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Research Paper

Model predictive temperature control and ageing estimation for an insulated cool box

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HIGHLIGHTS

- Offset-free model predictive control for an insulated cool box (ICB) is presented.
- An ageing estimation of the ICB is proposed for predictive maintenance.
- A dedicated unknown input observer estimates the unmeasured heat inputs.
- Based on the observer and the ageing estimate the solar irradiance is also estimated.

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ABSTRACT

The transport of perishable goods in insulated cool boxes (ICB) is affected by strong disturbances and requires an effective temperature control scheme. Model predictive control (MPC) can provide such a performing control scheme, however, the strong disturbance of irradiation by the sun can be rarely measured. Furthermore, the ageing of the ICB's insulation is a parameter of vital interest for logistic and economic planning although it cannot be directly measured. In this work a MPC and a custom disturbance observer is presented, which provide an estimate of the current irradiation and the ageing state, respectively. This is obtained by first estimating the excess heat loss of the ICB, and then splitting up this heat loss into an irradiation part and a part due to ageing of the ICB's insulation. The ageing model is assumed to be parametric, and a nonlinear estimation scheme is employed for parameter tuning. A suitable MPC formulation guarantees offset-free tracking of the desired temperature. The performance of the overall concept is demonstrated in a simulation for the nominal case, for increasing measurement noise, and for an abrupt change in the ageing parameters. Additionally, a non-parametric estimate for the confidence interval of the end-of-life prediction of the ICB is given.

1. Introduction

Cooled transport systems for perishable goods and especially food are indispensable. In order to optimize the economic gain the availability of the system should be ensured and the energy efficiency should be maximized. Aside from technological improvements for the refrigeration circuit (RC) and the ICB the control structure for the system has been continuously improved. Over the past decade model predictive control (MPC) has been broadly adopted for heating, ventilation and air conditioning (HVAC) applications, especially as a promising means to deal with multivariable constrained control problems.

The present paper addresses the specific problem of the non-measurable solar irradiation and the ageing of the thermal insulation of the ICB. The combined effect of these disturbances affects the control performance of a linear constrained MPC, hence the estimation of these two disturbances improves the MPCs performance and also facilitates an end-of-life prediction of the ICB. Since both effects act additive on the ICBs temperature the custom disturbance observer first estimates the respective combined heat loss, and the contributions of irradiation and ageing are reconstructed based on a parametric ageing model. The concept presented here therefore provides superior performance of a simple to implement linear constraint MPC for computation of the necessary cooling capacity and the opportunity to implement predictive maintenance for the ICB. A suitable control and observer structure is proposed, and flexible models for ageing including the possibility of sudden changes caused by damages to the ICB can be used.

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One typical problem for MPC design is the hybrid nature of the refrigeration system; this means that both continuous and switching control variables have to be optimally set by the control scheme. Early applications of hybrid MPC to supermarket refrigeration systems can be found in [1,2]. Whereas in [1] a mixed logical dynamic plant formulation is directly utilized in the MPC design, a high-level nonlinear MPC in combination with a low-level process control is proposed in [2]. A general approach to MPC for hybrid systems is given in [3], where a piece-wise affine model for the hybrid system is proposed. The application to a solar air conditioning plant demonstrates that the hybrid MPC optimally switches between operating modes and computes the continuous control variables. In [4] an MPC for hybrid thermal systems in transport refrigeration is presented. It is shown that MPC can be successfully utilized for hybrid systems with both switched and continuous control variables. In [5] different MPC variants are designed for an automotive air-conditioning/refrigeration system, and it is shown that an adaptive hybrid MPC is the best performing concept. In the present paper the hybrid nature of the RC is not explicitly considered, and a suitable control of the RC is assumed to exist. Such a control could be either a low-level mixed-integer (MI)-MPC as utilized in [6] or simple look-up tables obtained by an off-line optimization [7]. Thus, in the current work it is assumed that the RC is always able to provide the required cooling capacity computed by the MPC.

Since the application of MPC to hybrid systems leads to computationally expensive MI-optimization, different approaches have been proposed to simplify the optimization problem. In [2] a simple low-level controller is employed at a high sampling frequency to ensure that control variables remain within admissible bounds. A nonlinear MPC on the high-level delivers the optimal control variables at a lower frequency. Another hierarchical approach is given in [6], but the high-level MPC is a computationally efficient linear MPC at low sampling rate and long prediction horizon while the low-level controller is an MI-MPC at high sampling rate and a short prediction horizon. An even more simplified solution is presented in [7] where the nonlinear optimal control combinations for the RC are computed off-line and stored in look-up tables. This approach enables the use of affordable microcontrollers for implementation. Similar to the approach in [6] in this paper also a linear constrained high-level MPC is employed, and a suitable low-level control is assumed to exist.

