Performance improvement clarification for refrigeration system using active system monitoring

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Abstract: This paper addresses the problem of determining whether a refrigeration plant has the possibility of delivering a better performance of the operation. The controllers are well-known but detailed knowledge about the underlying dynamics of the refrigeration plant is not available. Thus, the question is if it is possible to achieve a better performance by changing the controller parameter. An approach to active system monitoring, based on active fault diagnosis techniques, is employed in order to evaluate changes in the system performance under operation.

Keywords: Performance assessment, Performance optimisation, Active system monitoring, Refrigeration systems

1. INTRODUCTION

The operation quality of a supermarket refrigeration system is crucial to ensure the profit of the supermarket because the system enables sale of refrigerated goods and furthermore the running cost of the system is considerably high. Thus, ensuring high operation quality of the refrigeration plant is important. Achieving optimal performance requires performance measurement, assessment and possibly adjustment of the control system. In addition, determining a possible improvement potential is required. Green et al. [2010] presents an adequate performance function which captures the main features of the system. To utilise the results for reconfiguration of the controllers the improvement potential for the particular plant has to be evaluated. This paper describes a method that can be used to determine the improvement potential that the control system will be able to deliver, with respect to the operation quality.

The usual way to evaluate the operation performance of a given plant is to compare the achieved performance against a predetermined benchmark. These techniques require a model of the benchmark and are therefore hard to handle in applications where the knowledge of the system under assessment is restricted. This situation is exactly what the industry for supermarket systems is faced with. The design of control software is usually done without exact knowledge of the layout of the refrigeration plant.

Assessing performance based on a model of the system under assessment has been done in a large number of publications. In, Harris [1989], Qin [1998], Huang and Shah [1998], Harris et al. [1999] and Ordys et al. [2007], the minimum variance benchmark is used to assess the performance and even though the minimum variance benchmark is considered to be a data driven method in the literature it does require a benchmark model. In Schäfer and Cinar [2004] a model-predictive control benchmark is introduced. Common for these publications are that they all assume that enough information about the system is present, at the design phase for the assessment scheme, to derive a model.

This paper shows that the need of a model can be circumvented by utilising the fact that full knowledge about the controller is given at the design phase for the assessment scheme. In addition, the question that should be answered is whether the performance can be improved by changing controller parameters for a particular plant operating under a particular set of conditions. Answering that question has much higher value than determining whether an achieved performance is worse than some theoretical level.

In section 2 the problem is formulated and described and the new approach is described in 3. The basic supermarket refrigeration system is described in 4. An illustrative example is presented in 5 along with a description of the model used for simulating the supermarket refrigeration system. Section 6 presents results from different test scenarios and the paper ends with a discussion in 7.

2. PROBLEM FORMULATION

The main problem is to assess whether a certain closed loop subsystem has the parameter freedom to improve the overall performance of the entire system. Therefore, to address this problem a performance measure for the entire system is needed along with a method for determining the
A refrigeration system for a supermarket will most of the time run in steady state, hence not all parameter changes will be observable from the measurements or the performance measure. Thus, to ensure that the parameter changes will affect the behaviour of the measurements and thereby also the performance measure, excitation of different closed loop controlled subsystems is required.

A refrigeration system for a supermarket can be divided into a number of subsystems. The different subsystems influence the operation of each other in both positive and negative direction. Therefore, the evaluation of both a local and global performance is important, because evaluation of the local performance is not the same as evaluating the global performance. Changing the parameters in the controller for a specific closed loop might deteriorate the local performance. However, that does not necessarily imply that the global performance will also deteriorate.

The evaluation of the performance should ideally be done using as little knowledge about the system as possible. That is due to the fact that the structure of the control system is usually designed without any specific knowledge about the particular refrigeration system, i.e. detailed knowledge about the underlying system dynamic is basically non-existent. However, full description of all the utilised controllers are available. Therefore, basing the performance evaluation on the knowledge about the nominal controllers and omitting a reference model of the refrigeration system would be the ideal solution.

### 3. NEW SETUP

The aim is to assess whether it is possible to improve the overall system performance. The approach to determine the improvement potential will be based on the performance measure introduced in Green et al. [2010]. As mentioned earlier a refrigeration system is usually operating in steady state conditions and will therefore not be affected by a change in a controller parameter unless the dynamics of the system is excited. A simulation model will be used to select a probe signal that can be used to evaluate the performance change created by a parameter change in the controller. The probe signal has to be designed to generate enough variations on the performance measures to enable an evaluation of a parameter change, but without compromising the operation of the refrigeration plant.

