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Capacitive Sensing for Robot Safety Applications

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Abstract

“Capacitive sensing is a mature measurement principle with wide application ranging from chemical sensing, over acceleration, pressure, force and precision position measurement to human machine interfaces found in billions of modern consumer electronic products. In this paper we present several approaches how capacitive sensing can be used for safety applications - an emerging field of usage of capacitive sensors. Capacitive sensing offers unique features that can help to overcome problems of other safety systems such as vision based principles. However, due to the uncertain environment and parasitic effects no general capacitance measurement system exists, which can be readily used for safety applications. Thus, we present concepts targeting the usage of capacitive sensing technology for a wide field of applications. An example sensor system including an evaluation circuitry to protect humans and sensitive objects from collisions with e.g. machinery is presented.” [SZ14]

Kurzfassung

Kapazitive Sensorik bietet die Möglichkeit verschiedenste Aufgaben in der Messtechnik zu lösen. Diese reichen vom Messen chemischer Zusammenhänge über Beschleunigungen, Druck, Kraft und hoch präziser Positionsmessung bis zum Mensch-Maschinen-Interface, wie es in Milliarden moderner elektronischer Geräte (z.B. Smartphone) verwendet wird. In dieser Arbeit werden verschiedene Möglichkeiten aufgezeigt, wie kapazitive Sensorik für sogenannte Sicherheitssysteme – ein aufstrebendes Einsatzgebiet für kapazitive Sensoren – verwendet werden kann. Dabei besitzen kapazitive Sensoren einzigartige Eigenschaften und Möglichkeiten, welche es ermöglichen Probleme von existierenden Sicherheitssystemen, welche auf z.B. kamerabasierten Messsystemen arbeiten, zu lösen. Eine Schwierigkeit beim Messen mit kapazitiven Sensoren in Sicherheitsanwendungen besteht in der nicht definierten Umgebung und parasitischen Effekten, die den Einsatz eines generellen kapazitiven Messsystems bisher verhindert haben. In dieser Arbeit wird gezeigt wie kapazitive Messungen verwendet werden können um sie in einem weiten Einsatzgebiet anwenden zu können. Am Beispiel eines selbst entwickelten Sensorsystems wird gezeigt wie es möglich ist, Menschen und empfindliche Objekte von z.B. Robotern zu beschützen.

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1 Introduction

1.1 Motivation and Aims

Every year a high number of people get injured or even die because they reside in areas where they just should not be. This is not a specific application problem but happens in all areas ranging from industry (e.g. people controlling machinery) to leisure time or working at home (e.g. housework).

A lot of these injuries could be prevented if there was a sensor system detecting and classifying objects (e.g. humans) in those dangerous areas. If such an detection and classification system identify a dangerous situation, special actions can take place to prevent an accident (e.g. in an industrial environment: stop a machine).

In the future, such detection and classification systems (safety devices) will get more important as we can expect that more and more autonomous devices and robots will become part of our lives. These robots for example will operate in fairly undefined environments, where little prior knowledge is available. Thus, it is very important to have safety devices which can help to avoid e.g. collisions of machinery with humans.

Although special sensor systems exist for special applications (compare Section), only a few measurement principles exist which can cope with the requirements arising in such applications. These requirements e.g. can be:

- Limitations with respect to spatial dimensions.
- Weight.
- Power consumption.
- No line of sight
- etc.

Capacitive sensing has the potential to cope with most of the requirements arising in the presented safety applications. Although capacitance measurement is a well known measurement principle it has not yet been used very often for open environment sensing and object classification. Reasons for this will be presented in the following sections.

In this thesis an environment will be presented with which it will be possible to:

1. Attach the developed capacitance measurement system to nearly any application (occurring restrictions are described in the corresponding sections).
2. Deal with the arising (parasitic) effects occurring in open environment measurements.
3. Use of the presented algorithms adopted from Electrical Capacitance Tomography (ECT) to implement a proximity and classification system which can be used for safety applications.

1.2 Problem Statement

For the stated aims no general measurement system exists which can deal with the different arising requirements for different applications. Several measurement systems can be used for a specific safety task but have drawbacks if they should be used in a different task. An overview of possible measurement principles, their benefits and drawbacks is given in Chapter 3.

In this thesis capacitive sensing is used for open environment sensing and to realize a proximity and classification system which can be used in the stated aims. Although capacitive sensing is widely used for different tasks, several effects occur when it is used in a fairly undefined open environment (compare Section). For example, the capacitance measurement system has to deal with:

- Disturbers.
- Noise.
- Leakage.
- Shielding and coupling effects.
- Very high offset capacitance and low measurement capacitance (differ by several orders of magnitude).

As shown in [Zan05] capacitive sensing is able to deal with these effects if it is used in a defined environment. However, for open environment sensing in different applications the environment is fairly undefined and different (sometimes competing) effects can occur (compare Section). Thus, measurement hardware has to be able to deal with these uncertainties.

With a measurement hardware able to deal with the stated requirements, software is necessary which can be used to interpret/transfer the measurements to proximity and classification data (also called reconstruction). Additionally, the used software has to deliver results below a certain time to be able to implement real time systems (different levels/realisitionas/levels of real time occur for different applications).

Having hardware and software for an open environment sensing application, tools are necessary which allow to transfer the hard- and software from one application to another.This transformation has to be simple and easy and should not change the properties of the measurement hardware nor the reconstruction software.

1.3 Proposed Solution

A capacitance measurement system for open environment sensing has been developed by the author at the Institute of Electrical Measurement and Measurement Signal Processing. This thesis presents comprehensive investigations towards the use of this measurement system for different applications and different environments. Details on the measurement system can be found in the Appendix .

A software framework originally used in ECT was adopted with respect to different requirements in open environment sensing. This includes the incorporation of parasitic effects and additionally available measurements due to the developed measurement system. This enables to reconstruct not only the proximity of approaching objects but also classify approaching objects due to their properties.

The following aspects are described within this work:

The results achieved in this work were used in several applications such as a robot arm at the Stanford Robotics Group at the Stanford University which are also described in this thesis.

1.4 Original Knowledge Contribution

Investigations leading to this thesis were conducted during research work of the author at the Sensors and Instrumentation Group at the Institute of Electrical Measurement and Measurement Signal Processing at Graz University of Technology and during a research stay at the Stanford Robotics Group at Stanford University. In these times several conference proceedings, journal articles and patent applications were published. A summary of the publications with a contribution leading to this thesis are given below.

1.4.1 Sensor Design and Fusion

- **T. Schlegl**, T. Bretterklieber, and H. Zangl. "Curvature Effects on Elongated Capacitive Proximity Sensors." In: Sensor+Test Conference. June 7–9, 2011. [SBZ11]
- **T. Schlegl** and H. Zangl. "Simulation and Verification of a Capacitive Proximity Sensor." In: COMSOL Conference. Oct. 26–28, 2011. [SZ11]
- **T. Schlegl**, S. Mühlbacher-Karrer, M. Neumayer, and H. Zangl. "A GMR Based Magnetic Pretouch Sensing System for a Robot Grasper." In: 2012 IEEE International Instrumentation and Measurement Technology Conference (I2MTC). IEEE. 2012, pp. 1506–1510. [Sch+12]

- **T. Schlegl**, M. Neumayer, S. Mühlbacher-Karrer, and H. Zangl. “A Pretouch Sensing System for a Robot Grasper Using Magnetic and Capacitive Sensors.” In: Instrumentation and Measurement, IEEE Transactions on 62.5 (2013), pp. 1299–1307. [Sch+13]
- **T. Schlegl** and H. Zangl. “Sensor Interface for Multimodal Evaluation of Capacitive Sensors.” In: Journal of Physics: Conference Series. 2013. [SZ13]

1.4.2 Capacitive Sensor Applications

- **T. Schlegl**, T. Bretterklieber, M. Neumayer, and H. Zangl. “A novel sensor fusion concept for distance measurement in automotive applications.” In: IEEE Sensors. 2010, pp. 775–778. [Sch+10]
- **T. Schlegl**, T. Bretterklieber, M. Neumayer, and H. Zangl. “Combined Capacitive and Ultrasonic Distance Measurement for Automotive Applications.” In: Sensors Journal, IEEE 11.11 (Nov. 2011), pp. 2636–2642. [Sch+11]
- **T. Schlegl**, M.J. Moser, and H. Zangl. “Directional human approach and touch detection for nets based on capacitive measurement.” In: Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International. 2012, pp. 81–85. [SMZ12]
- **T. Schlegl**, M. Neumayer, and H. Zangl. “A Mobile and Wireless Measurement System for Electrical Capacitance Tomography.” In: Mikroelektroniktagung ME12. Apr. 2012. [SNZ12]
- **T. Schlegl**, T. Kröger, A. Gaschler, O. Khatib, and H. Zangl. “Virtual Whiskers - Highly Responsive Robot Collision Avoidance.” In: Intelligent Robots and Systems, 2013. IROS 2013. IEEE/RSJ International Conference on. [Sch+ed]
- **T. Schlegl** and H. Zangl. Chaper: “Capacitive Sensing for Safety Applications.” In: Technologies for Smart Sensors and Sensor Fusion. in press,

2014. [SMZ13]

1.4.3 Patent Application

- **T. Schlegl**, M. Moser, and H. Zangl. „Vorrichtung zur Erkennung eines Naheverhältnisses und Erfassung von Eigenschaften von Objekten.“ Austrian patent application, 2013.

Some of the publications above are part of this thesis. Sections containing content already published are marked by footnotes and corresponding citations. Publications by the author are additionally marked with an apostrophe ([Ref]') to indicate work already presented to the scientific community.

2 Safety Standards for a Safe Human Environment

In the following a short introduction to the topic “safety” in terms of international standards is given. First an overview of safety standards is given. The most relevant terms and definitions used in the standards are explained and aim to clarify ambiguities in the second subsection. A more detailed insight into functional safety and the IEC61508 standard ([IEC10b]) is given afterwards. This section closes with an application example using safety patterns for an easy implementation of safety standards in an example product development.

2.1 History of (Safety) Standards

With the foundation of the International Electrotechnical Commission (IEC) in 1906 the first development of international standards started. In the beginning the IEC focused on standards for units of measurement and in 1930 following electrical units were established (taken from [IEC13a]):

- Hertz, the unit of frequency
- Oersted, the unit of magnetic field strength

- Gauss, the unit of magnetic flux density
- Maxwell, the unit of magnetic flux
- Gilbert, the unit of magnetomotive force
- Var, designating the unit of reactive power
- Weber, the practical unit of magnetic flux

Consequential the Giorgi System was proposed, which was the first comprehensive system of physical units. It later became the International System of Units (SI).

In 1946 the International Organization for Standardization (ISO), which is now the world's largest developer of voluntary International Standards ([Sta13]) was founded in London. Five years later in 1951 its first standard was published: "ISO/R 1:1951 Standard reference temperature for industrial length measurements" [Sta97]. For more information about the history of (safety) standards it is referred to [SS11].

Today, ISO and IEC cooperate closely together and standards published together carry both acronyms (e.g. "ISO/IEC 27001 Information technology – Security techniques – Information security management systems – Requirements"). Since "Safety" is a matter of nearly all fields where standards exist, both organizations are publishing standards relating to different safety aspects together and on their own (shown in Fig. 2.1). Thus, ISO and IEC have published a technical report named "Guidance on the application of ISO 13849-1 & IEC 62061 in the design of safety-related control systems for machinery". This report was created by members of both organisation, ISO and IEC and shows the close relationship between both standards. A drawback can be the difficulty to decide which standard applies for which product or system. Fig. 2.1 from [Fuk11] shows an overview of different safety standards by ISO and IEC and the standard types in which they belong (it makes no claim to be complete).

