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Investigating the precision of an induction-based localization system for medical applications

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Abstract

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1 Introduction

The Fraunhofer Institute for Integrated Circuits developed an inductive localization system called IndLoc. It is used to localize passive objects in real-time in 3D space. Its current main application is to monitor the picking process in logistics to prevent wrong picks. The motivation of this thesis is to find out whether the IndLoc system could be used in any medical application. Medical applications require very precise localization systems. Usually within the millimetre range ($\pm$ 3 mm) as shown in Table 1. The IndLoc system is accurate in the centimetre range ($\pm$5 cm) [1]. During this research work some of the IndLoc system components will be modified and optimized in order to improve its localization accuracy.
In this chapter, the advantages and disadvantages of three medical localization systems and the IndLoc system will be discussed. Namely, Image-guided neurosurgery, wireless endoscopic capsule localization and infrared image-patient registration. Afterwards the presented systems will be compared.

1.1 Localization in neurosurgery

In neurosurgery minimal damage of the patients brain tissue is desired. Thus several systems are commercially available to help surgeons navigate safely inside the patients brain. The minimal invasive procedures where these systems are used, are often referred to as image-guided neurosurgery or neuronavigation. The development of image-guided neurosurgery represents an improvement in several minimal invasive neurosurgery procedures [2]. The most-widely used neuronavigation systems uses two infrared cameras to track infrared markers fixated on the surgical instruments (as shown in Figure 1b[3]. By a registration process the position of the instrument is overlapped with pre- or intraoperative medical (MRI/CT) scans and displayed on a monitor. This way the surgeon has a sense of where his instruments are inside the patients brain in 3D and real-time (as shown in Figure 1a). The advantage of infrared based neuronavigation systems are their high precision (1.8mm - 5.0mm mean) [4, p.796]. The disadvantages of infrared based systems are that they need a direct line of sight [5] and their long setup time before surgery. Alternative systems use ultrasound or inductive localization to track the surgical instruments. Their advantages and disadvantages are shown in table 1.

This paper: [3] cites this paper: [5 but I can not access the second paper)

1.2 Image-patient registration

Image-guided surgery requires precise registration of preoperative medical images and the patients position in the operating room. A widely used registration method is called surface matching. During surface matching the surgeon points a laser at the patients face and moves it around (as shown in Figure 2). The infrared camera system detects the skin reflections and produces a virtual

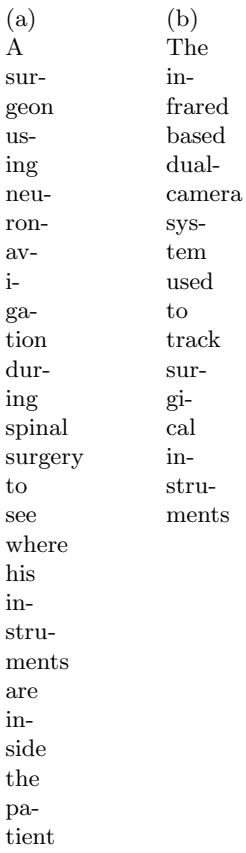

Figure 1: Neuronavigation/image-guided surgery

representation of the patients face. After completing the scan, the surface is then matched onto the facial surface of the preoperative MRI or CT scans using surface-matching algorithms. These systems show a high precision (mean 2.4mm $\pm$ 1.7 mm) [6].

Figure 2: A surgeon performing patient-image registration by scanning a patients facial surface. The scanned surface is then superimposed onto preoperative MRI images, as seen on the monitor.

Other systems use fiducal markers attached to the patients skin or bone structures. The markers radiopaque material can be easily seen during pre- or intraoperative CT or MRI images. During surgery they are detected using an infrared based camera system. These systems show a high precision (mean localization error 0.68 mm) [7, p.124].
Both methods need a direct line of sight. The surface scanning may take up to 8 *min*, thus increasing mean operating time [6]. The IndLoc System may be able to locate fiducial markers faster. It could maybe locate tooth fillings or implanted metal screws as markers that are built into the patient.

find a good disadv of fiducial marker

1.3 Wireless capsule endoscopy

The human gastrointestinal (GI) tract can reach a length of up to 9 metres and is difficult for physicians to inspect. In order to look inside the GI tract ingestible pills with internal cameras have been developed. They are often referred to as wireless capsule endoscopes (WCE), capsule endoscopes (CE) or video capsule endoscopy (VCE). WCE are an important tool for the diagnosis of small-intestine disorders. Most commonly induction based localization systems are being used to track the capsule inside the patient. However these systems are often not precise (average precision of 3.77 cm) [8]. Other localization systems have been investigated, but they either use radiation, are sensible to outer magnetic fields or take up extra space in the capsule [9].

