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Estimation of ventricular volume changes for hydrocephalus treatment

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Abstract: Hydrocephalus is a medical condition that is treated by draining excessive cerebrospinal fluid out of the brain's ventricles using a shunt system. While direct control of ventricular volume is aspired, monitoring and treatment of hydrocephalus still mainly rely on measurements of intracranial pressure. To address this challenge, we introduce a method to estimate ventricular volume changes with a Kalman Filter based on intracranial pressure and bioimpedance measurements. High accuracy during in vitro validation on a mechatronic testbench demonstrates the method's potential as a new sensor technology for monitoring hydrocephalus patients and controlling shunt drainage.

I. Introduction

Hydrocephalus is a medical condition characterized by the disturbed dynamics of cerebrospinal fluid (CSF) and its excessive accumulation in the brain's ventricles [1]. The current therapy is a shunt system that drains CSF from the brain's ventricles into the peritoneal space. While direct control of the ventricular CSF volume (V_{CSF}) is aspired, the drainage rate of today's passive mechanical shunts is determined by the pressure gradient between intracranial (ICP), intraperitoneal (IPP) and hydrostatic pressure. As ICP and IPP are not directly physiologically related, the efficacy of these shunt systems is limited and complications such as over- or underdrainage may occur specifically due to posture induced hydrostatic pressure changes [2]. Information about actual V_{CSF} could significantly improve hydrocephalus patient monitoring and enable physiological shunt drainage control. To determine V_{CSF}, bioimpedance (BI) measurements that exploit the difference in electrical conductivity of CSF and brain parenchyma were proposed [3, 4]. These studies demonstrated a negative correlation of V_{CSF} and BI *in silico*, using finite element simulations, and *in vitro*, using silicon or gel phantoms filled with artificial CSF. The proposed approximations of V_{CSF} are affine functions of BI that rely on geometric simplifications of the complex ventricular shape. Here, a new approach with two contributions is presented and validated *in vitro*. Firstly, data-driven measurement models are derived that do not rely on geometric approximation. Secondly, a Kalman Filter (KF) is designed that performs sensor fusion of ICP and BI measurements for V_{CSF} estimation.

II. Materials and methods

A previously introduced mechatronic testbench, as shown in Fig. 1, is used to simulate changes of V_{CSF} *in vitro* [5]. An electrically conducting silicone-carbon brain phantom ($\sigma_{parenchyma} \approx 0.17\ Sm^{-1}$) is mounted in a cylindrical water tank. The brain phantom's ventricle is a 40 mL large ellipsoid filled with saline solution ($\sigma_{CSF} \approx 1.6\ Sm^{-1}$). It is connected to a bellows that is attached to a linear voice coil motor (LVCM) with an integrated position encoder. As the brain phantom is the only compliant material, the motor movement causes a change in V_{CSF} proportional to the bellows' surface area. For this study, a measurement catheter with ten electrodes (SPR-877, Millar, Houston, TX, US) is inserted into the brain phantom's ventricle and connected to a newly developed tetrapolar measurement system that is based on an integrated BI measurement chip (AD5940, Analog Devices, Wilmington, MA, US). A high-frequency dc-free current is applied at the two outer excitation electrodes. The voltage drop across the two inner measurement electrodes is recorded and BI computed as the quotient of voltage over current. Simultaneously, ICP is recorded with a medical pressure transducer (Meritrans DTXPlus, Merit Medical Systems, Jordan, UT, US).

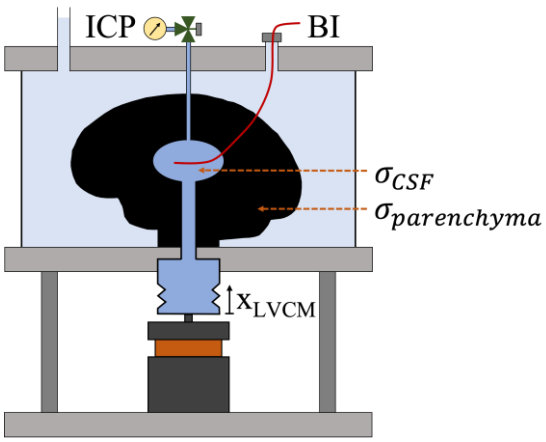

Figure 1: Sketch of the mechatronic testbench for in vitro simulation of ventricular volume changes in hydrocephalus [5].

