CHAPTER 1

Introduction

1.1 Publications

This cumulative dissertation is mainly based on the following publications of the author:

- In Sections 4.1.1 and 5.1.1, the methods and results for the simulation-based evaluation of the differential geomagnetic compensation method are described. These Sections are based on the journals [1, 2].

  [1] S. Zeising, D. Anzai, A. Thalmayer, G. Fischer, and J. Kirchner: Innovative Differential Magnetic Localization Method for Capsule Endoscopy to Prevent Interference Caused by the Geomagnetic Field, Adv. Radio Sci., 19, 207–213, 2021. (**Invited paper for the presentation [3] at the Kleinheubach Conference 2020, for which the author was award the Young Scientist Award**)

  [2] S. Zeising, K. Ararat, D. Anzai, A. Thalmayer, G. Fischer, and J. Kirchner, Systematic Performance Evaluation of a Novel Optimized Differential Localization Method for Capsule Endoscopes. MDPI Sensors, vol. 21(9), p. 3180, 2021. (**Impact Factor: 3.576, extended paper of [4]**)

- In Sections 4.1.2 and 5.1.2, the methods and results for the experimental evaluation of the differential method are described. These sections are based on the journals [5, 6] as well as the conference paper [7].

  [5] S. Zeising, A. Thalmayer, G. Fischer and J. Kirchner, "Differential Geomagnetic Compensation Method for the Static Magnetic Localization of Capsule Endoscopes During Activities of the Daily Life," in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–10, 2022. (**Impact Factor: 4.016**)

[6] S. Zeising, L. Chen, A. Thalmayer, M. Lübke, G. Fischer, and J. Kirchner, ”Tracking the Traveled Distance of Capsule Endoscopes along a Gastrointestinal-Tract Model Using Differential Static Magnetic Localization”. MDPI Diagnostics, vol. 6(3), p. 1333, 2022. (**Impact Factor: 3.706**)

[7] S. Zeising, A. Thalmayer, G. Fischer and J. Kirchner, ”Toward Magnetic Localization of Capsule Endoscopes during Daily Life Activities,” 2021 Kleinheubach Conference, pp. 1–4, 2021. (**For this paper the author was awarded the Young Scientist Award and the Young Scientist Best Paper Award**)

- The methods and results for the relative movement compensation method are given in Sections 4.2 and 5.2. These Sections are based on the journal [8].

  [8] S. Zeising, A. Schneider, A. Thalmayer, G. Fischer and J. Kirchner, ”A Compensation Method for Relative Movement Between a Sensor Array and the Abdomen for Magnetic Localization of Capsule Endoscopes,” in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–9, 2022. (**Impact Factor: 4.016**)

- All other parts of the thesis are so far unpublished work.

The individual author contribution statements can be found in the corresponding papers, which are provided in the Appendix of this thesis. For the conference paper [7] the authors’ contribution was as follows:

Methodology, Samuel Zeising; Conceptualization of Evaluation, Samuel Zeising; Software and Hardware, Samuel Zeising; Measurements, Samuel Zeising and Angelika Thalmayer; Supervision, Georg Fischer and Jens Kirchner; Validation, all authors were involved; Visualization, Samuel Zeising and Angelika Thalmayer; Writing – original draft, Samuel Zeising; Writing – review and editing, all authors were involved.

Furthermore, the author has supervised two bachelor theses, two research internships and four master theses on magnetic localization of capsule endoscopes, which are listed at the end of this dissertation in ”List of Supervised Student Theses”.

1.2 Endoscopy of the Gastrointestinal Tract

The gastrointestinal tract (GIT) of humans extends from the mouth to the anus and has a typical length of approx. 8 m [9]. Food is ingested orally and then digested in the GIT to extract, metabolize, and absorb vital nutrients. Subsequently, the residue is excreted through the anus. The main organs of the GIT are the esophagus, stomach, duodenum, large intestine, and small intestine (Fig. 1.1). The inner diameters of the small and large intestine of the human GIT are on average 25 mm and 48 mm, respectively [10].