(a) The size and components of an ingestible endoscopy capsule

(b) The portable capsule tracking system, including an localization antenna belt and a video receiving memory unit

(c) The tracked position of the capsule inside the human body with a progress bar

Figure 3: Wireless capsule endoscopy

1.4 Introduction to the IndLoc system

IndLoc stands for inductive localization. The system is able to track objects in 3D space in real-time. It was derived from the FIFA certified Goal line technology GoalRef, also developed by the Fraunhofer Institute for integrated circuits. The GoalRef system, which was built into the football goal frame, used to detect three coils inside a specially designed football. Nowadays the IndLoc system is used for industry 4.0 applications in logistics.

(a) The IndLoc system consisting of an exciter, sixteen receiving coils integrated into fiberglass tubes forming a picking shelf.

(b) The wearable is attached to the wrist and can be localized in real-time in 3D space

Figure 4: IndLoc system

Figure 4a shows the IndLoc picking shelf. The frame of the shelf is made out of fibreglass tubes. Inside of them is a closed wired loop (as shown in Figure 4a), called the exciter. An AC current flows through the exciter generating a magnetic field inside and around the shelf. The wearable localization object, as seen in Figure 4b, contains three coils. Once these coils enter the magnetic field a current is induced in them. This current then generates a second smaller magnetic field, which induces a voltage in the receiving coils placed around the shelf. From these voltages the position of the hand is then calculated. A more technically detailed explanation will be given in

chapter 3.

Whether or not the IndLoc system may be applied in medical applications, depends on how precise it can localize. During this paper several changes will be made on the system in attempt to increase its precision.

1.5 Comparison of medical localization systems and the IndLoc system

Table 1: Localization system comparison

Medical field	Localization system	Precision	Advantages	Disadvantages
Image-guided surgery	Infrared camera system [4]	$1.8 - 5.0\,mm$ (mean)	High precision, contactless	Line of sight necessary, increases mean operating time, bending of instruments not registered
	Inductive localization (Mc Millen) (Hermann) (Weiner) (Hayhurst)	do lit research	No line of sight necessary, bending of instruments registered, no frame necessary, contactless, mean operation time decreased	Affected by other magnetic fields, affected by metal objects
	Ultrasound do lit research	do lit research	Surgeons have experience and trust in ultrasound	Requires contact, poor penetration of bone tissue, accuracy decreases in deeper regions,
Wireless capsule endoscopy	Inductive localization [8] (old source from 2006)	$3 - 7\,mm$ (mean)	Portable, no negative health effects	Low precision, requires extra space in capsule
	X-Ray, Gamma ray			Radiation exposure, not portable
	MRI	-		Expensive, long scan times, not portable
	Ultrasound	-	No negative health effects	Takes up extra space in capsule, accuracy decreases in deeper regions
Image-Patient registration	Inrared surface scan [6] (source from 2002)	$2.4\,mm \pm 1.7\,mm$ (mean $\pm$ std. dev.)	Easy to use	Long scan times ($3 - 8\,min$), accuracy may decrease over time
	Infrared camera system with feudical skin markers [7, p.124]	$0.68\,mm$ (mean)		Line of sight necessary
To be determined	IndLoc system	-	Faster setup time, No line of sight necessary	Low precision, affected by other magnetic fields

2 Theoretical background

Rafael: "Write this chapter later on when you know what parts of the system you want to optimize. Then write down the physical laws necessary to explain why its smart to change this part the way I did."

2.1 Faraday's Law

3 The IndLoc system

Figure 5: An overview of the main components of the IndLoc system and how they are connected to each other.

