Wearable sensors for patient-specific boundary shape estimation

Andrew Tizzard[1] Joo Moy Khor[1] Andreas Demosthenous[2] and Richard Bayford[1]

[1] Middlesex University, London, UK

[2]University College, London, UK

Abstract: It has been shown that accurate boundary form of the forward model is important to minimise artefacts in reconstructed EIT images. This paper presents a proposal for a wearable device based on a network of flexible sensors to evaluate patient-specific boundary form of the forward model for lung EIT. Simulation of approaches using ideal sensors are presented that reconstruct boundaries with low shape error.

1 Introduction

The rapid generation of accurate forward models of subject-specific human thorax for EIT still presents a challenge. Despite the fact that some numerical methods e.g. [1], mechanical methods e.g. [2] and computational methods e.g. [3] have been proposed, these are either computationally demanding or impractical for the pediatric clinical environment.

At present, there is no sensor-net available for dynamic measurement of boundary shape for EIT. Use of line-of-sight measurements for monitoring paediatrics is impractical for continuous monitoring within the ICU.

Conductive bend sensor technology [4] has received considerable attention in health rehabilitation applications with advantages of being low cost, flexible, light, wearable and require simple interfacing circuitry. Bend sensors have been investigated for use in geometry reconstruction [5] but no records have been found for patient-specific model reconstruction.

2 Methods

The proposed boundary shape evaluation system is comprised of a series of bend sensors to measure curvature of boundary section and reconstruct a B-spline curve. Perimeter can be further estimated by the inclusion of a stretch sensor. Work was undertaken to select and calibrate a suitable sensor, test reconstruction algorithms, establish optimum number of bend sensors and validate reconstruction algorithms.

Of the commercially available resistive type bend sensors compared one provided acceptable repeatability and consistent linear resistance-curvature relationship. This was the Abrams Gentile sensor (www.ageinc.com).

A geometric *rotational* transformation algorithm proposed by [5] was modified and used to simulate reconstruction using ideal bend sensors:

$$P_1^i = O_1 + r_1 \tag{1}$$

$$P_1^f = O_1 + \begin{bmatrix} cos(s\kappa_1) & -sin(s\kappa_1) \\ sin(s\kappa_1) & cos(s\kappa_1) \end{bmatrix} (P_1^i - O_1) \tag{2}$$

$$O_{i+1} = P_i^{final} - \kappa_i / r\kappa_{i+1} \left(P_i^{final} - O_i\right) \tag{3}$$

$$P_{i+1}^f = O_{i+1} + \begin{bmatrix} cos(s\kappa_{i+1}) & -sin(s\kappa_{i+1}) \\ sin(s\kappa_{i+1}) & cos(s\kappa_{i+1}) \end{bmatrix} (P_i^f - O_{i+1}) \tag{4}$$

Where P^i is the initial point, O, the centre of bend radius, P^f, the final point, s the sensor length and κ_i the curvature.

An alternative algortihm is also proposed where the cumulative sum of subtended angle $s\kappa_i$ is used to evaluate the *derivative* of the curve at each sensor end-point. A degree 2 B-spline is interpolated through these values and the curve is reconstructed by integrating the derivative spline over its length and scaling by the sum of sensor lengths resulting in a degree 3 curve.

In both cases errors can be reduced by evaluating the difference of the sum of angles and 2π rads, dividing by the number of sensors give mean angular error to apply to each angle before reconstruction.

Two approaches to reconstruction were used: the whole curve in one direction (uni), and two halves starting from one point and reconstructing in CW and CCW directions and averaging the two final points (bi).

The rotational algorithm was used to reconstruct an ellipse using 4 to 20 sensors in steps of 2 and the mean error defined as distance of reconstructed points from the true curve to determine if an optimum number of sensors could be found

Both algorithms were used on a B-Spline section from a neonatal CT by calculating mean curvatures over a sensor length and reconstructing. Errors were measured as distances from true parametric point and projected distance to true curve for different numbers of sensors.

3 Results

When the rotational algorithm was used to reconstruct and ellipse using 4 to 20 sensors then mean error ($\bar{\varepsilon}$) vs no. of sensors (n) displayed the relationship $\bar{\varepsilon} \approx \frac{750}{n^3}$ (R^2 = 0.99). Using 8 sensors, $\bar{\varepsilon}$ is a little more than 1 mm, 6 sensors almost doubles the error. With the neonate boundary, there was insignificant difference between the uni-directional and bi-directional errors, though this was not so for the 16 sensor reconstruction, where the bi-directional approach showed significant improvements.

The derivative algorithm appears not to yield greater accuracy for 8 sensors, but initial indications are that with 16 sensors there are significant improvements.

4 Conclusions

There are initial indications that the use of bend sensors within a wearable device could provide boundary shape reconstruction. This has been demonstrated using a 2D boundary and further work is required for increasing accuracy and establishing methods for 3D boundary to improve the forward model.

References

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