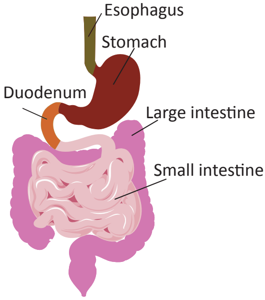

Figure 1.1: Main organs of the human gastrointestinal tract (GIT).

Several diseases can affect this complex system; the most common are tumors, ulcer disease, celiac disease, and chronic inflammatory bowel diseases, which are commonly diagnosed using gastrointestinal endoscopy. Furthermore, preventive endoscopy of the GIT for older people is recommended, e. g. in Germany, for women and men from 55 years and 50 years, respectively. In Germany, a considerable high number of more than 6 million endoscopic treatments of the GIT were conducted in 2014. [11]

1.2.1 Traditional Endoscopy

In traditional endoscopy, a flexible fiber-optic tube (Fig. 1.2) is inserted through the mouth or rectum into the GIT, which requires sedation. Consequently, traditional endoscopy is an overall uncomfortable medical intervention. In particular, the small intestine is challenging to reach since it is winding, tightly folded, and flexible [13]. Therefore, the small intestine is seen as a 'black box' by doctors using traditional endoscopes. In this regard, push and pull endoscopes have been proposed. These are flexible endoscopes with two mounted latex balloons. The balloons are successively inflated and deflated so that the flexible endoscope can move through the small intestine. However, those medical tools can cause complications such as bleeding of the intestine [13], and side effects due to sedation of the patient such as hypo-, hypertension, vomiting, cardiac and respiratory arrest, angina, hypoglycemia, and/or allergic reaction [14].

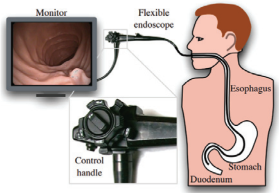

Figure 1.2: Schematic scenario of a gastrointestinal examination with a flexible endoscope and its control handle, inserted from the mouth in the upper gastrointestinal tract © 2010 IEEE [12].

1.2.2 Capsule Endoscopy

The invention of capsule endoscopy (CE), more than 20 years ago [15], made the procedure of recording a video of the entire GIT, including the small intestine, much more comfortable. Moreover, this procedure does not require sedation. In 2001, capsule endoscopy was approved by the food and drug administration (FDA). Since then, this technology has been developed rapidly and has significantly enhanced the diagnosis of the GIT. For instance, in [16], it was revealed that the willingness of patients to undergo endoscopic cancer screening was significantly increased. In addition, in [17], it was found that tumors inside the small intestine could be classified with considerable high specificity and sensitivity of 93.1% and 93.9%, respectively.

Capsule endoscopes can be classified into passively and actively guided ones. The former are commercially available and are moved through the GIT by natural peristalsis (muscle contractions of the GIT) [18]. On the other hand, actively guided capsule endoscopes are either equipped with locomotion systems or externally steered by a magnetic field [19]. Nevertheless, since the small intestine has a thin diameter and is highly curved, it is, to the best of the author's knowledge, not yet possible to actively guide the capsules through the entire GIT [20]. The remainder of this thesis focuses on passively guided capsule endoscopes.

The main components of a passive capsule endoscopy system are an optical dome, camera unit, light-emitting diodes, batteries, an antenna, a transceiver, as well as a bio-compatible dielectric shell (Fig. 1.3). In addition, multiple antennas for receiving the transmitted video of the capsule are attached to the abdominal surface, and a belt with a data recorder is part of the system. Commercial capsules measure up to to 33 mm in length and up to 12 mm in diameter (Tab. 1.1).