In this chapter the technical details of the IndLoc system will be explained. Hereby the order of explanation follows the chronological order in which the systems components interact with each other. This order is also displayed by the structure of the whole chapter.

- The localization area (section 3.1) consists of:
  - The exciter (subsection 3.1.1):
    A wire loop surrounding the localization area. An AC current flows through it, which generates the primary magnetic field.
  - The localization object (subsection 3.1.2):
    Three orthogonal closed wire loops that are excited by the primary magnetic field. The primary magnetic field induces a current in the coils. This current then generates the secondary magnetic field.
  - The receiving coils (subsection 3.1.3):
    Consist of two coils with open ends. They act as magnetic field sensors. The secondary magnetic field induces a voltage in the receiving coils depending on the position of the localization object. (Note: Figure 5 only shows one pair of receiving coils for simplicities sake. Usually six to eight pairs are placed symmetrically around the exciter.)
- The signal processing (section 3.2) is done by:
  - The reader (subsection 3.2.1):
    Generates the AC voltage for the exciter. It simultaneously receives all receiving coil(s) voltages and processes them.
  - The host system (subsection 3.2.2):
    A PC running software which does some final signal processing. It determines the final position and shows in in a Graphical User Interface. The user can also configure the system via this GUI.

3.1 The localization area

Figure 6: IndLoc a schematic sketch of the localization area and its components

The localization area is what the user interacts with. Figure 6 shows a schematic sketch of the shelf shown in Figure 4a. Here a sequence of inductive excitations occur. The sequence starts at the exciter, producing the magnetic field. This magnetic field then induces a current in the localization object, thus generating a second smaller magnetic field. This secondary magnetic field then induces a voltage in the receiving coils. In summary the inductive excitations sequence occurs in this order: Exciter (Current) $\rightarrow$ Localization object (Current) $\rightarrow$ Receiving coils (Voltage)

3.1.1 The exciter

The exciter is a rectangular closed circuit (as shown in Figure 6. Fibreglass tubes surround the exciter protecting it and forming the shelf (as shown in Figure 4a. The exciter is attached to an AC current source, placed inside the reader (as shown in Figure 5). Thus it conducts an AC current with an amplitude of $0.5 - 2\,A$ and a frequency of $50 - 150\,kHz$. Both amplitude and frequency are configurable and are mostly adjusted to the localization object in use. Here should be mentioned, that the AC current is only necessary to produce an alternating magnetic field, which can induce a current without movement of the object. According to Farraday's Law the current produces an alternating magnetic field of with a maximum field strength of $150\,mT$ (complete guess). This magnetic field is called the primary magnetic field, as it is the primary source of magnetic field strength (/energy?) in the system. All following magnetic fields, voltages and currents in this chapter are a direct or indirect result of the exciters magnetic field. The coordinate system (as seen in Figure 6) is defined such as reaching into the shelf would be a movement on the z-axis. Switching between shelf compartments would be a movement on the x-y-plane. The primary magnetic field also emits outwards around the exciter as far as $50\,cm$, thus making it possible to track the localization object in a small area around of the shelf as well.

3.1.2 The localization object

The localization object is what the system tracks in 3D space, in real-time. Before usage the logistic worker puts on a wearable, that contains the localization object (as shown in Figure 4b). The localization object consists of three orthogonal coils (as shown in Figure 6). The names of the three coils originate from their surface normal vector. By using three orthogonal coils it is ensured that, regardless of the rotation of the hand, at least one coils is excited by the primary magnetic field. Each coil has N-windings. By including a resistor and a capacitor into the coils, each coil forms a series resonant circuit. Hereby the resonance frequency is set to the frequency of the primary magnetic field. Thus creating magnetic coupling between the exciter and the localization object. Using the principle of resonance here improves the signal-to-noise-ratio. The alternating primary magnetic field induces an AC current in the coils. This AC current then generates a magnetic field, called secondary magnetic field. Amplitude of the secondary magnetic field is influenced by position

and rotation of the object inside the primary magnetic field.