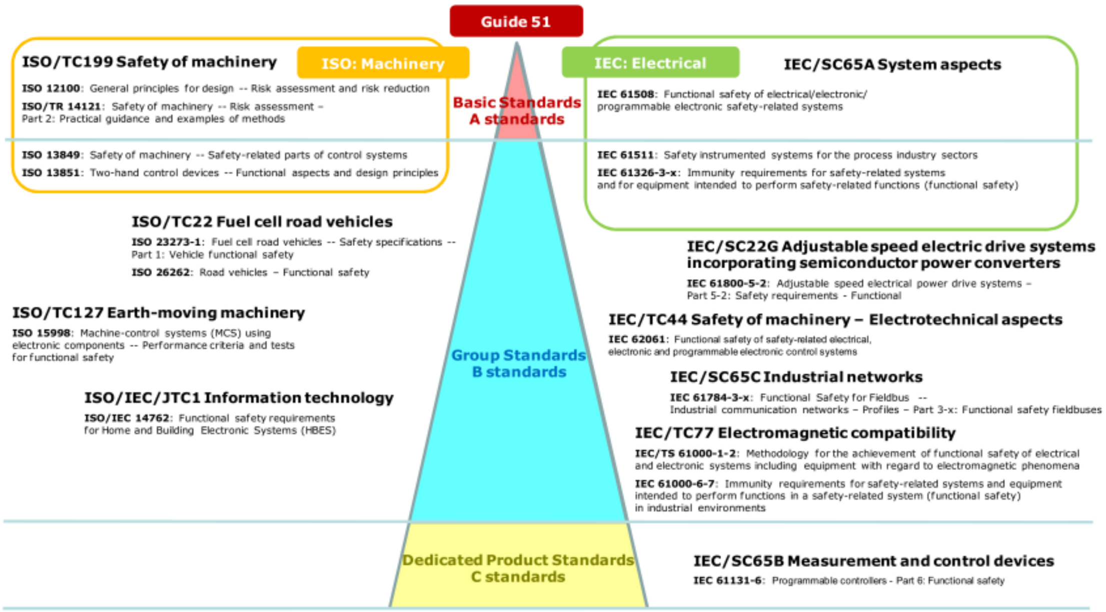


Figure 2.1: Overview of safety standard groups by different standardization organisations [Fuk11].

It is stated in [ISO12b]: "Close coordination within and among committees responsible for preparing standards on different products, processes or services is necessary in order to achieve a coherent approach to the treatment of risk". This results in different types of safety standards. Implied in Fig. 2.1 the different types of standards are [ISO12b]:

- Basic safety standards: For general concepts and requirements regarding a wide range of products and systems
- Group safety standards: For a family of products or systems (dealt by more than one committee). It should reference to basic safety standards.

- Product safety standards: For one product or system dealt by one committee. It should reference to basic safety standards and group safety standards.
- Safety standards containing safety aspects (not shown in Fig. 2.1) but do not deal only with safety aspects. They should reference to basic safety standards or group safety standards.

Standard guides to a structured approach in other fields can be found e.g. in the IEC Guide 104 [IEC10a] (fields of electrical and electronic engineering), ISO Guide 78 [ISO12a] (field of machinery) and ISO/IEC Guide 50 and 70 [ISO02; ISO01] (safety of children and vulnerable consumers).

Fig. 2.2 [SS11] shows the relation of the IEC 61508 to other industry specific standards. As can be seen from Fig. 2.2, the measurement system presented in this work would relate to different standards, depending on where it is used and which function or task it will have in the final product or system. The standard IEC 61508 [IEC10b] is a generic standard. It is a basis for industry, product or system specific standards but can also be used on its own for products or systems, where specific standards not (yet) exist. Thus, Section 2.3 will give an introduction to the IEC 61508 and some insights into IEC 62061. The standard IEC 62061 (Functional Safety of safety-related electrical, electronic, and programmable electronic control systems) is an example for an system specific standard in which the presented measurement system could be used. The complementary ISO 13849 (Safety of machinery - Safety-related parts of control systems) can also be used instead of IEC 62061. A detailed understanding of both standards and the product or system is necessary to decide which standard will deliver the best result for each product or system.

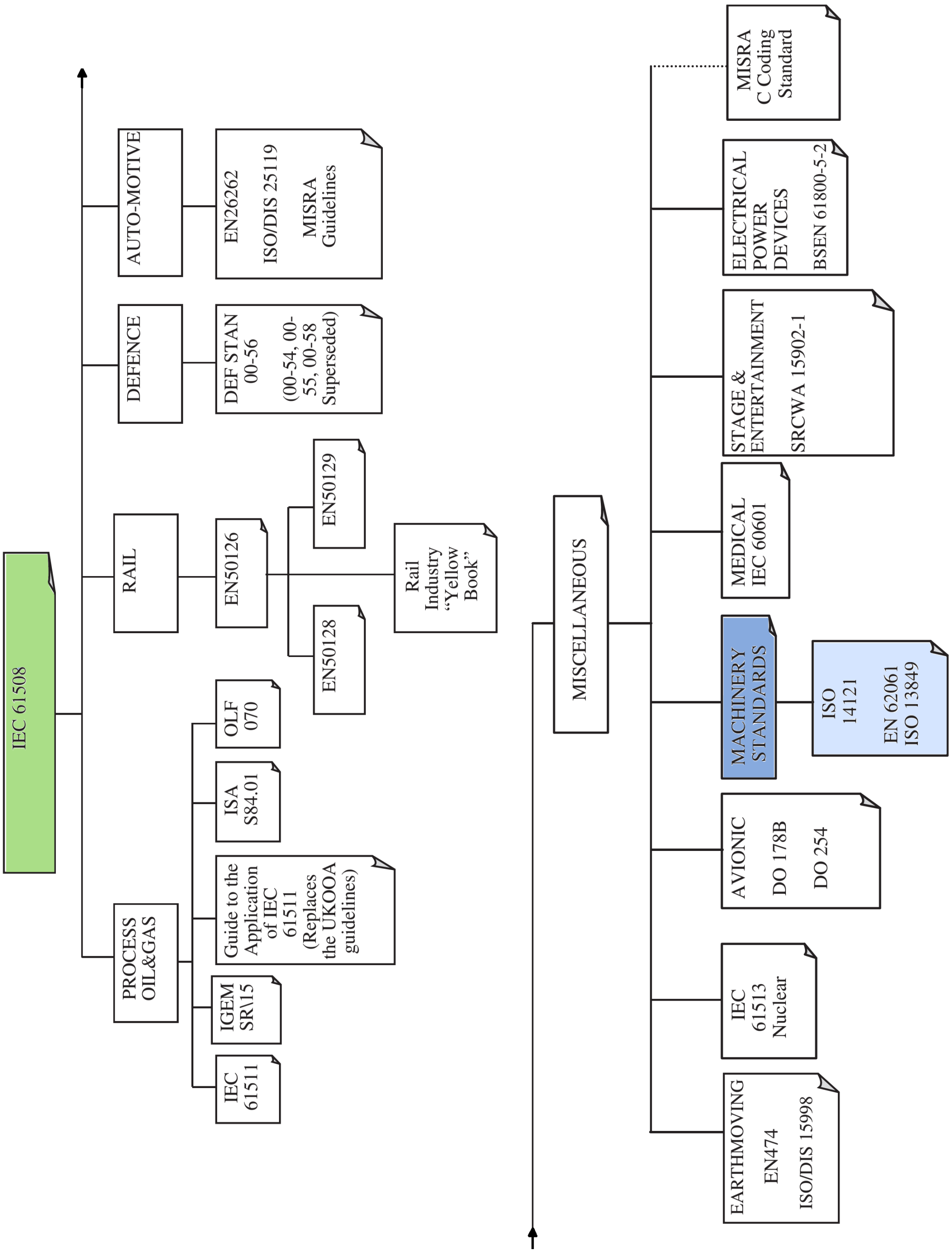


Figure 2.2: Relation of the IEC 61508 standard to other industry specific standards (from [SS11]). The presented measurement system in this thesis will most likely be used in the machinery sector. Thus, the standards shaded in light blue would apply.

2.2 Terms and Definitions

The presented terms and definitions in Table 2.1 are taken from [ISO12b]. Although, slightly different definitions may apply for the same terms in other standards (e.g. [ISO10; IEC13b]) the concepts are broadly the same and thus are used in this work.

Additional standards, necessary for understanding and applying the presented safety standards are:

- ISO3864, all parts, "Graphical symbols - Safety colours and safety signs"
- ISO7000, "Graphical symbols for use on equipment – Index and synopsis"
- ISO7001, "Graphical symbols – Public information symbols"
- IEC60417, all parts, "Graphical symbols for use on equipment"

For the goal to make a product or system "safe", the state "safe" has to be defined. According to [ISO12b] "safe" is a state "of being protected from recognized hazards that are likely to cause harm". Thus, there is no alternative to be absolutely safe or having a complete absence of risk. Table 2.2 shows the probability of every day risk of death from different causes (from [SS11]).

Therefore it can be stated that every product or system includes some risk. The different elements of risk are shown in Fig.2.3

A more detailed explanation about risk assessment, safety integrity levels (SIL), etc. is given in the following section.

Table 2.1: Terms and definitions used in safety standards from [ISO12b].

Terms	Definition
Safety	Freedom from unacceptable risk
Risk	Combination of the probability of occurrence of harm and the severity of that harm
Harm	Injury or damage to the health of people, or damage to property or the environment
Hazard	Potential source of harm
Hazardous event	Event in which a situation may result in harm
Hazardous situation	Circumstance in which people, property or the environment are exposed to one or more hazards
Tolerable risk	Risk which is accepted in a given context based on the current values of society
Risk reduction measure (protective measure)	Any action or means to eliminate hazards or reduce risks
Residual risk	Risk remaining after risk reduction measures (protective measures) have been taken
Risk analysis	Systemic use of available information to identify hazards and to estimate the risk
Risk evaluation	Procedure based on the risk analysis to determine whether a tolerable risk has been achieved
Risk assessment	Overall process comprising a risk analysis and a risk evaluation
Intended use	Use of a product or system in accordance with information provided by the supplier
Reasonably foreseeable misuse	use of a product or system in a way not intended by the supplier, but which may result from readily predictable human behaviour (compare [ISO13])

In [ISO12b] and in this work the terms "acceptable risk" and "tolerable risk" are considered to be equal. In the context of consumer safety the terms "reasonably foreseeable use" and "intended use" are used as synonyms.

Table 2.2: Probability of everyday risk of death from different causes from [SS11].