A block diagram of the setup can be seen on fig. 1, which illustrates a closed loop under assessment plus the global performance measure and the detector. The parameter change of the controller \( K \) is denoted by \( \Delta \xi \) and \( \eta \) denotes the excitation signal. The control input to the system is denoted by \( u \) and \( J \) denotes the performance measure which is directly used as residual by the detector to decide whether a given parameter change, \( \Delta \xi \), has changed the overall performance measure. The input to the performance measure, from the other subsystems, is denoted by \( \Gamma \).

#### 3.1 Performance indicators

The performance indicators are basically chosen to cover three performance criteria which are food quality, energy efficiency and actuator life time. The indicator for food quality are the control errors, of the temperature controller in the display cases and the suction pressure controller, which are gathered in a vector described in (1).

\[
e = \left| \frac{T_{\text{ref},i} - T_{\text{act},i}}{T_{\text{act},i} - P_{\text{act}}} \right|
\]  

The coefficient of performance, \( COP \), which is described by (2), is used as an indicator for energy efficiency.

\[
COP = \frac{Q_{\text{cool}}[w]}{W_{\text{ref}}[w]},
\]  

In (2) the delivered cooling capacity is denoted by \( Q_{\text{cool}} \) and the electrical energy supplied to the refrigeration plant is denoted by \( W_{\text{ref}} \). The indicator with respect to actuator life time is the switch frequency of the compressors in the compressor rack, which is denoted by \( f_{\text{sw}} \). It is used as a simple indicator since switching of compressors reduces the life time of the compressors.

Combining the three different performance indicators in a single performance function yields

\[
J(t) = \sum_{n=1}^{N} \left| \frac{Q(n)}{|Q|} \right|_2^2 + \sum_{n=1}^{N} \left| \frac{1}{COP(n)} \right|_R^2 + \sum_{n=1}^{N} \left| f_{\text{sw}}(n) \right|_S^2
\]  

where \( Q, R \) and \( S \) denotes the weights that determine the impact of each term on the performance function. Since the \( COP \) is a number that will increase with efficiency the inverse is used to ensure that minimising the performance function is still the target. The choice of weights has to be done with respect to the application under investigation. The choice of weights will have a significant influence on which parameter changes can be detected using reasonable size of both the excitation signal and the parameter changes. In other words, the weights determine the definition of optimality for a particular system and should therefore be chosen with care. Even though the weights are usually chosen based on empirical knowledge they should not be considered as tuning parameters for the detector.

#### 3.2 Active performance assessment

To ensure an adequate result from the excitation of the system some considerations have to be done to design the excitation signal \( \eta \). Since the task of the excitation signal is to excite the dynamics of the controller and the system the
frequency range of the signal has to be chosen with care. If
the excitation signal is too fast the effect will not be visible
on the output because of the low pass filtering effect of the
closed loop system. In contrast if the frequency is chosen
too slow it will not be possible to detect the change within
reasonable time. In addition, the impact on the operation
of the system should be minimal since the excitation is
carried out under normal operation of the system. Hence,
the operation quality must not be compromised. In this
paper a sinusoid signal has been chosen, however any
periodic signal with appropriate frequency and amplitude
properties can be used. The excitation signal is given by:
\[ \eta = A \cdot \sin(\omega t) \] (4)
The choice of the frequency, \( \omega \), for the excitation signal
is important for the method to work. It is worth mentioning
that the frequency of the excitation signal should lie within
the bandwidth of the closed loop both before and after the
parameter change to ensure that the influence of the signal
is not filtered away by the closed loop. However, since the
bandwidth of the closed loop is unknown a conservative
choice of both the excitation signal frequency and the size
of the parameter change is recommended.

3.3 Detector

To ensure that a significant change in the performance
measure has occurred a statistical change detector has
been used. In addition, a statistical method is applied
to ensure that a decision can be made with confident
and without the need of unreasonable amplitude of the
excitation signal \( \eta \). The detector has to decide between
two hypothesis which can be formulated as,
\[ H_0 : \bar{J}_0 + w[n] \] (5)
\[ H_1 : \bar{J}_1 + w[n] \] (6)
where \( w[n] \) denotes a noise contribution and \( \bar{J}_0 \) and \( \bar{J}_1 \)
denoted the initial mean value of the performance function
and the estimate of the unknown change in mean of the
performance function respectively. The outcome of this
simple hypothesis test will only be that a change has
occurred. To evaluate whether the performance has been
improved or degraded a separate test will have to be applied.
The test will be to check if \( J_0 > J_1 \) or \( J_0 < J_1 \) is
true. If \( J_0 > J_1 \) is true the performance of the system has
improved and an flag will be set to 1. In contrast if \( J_0 < J_1 \) is
true the performance has been degraded by the parameter
change and the alarm state will therefore be set to -1.
When the system dynamics is excited and a parameter in
the controller has been changed then the detector has to

a) detect whether a significant change in the performance
measure has been created by the parameter change
b) determine whether the performance has been im-
proved or degraded.

