Online temperature control of focused ultrasound heating using an adaptive PID feedback loop

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Introduction

Focused ultrasound induced heating for use in thermal therapy requires reliable temperature control to assure safety and therapeutic accuracy. MR thermometry based on the proton resonance frequency shift (PRFS) [1] in combination with a proportional, integral, derivative (PID) feedback control [2] has been suggested as a precise solution for controlling high intensity focused ultrasound devices in applications such as local drug delivery. Nevertheless, depending on the desired target temperature profile and the measurement noise, overshoots and oscillations can occur if the initially chosen controller gains remain static, which lead to undesired tissue damage. The presented adaptive PID [3] controller continuously adjusts the controller gains as a function of the current temperature error, the measurement noise and an assumed uncertainty in the determination of the absorption coefficient. Its superior performance in comparison to a conventional and an improved PID controller with static controller gains is demonstrated in phantom experiments.

Materials and Methods

Conventional PID: The PID controller implemented here, combines basic PID control with a simplified model of the heat evolution in tissue neglecting perfusion and diffusion $P_w(t)=\frac{1}{K_D\alpha_s}\left(K_P\epsilon(t)+K_I\int\epsilon(\tau)\,d\tau+K_D\frac{T_T(t)}{dt}\right)$ (1) [4]. Based on the controller gains (K_P, K_I, K_D), the target temperature $T_T(t)$ and the current control error $\varepsilon(t)=T(t)-T_T(t)$, the power $P_w(t)$ to be applied is calculated. The true heat absorption coefficient of the tissue α is estimated and the value α_s is used for PID control. For the optimal case of $\alpha = \alpha_s$ and a temporal resolution of t_{dyn}, fastest convergence is achieved with $K_P=1/t_{dyn}$. Furthermore, stability theory and an analysis of the closed loop transfer function of this system yields a stability criterion for the choice of the controller gains in order to achieve convergence without oscillations $\frac{1}{4}\left(\frac{\alpha}{\alpha_s}\frac{K_P}{K_D}\right)^2\geq\frac{\alpha}{\alpha_s}\frac{K_I}{K_D}$ (2) . In the presented implementation $K_D=1$ was used.

Improved PID: In order to avoid overshoots in the case of limited maximal power and sudden changes of the target temperature profile, a higher proportional gain and lower integral gain can mitigate these effects. However, this may lead to instabilities once the set point is reached since small control errors will lead to a larger controller output.

Adaptive PID: The presented adaptive PID is based on proportional and integral controller gains which are modified depending on the current control error ε(t) (Figure 1). For high control errors, a low integral gain is chosen to prevent an accumulation of the error which may result in overshoots. Close to the set point however, a high integral gain coupled to a low proportional gain ensures stable control. The limits for the controller gains are defined as $K_{P,min}=1/t_{dyn}$, $K_{P,max}=\alpha/\alpha_s K_{P,min}$ and $K_{I,max}=K_{P,min}^2/4$, $K_{I,min}=K_{I,max}/4$. As a result, an inaccurate determination of α is taken into account.

Experimental setup: An agar gel (3 cm diameter) was placed on a single element ultrasound transducer (focal length = 8 cm, aperture = 12 cm, operating frequency = 1.5 MHz, Imasonic, Besançon, France) which was integrated into the MR examination bed. The PID calculations were carried out in real time using the RealTI software and the updated power values were streamed directly to the ultrasound generator (AG 1006 Series Amplifier, T & C Power Conversion Inc., Rochester, NY, USA). A maximal power output of 20 W was chosen. As an application example, a step function of 6K was chosen as target temperature profile and the temperature was maintained during 8 min. MR-imaging was performed on a 1.5 T Philips Achieva MR scanner (Philips Healthcare, The Netherlands) using a 47-mm-diameter surface coil and a gradient echo sequence (TR/TE = 40/20 ms, bandwidth = 28 Hz, matrix 64x64, voxel = 0.78x0.78x3mm³, flip angle = 35°) was used for image acquisition. PRF-thermometry was performed online using the RealTI software (RealTech, Bordeaux, France) delivering a temperature image every t_{dyn}=1.3 s.