Cause	Probability per year
Natural disaster (per individual)	2×10^{-6}
Road traffic accident	6×10^{-5}
Accident in the home	4×10^{-4}
All accidents (per Individual)	5×10^{-4}
All causes (mid-life including medical)	1×10^{-3}

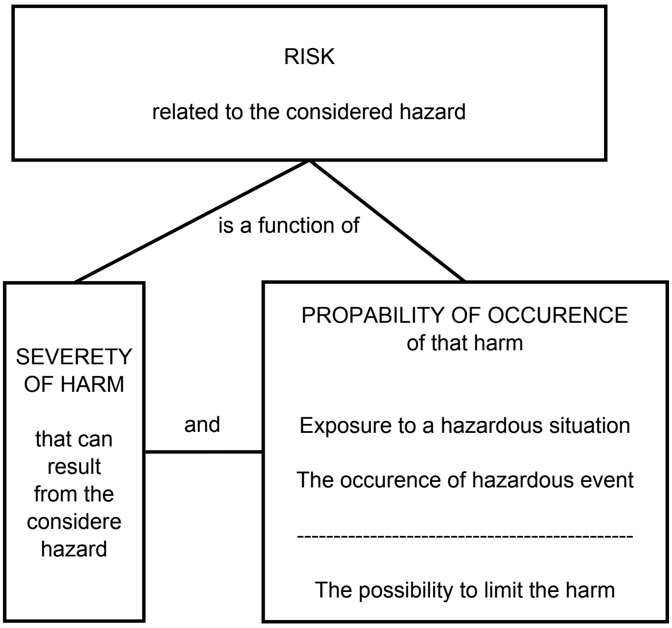


Figure 2.3: Elements of risk (adopted from [ISO12b]).

2.3 Functional Safety and IEC 61508

This section describes the term functional safety, the targets which apply (e.g. Safety Integrity Levels) and the according standard IEC 61508. As shown in Fig. 2.2 many industry specific (also called "second-tier") documents exist. These documents are derived from IEC 61508, but compliance with one of the industry specific documents does not imply compliance with IEC 61508. Thus, an introduction to IEC 61508 is given and the interested reader can refer to [SS11] and the references in there for more information.

Functional safety is the capability of a electrical/electronic/programmable electronic (E/E/PE) system to remain in a safe state or go to a safe state if random (hardware) failures or systematic failures apply. According to [SS11] random failures can be quantified in terms of e.g. failure rates but systematic failures can not. Thus, it is necessary to introduce integrity levels to address systematic failures in the design and operating activities. Additionally a life cycle approach is needed to achieve functional safety, since systematic failures can happen in the design and operating life of an equipment. The IEC 61508 is based on such a safety life cycle approach.

2.3.1 Safety Integrity Level (SIL)

A short description and the impacts of the four existing SILs according to IEC 61508 [IEC10b] is shown below.

SIL 4 It is the highest target to achieve. According to [SS11] it should be avoided and other or additional protection levels should be used. The reason for this suggestion are the extreme high costs resulting from using state of the art practices (e.g. "formal methods" in design) and the needed competencies for all techniques which are required (and also not easy to find).

SIL 3 It still needs sophisticated design techniques for SIL 3 but it is not as onerous as SIL 4. Although, there will be a limited number of vendors for example, which can provide SIL 3. Time and costs will also be not negligible.

SIL 2 To achieve this level good design techniques and good operating practice will be needed at a level as it would be found in "ISO 9001:2008 - Quality management systems - Requirements". SIL 2 is much easier to achieve than SIL 3 and not very different of SIL 1 in terms of life cycle activities.

SIL 1 That is the lowest level which still implies good design techniques. According to IEC 61508 SIL 1 is referred to as "not safety related".

The reason for having SILs arises from having two different kind of failures:

- Random hardware failures and
- Systematic failures

As mentioned before random hardware failures can be expressed quantitatively in e.g. failure rates. The frequency of hardware failures is predicted and compared to a maximum tolerable risk. Table 2.3 shows the maximum tolerable risk rate for each SIL according to IEC 61508 (and most other standards using SILs). Additionally, the so called "demand rate" has also to be taken into account. A system or product is called to have a "high demand rate" if the demand on the safety function is higher than once a year [IEC10b]. If it is less frequent it is called "low demand rate".

On the other side, systematic failures cannot be quantified by e.g. failures rates. These failures are unique to a given product or system and the environment

Table 2.3: Definition of Safety Integrity Levels (SILs) according to IEC 61508 [IEC10b].

SIL	High demand rate (dangerous failures / hour)	Low demand rate (probability of failure on demand)
4	$\geq 10^{-9} to < 10^{-8}$	$\geq 10^{-5} to < 10^{-4}$
3	$\geq 10^{-8} to < 10^{-7}$	$\geq 10^{-4} to < 10^{-3}$
2	$\geq 10^{-7} to < 10^{-6}$	$\geq 10^{-3} to < 10^{-2}$
1	$\geq 10^{-6} to < 10^{-5}$	$\geq 10^{-2} to < 10^{-1}$

the product or system is used in. Systematic failures arise from e.g. [SS11]

- Design tolerances
- Inadequately assessed modifications
- Software

Thus, systematic failures have to be taken into account by addressing qualitatively and not only quantitatively safety targets. With applying different defenses and design disciplines appropriate to the strictness of the tolerable risk target [SS11]. Therefore, SILs address safety targets quantitatively (e.g. through failure rates) and qualitatively (e.g. through design rules). One cannot assume that quantitative (failure rates) targets will be automatically achieved by applying the right qualitative requirements according to a certain SIL level. These two issues are quite seperate [SS11]. Since qualitative requirements of a system or product apply through the whole life of a system or product, IEC 61508 includes a so called life cycle approach, which will be presented in the following section.

2.3.2 Life Cycle Approach

IEC 61508 defines, describes and is based on a safety life cycle. It is necessary to reduce systematic failures to achieve functional safety. This reduction has to have happen at different stages during the design and during the operation of a product or system.

Fig. 2.4 shows a simplified version of the life cycle presented in IEC 61508, which is adopted from [SS11].

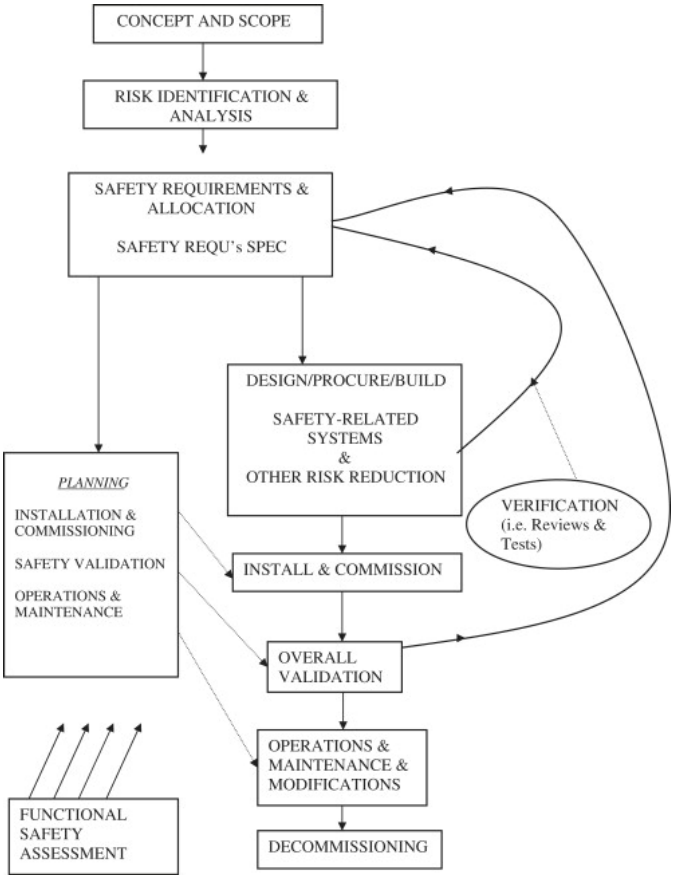


Figure 2.4: Safety life cycle of a product or system according to IEC 61508 [SS11].

The different stages of this safety life cycle are [SS11]:

Concept and scope Defines the specific product, which parts are controlled, its boundaries and the safety requirements. Defines the hazard and how it is identified (e.g. hazard and operability study). A safety plan for all life cycle activities is needed.

Hazard and risk analysis It is a quantified risk analysis including the consequences of failure.

Safety requirements and allocation A maximum tolerable risk target is set for the whole system. Each safety function is defined and each gets its own SIL.

Plan operations and maintenance The definition of the effects on functional safety during operation or maintenance is done here. An important factor is the human error.

Plan the validation The validation of all functions has to be planed (e.g. putting together evidences from the verifications).

Plan installation and commissioning Everything (including human error) that can effect functional safety during the installation has to be planned here.

The safety requirements specification Description of all safety functions in detail.

Design and build the system The realization of the safety system.

Install and commission Implementation of the product or system including documentation of all events especially failures.

Validate that the safety-systems meet the requirements The allocated targets have to been checked through predictions, reviews and tests. The product or system has to be validated several times during its life.

Operate, maintain, and repair Again, documentation is important, especially documentation of failures.

Control modifications A modification is a kind of a re-design and thus, life cycle activities have to be taken into account.

Disposal Also decommissioning can have safety hazards which have to be observed.

Verification The demonstration of the implementation of all life cycle activities.

Function safety assessments An assessor demonstrates compliance with the according SIL (compare Table 2.4)

For the assessment process, which is part of the safety life cycle, following steps have to be made (from [SS11]):

1. Establish functional safety capability (of the assessor and the design organization)
2. Establish a risk target (through e.g. formal hazard identification)
3. Identify the safety related functions
4. Establish SILs for the safety related elements
5. Quantitative assessment of the safety related product or system
6. Qualitative assessment against the according SIL
7. Establish ALARP (as low as reasonably practicable)

The assessor has to be independent from the assessed product or company. The minimum of independence depends on the target SIL. Table 2.4 shows the different levels of minimum independence.

2.3.3 Overview of IEC 61508

The standard IEC 61508 [IEC10b] is divided into 7 parts. Parts 1 to 3 are the main parts and parts 4 to 7 provide additional material. As can be seen from Fig. 2.5 the general process is to establish SIL targets by different methods and

Table 2.4: Minimum independence of the assessor according to the SILs [IEC10b].

SIL	Consequence	Assessed by
4	Many deaths	Independent organization
3	More than one death	Independent department
2	Severe injury or one death	Independent person
1	Minor injury	Independent person

then design the product or system. This design phase has to realize a targeted integrity level including random failures and systematic failures.

In the following the 7 parts of the standard are shortly described:

Part 1 - General Requirements Including topics like the definition of SILs, the life cycle approach, etc.

Part 2 - Requirements for E/E/PES safety-related systems It covers the hardware aspects of the safety related system.

Part 3 - Software requirements Everything concerning the design of software.

Part 4 - Definitions and abbreviations Terms and definitions used in the standard.

Part 5 - Examples of methods for the determination of safety-integrity levels General concepts and methods for information (e.g. methods for determining SIL targets, application of ALARP, qualitative methods of establishing the SILs, etc.)

Part 6 - Guidelines on the application of part 2 and part 3 Provide material for e.g. calculating probability on hardware failures, common cause failures, etc.

Part 7 - Overview of techniques and measures Reference guide to measures and techniques.

