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Tube-based MPC for pressure-controlled ventilation

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Abstract: In this article, we propose a robust model predictive control (MPC) approach for pressure-controlled ventilation, with the goal to increase the safety of the patient by introducing safety constraints to the controller on a physiological basis. For the theoretical guaranties of MPC to hold in practice, the model must represent the reality sufficiently well. Yet physiological lung models of individual patients are not readily available, and parameters need to be estimated from pressure and flow data at the patient's airways. In this article, the estimation uncertainty as well as modelling errors are considered as disturbances to the system against which an MPC is robustified. By using an auxiliary control law together with the MPC, it is possible to confine the state error to a closed set around the trajectory of a nominal system, allowing to guarantee constraint satisfaction in the presences of (bounded) disturbances.

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I. Introduction

Mechanical ventilation, when applied incorrectly, holds a severe risk for worsening the patient's health. The application if positive airway pressure, increased oxygen concentrations and large tidal volumes can severely damage the lung tissue, increasing the morbidity and mortality in critically ill patients [1]. Thus, ventilation therapy requires to compromise between maintaining vital functions such as the gas exchange and protecting the lung. Model predictive control (MPC) holds great potential on increasing patients' safety by explicitly incorporating physiological constraints directly within the controller. For one, the control paradigm of online optimization of the forward prediction allows the direct consideration of constraints on the system states as well as its inputs. Secondly, information about the patient can be incorporated by means of a physiological model.

Recently, Scheel et al. [2] proposed and implemented MPC for the pressure regulation of a medical device maintain a continuous positive airway pressure (CPAP) commonly used in the therapy of obstructive sleep apnea with a patient breathing on its own. Our goal here in contrast is to support patients, suffering respiratory failure and thus requiring active respiratory support. Since the lung parameters cannot be measured directly and have to be estimated, they come with a certain level of uncertainty. This uncertainty, as well as other modelling errors in general can be considered as disturbances on the nominal system, against which the controller needs to be robust for all theoretical guarantees to hold.

II. Material and methods

We propose a two layered hierarchical control architecture, as depicted in figure 1, to achieve the given requirements of this control task. The primary level of the control architecture comprises of a Kalman filter for state estimation together with a robust model predictive controller [3]. The MPC uses a linear model of the system with five states and two inputs. For the patient model it is assumed, that the lung comprised of a single elastic compartment with a fixed compliance C_{alv} and the airways form a single rigid tube with a fixed flow resistance R_{aw}. The actuators are modeled as first order system as well, modeling the blower and the expiratory-valve as pressure and flow source, respectively together with two fixed compliances modelling the ventilation hoses. For both actuator models, linear constraints are in place to incorporate physical limitations. The lower level controller comprises of two distributed controller, one for each actuator. The lower level controller simplify the actuator model to be used in the higher level MPC.

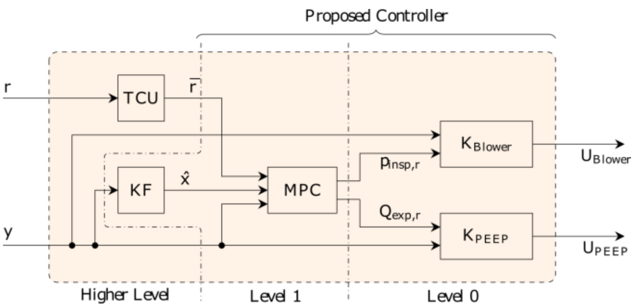

Figure 1: Proposed hierarchical control approach, with level 0 abstracting the nonlinear actuator dynamics and level 1 controlling the pressure level at the patient airway. Level 1 implements a linear robust model predictive controller (MPC) and a Kalman filter (KF). The higher control layer only contains the therapy control unit, which generates the reference.

This approach holds several advantages over a single central controller. For one, the two layered approach decouples the controller relevant for the therapeutic function from the device related controller on the lower level. Thus, the therapeutic controller components can be developed independently form the actual high-level ventilation functions. Secondly the MPC scheme provides a means to incorporate constraints into the system and guarantees that model boundaries are not violated. This will also be used to directly introduce physiological boundaries during therapy. The internal model itself additionally holds great potential, since it can be easily adapted and extended, e.g. by incorporating spontaneous breathing.