3.1.3 The receiving coils

The receiving coils are rectangular coils with N windings and. They act as magnetic field sensors. Each sensor consists of two orthogonal coils, namely the main- and frame- coil (ash shown in Figure 6). The antennas contain an instrument amplifier. Eight pairs of receiving coils are placed inside the fibreglass tubes (as shown in Figure 4a) that form the shelf. The primary and secondary magnetic field induce a voltage in the receiving coils. The reader will later subtract the signal created by the primary magnetic field (a more detailed explanation is given in chapter 3.2.1). Since the exciter and the receiving coils are both connected to the reader (as shown in Figure 5), the reader has the necessary information to filter out the primary magnetic field signal. So effectively the receiving coils only measure the secondary magnetic field, emitted by the localization object. If the localization object is moved closer towards a receiving coil, its measured voltage will rise. Hereby the signal of the main-receiving coils are used for the localization in the x-y-plane. The signal of the frame-receiving coils are used for the localization in the z-axis. All receiving coils have an electrically conductive connection to the reader.

3.2 The signal processing

3.2.1 The reader

The reader consists of an AC current source, a filter module, an FPGA, an amplification module, a power input, 16 input cables for the receiving antenna signals and a data output. Its two main functions are, processing all of the 16 receiving coil voltages while also operating the AC current connected to the exciter. These two functions are combined in one hardware components, because they are interlinked, but more on that later in this section.
The AC current source can be set to a frequency of 50 kHzto 150 kHz. The frequency is controlled by an internal clock of the FPGA. The signal coming from the FPGA is then amplified by a specially designed amplification module and then flows into the exciter.
In total the reader receives the analogous voltages of 16 receiving coils. This means the following signal processing is done on 16 identical parallel paths. The signals first have to pass an anti-aliasing filter. They then get quantized by a 16Bit analog-to-digital converter at a rate of 1 MS/s. By far the highest frequency component of this signal has the frequency of the exciter ($50\,kHz - 150\,kHz$ depending on the settings). In most cases there is also high frequency noise originating from surrounding electronic devices or the earth's magnetic field and maybe a DC offset from metallic objects nearby. Now the signal proportion coming directly from the primary magnetic field (thus skipping the localization object) is subtracted from the signal. The positional information of the localization object is amplitude modulated onto the current signal. As a quick reminder, the voltage

of a receiving coil will rise once the object gets closer to it. Now the amplitude modulated signal will get demodulated by the FPGA to a frequency of 0Hz. This is the reason the AC current source is also controlled by the FPGA. It requires to know the frequency of the AC current source for the demodulation. Now the 16 parallel channels get down sampled and filtered to a frequency of $250S/s$. The reader then finally sends all 16 voltages via an Ethernet cable to a host system.

3.2.2 The host system

The host system receives the 16 receiving voltages from the reader via an Ethernet cable. The UDP communication protocol used to be able communicate between reader and host system. UDP provides fast data transmission, which is necessary for real-time tracking. It is also possible to send messages from the host system back to reader in order to configure exciter frequency, exciter current and other parameters. The user can do via a Graphical User interface, written in Python. In the background this GUI also performs multiple additional signal processing steps on the receiving coil signals.

Namely a moving average filter is used to smooth out remaining noise. Then the DC offset is measures and removed. Then a discrete Fourier transformation is performed in order to only focus on the localization objects resonance frequency.

Now the position of the object determined, using a fingerprinting table. The table contains all realistic possible values of the 16 receiving coils and connects each variation to a specific X-,Y-,Z-position. In order to improve 3D-real-time tracking a Kalman-filter is used to estimate future positions, based on the latest positions. A Kalman filter is then used to estimate future positions based on the movement pattern of the localization object.

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The position is then shown in the GUI and superimposed with a digital representation of the picking shelf.