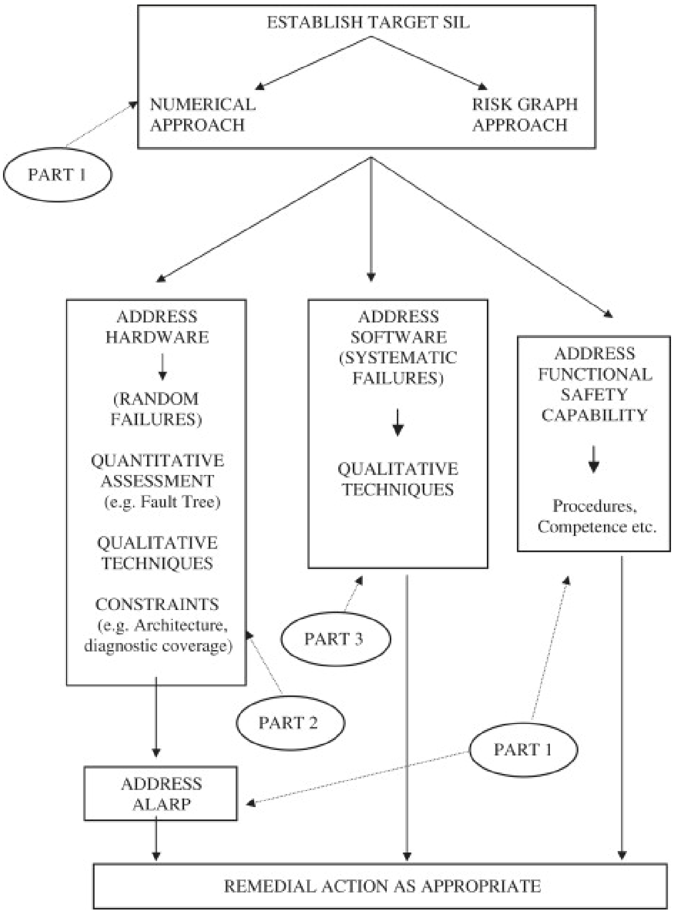


Figure 2.5: Description of the main parts (parts 1 to 3) of the standard IEC 61508 [SS11].

3 Survey of Measurement Systems for Safety Applications

Many measurement principles might be applied to prevent injuries of humans in areas where they just should not be. Although, only a few can cope with the requirements stated in Section .

An[Ryb+12]emerging research topic in robotics is the save human-robot interaction. The essential goal of this research is to enable robots to safely interact with humans [Had+12]. Since a save human-robot interaction

- is an up-to-date research topic (e.g. [VB13; LV12; OHF12; NLH12; Hey10]),
- covers the requirements which were proposed in Sections 1.1 and 1.2 ([BPC08]),
- can be easily transferred to other fields of applications thinking in terms of sensory and algorithms,

it will be used as a reference in this theses. If a sensor system is found, which is able to prevent a robot from collisions with e.g. a human, it will be possible to adapt this sensor system to other applications under certain constraints.

The following section presents state of the art sensor technology for object detection and classification, which can also be used for safety applications. Although the majority of the presented sensor systems are used in robot applications they could easily be used in other applications (e.g. applications presented in this work). According to [CH08] these sensors belong to the class of exteroceptive sensors, since they obtain information of the external environment. This information can e.g. be

- distance to an object,
- interaction forces,
- tissue density,
- or other physical properties.

At the end of the following section a comparison of the presented sensing technologies is made. Table 3.1 gives an overview of the presented sensors. It is attended to give the reader an idea of which sensor systems could be used for object detection and/or object classification for safety applications (adapted from [CH08]). It also concludes the benefits and drawbacks if these technologies if they are used to prevent injuries of humans in areas where the humans just should not be.

The second part of this chapter presents existing capacitive sensing technologies for object detection and classification. Different state of the art approaches are presented and compared. Benefits and drawbacks of the existing systems are presented.

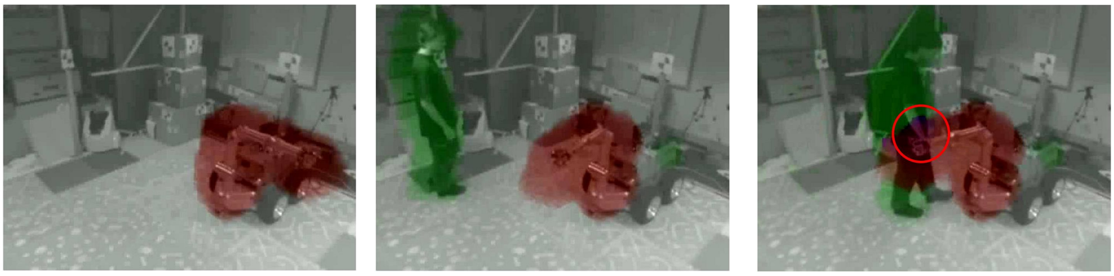
3.1 State of the Art Sensor Technology

3.1.1 Vision

Vision sensors (e.g. monocular cameras, stereo cameras, panoramic vision, etc.) have been studied for robot-human interactions for a long time.Recently RGB-D cameras such as the Asus Xtion or the Microsoft Kinect got affordable and thus, depth image based human detection has attracted attention in robotics research [Fos+12; Cho+13]. Vision sensors can be mounted on the robot or observe predefined areas from the outside. In the following two examples (one with vision sensors on the robot and one with observing cameras from the outside) with promising results are given. The presentation of the two examples in this thesis is limited to the used sensors and measurement hardware. The examples tend to give an idea of the possibilities when using vision sensors for robot-human interaction. The examples are also used to shown drawbacks and potential verbesserungen due to other sensors, such as pretouch sensors. The interested reader can refer to [DE08] and to the literature referenced there for more information on this interesting and extensively studied subject.

Human Safety in Industrial Workcells [Ryb+12]

There is a high demand of industry to no longer separate humans and active industrial robots, which up to now is necessary because of safety concerns. Sharing workcells would for example be more efficient in terms of time and resources. Thus, in [Ryb+12] a system is presented which uses multiple 3D imaging sensors to separate background, robots and humans (compare Fig. 3.1) and detect possible collisions.



(a) (b) (c)

Figure 3.1: A vision sensor system for human safety in industrial workcells from [Ryb+12]. (a) A picture of one of the four used cameras. The red region indicates an adaptive danger zone around the robot, which is based on the robot's position and trajectory. (b) A human is surrounded by an adaptive (green) safety zone. It also follows the human as the human moves around in the workcell. (c) The danger and safety zone intersect, because the human comes too close to the robot (indicated by the red circle). In such situations the robot stops or slows down to avoid collisions.

The presented system in [Ryb+12] can be used with a variety of 3D cameras such as stereo cameras, range cameras (i.e. flash lidar), structured light or the Kinect sensor. The experiments in [Ryb+12] were done with four cameras (two range cameras and two stereo cameras). This sensor fusion approach enables the system to use the benefits of the different sensing devices and avoid/eliminate their drawbacks.

As stated in [Ryb+12] the presented approach has several drawbacksfor safety applications. Examples are:

- The necessary calibrations (intrinsically and extrinsically) for each workcell to obtain distance information and a reference frame from multiple cameras.
- The robots in the workcell (i.e. dangerous objects) have to be known (e.g. joint positions and velocities).

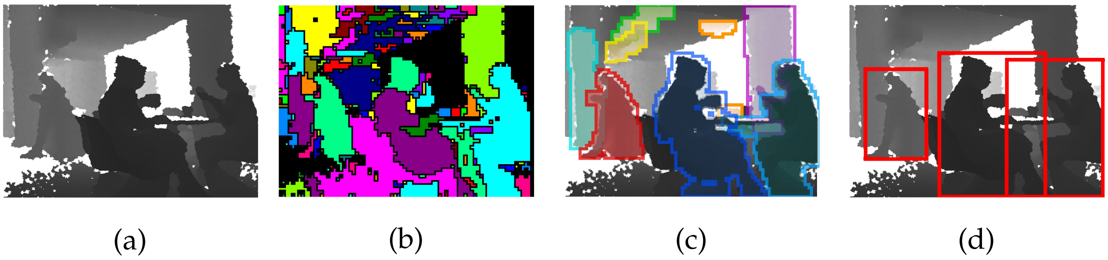


Figure 3.2: Different stages of the detection process for RGB-D camera based human detection from [Cho+13]. (a) Picture of the raw depth image from the Microsoft Kinect camera. (b) Different regions after the segmentation process. (c) Possible candidates after the filtering and merging step. (d) Final detected humans indicated by red squares.

- Occlusions in the workcell can lead to blind zones for safety applications where no collision avoidance is possible.
- All other moving objects (other than the known robots) are interpreted as humans.
- Heavy signal processing (due to e.g. sensor fusion).
- Rather slow detection rate at approximately 10 Hz.

Depth cameras on indoor mobile robots for fast human detection [Cho+13]

In this work a Microsoft Kinect sensor was mounted on a mobile robot to detect humans in different environments. The algorithm runs at 30 Hz on a mobile robot using a single core CPU [Cho+13]. The algorithm consists of four different stages shown in Fig. 3.2:

1. Taking the depth image with a Microsoft Kinect camera.
2. Depth image segmentation.
3. Region filtering and merging.
4. Candidate classification.

Advantages of the presented algorithm are

- High speed for a computer vision detection algorithm (30 Hz).
- Relatively low computational effort.
- Detection of partly occluded humans.

On the other side, the algorithm is only used for the detection of humans. No distance or proximity determination is done. This prohibits the use for a general safety measurement system in terms of the requirements of this work. Additionally more than one camera has to be used if an 360° observation angle around the robot is necessary. This would increase the computational effort and reduce the detection rate.

3.1.2 Radio frequency identification (RFID)

RFID is mostly used in the area of field and service robots (e.g. domestic robots) for positioning purposes (i.e. determination and control) [PK08; SK08].

Using such a sensor system for safety applications makes it necessary to attach so called tags to each object of interest. Thus, approaching objects can be identified and their distance can be estimated. Uncertainties in the distance estimation due to can be improved by sensor fusion with e.g. ultrasonic sensors [Cho+11].

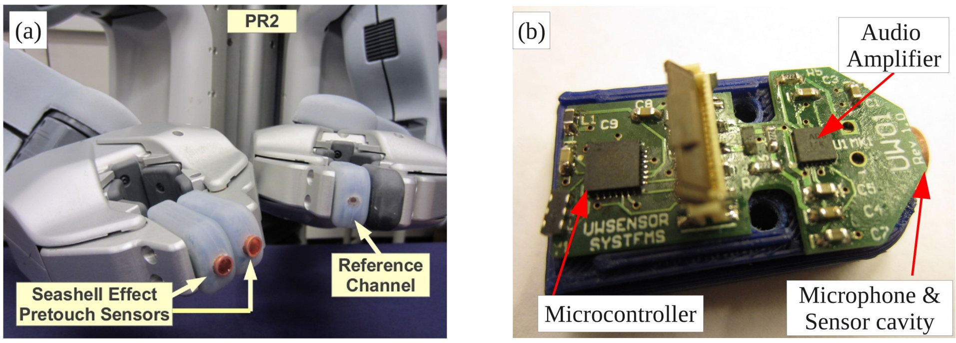
3.1.3 Time-of-flight Sensors

Time-of-flight sensors are capable to determine the distance between the sensor surface and an object in front of the sensor surface. For most sensors there has to be a line of sight between theses two points [FK08]. The distance estimation is achieved by measuring the time of e.g. an excited wave with a certain frequency traveling from the sensor to the object of interest and back to the sensor. Thus, the majority of sensors are only capable of determining distances. In [KK08] sonar systems are described, which are also able to do simple target classification. The targeted object surfaces can be classified into planes, cylinders or edges. As far as the author knows there is no time-of-flight measurement system capable of doing object classification in terms of this thesis (e.g. distinguish between human and metallic work tool). Nevertheless, these systems are often used in a fusion approach to improve sensors accuracy [DH08]. Other drawbacks of these sensors are e.g. a limited observation angle which results in blind spots or the need for a high number of sensors. Additionally, these sensors are usually too big to be mounted on e.g. robot arms or fingers (or other applications mentioned in Section).

In the following the most prominent time-of-flight sensors are mentioned:

- Ultrasound (US) and Sonar.
- Light detection and ranging (Lidar).
- Flash Ladar (lasar radar or laser detection and ranging).
- Radar
- Laser

2D and 3D laser range sensors are mainly used for localisation, map building and SLAM (simultaneous localization and mapping) [DE08]. If not used on the robot but fixed around a region of interest, it was shown in [Sat+13], that they can also be used to identify people and robots.