To fulfill the detection task stated above a statistical test
method is needed due to the presence of noise. A well
known test that can cope with detecting an unknown
change in mean value is the generalised likelihood ratio
test, (GLRT), see Kay [1998]. Oppose to the cumulative
sum, see Blanke et al. [2006], which requires knowledge
about the mean value after the change has occur, that
knowledge is not required by the GLRT. In addition, a bi-
product of the GLRT is an estimate of the mean values,
which can be used to determine if an improvement or
a degradation has been detected. Basically the GLRT decides \( H_1 \) if the likelihood ratio, \( L_G \), in (7) crosses the
threshold, \( \gamma \).
\[ L_G(J) = \frac{p(J; \bar{J}_1, H_1)}{p(J; \bar{J}_0, H_0)} > \gamma \] (7)
In (7) \( p(\cdot) \) denotes the probability density function. The probability density function is given by:
\[ p(J; \bar{J}_i, H_i) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} (J(n) - \bar{J}_i)^2 \right) \] (8)
where \( i \in \{0, 1\} \) and \( N, \sigma^2 \) denotes the window size and the variance, respectively. To ensure the theoretical
performance of the detector it is necessary to assume that
\( \omega \) in (5) and (6) is white Gaussian noise to fulfill the
conditions for the GLRT. The fulfillment of that condition
has not been treated in this paper. In addition, it is not
considered to be an issue in this application of the
GLRT, since the performance of the detector is non-
critical. The choice of the threshold, \( \gamma \), is usually a tradeoff
between time to detect and probability of false alarms
when the detector is used in a normal fault detection
application. The threshold, \( \gamma \), can be computed to fit
a desired probability of false alarms by utilisation of a
right-tail function, for details see Kay [1998] chapter 6.
However, the use of the detector proposed in this paper
requires another way of thinking of the quality of the
detector. In the proposed setup missing an alarm is not
hazardous and the notion of firing a false should also be
reconsidered. Missing an alarm is not an issues in this
setup because it is known when the parameter change
in the controller happens. Hence the detector will only
be active when a change in the performance measure is
expected. On the other hand firing a false alarm is not a
problem because as mentioned before the detector will
only be active when a change is expected. Even though
the normal tradeoff problem does not apply, it is of course
still the target to chose \( \gamma \) so that the noise level in the
performance function cannot trigger an alarm. In addition,
it will still be desirable to chose a \( \gamma \) that enables the
detector to fire an alarm within reasonable time of the
parameter change that the detector is trying to detect. The
threshold can be chosen relatively defensive with respect to
the probability of false alarms because time to detect is
not critical. The probability of making the wrong decision
based on an alarm is more relevant in this application of
the GLRT, since it implies that a parameter change
that deteriorates the performance can be interpreted as a
performance improvement.

4. SUPERMARKET REFRIGERATION SETUP

The supermarket refrigeration setup, which can be seen
on figure 2, is comprised of a number of display cases,
a compressor rack and a condensing unit. The display
cases are where the stored good are refrigerated and the
condensing unit is where the heat removed from the stored
goods is emitted to the surroundings. The compressors
generates the flow of refrigerant and the control task for
the compressor rack is to maintain a certain saturation
temperature for the refrigerant. The saturation temperature determines the cooling capacity of the display cases. The temperature in each of the display cases is controlled by the inlet valve. The condensing pressure is controlled by fans to ensure that the heat can be transferred to the surroundings. The control of the saturation temperature is achieved by switching the compressors on or off. Hence, to avoid excess switching of the compressors their sizes should ideally be chosen to match the common load of the system with a fixed number of compressors. However, the compressors cannot be chosen to fit the load exactly in practice. Thus, the compressors will have to switch on and off to accommodate the required refrigeration load. The

\[
\frac{dT_{\text{air},i}}{dt} = \frac{Q_{\text{goods-air},i}(t) + Q_{\text{load},i}(t) - Q_{\text{air-wall},i}(t)}{M_{\text{air}} C_{\text{p,air},i}} 
\]

