Performance Optimization of a Differential Method for Localization of Capsule Endoscopes

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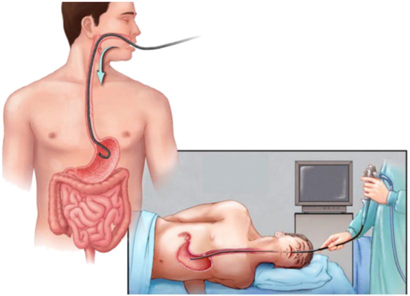

[1]

Does this look comfortable?

Overview

- Capsule Endoscopy
- Static Magnetic Localization
- Differential Localization Method
- Simulation Setup and Evaluation Procedure
- Results and Discussion

Capsule Endoscopy (CE)

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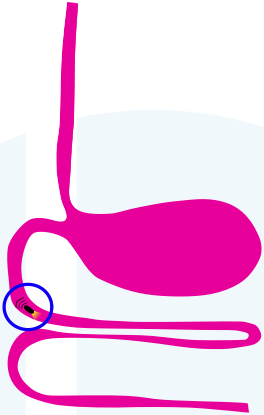
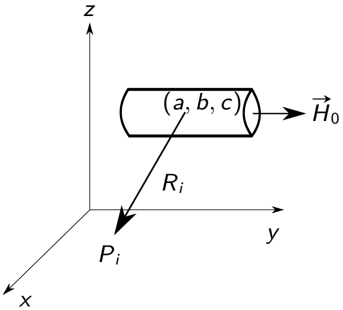
- Swallowable capsule with integrated camera for gastrointestinal diagnosis
- Goal: enable patients daily life activities during diagnosis (8–12 hours)
- Capsule location for a certain video frame required
- Research topic since $\sim$20 years
  $\rightarrow$ Still no reliable localization method



Fundamentals: Static Magnetic Localization

- Showed best localization performance in literature [2, 3]
- Embedded permanent magnet generates static magnetic field



Variable	Description
B	Mag. flux density
M_0	Magnetization
H_0	Orientation of magnet
(a, b, c)	Position of magnet
l	Length of magnet
k	Radius of magnet
P_i	Observerpoint
R_i	Distance from magnet to P_i

- Standard magnetic dipole model for $\vec{B}$:

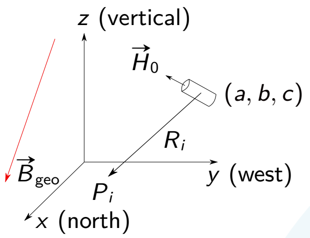
$$\vec{B}(x_i, y_i, z_i) = \frac{\mu_0 \mu_\mathrm{r} M_0 l \pi k^2}{4\pi} \left(\frac{3\langle \vec{H}_0, \vec{P}_i \rangle \vec{P}_i}{R_i{}^5} - \frac{\vec{H}_0}{R_i{}^3} \right)$$

Absolute Localization Method

Determine position (a, b, c) and orientation (m, n, p) of magnet
$\rightarrow$ 6 unknowns

- Arrange ith sensor at observer point P_i around the abdomen
- Derive analytic $\overrightarrow{B}_i$ with dipole model for an observer point P_i
- Derive estimated $\overrightarrow{\hat{B}}_i$ with ith sensor
- Minimize error function ϵ according to (a, b, c, m, n, p)
  $\epsilon = \sum_{i=1}^{N}(B_{x_i} - \hat{B}_{x_i})^2 + (B_{y_i} - \hat{B}_{y_i})^2 + (B_{z_i} - \hat{B}_{z_i})^2$
- Need N sensors for an over-determined equation system solved by Levenberg-Marquardt (LM) algorithm

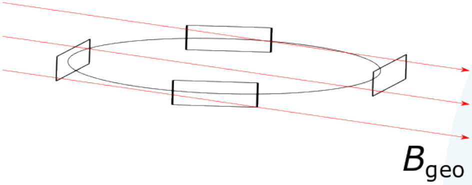
Geomagnetic Flux Density



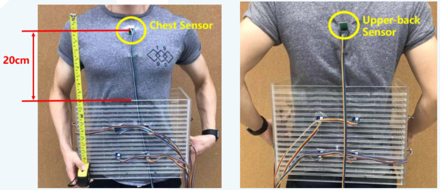
- Geomagnetic field $\vec{B}_{\text{geo}}$ interferes with $\vec{B}$ of magnet
- This leads to localization errors

State-of-the-art: Geomag. Compensation

- **Static compensation. [2]**: sensor calibration according to geomagnetic field
  → Only valid if localization system is static



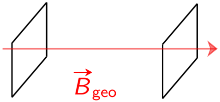
- **Dynamic compensation [3]**: two extra sensors were used
  → Localization performance significantly varied for different rotations



Shao et al. [3]

Differential Localization Method

$$\text{I:}\quad \underbrace{\vec{B}_{\text{magnet},1} + \vec{B}_{\text{geo},1}}_{\text{measured value at sensor 1}} - \vec{B}_{\text{analytic},1} = 0$$



$$\text{II:}\quad \underbrace{\vec{B}_{\text{magnet},2} + \vec{B}_{\text{geo},2}}_{\text{measured value at sensor 2}} - \vec{B}_{\text{analytic},2} = 0$$