(a) (b)

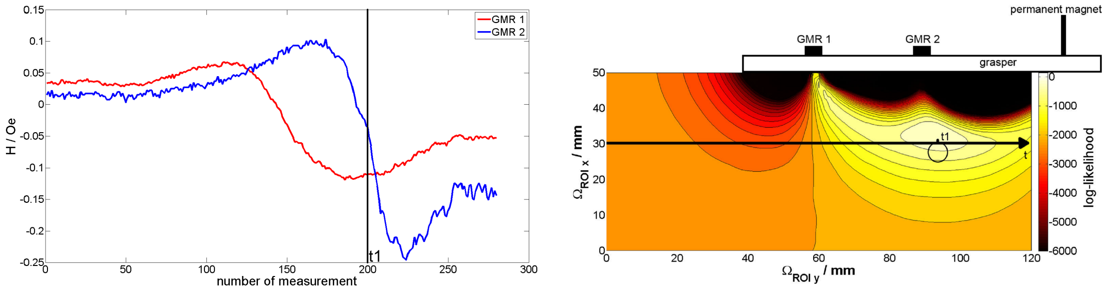
Figure 3.3: Measurement system using the seashell effect from [JS13]. (a) Fingertips comprising the integrated seashell effect sensor. A microphone is attached to an acoustic cavity to attenuate the ambient sound. The reference channel is used to suppress noise from the ambient sound. The printed circuit board comprises the necessary electronic parts and fits into the fingertip of a Willow Garage PR2 robot.

3.1.4 Seashell Effect

In [JS12], a so called seashell effect is introduced for pretouch sensing. It uses the resonant frequency of a cavity, which changes as an object approaches the cavity. This resonant frequency is measured with a microphone, and thus, a distance to an approaching object can be estimated (up to approximately 6 mm). The authors were able to mount the cavity and the microphone into the fingertips of a robotic hand and thus, improve certain grasping tasks.

3.1.5 Magnetic Sensing

Magnetic sensors are useful in pretouch applications to sense conductive objects. In [Sch+13] it could be shown that with only two giant magnetoresistance (GMR) sensors and a static magnetic field, a pretouch sensing system for ferromagnetic



(a) (b)

Figure 3.4: Measurements using a static magnetic field and two GMR sensors to reconstruct the position of an iron rod in the region of interest Ω_{ROI} from [Sch+13]. A picture of the measurement setup is shown in Fig. 3.10(a). (a) Measurement readouts of the two GMR sensors. The iron rod was moved in the region of interest Ω_{ROI} from left to right at a distance of 30 mm. (b) Snapshot of the real time reconstruction of Ω_{ROI} while the iron rod was moved along the y-axis at time t1 (according to (a)). The black circle depicts the true position of the rod and the colorbar depicts the value of the log likelihood.

objects is feasible. The developed algorithm, comprising Gaussian regression and a maximum likelihood estimator, allows an online reconstruction of the position of a ferromagnetic object in the region of interest. Experimental investigations demonstrate the feasibility of this approach. It permits a maximum detection range of 30 mm [Sch+13]. Fig. 3.4 shows the measurement setup and the result for one position of the iron rod in the region of interest (Ω_{ROI}).

In [Ren+10] a measurement system was presented which uses GMR sensors to measure eddy current effects. The system is able to detect hidden conductive objects inside a tube with a diameter of 60 mm. Thus, it seems possible to use such a system also for collision avoidance in open environment sensing applications.

3.1.6 Tactile Sensing

Tactile sensors are not able to do collision avoidance since these sensors get "active" if a collision already occurred. Although, tactile sensors can be used for impact force reduction and collision detection. Collision detection can also be used for future force reduction behaviors [Pha+11]. There exist a huge variety on tactile sensors. The following list is not intended to be exhaustive but to give an brief overview of possible measurement principles which could be used [CHP08]:

- Optical sensors [Kam+04],
- Piezoresistive sensors [Shi+04],
- Piezoelectric (stress rate) sensors [HC93],
- Skin acceleration sensors [HC89],
- Capacitive sensors [Pha+11],
- Whiskers and antenna sensors [RB+11].

All mammals but humans use whiskers in order to rapidly acquire information about objects in the vicinity of the head. Collisions of the head and objects can be avoided as the contact point is moved from the body surface to the whiskers [Sch+ed]. Thus, whiskers and antenna sensors can also be seen as proximity or pretouch sensors [RB+11].

3.1.7 Proprioceptive Sensing

Proprioceptive sensors are sensors which measure the internal state of a robot. This might include

- position and/or velocity of different joints,

- temperature of different parts,
- voltages,
- motor current,
- forces and torques,
- etc.

The motor current, force and torque sensors can be used to reduce impact effects in the case of collisions with machinery comprising these sensors. This is especially necessary, if no other sensor can be mounted on the machinery or robot and a physical human-robot interaction is unavoidable. For further details on theses proprioceptive sensors the interested reader is referred to [BPC08; Shi+11; Had+12] and the references in there.

3.1.8 Comparison of State of the Art Sensor Technology

Table 3.1 gives an overview of the presented measurement systems as they are used for safety applications. The benefits and drawback of the different measurement principles are highlighted.

As can be seen, no measurement system...

3.2 Safety Through Capacitive Sensing

This section will present an overview of existing capacitance measurement system which are used for open environment (safety) applications according to the introduced definition in Section before: "To measure objects where they are not allowed to be". Several examples show the wide field of application where

Table 3.1: Overview of exteroceptive sensors, which could be used for safety applications in terms of object detection and/or object classification (adopted from [CH08]).

Sensor type	Sensing range	Classify objects	Sensitivity diff. obj.	Parasitic influence	Size	Hardware complexity	Power consumption	Meas. rate	Costs
Vision	+	1	+	+	+	+	+	+	+
RFID	+	2	+	+	+	+	+	+	+
Tof			+	+	+	+	+	+	+
Tof 1	-	2	+	+	+	+	+	+	+
Tof 2	-	2	+	+	+	+	+	+	+
Tof 3	-	2	+	+	+	+	+	+	+
Seashell	-	2	+	+	+	+	+	+	+
Magnetic	-	2	+	+	+	+	+	+	+
Tactile	–	2	+	+	+	+	+	+	+
Propriocep.	-	2	+	+	+	+	+	+	+

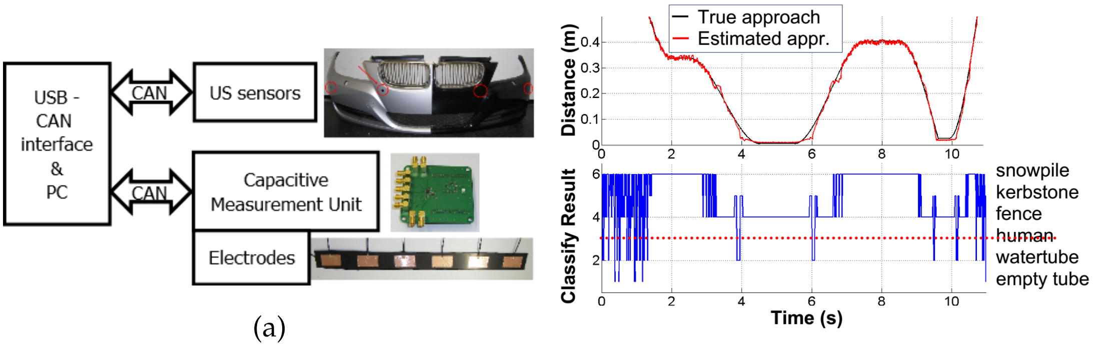
In this preliminary version not yet investigated.

capacitive sensing can be used. It also describes the benefits and drawbacks of each application and the applied measurement hardware (e.g. in the given examples each measurement hardware is only made for each unique application). The differences between the approach presented in this theses and the approaches in the presented applications in the following will be explained.

3.2.1 Car Bumper

In [Sch+10; Sch+11] a sensor fusion concept is presented which incorporates capacitance and ultrasonic (US) measurements for proximity determination in automotive applications (compare Fig. 3.5(a)). Although ultrasonic sensors are a well accepted technology for distance sensing applications, they reveal drawbacks in the closest vicinity of a vehicle (e.g. blind spots due to limited observation angle). Capacitive sensors used in this application are suited for proximity measurements of up to 0.3 m and also provide information about the approaching object itself. Thus, it can be used as a safety feature in terms of object classification. The measurement range of this fusion concept reaches up to 2 m whereby blind spots are avoided. The feasibility of this approach and its robustness against environmental influences is demonstrated by means of experimental investigations in [Sch+10; Sch+11].

The capacitance measurement system uses a commercially available capacitance to digital converter integrated in the Analog Devices IC AD7143 [Ana13]. Measurement results are shown in Fig. 3.5(b). It shows the sensor fusion systems estimated approaching line of a human (capacitance measurement system in combination with an US system). Several other approaching objects were measured and the their capacitance measurement traces were stored. To simulate real world conditions the capacitance measurement trace of the approaching



(a)

(b)

Figure 3.5: Sensor fusion system comprising capacitance and US measurements on a car bumper [Sch+11]. (a) Measurement setup for a sensor fusion system in automotive applications. It comprises US and capacitive sensors for proximity sensing and classification. (b) Distance estimation of an approaching and leaving human and selected object class based on a Kalman filter with a ML criterion [Sch+11]. The object class human was deleted from the stored measurements to simulate real world situations and demonstrate the robustness of the used algorithm.

human was deleted from the stored ones for the presented case. As can be seen from Fig. 3.5(b) the estimated approaching line nearly matches the true approaching line. The algorithm, which is based on a Kalman filter with a maximum likelihood (ML) criterion, estimates the objects which are most similar to the one of the human (in the presented case it was the object fence). Thus, the proximity sensor works as desired and also features a classification scheme which can be used to differ between different approaching object classes. This classification scheme enables the system for further safety features.

3.2.2 Icing

Another kind of application is shown in Fig. 3.6. A capacitive ice sensor working with a capacitive energy harvesting system is used for monitoring overhead power lines ([Mos+09; Mos+10; Mos+11]). Although the sensor is especially used to detect the beginning of icing, it represents a safety device according to our definition because it detects an object (i.e. ice) in a region where it just should not be (e.g. overhead power line). Other sensor systems for icing (e.g. presented in [Di +04; BLB08]) are wired and thus, limited to, e.g., transformer stations [Mos+11].

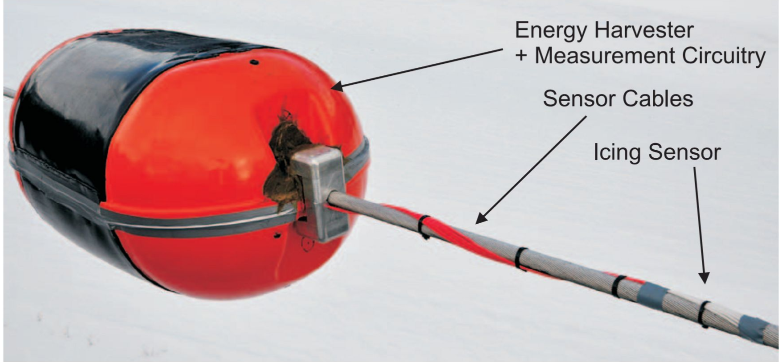


Figure 3.6: Photo of a capacitive ice sensor mounted on an overhead power line [Mos+10]. The energy harvester shell also comprises the measurement circuitry. The sensing electrodes are directly mounted on the power line.