(9)

\[
Q_{\text{load},i} = U A \Delta T_{\text{amb} - T_{\text{air},i}} 
\]

(10)

\[
\frac{dM_{\text{r},i}}{dt} = OD_i \cdot \alpha \cdot \sqrt{\frac{P_c - P_{\text{suc}}}{\Delta h_{lg}}} - \frac{\dot{Q}_i}{\Delta h_{lg}} 
\]

(11)

\[
\frac{dP_{\text{suc}}}{dt} = \dot{m}_{\text{in-suc}}(t) - \dot{m}_{\text{comp}} \n\]

(12)

The common state between the display cases, the suction manifold and the compressors is the suction pressure, \(P_{\text{suc}}\), for which (12) describes the dynamics. The refrigerant density and the pressure derivative of the refrigerant density is denoted by \(\rho_{\text{suc}}\) and \(\nabla \rho_{\text{suc}}\), respectively in (12). The mass flow rate into the suction manifold, \(\dot{m}_{\text{in-suc}}\), is described by:

\[
\dot{m}_{\text{in-suc}}(M_{\text{r},i}, T_{\text{wall},i}, P_{\text{suc}}) = \sum_{i=1}^{N} \frac{Q_{\text{req},i}(t)}{\Delta h_{lg}(P_{\text{suc}})} 
\]

(13)

The mass flow rate generated by the compressor rack is described by

\[
\dot{m}_{\text{comp}} = \text{Cap} \cdot \frac{1}{100} \cdot \eta_{\text{vol},i} \cdot V_{\text{sl},i} \cdot \rho_{\text{suc}}. 
\]

(14)

where \(\text{Cap}\) is the total running compressor capacity of the rack and \(\eta_{\text{vol}}\) and \(V_{\text{sl}}\) is the volumetric efficiency and the swept volume flow rate, respectively. No dynamics of the condenser is modelled, it simply defines the high pressure as being static. Hence, the condenser is assumed to be able to maintain a constant pressure and a constant sub-cooling.

The controllers for the display cases and the compressor rack are PI controllers and can be described by the following equations.

\[
OD(t) = K_{P,d} \cdot (T_{\text{ref},i}(t) - T_{\text{air},i}(t)) + \frac{1}{T_{\eta,d}} \int_{0}^{t}(T_{\text{ref},i}(\tau) - T_{\text{air},i}(\tau))d\tau 
\]

(15)

\[
\text{Cap}_{\text{req}}(t) = K_{P,c} \cdot (P_{\text{suc},i}(t) - P_{\text{suc}}(t)) + \frac{1}{T_{\text{eta,c}}} \int_{0}^{t}(P_{\text{suc},i}(\tau) - P_{\text{suc}}(\tau))d\tau 
\]

(16)

where \(K_{P,d}\), \(K_{P,c}\), and \(T_{\eta,d}\), \(T_{\text{eta,c}}\) denotes the proportional gain and the integration time respectively. In (15) the desired temperature in the ith display case is denoted by \(T_{\text{ref},i}\) and the measured air temperature is denoted by \(T_{\text{air}}\). The reference and the measured suction pressure is denoted by \(P_{\text{suc},i}\) and \(P_{\text{suc}}\) respectively. The requested compressor capacity is in (16) denoted by \(\text{Cap}_{\text{req}}\), which is used by the distributor algorithm to decide the compressor combination by determining the values of \(\delta \in \{0,1\}\) in (17).

\[
\text{Cap} = \sum_{i=1}^{N} \delta_{i} \text{Cap}_{i} 
\]

(17)

In (17) \(N\) is the number of compressors in the rack and \(\text{Cap}_{i}\) denotes the capacity of the ith compressor.