The induced volume changes by the motor movement are modelled as a random walk with

$$x(k) = x(k-1) + v(k-1), \quad (1)$$

where $x = \Delta V_{CSF}$ is the state and $v \sim N(0, Q)$ the Gaussian process noise. The changes in ICP and BI are modelled to linearly depend on the change in V_{CSF} with

$$y(k) = G\,x(k) + H + w(k), \quad (2)$$

where $y = [\Delta ICP,\ \Delta BI]^T$ is the output and $w \sim N(0, R)$ the Gaussian measurement noise. A physiological scenario is run on the testbench with two superimposed oscillations, respiration at $0.25\ Hz$ and the cardiac cycle at $1.16\ Hz$. The recorded data is split into a training and testing dataset. The parameters G and H of eq. (2) are computed via least-squares fitting, while Q and R are computed as the residual error variances of the process and measurement model. Finally, the KF is defined as

$$\hat{x}_p^k = \hat{x}_m^{k-1} \quad (3)$$

$$P_p^k = P_m^{k-1} + Q \quad (4)$$

$$K^k = P_p^k\, G'\, (G\, P_p^k\, G' + R)^{-1} \quad (5)$$

$$\hat{x}_m^k = \hat{x}_p^k + K^k\, (y^k - G\, \hat{x}_p^k - H) \quad (6)$$

$$P_m^k = (1 - K^k G)\, P_p^k\, (1 - K^k G)' + K^k\, R\, K^{k\prime}, \quad (7)$$

where $\hat{x}$ is the state estimate, P the covariance matrix, and K the Kalman gain. The superscript k indicates the time step, whereas subscripts p and m indicate the prediction and measurement update step, respectively.

III. Results

While ICP and BI are in general nonlinearly dependent on V_{CSF}, the dynamic changes around the testbench's operating point can be well approximated with affine functions. The fitted measurement models are shown in Fig. 2. They have a rmse of $0.423\ mmHg$ and $0.057\ \Omega$, respectively. In line with the findings of previous studies, the increase in ΔV_{CSF} causes an increase in ΔICP and a decrease in ΔBI [3, 4]. Described quantitatively in terms of the Pearson correlation coefficient, ΔV_{CSF} and ΔICP are strongly positively correlated ($R_{\Delta V - \Delta ICP} = 0.954$), whereas ΔV_{CSF} and ΔBI are strongly negatively correlated ($R_{\Delta V - \Delta BI} = -0.996$) in the fitting data set. The comparison of estimated and actual ΔV_{CSF} is shown in Fig. 3. The designed KF can estimate the system's state with high accuracy, achieving a rmse of $0.137\ mL$ in the testing data set.

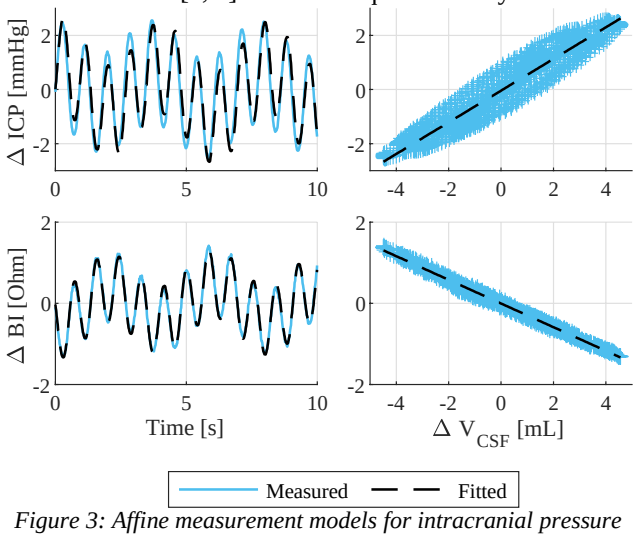

Figure 3: Affine measurement models for intracranial pressure (top) and bioimpedance (bottom).

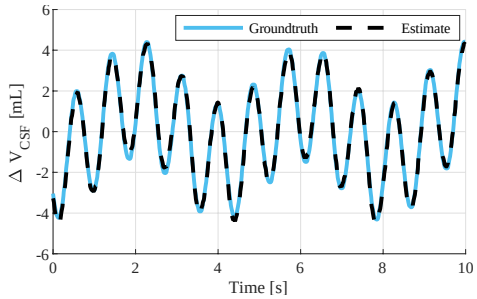

Figure 2: Estimation of ventricular volume changes with a Kalman Filter using pressure and bioimpedance measurements.

IV. Discussion and conclusions

This work presents a new method to estimate changes in V_{CSF} with a KF that performs sensor fusion of simultaneous ICP and BI measurements. High accuracy during *in vitro* validation demonstrates the method's potential as a novel sensor technology for hydrocephalus patient monitoring and shunt drainage control. Modelling the process dynamics as a random walk is a simple approach as only the residual error variance of the state is leveraged to adjust the Kalman gain. A dynamic system that integrates shunt drainage and models cardiac and respiratory influences may improve the prediction step in a wider range of conditions and scenarios, which will be investigated in future work. Similarly, the data-driven measurement model was limited to an affine function, which enables comparison with existing work. An Extended KF using nonlinear functions may improve the measurement update when brain phantoms of more complex ventricular shape and varying compliance are utilized, which is another potential direction of research. Ultimately, the proposed method will also have to be validated *in vivo*.

Author's Statement

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