4 MATERIALS AND METHODS

5 RESULTS

6 DISCUSSION

7 SUMMARY, OUTLOOK INTO THE FUTURE

8 Meine Textschnipsel for later use

8.1 Kurze erklärung vom IndLoc system

The localization area is surrounded by a rectangular wire loop inside a fibreglass frame, called the exciter. A low frequency AC current source is attached to the exciter, making it generate a magnetic field. This magnetic field is referred to as the primary magnetic field. The primary magnetic field it is the primary source of energy for following the localization process.
In order to localize the hand of a logistics worker a passive localization object is attached to their hand. This localization object is a sphere consisting of three coils. The three coils are attached orthogonal to each other and have a diameter of 2 cm [10]. Once the hand of the logistics worker enters the primary magnetic field a current is induced in these coils. This current generates a secondary magnetic field.
Eight antennas are placed on the plastic frame surrounding the localization area. Each antenna consists of two coils orthogonal to each other. The secondary magnetic field induces a voltage in the antennas. If the hand is then moved close to an antenna, it's voltage will rise. At this point one can maybe start to fathom the localization principle here.
The antenna voltages are then forwarded to a reader unit. The reader is hardware that filters the signals, amplifies them and performs most of the signal processing. The processed voltages are then transferred via LAN cable to a windows computer. Here a python software then determines the position of the hand based on the given antenna voltages in real-time. In order to connect the antenna voltages to a X,Y,Z position a look-up table is used. The look-up table contains all possible antenna voltage values in all possible variations. Each variation is connected to a specific X,Y,Z location. The algorithms used for creating the lookup table are explained in chapter 2.

8.1.1 Reader

The Reader consists of power plug, high frequency generator, up to 21 electrical inputs for the antenna voltages, an ADC, amplifiers, an FPGA, a metal case and a data output cable.

8.1.2 Exciter

The exciter in itself is a recangular copper coil consisting of N windings surrounding the area of localization.

8.1.3 Localization Object

The localization object consists of of three different copper coils each with N windings. The copper coils are have an RC resonant circuit trimmed to a specific frequency. The resonance frequency is trimmed towards the frequency of the primary magnetic field in order to achieve higher excitation and thus stronger secondary magnetic field strengths.

8.1.4 Antennas (magnetic field sensors)

The antennas are also copper coils with N windings and are placed symmetrically around the localization area.

8.1.5 host system

8.2 Relevant medical fields where localization systems are being used

In this section some of the ..... will be presented. Additionally, the advantages and disadvantages of each used localization system will be discussed.

8.2.1 Neuro-navigation

In neurosurgery high precision is necessary to prevent damaging the patients brain. In order to achieve this neuronavigation systems has been developed. These neuronavigation consist of a monitor showing preoperative MRI (or orther modalities) images of the patients brain and a infrared based system to track the surgical tools. By performing a patient-image registration process, which will not be explained here, the brain images get overlapped with the surgical tools. This way the surgeon always knows the exact position of the surgical tools inside the patients brain. The infrared based system can not track the surgical tools directly, but rather feudical markers that are attached to the surgical tools. The most commercially used neuronavigation systems are made by BrainLab and is called (I think its StealthStation, but they are not very informative about the whole system name. It‘s kind of confusing what the name StealthStation consists of. Maybe its just the camera, maybe Patient-image registration and preoperative planning involved aswell).

8.2.2 Wireless capsule endoscopy

The human gastrointestinal (GI) tract can reach a length of up to 9 metres and is one of the most difficult parts for doctors to inspect. In order to take a look at the depths of the GI tract ingestible pills with cameras have been introducted. These pills are called wireless capsule endoscopes (WCE). They normally consist of a camera, a lightsource and a wireless data transmission system to send the captured images to the physicians computer. [11] ”Several studies have validated WCE as the most effective in its ability to diagnose early Crohn’s disease in comparison with other conventional

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Figure 7: Overview of WCE localization methods

methods, such as colonoscopy and radiology techniques [4]. In finding the cause of bleeding, WCE has outperformed several traditional techniques such as the traditional colonoscopy technology [5]."
It is necessary for the physician to know where the images are coming from in order to diagnose the patient correctly. The positional information is also important in further treatment planning.

All the magnetic based localization systems use the same principle of localization. By placing a permanent magnet inside the WCE is produces a magnetic field. Then multiple magnetic field sensors are positioned around the body to sense how strong the magnetic field is at their specific location. By combining the sensed data of multiple sensors one can localize the WCE fairly precise. In some systems a secondary coil is placed inside the WCE which is then excited by an external magnetic field source.
In some cases the magnetic field source is inside the WCE and the magnetic field sensors are placed outside the body, but in other cases this can be vice versa. The principle stays the same.
The problem with the systems using passive WCEs is that they are very sensible to other magnetic field sources. There is scientific efforts being made to move the WCE through the GI tract by using a magnetic field. This can interfere with the localization systems magnetic field.

