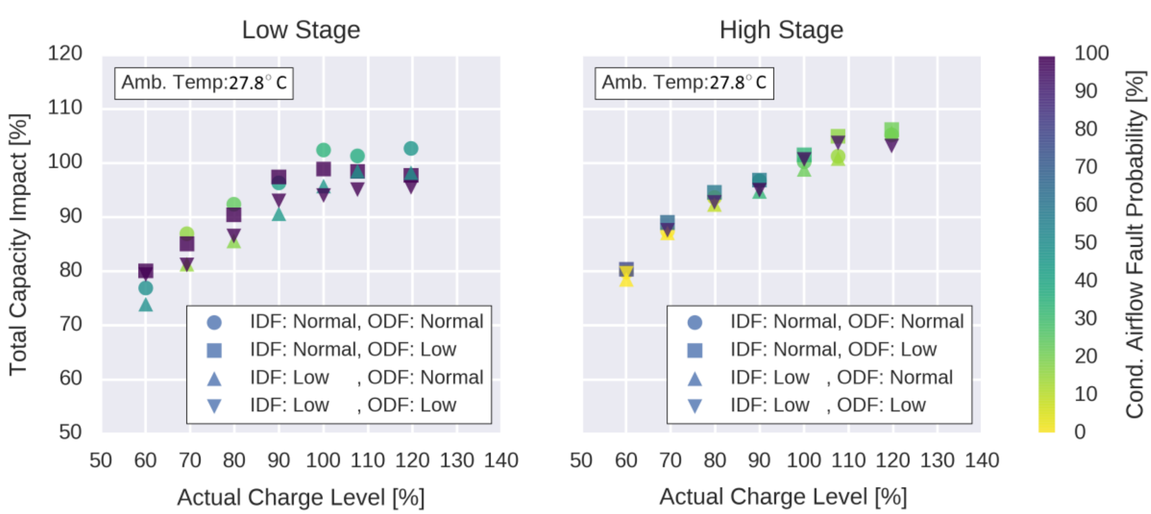

Figure 10. The FDD system is able to identify test cases with low condenser airflow using the statistical fault detection and diagnostics method for test cases under 27.78 °C (82 °F) outdoor ambient temperature. Test cases without reductions in condenser airflow were not identified with high fault probabilities. IDF indicates the indoor fan torque setting; ODF indicates the outdoor fan speed setting.

4. CONCLUSIONS AND FUTURE WORK

Previous research on automated fault detection and diagnosis (AFDD) for building systems has shown that identifying problems that cause degradation in system and equipment performance is technically feasible and has the potential to significantly reduce energy consumption. However, manufacturers have faced hurdles such as high instrumentation costs, lack of integration with other building system equipment, and uncertainty in regards to savings that has prevented technologies from seeing market adoption. In this work, an AFDD system for packaged rooftop air conditioning equipment has been described. The AFDD algorithms have been described as well as the open-source software implementation of the system. Additionally, low-cost electronics hardware has been designed to implement the data acquisition, communications, and computational requirements of the system. All hardware designs and VOLTTRON™ compatible software agents have been made publically available (Hjortland 2016b). It is envisioned that this work can be adapted by future researchers as well as equipment manufacturers to reduce initial engineering and development effort.

Extensive psychrometric chamber testing has been conducted in an effort to assess the performance of a FDD system designed for rooftop units. Testing was performed under a wide range of outdoor and indoor ambient conditions while also injecting combinations of improper refrigerant charge, evaporator airflow reduction, and condenser airflow reduction faults. A statistical method for determining the probability of a fault being present in the system was able to identify improper charge levels, evaporator airflow reduction and condenser airflow reduction. Additionally, tests with multiple faults also showed good fault isolation, especially when impacts on total capacity and COP were significant. This indicates that the FDD system is able to identify problems that may cause significant additional energy consumption. Field study on actual equipment is still necessary to demonstrate the performance of the RTU AFDD system in real-world scenarios. Using the described system, wide-spread field demonstration is much more attainable.

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