The ice detection system presented in [Mos+10] uses an integrated capacitance to digital converter operating at a nominal frequency of 240 kHz. The measurement system works in the mutual capacitance mode with one transmitter and two receiver electrodes. It was shown that occurring icing on an overhead power line can be detected in laboratory measurements (e.g. climate room) as well as in a field test. There, the sensor system was mounted on a power line at a hilltop location in Austria. In both cases early icing could be detected and distinguished from melting. This is especially important for the de-icing process. The safety system comprises a capacitance measurement system for object detection (i.e., ice detection) and object classification (i.e., distinguish between ice and water).

3.2.3 Protection of Power-line Contacts

In [ZPN10] a protection system for construction workers to prevent electrocutions is presented. The worker has to wear the proposed capacitance sensor and if he approaches a live power-circuit, the system gives an alarm. Since contact with overhead power lines was the most frequent occurring event in construction industry in the United States from 2003 to 2006 ([Jan08]), such kind of safety sensor systems are of special interest.

The protection system for construction workers uses capacitance measurement hardware comprising a variable high-gain preamplifier, a narrow 60 Hz band-pass filter, a fixed gain post amplifier, an ADC and a communication unit for the connection with a host computer [ZPN10] (compare Fig. 3.7. The measurement results presented in [ZPN10] show, that an approach towards a power-line with both 120 V and 9000 V can be detected starting at a distance of approximately 1 m. Thus, a proximity sensor for an energized power circuit for the safety of construction workers was presented in [ZPN10].

3.2.4 Chainsaw

In [NS07] a capacitive sensor system is presented which switches off a machine (e.g. a chainsaw) if an object (e.g. human hand) comes too close. A conductive material has to be integrated into the object of interest (e.g. a dress with a garment with a wire cloth inserted). This conductive material is connected to a radio frequency generator. The generator is a 80 kHz Wien bridge oscillator and

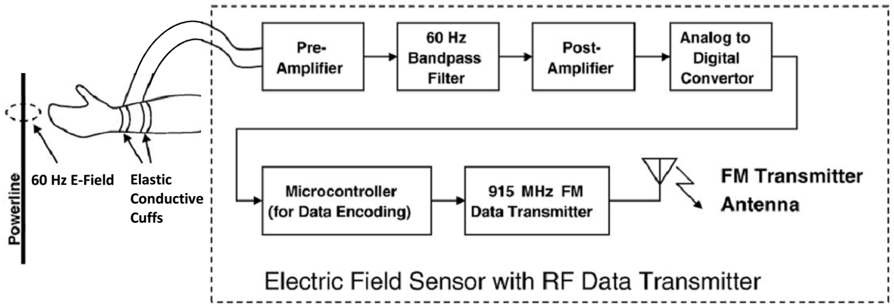
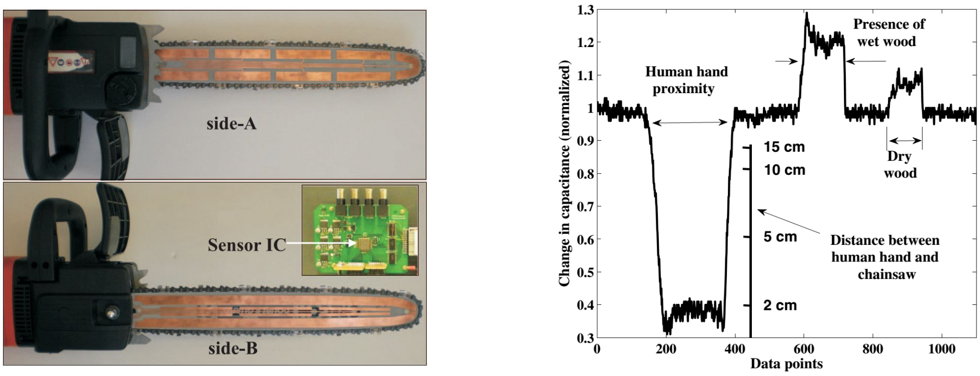


Figure 3.7: Block diagram of the power line contact protections system [ZPN10]. A FM transmitter is used to send the measurement data to a receiver for indication signaling and further decoding and analysing purposes.

the receiver detection unit, mounted on the chainsaw, has to measure this signal level. The 80 kHz signal level directly depends on the distance between the object and the chainsaw. It could be shown in [NS07] that a rectified mean value detector is able to measure the signal value through the capacitive connection between the transmitter and the receiver. Thus, a proximity switch is realized. It switches off the chainsaw at a distance of about 100 mm (equals a threshold of 300 mV which is early enough expecting a maximum blade speed of 2 m/s and a response time of 10 ms of the whole system.

In [GZB08] it could be shown that it is possible to detect humans and animals with a capacitance measurement system mounted on the chainsaw without the counter part on the object of interest (i.e. no generator is necessary, compare Fig. 3.8). Thus, the safety feature is not only limited to one object. As can be seen in Fig. 3.8(b) different approaching objects (humand hand and wood) can be distinguished by the proposed measurement system in [GZB08].



(a) (b)

Figure 3.8: Capacitive safety system on a chainsaw [GZB08]. (a) Picture of both sides of the chainsaw sword and the measurement circuitry. (b) Measurement results for different approaching objects.

3.2.5 Object Ranging and Material Type Identification

Not only proximity sensing but also material type identification was done in [Kir+08]. It is shown that the complex permittivity ε of an object is a function of the frequency of the measurement signal ω, given by the following equation

$$\varepsilon' = \varepsilon + i\frac{\sigma}{\omega}, \tag{3.1}$$

where ε denotes the permittivity and σ denotes the conductivity of the object. Thus, a material identification (i.e., identification of the complex permittivity ε) is possible with a varying measurement signal frequency. This kind of classification is necessary for safety applications since certain objects are allowed to be in areas where others are not.

The proximity and classification sensor presented in [Kir+08] uses two electrodes in a mutual capacitance system. The used measurement hardware was presented in [NW91; NF92; FN94]. It uses as sinusoidal signal as transmitter (first electrode) and a charge amplifier as receiver (second electrode). The measurements are done at three frequencies to obtain a material classification. Four types of material were tested: human, concrete, wood and metal. The promising results are shown in Table 3.2. The material classification result is used in the proximity determination algorithm resulting in a better distance estimation compared to the distance sensing without a classification.

Table 3.2: Material classification results in [%] [Kir+08].

Material under test	Concrete	Metal	Wood	Human
Concrete	**100**	0	0	0
Painted mild steel	0	**99.7**	0	0.3
Aluminum	0	**99.3**	0	0.7
Thick mild steel	0	**100**	0	0
Wood	0	0	**88.3**	11.7
Thick wood	0	0	**97.3**	2.7
Human	0	0	0	**100**

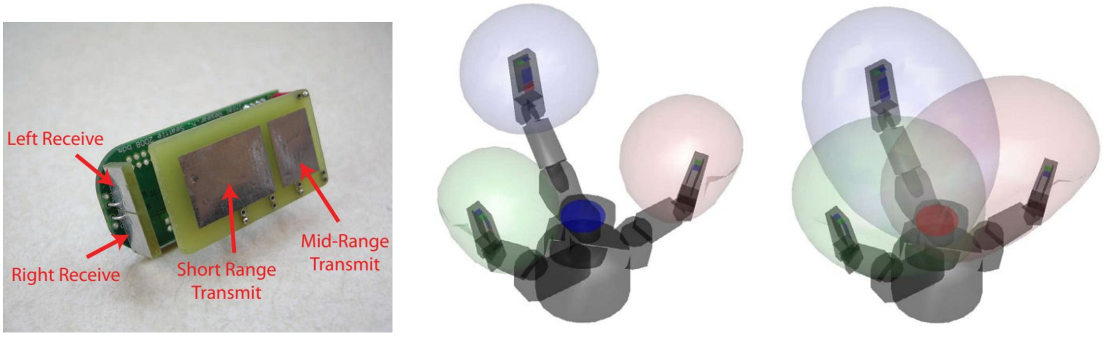
Bold values highlight the correct classification.

3.2.6 Pretouch for Robot Grasping

So called pretouch sensors are especially useful in robotic applications to close the gap between vision and tactile sensors. Pretouch sensors are not only able to benefit manipulation but also add a safety feature if an object classification is possible (e.g. a robot grasper is not allowed to grasp if a human hand is in the way). In the following two different approaches are presented:

Pretouch sensing for object alignment

In [MLS10; Lia12] a capacitive (also called electric field) pretouch sensor is presented, which is designed to be mounted into the fingers of a robot hand (Barret hand in the presented case). The sensor shown in Fig. 3.9(a) is used to align the three fingers of the robot hand around the object to grasp. Thus, when grasping the object all three fingers make contact with the object without displacing it.



(a) (b) (c)

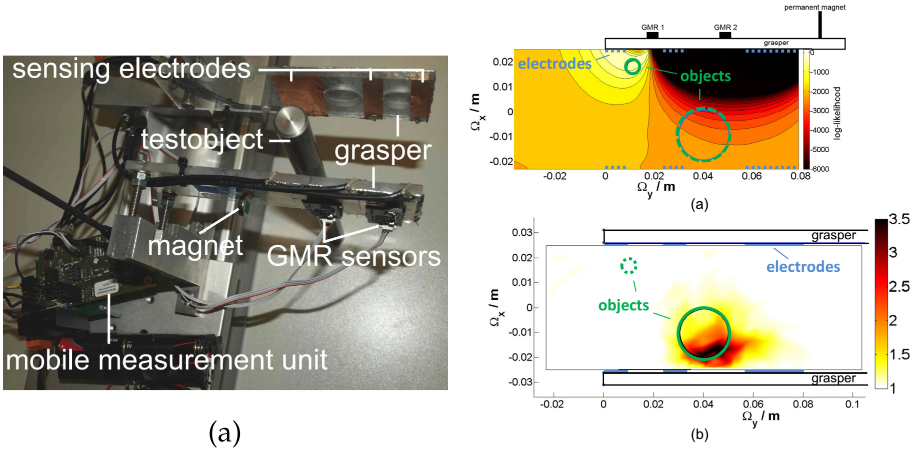
Figure 3.9: Robotic pretouch sensor mounted on the fingertips of a robot hand from [MLS10]. (a) Sensor hardware presented in [MLS10] which is mounted in the fingertips. (b) Iso signal surfaces for short range sensing. (c) Iso signal surfaces for mid range sensing.

As shown in Fig. 3.9(a) each fingertip consists of four electrodes (two transmitter and two receiver electrodes) which are used for short range (< 2 cm, Fig. 3.9(b)) and mid range (< 5 cm, Fig. 3.9(c)) sensing, respectively. Another electrode is positioned in the palm and is used as transmitter electrode. Using this palm transmitter and the fingertip receiver long range sensing (10 cm to 15 cm) is possible. The robot hand was able to pick up an object it was tuned for. Additionally it was able to grasp for an object which was brought into the vicinity by a human. As soon as the human disengage the object, the robot hand moves to a certain position with the object. Little information about the measurement circuitry and speed is given in [Lia12]. Although the sensor system showed promising performances for objects it was tuned for, it failed for objects which differed in size. However, the experiment with the human interaction showed the possibilities of such a capacitive sensing system for safety applications in robot applications.