For CE diagnosis, a patient swallows the capsule, and the video is transmitted outside the body to an antenna array. The video is usually transmitted using the

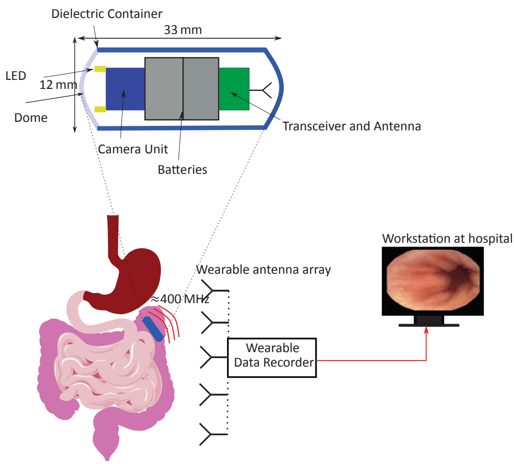

Figure 1.3: Schematic of a state-of-the-art capsule endoscopy monitoring system.

Table 1.1: Specifications of commercial endoscopy capsules.

Capsule	Size (l. × dia. in mm)	Operating Time	Operating Frequency
PillCam™ SB 3 Capsule [21]	26 × 11	≥ 8 h	434 MHz
PillCam™ Colon 2 [21]	33 × 12	≥ 10 h	434 MHz
wc MiroCam® MR2000 [22]	30 × 11	>10 h	≈3 MHz

industrial, scientific and medical (ISM) frequency band around 400 MHz [23]. In contrast, for the MiroCam™ MR2000, human body communication around 3 MHz is applied [24] for video transmission. Therefore, two electrodes are placed on the capsule surface. Apart from that, the MiroCam™ MR2000 allows for external magnetic steering of the capsule through the stomach and duodenum since two small disc magnets are integrated into the capsule [25].

While the capsules pass the GIT, the video is recorded and stored on the wearable device, and after the capsules have passed, they are deposited. Subsequently, the stored video is available for analysis and diagnosis on a workstation at the hospital. Since commercial capsules are passively moved through the entire GIT by the natural peristalsis, it takes them about 8 to 12 h to pass the entire GIT. Therefore, more than 50000 images of the GIT are usually recorded since the capsules take a couple of frames per second. The current procedure of capsule endoscopy diagnosis is conducted manually by doctors. Therefore, screening long videos by doctors is time-consuming and yields the potential risk of overlooking abnormalities [26]. Hence, automatic detection of abnormalities in capsule en-

Figure 1.4: Representative commercial capsule endoscope (PillCam™ Colon 2) [21].

doscopy videos is a promising research direction [26–29]. Due to the relatively long video, it would be more practicable to automatically detect abnormalities such as e. g. bleeding or polyps (tumors). Overall, the automatic and manual detection and diagnosis using capsule endoscopy videos would be even more helpful for doctors to know the accurate traveled distance and orientation of the capsule for each video frame. The latter could also significantly help to estimate the trajectory along the winding human GIT. For instance, when the movement direction of the capsule does not match with the capsule orientation, e. g. for lateral movement of the capsule within the intestine, this movement could be excluded from the total traveled distance. Furthermore, the stomach and large intestine diameters extend the largest dimension of the capsule. Therefore, the capsule may rotate around all axes relative to the GIT, which could be detected with precise knowledge of its orientation. For surgery planning, e. g. when a catheter must be inserted into the GIT at a specific section, it would be highly relevant to know the distance from e. g. the entrance of the small intestine to the section of interest. Consequently, the doctors could either insert the catheter from the mouth or the anus, resulting in higher efficiency. Therefore, a precise localization method for these capsules is demanded. Unfortunately, in commercial capsule endoscopy systems, the position of the capsules is tracked with an insufficient accuracy of approx. 40 mm and the orientation is not determined [30, 31]. On the other hand, promising localization errors of several millimeters and degrees were reported in state-of-the-art scientific approaches [32, 33].

1.3 Research Problem

Compared to traditional endoscopy, the diagnostics procedure using capsule endoscopy is overall more comfortable and yields lower risks because no sedation is required. Thus, capsule endoscopy significantly increases patients' willingness to undergo pre-screening and diagnosis of the GIT. Furthermore, capsule endoscopy enables the diagnosis of the small intestine. Nevertheless, for precise diagnosis and surgery planning, the accurate traveled distance and orientation of the capsules must be documented for each captured video frame. Moreover, it takes the capsules approximately 8 to 12 h to pass the GIT, and thus, the patient must be enabled daily life activities outside the hospital.