Another big subsection of these magnetic localization fields use active WCE that have an internal power source. In most cases the power source is a small battery placed inside the pill. This battery is used to produce a high frequency alternating magnetic field from inside the WCE. This field is then measured with external magnetic field sensors. Sometimes the

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how are the magnetic field sensors powered?

8.2.3 Anatomical marker localization for patient registration

Anatomical marker for patient-image registration (e.g. tooth-filling, metal plates or screws) localization for patient to image registration that does not need additional installation of electronic equipment, may be a huge time saving factor for computer assisted surgeries. As image registration is a big problem of all surgeries that need three dimensional assistance. For example head surgeries use an assistive side screen that shows premade MRI, CT or X-Ray scans of the skull. A biopsy is one of the most common head surgery procedures as it can provide certain proof if tissue is a cancerous. In order to navigate the biopsy needle to the target area one needs to align these three coordinate systems: Image-Patient-Needle (In literature sometimes just called Image to patient registration). Currently infrared-based camera systems with infrared-markers are being used to align the image to the patient and estimate where the needle is inside the brain. With the highest negative to this procedure is time consumption. The doctors need to apply markers onto the patient before taking the images (plastic casks around the patients head), then carefully move

Medical field	Localization system	Precision	Main disadvantages
Neuronavigation	Infrared camera system	$1.8 - 5.0\,mm$ [4] (mean)	• Line of sight necessary • Long setup times
	Inductive localization	-	•
Wireless capsule endoscopy	Inductive localization	$3.77\,cm$ [8] (mean)	• Low precision, • Sensible to magnetic fields
	X-Ray, Gamma ray	-	• Radiation exposure
	MRI	-	• Expensive • Long scan times
	Ultrasound	-	• Takes up extra space in capsule [9] • Precision decreases in deeper tissues [12]
Patient-Image registration	Inrared surface scans	$2.4\,mm \pm 1.7\,mm$ [6] (mean $\pm$ standard deviation)	• Long scan times $(3 - 8\,min)$ [6] • Accuracy may decrease over time [6]
	Infrared feudical marker tracking	$0.68\,mm$ [7, p.124] (mean)	• Line of sight • Frame structure hindering surgeon?
To be determined	IndLoc system	To be determined	• Low precision • Sensible to magnetic fields

the patient back into operating position, then remove some parts of the marker holding system, then moving the camera system into the room and into position, then calibrating everything and making sure that no optical occlusion happens. The IndLoc System could be implemented into the operating table and the marker would be inbuild into the patient and thus a lot of the installation process would become no longer necessary. The materials being used in tooth fillings and metal objects that stay permanently in the patient have to be further investigated

8.3 Orthopedic screw localization

Screw-, stent- and bullet-localization are further topics that came to my mind, that I have not yet researched any further. It is necessary to see if it is even necessary to localize these parts or if it is not done at all. Furthermore the materials of the parts need to be conductive and have fairly good magnetic properties for our localization system to function.

8.4 Comparison tables, mb take some Refs from them

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Medical field	Localization precision	Localization system	Reference
Neuro-navigation	4 ± 1.4 mm (mean ± standard deviation)	Infrared marker	[13] [14] (beide Zeitschriftaufsätze, Probl
Neuro-navigation	mean 1.0mm (max error 1.8mm) in (26X26X40)mm^3	Inductive localization	[15]
Anatomical marker registration	1.1 ± 0.2 mm (mean ± standard deviation)	Infrared surface scan	[16]
Wireless endoscopic capsule	3-7mm (mean)	Inductive localization	[17] [18] [9]
Orthopedic screws	X-Rays are often used as reference for pos measurements	X-Ray	•
Coronary stent	-	Angiography	•
Dental filling	-	X-Ray	•
Bullet shrapnels	-	X-Ray	•

Maybe check if I can find the precision of current WEC and maybe check if I can find data sheets of all of these systems.

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