Depending on the nature of the chosen MPC-concept a state observer for estimating unmeasurable states may become necessary. Classical state-observers like the Kalman-filter have been used for state-feedback control of a refrigeration system in [8]. In [9] a full-order state observer is employed for temperature control of power electronics. The observer concept can also be combined with fault detection and isolation (FDI) methods: A Kalman-filter based FDI concept is presented in [10] for a supermarket refrigeration system. The observer proposed in this paper is not only employed to estimate the full state vector but also to estimate the unknown disturbance composed of solar irradiation and declining insulation. A similar approach is presented in [11] where the unknown disturbance is the non-measurable heat input due to ambient air. This enables effective decoupling of the FDI residuals from the non-measurable disturbance. In [12] unknown disturbance and model mismatch of a boiler-turbine unit are estimated using an unknown input observer. The state estimate is used for feedback with a fuzzy MPC while the disturbance estimates are utilized in a feedforward compensation. A similar approach has been given in [13] where a disturbance observer estimates the unknown heat input as in [11] and uses the estimate in a feedforward compensation. In contrast to these references the disturbance observer proposed here delivers the estimates of state and disturbance only to the MPC and hence to a feedback compensation. Furthermore, the estimation of the time-varying heat transfer coefficient α also utilizes the disturbance estimate.

Such parameter estimation in refrigeration or HVAC systems has been presented in [14–17]. In [15,16] only off-line parameter estimation is performed for a refrigeration system and a cold water chiller, respectively. An artificial neural network is utilized in [15] and in [16] different linear models are compared in their validation performance. On-line parameter estimation has been applied to HVAC systems by [14] where recursive least squares with a variable forgetting factor was used to estimate model parameters. An unscented Kalman-filter was used to estimate the thermal parameters of a building model in [17]. In opposition to these methods in this paper the ageing parameter of the insulation is estimated from the output of the disturbance observer based on the strictly monotonous increase of a parametric α model.

The remainder of this paper is structured as follows: In Section 2 a system description presents the model, control, and estimator structure, respectively. Section 3 brings more details on the disturbance model and the ageing model. The nonlinear estimation of α is presented in Section 4, and the controller design is given in Section 5. After a short Section on stability simulation results in Section 7 demonstrate the performance of the methods. A discussion and conclusion finalizes the paper.

2. System description

2.1. Overview

Transport systems for perishable goods consist of an insulated cool box (ICB) which includes the goods and the refrigeration system which provides the necessary cooling capacity for cooling the ICB. The refrigeration system (RS) consists of a refrigeration circuit which includes a condenser, an evaporator, an electronic expansion valve and a compressor, see Fig. 1.

The RS provides a cooling capacity $\dot{Q}$, which is the only control variable. Main disturbances of the ICB are the solar irradiation $\dot{Q}_{\mathrm{sol}}$ and the slowly time-varying heat transfer coefficient $\alpha(t)$.

2.2. Dynamic model

The behavior of the ICB is approximated with a first order linear differential equation

$$mc_{\mathrm{p}}\frac{d\vartheta_{\mathrm{ICB}}}{dt} = -\dot{Q} + \alpha(t)A_{\mathrm{ICB}}(\vartheta_{\mathrm{amb}}-\vartheta_{\mathrm{ICB}}) + \dot{Q}_{\mathrm{sol}}, \tag{1}$$

with the total thermal capacity mc_{p} of the ICB and content, the time-varying heat transfer coefficient $\alpha(t)$, the surface area A_{ICB} of the ICB, the ambient temperature ϑ_{amb}, the temperature of the ICB ϑ_{ICB}, the cooling capacity $\dot{Q}$ and the solar irradiation $\dot{Q}_{\mathrm{sol}}$, see Fig. 1.

The ICB model, Eq. (1), can be rewritten as

$$mc_{\mathrm{p}}\frac{d\vartheta_{\mathrm{ICB}}}{dt} = -\dot{Q} + \overbrace{\alpha_0 A_{\mathrm{ICB}}(\vartheta_{\mathrm{amb}}-\vartheta_{\mathrm{ICB}})}^{\dot{Q}_{\alpha 0}} + \underbrace{\alpha_1(t)A_{\mathrm{ICB}}(\vartheta_{\mathrm{amb}}-\vartheta_{\mathrm{ICB}})}_{\dot{Q}_{\alpha}} + \dot{Q}_{\mathrm{sol}}, \tag{2}$$

where α_0 is the known heat transfer coefficient of a new ICB and $\alpha_1(t)$ is the deterioration of α over time.

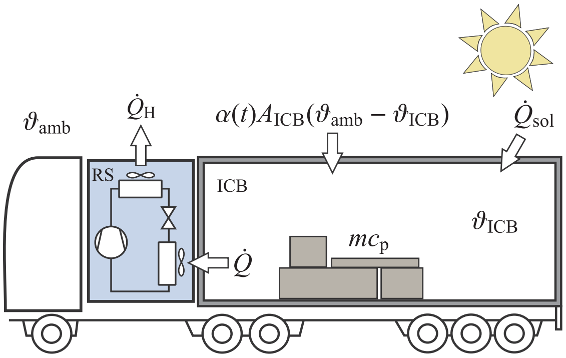

Fig. 1. Model of the insulated cool box with refrigeration system.