- Apply I – II for each sensor pair $\rightarrow$ $\vec{B}_{geo}$ is homogeneous $\rightarrow$ it cancels out under the made assumptions
- Differential method reduces the dimension of the non-linear equation system by a factor of 2
- Localization accuracy is invariant for different rotations of the localization system

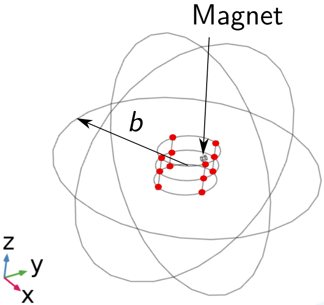
Performance Optimization Procedure

- Proposed differential method[1] achieved position and orientation errors of 0.95 ± 0.66 mm and $0.58 \pm 0.45^\circ$
- Orientation of magnet had high impact on position and orientation errors
- Size of magnet was $10 \times 10\,\mathrm{mm}^2 \rightarrow$ state-of-the-art capsules have limited space
- Perform convergence test of computational domain size
- Variation of magnet size

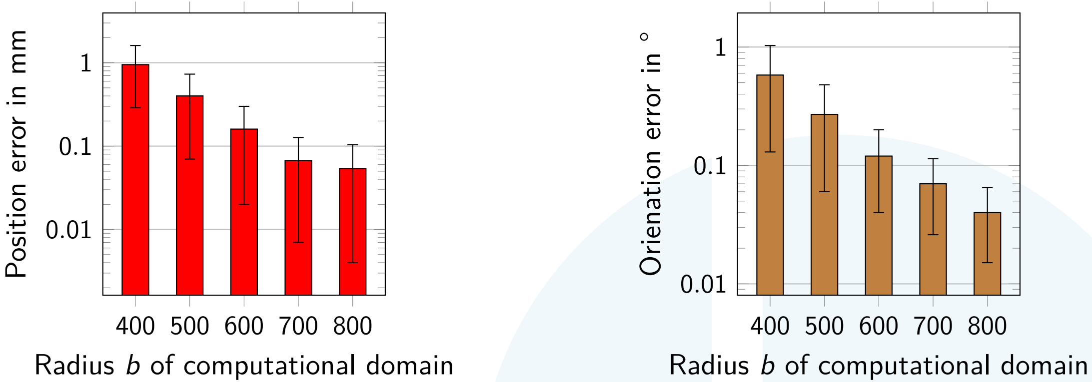
[1] Zeising, S.; Anzai, D.; Thalmayer, A.; Fischer, G.; Kirchner, J. Novel Differential Magnetic Localization Method for Capsule Endoscopy to Prevent Interference Caused by the Geomagnetic Field. Kleinheubach Conference (to be published in Book of Abstracts), 2020

Simulation Setup

- Homogeneous geomagnetic flux density was applied
- 3 stable elliptical rings $(40 \times 33)\,\mathrm{cm}^2$ with 4 Sensors each (12 in total)
- Sphere with radius b as computational domain
- Boundary condition is magnetic insulation ($\vec{B} \cdot \vec{n} = 0$)
- Cylindrical permanent magnet



Results for Convergence Test



- For a radius of 800 mm errors converged to less than 0.1 mm and 0.1 °
- Orientation of magnet has less impact as in our previous work

Results for Different Magnet Sizes

Diameter-to-length ratio R:	P_{err} in mm	O_{err} in °	$\varnothing\ \lvert\hat{B}\rvert$ in μT
(longest magnet) 0.5	0.22 ± 0.09	0.20 ± 0.12	17.41 ± 19.84
1	0.05 ± 0.05	0.05 ± 0.02	8.74 ± 9.97
$\sqrt{4/3}$	0.07 ± 0.05	0.04 ± 0.02	7.60 ± 8.67
2	0.10 ± 0.05	0.02 ± 0.01	4.37 ± 4.99
(shortest magnet) 5	0.11 ± 0.06	0.01 ± 0.01	1.75 ± 1.99

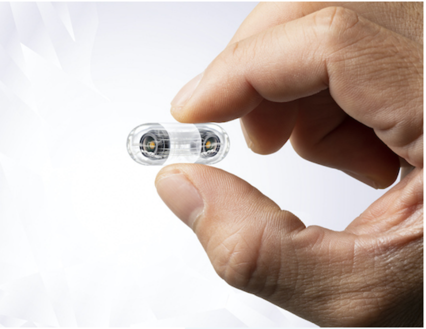
- For R of 1 and $\sqrt{4/3}$ errors significantly below 0.1 mm and 0.1 °
- Orientation errors decreases with shorter magnets
- $\varnothing\ \lvert\hat{B}\rvert$ is lowest for the shortest magnet

Discussion and Outlook

- Impact of magnet orientation on localization accuracy was significantly reduced
- Rotation-invariant position and orientation errors were significantly reduced
- Proposed method is feasible even for a small magnet
- Simulation-based results will be validated by means of experimental measurements

Thank you for your attention

Questions?



[5]

CE a little 'bite' more comfortable?

References

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3 Shao, G., Tang, Y., Tang, L., Dai, Q., and Guo, Y.-X.: A Novel Passive Magnetic Localization Wearable System for Wireless Capsule Endoscopy, IEEE Sensors Journal, 19, 3462–3472, 2019.

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5 https://greaterorlandogi.com/services/capsule-endoscopy/ (date of access: 18.09.2020)