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Towards model-based temperature-control for retinal laser therapies

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Abstract: Sophisticated control designs for retinal laser therapies, such as model predictive control, allow for safer treatment and a uniform outcome irrespective of spatially varying parameters such as the absorption coefficient. To enable model-based control, the internal states and unknown parameters need to be estimated, which can be done using non-invasive temperature measurements. We present experimental results for joint state and parameter estimation using an extended Kalman filter and a moving horizon estimator. The experiments were conducted on ex vivo porcine eye's explants.

I. Introduction

The investigation of retinal photocoagulation began in the 1950s and bacame a clinical standard for several retinal diseases such as diabetic retinopathy and macula edema. The proper dosage of laser radiation is crucial to prevent the patient from under- or overtreatment. However, it is a challenge for each ophthalmologist as the absorption of the laser light varies from spot to spot. Therefore, the laser power needs to be adjusted depending on the absorption at each spot. To overcome spot dependency and, hence, guarantee a uniform outcome at each spot, a noninvasive technique to measure the temperature at each spot was proposed in [1,2]. The determination of an averaged, depth-weighted temperature is based on the photoacoustic interaction between light and tissue. However, more important than the photoacoutic temperature is the peak temperature inside the irradiated volume for a safe treatment. An approximation of the peak temperature was successfully used in [3] for open-loop control. A further improvement of temperature control was investigated in [4] and [5]. As the laser power strongly depends on the absorption, the authors identified a first-order model offline and used the range of the identified parameters to design a robust H_∞-controller in a PID-controller fashion. A drawback of these controllers is a lack of performance for the sake of robustness. Online identification of unknown parameters can enhance the performance of controllers.

To further improve the safety of the treatment, a more accurate determination of the peak temperature using the underlying heat diffusion equation and a parametric model-order reduction technique was proposed in [6]. To enable more sophisticated control designs, such as model predictive control, the identification of the absorption coefficient and the estimation of the internal states of the system based on the optoacoustic temperature is necessary. In general, the spatial discretization of the heat diffusion equation results in a state-space model consisting of a large number of states. Thus, in order to enable real-time control, the model complexity must be reduced. To this end, a parametric model order reduction (pMOR) that allows identification of the absorption coefficient was developed for retinal laser therapies in [6].

A further step towards model-based temperature control is joint parameter and state estimation, which we realize by extended Kalman filtering (EKF) and moving horizon estimation (MHE). In this abstract, we show experimental results for joint parameter and state estimation based on EKF and MHE. We irradiate ex vivo explants of porcine eyes with a pulsed laser for both, heating the tissue and measuring the temperature. A more detailed presentation and discussion of state and parameter estimation in the context of retinal laser therapies can be found in the recently submitted paper [7].

II. Parameter and state estimation

After applying the above described model order reduction, we obtain a low-dimensional (discrete-time) state-space model that depends on the unknown parameter α

$$\begin{aligned} x(k+1) &= Ax(k) + B(\alpha)u(k), \\ y(k) &= C(\alpha)x(k), \end{aligned} \tag{1}$$

with $A \in R^{n\times n}$, $B(\alpha) \in R^{n\times 1}$, $C(\alpha) \in R^{1\times n}$ and the state dimension n, cf. [6,7]. The output y is the photoacoustic temperature, x is the reduced-order state and u is the laser power. The absorption coefficient μ can be calculated using the average absorption coefficient μ_0, which is used in pMOR, and the unknown prefactor α, i.e. $\mu = (\alpha + 1)\mu_0$.

The model (1) is used for the design of an EKF and MHE. The EKF is a de facto state observer for nonlinear systems subject to uncorrelated and normally distributed process and measurement noise, see [8]. The extended Kalman-filter algorithm is based on the successive linearization of the considered nonlinear system. Whereas the model (1) itself is linear in the states, it is not in the parameter α. We extend the state-space model (1) by the parameter to enable joint parameter and state estimation, i.e., we consider the extended state $\tilde{x}(k) = [x(k)^T \, \alpha(k)]^T$ and the additional dynamics $\alpha\,(k+1) = \alpha(k)$. We then apply the extended Kalman-Filter algorithm to the extended system with state $\tilde{x}$.

As a second state-estimation technique, we consider MHE. MHE is an optimization-based technique enabling state estimation for linear and nonlinear systems under consideration of constraints. In our case, these are constraints on the prefactor α as a result of the pMOR. The MHE algorithm takes a fixed horizon length N of past measurements and the dynamical system into account to estimate the current state and parameter at time instant k, see [9]. At the next time instant $k+1$, the horizon is shifted and the whole procedure is repeated.

III. Results

We conducted experiments with ex vivo porcine eye explants. We irradiated a spot with a constant laser power of 30 mW. For comparison, we chose equivalent design parameters in EKF and MHE. In Fig. 1, the measured optoacoustic temperature and the estimated temperature via MHE and EKF are shown. The overshoot of the EKF is slightly higher and also the estimation of the prefactor α is slower as shown in Fig. 2. However, after 0.1 s both estimators perform equally well. As an optimization problem needs to be solved at each time instant, the MHE is computationally more expensive than the EKF. On the other hand, a benefit of MHE is that constraints on α can be incorporated. Further investigations of both estimators, especially tuning of the design parameters, are subject of current work.

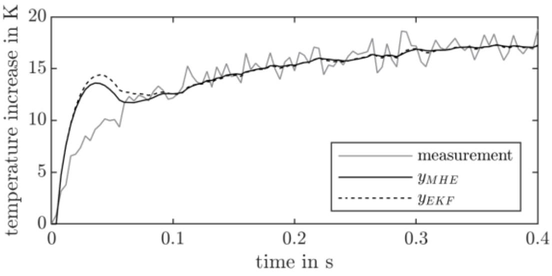

Figure 1: Measured temperature increase in grey, the estimated temperature using MHE in black and the estimated temperature using EKF in dashed black.

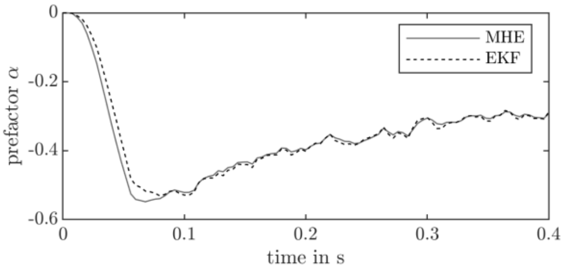

Figure 2: Estimated prefactor α of the absorption coefficient using MHE in grey and using EKF in dashed black.

IV. Conclusions

We have presented experimental results for state and parameter estimation of a parametric reduced-order model for retinal laser treatment. We have shown that both EKF and MHE are suitable for state and parameter estimation, although, the MHE seems to perform slightly better. A remaining challenge is the real-time implementation of the MHE so that both EKF and MHE can be used in a real-time application of a model-based controller.

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