With the described setup of a CE system and the prevailing conditions, the requirements of such a localization method are defined as follows:

- the traveled trajectory and the orientation must be precisely tracked throughout the entire GIT to localize abnormalities;
- the localization system must be compatible with the limited volume of commercial capsules; and
- the system must be robust in daily life situations of a patient and when ferromagnetic objects of the daily life are nearby.

Although capsule endoscopes have been commercially available for about 20 years, no reliable localization method that satisfies these requirements has been proposed. This thesis, therefore, presents a novel differential static magnetic localization method for capsule endoscopes. Moreover, the limited volume of commercial capsules was considered in the system design. Furthermore, a compensation method for relative movement between the sensor array and a patient's abdomen was proposed. In combination, these two methods were designed to enable tracking of the traveled distance and orientation of capsule endoscopy during the daily life of a patient outside the hospital and throughout the entire GIT with accuracy comparable to state-of-the-art localization methods.

Chapter 2

State of the Art in Localization of Capsule Endoscopes (CE)

The localization methods for CE can be subdivided into the video-based, radio frequency (RF)-based, and magnetic field-based (Fig. 2.1). A comprehensive literature review on scientific and commercial localization methods is given in the following.

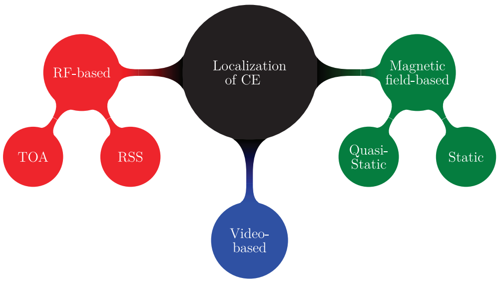

Figure 2.1: Classification of the main state-of-the-art localization methods for capsule endoscopy (CE).

2.1 Scientific Approaches

This chapter begins with a review of the most relevant scientific approaches in the literature for localization of capsule endoscopes.

2.1.1 Video-Based Localization

Fundamentals of Video-Based Localization of CE

Capsule endoscopes are equipped with cameras and thus, several approaches in the literature use image analysis and computer vision (CV) to determine the motion of the capsule inside the GIT by utilizing image features such as colors, textures or points of interest. The first step in these methods is the image registration of consecutive video frames, where one image is chosen as the reference image R and the other as template image T. During the registration step, features of consecutive frames are found and matched (Fig. 2.2). Assuming that two

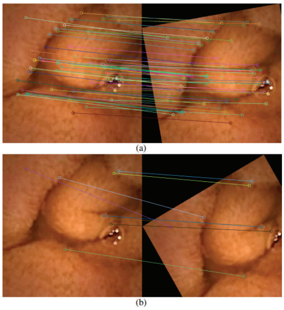

Figure 2.2: Example of two consecutive frames that are artificially rotated by 10° (a) and 30° (b). The selected features are connected in both images © 2012 IEEE [34].

consecutive frames of a capsule are given as reference image R and template image T then the homogeneous coordinates of the pixels are given as I_R and I_T and the following relationship applies:

$$I_R^T E I_T = 0 \quad (2.1)$$

where, E is the Essential matrix, which is expressed by the product between the rotation and translation matrices between the two capsule positions of frame R and T. Therefore, image registration aims to find the geometric transformation (i. e. E), such that R and T are similar or equivalent. [35, 36]

Well-established image registration methods for CE are deep matching (DM) [37], scale-invariant feature transform (SIFT) [35, 38, 39], speeded up robust features (SURF) [34, 35, 39], multiscale elastic image registration (MEIR) [36], multiscale parametric image registration (MPIR) [36], maximally stable extremal regions (MSER) [35, 39] as well as deep learning approaches for optical flow