The model predictive control is robustified by using a tube-based formulation (tMPC) as proposed in [3]. The approach was originally proposed for linear systems with additive bounded disturbances. Therefore, the uncertain model part needs to be separated from the nominal model. Multiplying the uncertain model part with the set of allowed states results in an over-approximation of the set of bounded disturbances acting additively on the nominal system. If the system is stabilizable, it is possible to formulate an auxiliary control law to confine the error between the nominal model and the disturbed model to a robust positive invariant set, i.e. once the system state is in this set it is guaranteed to stay inside the set even in the presence of bounded disturbances. When tightening the original constraints by subtraction this set, the nominal system can be controlled such that for the disturbed system the original constraint still hold.

The system used to evaluate the proposed control approach, is a modular research demonstrator of a commercially available anesthesia workstation. The workstation uses a semi-closed rebreathing circuit with two main actuators, controlling the pressure level at the patient airways. The flow to and from the patient is directed by check valves. In pressure-controlled ventilation (PCV) the airway pressure is controlled between the positive inspiratory pressure level (PIP) and the positive end expiratory pressure level (PEEP). During the inspiration, a blower increases the pressure. while the PEEP-valve closes the expiratory branch. In the expiration phase, the PEEP-valve opens, releasing the air from the system. During the inspiration, the increased pressure poses a risk to the patient, thus only a maximum overshoot of 10% but at most 2 hPa, is acceptable. Furthermore, an undershoot during the expiration may also be critical an is therefore to be avoided.

III. Results and discussion

The control approach is evaluated for general feasibility in-silico, using a nonlinear model of the ventilation system. The model was derived by first principle methods and implemented in Simulink. As a test case, a mandatory ventilated passive patient was considered, with a compliance of 20 ml/hPa and resistance of 20 hPa/l/s. The patient is ventilated with a frequency of 8 min^{-1} and inspiration time of 3 s, with the pressure levels for inspiration and expiration of 15 hPa and 5 hPa respectively. The selected scenario is one of the test cases for pressure-controlled ventilation defined by the international standard for basic safety and performance of critical care ventilators.

Next to the input and state constraints, resulting from the technical system the maximum pressure in the airways was constraint to not exceed 30 mbar. A parameter uncertainty of ±4.5 % was considered for the lung parameter C_{alv} and R_{aw} modelling estimation errors from the online parameter estimation procedure.

Figure 2 displays the simulated patient flow and expiratory pressure, as a surrogate for the airway pressure, of a single breath for different parameter samples within the range of ±10 % of the nominal value. The behavior for the nominal parameters is highlighted by the red graph. The controller is capable of following the given reference trajectory, dashed line in both breathing phases. The closed loop system shows almost no deviation from the nominal system behavior, for simulation runs with varied system parameter. In both respiratory phases the system shows a slight tracking error in steady state, which may be compensated e.g. by adding integral action to the auxiliary controller.

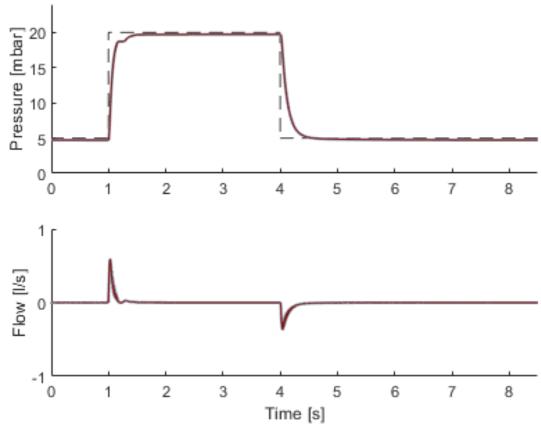

Figure 2: Expiratory pressure and patient flow of the simulated system with the nominal model parameters red and deviated parameters gray. The parameter were altered up to ±10%, nonetheless the robust controller can track the dashed pressure reference.

IV. Conclusions

The initial in-silico results of the proposed control approach show that tube-based model predictive control can be used for respiratory support ventilation, even in the presence of uncertain model parameter and modelling errors. The small variance of the closed loop performance is very promising, for the implementation on the real system. The implementation on the micro controller within the modular research demonstrator is the logical the next step.

Author's statement

Research funding: This work was partially founded by the Drägerwerk AG & Co. KGaA.

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