Pretouch sensing using an ECT approach

Another pretouch application is presented in [Sch+12; Sch+13]. It uses a robot grasper which is attached with capacitive and GMR sensors (shown in Fig. 3.10(a)). Using the capacitance measurement data in an ECT manner (refer to Section) the region of interest (ROI) is reconstructed by means of 2D images of the spatial permittivity distribution (compare Fig. 3.10(b)). The measurement results of the GMR sensors are compared to simulation results of a 3D finite element method (FEM). The FEM results were precomputed for several positions of the object of interest. A maximum likelihood estimator (MLE) was used to estimate the position of the ferromagnetic object. The results for one position (i.e., likelihood of the position of the used iron rod in ROI) is shown in Fig. 3.10(b).

The sensor fusion approach in this application is specific to two types of materials. These are dielectric and ferromagnetic materials, which are commonly found in many industrial environments. Electric and magnetic fields are applied in the ROI and the distortion of these fields caused by objects is measured. Thus, a safety feature can be added: The grasper shown in Fig. 3.10 only grasps for certain objects (e.g. ferromagnetic objects) and does not grasp for e.g. a human hand or dielectric object in the ROI.



(a)

(b)

Figure 3.10: Robot grasper with GMR and capacitive sensing capability [Sch+13]. The test object (metallic rod) can be detected by the GMR sensors, dielectric objects can be detected with the capacitance measurements. Reconstruction results of the ECT robot grasper for two different objects (ferromagnetic and dielectric). (ba) Likelihood for the position of an iron rod. The small green circle indicates the true position of the iron rod and the dashed green circle the true position of a PVC rod which is not recognized by the GMR sensors. (bb) Reconstruction of the region of interest in an ECT manner. The spatial permittivity distribution is reconstructed. The true position of the PVC rod (indicated by the green circle) matches the reconstruction result. However, the shape cannot be reconstructed.

Although the reconstruction algorithms for the capacitance measurement part are taken from an ECT application without adoption for the open environment, the reconstruction shows promising results (shown in Fig. 3.10(b)). Dielectric objects (e.g. PVC rod) and ferromagnetic objects (e.g. iron rod) can be detected by this measurement system. However, because of parasitic effects due to the open environment (explained in Section) the iron rod can not be reconstructed using the capacitance measurement system on its one. The capacitance measurement system uses the mutual capacitance mode in a Low-Z scheme. With an additional self-capacitance measurement system (i.e., measuring the displacement current originating the sensing electrodes) it should be possible to overcome the parasitic effects, which originally resulted in blind spots for certain objects.

3.2.7 Comparison of State of the Art Capacitive Sensing

This subsection comprises the presented sensing techniques in Table 3.3.

Table 3.3: Overview and comparison of presented capacitance measurement systems.

System	References	P. 1	P. 2	P. 3	P. 4
Car bumper	[Sch+10; Sch+11]	+	1	1	1
Icing	[Mos+09; Mos+10; Mos+11]	+	2	2	2
Protection of powerline contacts	[ZPN10]	+	3	3	3
Chainsaw	[NS07; GZB08]	+	4	4	4
Object ranging & Ident.	[Kir+08]	+	5	5	5
Pretouch for grasper 1	[MLS10; Lia12]	+	6	6	6
Pretouch for grasper 2	[Sch+12; Sch+13]	+	8	8	8

In this preliminary version not yet investigated.

4 Open Environment Capacitive Sensing

Capacitive sensing is known for a long time. The Theremin can be seen as the first capacitive proximity sensor. It is an electronic music instrument which is controlled without contact between the player and the instrument [Sal10]. It was presented in the early 1920s. Although capacitive sensing is known for such a long time, it did not get used in a wide field of applications until the last two decades. Since then, necessary hardware is available in integrated circuits (IC) and capacitive sensing is used in commercial applications such as touch screens ([SS91; Gou+90]), e.g. in mobile phones and for many other applications ([Pue93] [KLY11] [TRL12]).

As shown in Section 3.2, in most applications where capacitive sensing is used, the environment is known and (or) defined within certain limits. If using a capacitance measurement system for a wide field of applications in the open environment, this is not necessarily true as shown later in this section. A benefit of capacitive sensing is the ability to work with a wide variety of materials. However, it is therefore also sensitive to disturbers like objects of no interest, dirt, moisture, etc. Thus, certain issues have to be taken into account to use capacitive sensing in an uncertain environment.

The following section aims to give:

- An introduction to the physics behind capacitive sensing to understand the various effects occurring in the open environment.
- An overview of occurring parasitic effects.
- An explanation of the difference between short and long distance sensing (i.e., shielding and coupling effects).
- A presentation of a related technology called Electrical Capacitance Tomography (ECT) which is proposed to be adopted for the use in open environment sensing.

4.1 Physics behind Capacitive Sensing

Capacitive sensors consist of at least two conductors (called electrodes) which are separated by a non-conducting material. The distant ground potential can also be seen as one of these two electrodes. An electric field occurs whenever the two electrodes are on different electrical potentials. Capacitive sensing is well described by the Maxwell equations. After transformations and simplifications (e.g. wavelength of sensing signal is much larger than the sensing electrodes) the partial differential equation

$$\nabla \cdot ((\sigma + j\omega\varepsilon)\nabla V) = 0, \tag{4.1}$$

can be obtained, where V denotes the electric scalar potential, σ denotes the conductivity, ω denotes the wavelength and ε denotes the dielectric permittivity. This equation possesses a unique solution when boundary conditions (e.g. potentials and perhaps surface current densities on electrodes) are known. More details can be found e.g. in [Bax97; Dye04] and the literature referenced there .

4.2 Parasitic Effects

In order to assess advantages and disadvantages of possible circuitry for capacitive sensing a model of the sensor front-end is necessary. Fig. 4.1 shows a model, which is an extension to the equivalent circuit used in [Zan05; Bra+05]. It additionally considers an approaching object (if measuring in the open environment) and electromagnetic compatibility (EMC). The three main parasitic effects shown in Fig. 4.1 are:

- Parasitic connection to ground through the equivalent parallel circuits (R_{GND}, L_{GND}, C_{GND}, R_{1_GND}, L_{1_GND}, C_{1_GND} and R_{2_GND}, L_{2_GND}, C_{2_GND}) connected to the sensing electrodes 1 and 2 and the approaching object. Thus, only a part of the displacement current (indicated by red arrows) originating from electrode 1 is entering electrode 2 and is measured in the mutual capacitance mode (see Section 5.1).
- Capacitive crosstalk from disturbers and electrostatic discharge (ESD) to the sensing electrodes indicated by U_{D1} and U_{D2}. This is especially a problem in open environment measurements and its influence can be reduced by e.g. methods shown in [Bra03].
- Resistive path R_{1_2} parallel to the capacitance of interest C_{TR}.

The used measurement circuitry has to deal with these parasitic effects [ZN10]. Table 5.1 gives an overview of how these parasitic effects influence the different measurement circuitries.

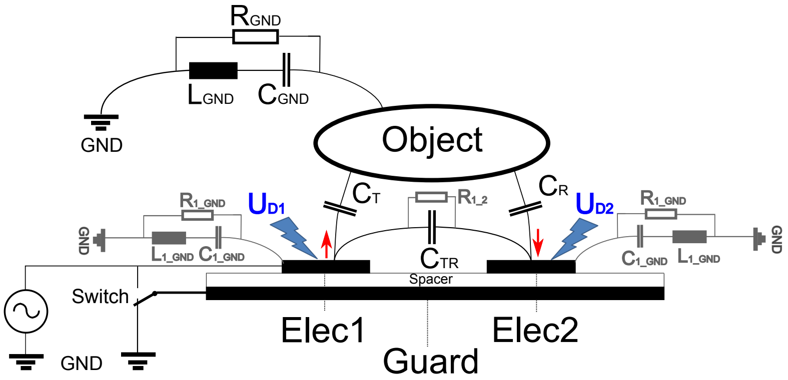


Figure 4.1: Sketch of a two-electrode capacitive sensor front end including several parasitic effects [SZ14]. Red arrows indicate the displacement current originating electrode 1 (Elec1) and entering electrode 2 (Elec2). U_{D1} and U_{D2} denote capacitive crosstalk from disturbers in the vicinity and ESD to Elec1 and Elec2. The main parasitic effects to ground are shown by the equivalent parallel circuits connected to the electrodes and the object. Depending on the measurement mode (refer to Section 5.1) the guard electrode can be set ground or the excitation signal (i.e., active guarding).

4.3 Shielding and Coupling

Two other effects which can be observed with capacitive sensing are the so called coupling and shielding effect [Zan05]. They occur for certain objects and depend on the properties of these approaching objects. Beside others, the capacitive connection of the objects to the distance ground is an important property. As shown in Fig. 4.1 it mostly depends on the capacitances C_{GND}, C_T, C_{TR} and C_R. If a capacitive sensor system is measuring in mutual capacitance mode (see Section 5.1) and an object approaches, the displacement current originating from electrode 1 can go to electrode 2 and to the distance ground GND. How much displacement current is entering electrode 2 depends on the relation between C_{GND} (which stays nearly constant for an approaching object) and the capacitance of the parallel circuit of C_T, C_{TR} and C_R (which increases for an approaching object). A bigger portion of the displacement current goes from electrode 1 through C_T and C_{GND} to the distance ground for an object further away (since the capacitance of the parallel circuit C_{GND}, C_T, C_{TR} is rather small). Thus, at first the measured capacitance decreases with an approaching object. This is called shielding mode. At a certain distance to the sensor surface the capacitance of the parallel circuit C_{GND}, C_T, C_{TR} gets a higher influence than C_T and C_{GND} and more displacement current goes from electrode 1 to electrode 2 than to the distance ground. The measured capacitance increases and this is called the coupling mode. Because these effects strongly depend on the approaching object, it can also be used for classification of the approaching object as shown in [SZ11]. Both effects can be observed in the presented measurements in Sections 5.2.2.

4.4 Geometric Effects

This section was already published in [SBZ11]. One benefit of capacitance sensors is their possibility to be installed on planar and non-planar surfaces. The sensor elements (i.e. the electrodes) are unparalleled simple while providing high versatility with respect to geometrical constraints. Hence, this technology also allows monitoring complex structures or machines, where traditional systems e.g. based on a line of sight principle fail. However, the individual shapes of the sensor electrodes dictate the coupling mechanisms between the electrodes to objects in the environment. In the following, analysis of the 3D sensitivity distribution of an example sensor setup by means of numerical analysis and comparative studies with equivalent circuit models are provided. Furthermore, impacts are analysed and demonstrated by means of experimental investigations and numerical simulations.