After introducing the system model an illustrative example will be presented. Passive detection methods rely on a change in the system that causes a change in the

5. ILLUSTRATIVE EXAMPLE

To illustrate the performance assessment problem introduced in section 2 a model of a refrigeration system is needed. The model setup given in Green et al. [2010], which is based on the model presented in Larsen et al. [2007], will be described shortly. In this model a refrigeration system comprised of; two display cases with individual inlet valve and temperature control, a compressor rack containing two compressors, and a condensing unit which is assumed to be able to keep the condensing pressure perfectly stable. The air temperature in the display cases can be described by (9), where the heat flow from the display case and to the surrounding air can be expressed by (10). The refrigerant mass flow rate into the ith display case is model by (11), where \(OD, P_c, P_{suc}, Q_e\) and \(\Delta h_{lg}\) denotes the opening degree of the valve, the condensing pressure, the suction pressure, the heat removed by the evaporator and the enthalpy difference across the two-phase region, respectively. For details about the calculation of the unmentioned terms see Larsen et al. [2007].
residual. However, in the performance assessment case it is not guaranteed that a change in a controller parameter will affect the performance indicators since a refrigeration system usually operates in steady state. In addition, due to a substantial amount of measurement noise the detectors have to be robust with respect to the noise level. Without any excitation of the refrigeration system the affect on the performance measure becomes undetectable, which is illustrated by Fig. 3, where the top plot is the cost function, the middle plot is the test statistics and the bottom plot is the controller parameter $K_{P,d}$ for one of the display case controllers. The same parameter change is carried out at 20000 and 50000 seconds and it is clear to see that the performance change is not visible without excitation. Fig. 4 is a plot of the temperature in the display case for which the controller parameters are changed. The signal in the figure shows that the parameter change in the controller is visible only in the case when the system is excited. To ensure that a parameter change is detectable and can be distinguished from influences on the performance measurement, in presence of significant noise, excitation of the system will be required, as well as employment of appropriate statistical detection methods.

6. TEST SCENARIOS FOR THE ACTIVE PERFORMANCE ASSESSMENT

In this section two different scenarios will be shown to illustrate the use of active performance assessment for supermarket refrigeration systems. In the first scenario the parameters, $K_{P,d}$ and $T_{n,d}$, of one of the display case controllers has been changed to improve the operation performance of that particular display case. On Fig. 5 it can be seen that the variations of the temperature declines significantly after the parameters have been changed in the controller. Since the control error of the temperature controller in the display case are represented in the performance measure a visible change can be expected. Fig. 6 shows change in the performance measure on the top plot, the middle plot shows the likelihood ratio and the bottom plot is the flag state. It is clear to see that a change in mean value of the performance measure has occurred. In addition, from the flag state it is possible to verify that the change in performance is an improvement because the flag changes from 0 to 1, a degradation of performance will result the flag state going to $-1$.

In the second scenario the parameters are changed to degrade the performance to illustrate that the detector can also handle deterioration of the performance. On Fig. 7 it can be seen that the temperature variation clearly increases when the controller parameters are changed at 17000 seconds. Fig. 8 shows the change in the performance on the top plot, the second plot is the likelihood ratio and the bottom plot is the flag state. It is clear to see that a change in mean value of the performance measure has occurred. In addition, from the flag state it is possible to verify that the change in performance is a degradation because the flag changes from 0 to $-1$. 

Fig. 3. Change in the performance function, $\Delta J = J - J_0$, likelihood ratio, $L_G(J)$, and controller gain $K_{P,d}$. Simulation without and with excitation of the system. Controller parameters changed at 20000, 30000 and 50000 seconds. Excitation started at 41000 seconds.

Fig. 4. Air temperature in the display case when the parameters are changed. Simulation without and with excitation of the system. Controller parameter changed at 20000, 30000 and 50000 seconds. Excitation started at 41000 seconds.

Fig. 5. Air temperature from a display case when the parameters of the controller is changed at 17000 seconds improve the performance.
Fig. 6. Change in the performance function, $\Delta J = J - J_0$, likelihood ratio, $L_G(J)$, and the flag when the controller parameters are changed at 17000 seconds to improve the system performance.

Fig. 7. Air temperature from a display case when the parameters of the controller is changed at 17000 seconds to degrade the performance. occurred. In addition from the flag state it is possible to verify that the change in performance is a degradation of performance because the flag changes from 0 to −1.

7. DISCUSSION

The paper proposed an approach for active performance assessment, based on active fault diagnosis techniques, in order to online optimize the overall system performance under operation. The approach is appealing for industrial applications where the knowledge about the underlying system dynamics is not available. The approach was justified by a illustrative example and the new setup was tested on different parameter changes of closed loop controlled subsystem of a supermarket refrigeration system. The approach presented in the paper governs the use a performance function introduced in Green et al. [2010] and the used of a statistical test method for detection of a change in the performance index. The method solely based on measured signals and does not depend on the existence of a model of the system under assessment. Future research will focus on utilising the method for systematic optimisation of the performance of a supermarket refrigeration plant.

REFERENCES