Results and Discussion

The measured temperatures presented in Figure 2 visualize the characteristics of the three different PID types. The conventional PID reaches the target temperature within 17 s but produces an overshoot of 1.4°C as a result of the previously accumulated error. After 35 s, stable control with a standard deviation of 0.13°C is established. A comparable rise time of 18 s is required by the improved PID which reduces the overshoot to 0.5°C and maintains the target temperature with a standard deviation of 0.23°C. Finally, the adaptive PID shows a slightly slower convergence with 27 s until the target temperature is reached. However, the overshoot is further reduced to 0.4°C and the standard deviation at the set point is comparable to the conventional PID. Figure 3 illustrates these results from the point of view of the proportional and integral terms and the applied power. The conventional PID accumulates the largest integral term while both the improved and adaptive PID can halve the maximal integral contribution. The improved PID shows the largest peak in the proportional term in the beginning due to the increased proportional gain which leads to fast convergence but also to increased oscillations once the set point is reached. This is also visible in the power output where both the conventional and the adaptive PID show power variations of approximately 5 W in contrast to 10 W for the improved PID.

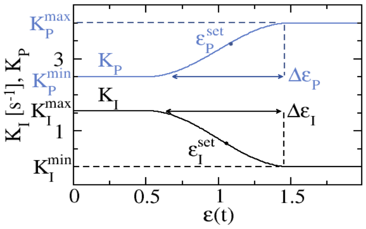

Figure 1: Adaptation of the controller gains K_P and K_I as a function of the control error ε(t).

	conventional PID	improved PID	adaptive PID
K_P	0.77	1.54	0.77/0.77
K_I [s^{-1}]	0.148	0.074	0.037/0.148

Table 1: Tested PIDs and the used controller gain combinations for t_{dyn}=1.3 s and $\alpha = \alpha_s = 0.07KJ^{-1}$.

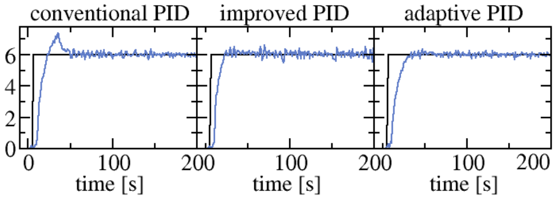

Figure 2: Target temperature (black line) and measured temperature (blue line) for the conventional PID, improved PID and adaptive PID using the controller gains given in Table 1.

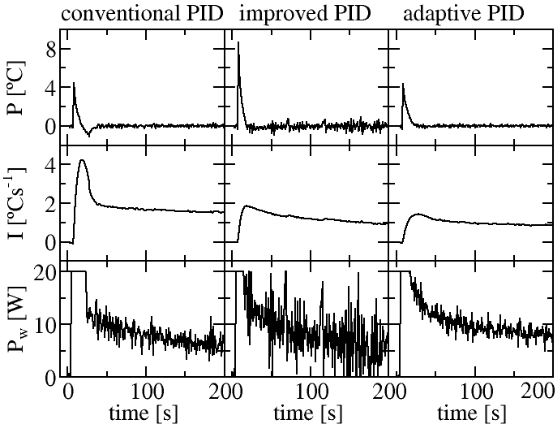

Figure 3: Proportional term (first row), integral term (second row) and applied power (third) row for the different PID implementations.

Conclusions

The presented adaptive PID controller provides a superior performance for applications which require a high-precision and stable temperature control over extended interventions. Overshoots are avoided even for rapid changes of the target temperature and limited transducer power. By incorporating inaccuracies in the determination of the thermal tissue coefficients into the controller logic, a high control precision is maintained even for applications where these coefficients can only be estimated with limited accuracy.

References

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