4.4.1 Experimental Setup

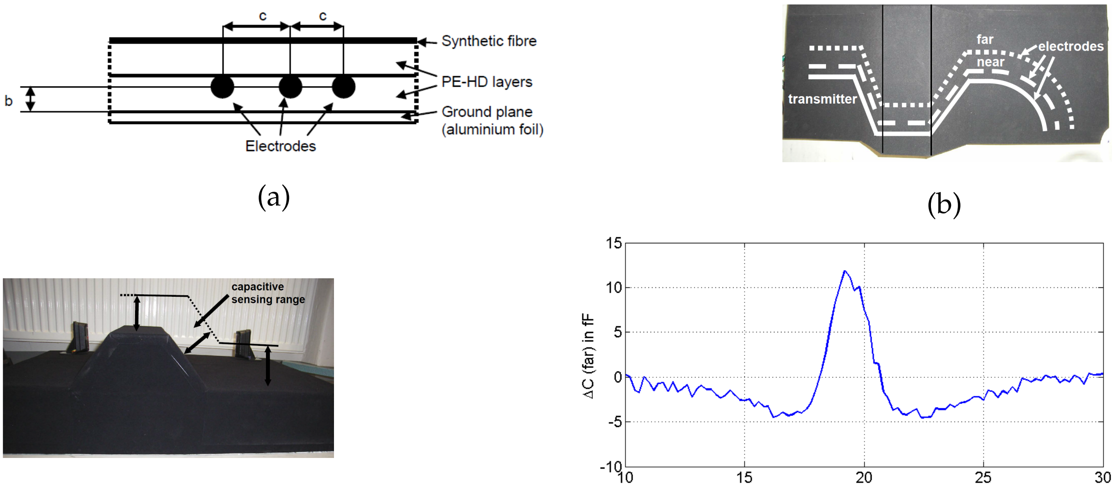
The developed test setup is shown in Fig. 4.2 . It uses three electrodes (one transmitter electrode and two receiver electrodes) to determine the distance to an approaching object. A sketch in Fig. 4.2(a) shows the different layers of the test setup. The electrodes are positioned under a sheet of black synthetic fibre and two layers of polyethylene of higher density. They are realized by 1 m long and 0.51 mm thick simple electric wires, which permit the realization of a very flexible electrode structure. To make the sensor sensitive in only one direction (above the electrodes) a ground plane made of an aluminium foil beneath the electrodes is used. The frame itself is built up with polystyrene (styrofoam). To determine the capacitance between a pair of electrodes, a commercial available capacitance to digital converter was used [Ana13]. A wireless transmitter connects to a host controller for evaluating the measurement results and permitting a portable and flexible experimental setup. Measurement results for an approaching human hand are shown in Fig. 4.2(d).

4.4.2 Sensitivity Analysis of the Electrode Structure

The capacitance between a pair of electrodes separated by c, with a length L, a radius a, and a distance b between the electrodes and the ground plane (all in metres) can be approximated by [Bax97]:

$$C \approx \frac{\pi \varepsilon_0 \varepsilon_r L \ln(1 + \frac{2b}{c})}{(\ln \frac{2b}{a})^2} \tag{4.2}$$

For the presented parallel electrode structure with the length of 1 m and a relative permittivity ε_r of 1, capacitances of 1276 fF and 361 fF for the near and the far electrode, respectively, can be calculated.



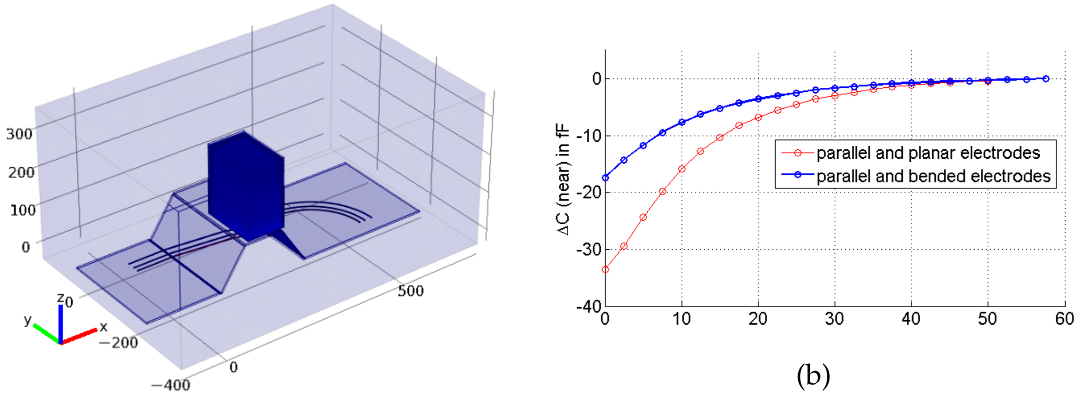
(a)

(b)

(c)

(d)

Figure 4.2: Experimental test setup used for sensitivity analysis of bending electrode structures [SBZ11]. (a) Cross section of the experimental setup with the different layers (drawn not in scale). (b) and (c) Pictures of the experimental test setup comprising three electrodes with a length of 1 m. (d) Measurement results for an approaching human hand above a parallel electrode area of the experimental test structure.



(b)

(a)

Figure 4.3: Simulation setup and results for an object approaching to different positions [SZ11]. (a) Picture of the FEM simulation setup to recreate the experimental setup. (b) Simulation results for two electrode structures (near and far) and one object approaching to different positions of the setup surface.

The investigation of impacts on the sensitivity due to bending electrode structures are based on finite element simulations. Two scenarios for an approaching object are chosen and compared with the ideal situation (i.e. parallel electrode structure, compare Fig. 4.2(b)). The simulation setup is shown Fig. 4.3(a), corresponding results are shown in Fig. 4.3(b). The approaching object was simulated as a whole block, with slices of different relative permittivity ε_r to simulate an approach while keeping the same mesh. As can be seen from Fig. 4.2(d) and Fig. 4.3(b), the simulation results match with the measurement results. Small differences originate from differences between the experimental setup and the simulated geometry (e.g. laying of electrodes).

In curved areas the sensitivity of the sensor deviates from the sensitivity obtained by a planar sensor arrangement. As can be seen Fig. 4.3(b) the sensitivity increases for objects approaching above curved electrode structures. Due to the increased covered electrode area, a higher capacitance is measured. Thus, the approaching object appears closer than it really is. Especially for short distances this effect would lead to a wrong distance measurement for the whole sensor arrangement if no countermeasures are made. If only the curved electrode structure is exposed to an approaching object, distance measurement is still possible because of the unambiguousness with the near and the far electrode. If an object approaches in a non parallel configuration (e.g. rising area of the experimental test setup in Fig. 4.2(c)) a smaller capacitance is measured as shown in Fig. 4.3(b). If an object enters the vicinity of such a structure, the measured capacitance is smaller compared to the ideal case. Thus, a measurement system would provide a distance which is farther away than the object.

To overcome these difficulties of elongated and non-planar capacitive sensors, the sensitivity of the sensor has to be increased or decreased in the special areas. Possibilities would be a decrease or increase of

- the distance between the sensor electrodes,
- the relative permittivity ε_r (e.g. another spacer material), or
- the electrode surface

in the desired areas.

4.5 ECT Approach

A related technology is Electrical Capacitance Tomography (ECT). It is used in industrial processes to obtain 2D cross sectional image of the material (i.e. permittivity) distribution within pipes [NSW12]. ECT is essentially an array of capacitive sensors with heavy signal processing to calculate an image of the region of interest ([Neu+11; WF09; YP03]). The calculation has to deal with a nonlinear and ill-posed inverse problem [SL05] with a higher number of unknowns (i.e. number of pixels) than independent measurements (i.e., number of capacitance measurements). Thus, the reconstruction method typically needs some kind of regularization or prior knowledge (e.g. Tikhonov regularization, total variation). The calculation or reconstruction methods for online reconstruction can typically be divided in two types [Isa96]: Non-iterative algorithms such as Offline Iteration/Online Reconstruction [Liu+04], Optimal Approximation [Zan+07] and Singular Value Decomposition as well as iterative algorithms (such as Gauss-Newton methods [BHW03] also in combination with statistical methods like Particle Filter [WSB07] or Kalman Filter [TGA04; M V+07]). Other approaches presented in [NBB95] and [Zan+06] use neural networks for solving this inverse problem. An example of an ECT system is given in the following section.

4.5.1 A Mobile and Wireless ECT System

This section was already published in [SNZ12]. In the following a multi channel capacitive measurement system used for an ECT sensor is presented. The system is capable to determine the capacitances of all pairs of electrodes of an arrangement consisting of N_elec electrodes. For simplified instrumentation the system features a wireless data transmission to a host. Thus, cabling can be avoided making the system versatile and in particular useful in applications with difficult measurand access like in the case of operation on high voltage parts or on moving parts. The system is not limited to specific electrode designs and thus permits using optimized electrode designs for specific tasks. With its small geometric outline, low weight and low power consumption the measurement systems is well suited for fast prototyping of ECT systems.

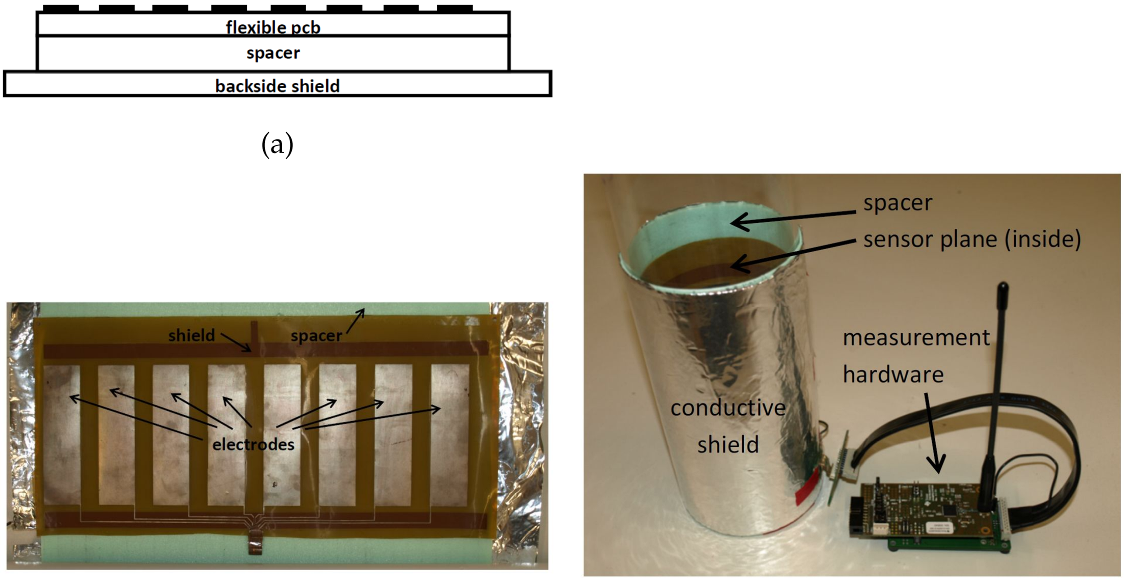
Fig. 4.4(a) depicts a sketch and Fig. 4.4(b) a photography of the flexible electrodes. Eight electrodes were placed on a flexible printed circuit board (PCB) material such that the sensor can be fitted to the circumference of a certain pipe. In order to be insensitive with respect to the backside region of the electrodes the sensor is shielded using a screen, which was realized by aluminium foil. This can be seen in Fig. 4.4(c). The screen is connected to the measurement ground. To minimize the offset capacitance caused by the screen, the relative permittivity of the spacer material has to be low. Following the recommendations on the design of ECT sensors presented in [Yan10] two axial screens in the upside and downside direction of the sensor were applied.

Fig. 4.4(c) depicts the complete system consisting of the ECT sensor and the multichannel capacitive measurement system. The pipe is made out of acrylic glass. As can be seen, the design and the setup of the ECT sensor is kept on an overall simple level. With the setup it is possible to determine the capacitance matrix C which contains the capacitances between all possible pairs of electrodes (8×8 matrix because of eight electrodes).

Solving the Inverse Problem

This section summarizes the algorithmic approach to determine the spatial permittivity distribution inside the pipe from measurements $\tilde{\boldsymbol{d}}$. For a brief overview and a general introduction to the inverse problem of ECT it is referred to [Neu+11].

Let $\partial\Omega$ denote the screen bounding of the problem domain Ω and Ω_{ROI} denote the domain inside the pipe. The boundaries of the electrodes are referred to as



(a)

(b)

(c)

Figure 4.4: A mobile and wireless ECT measurement system [SNZ12]. (a) Sketch of the different layers of the sensor plane. A spacer between backside shield and PCB is used to keep the offset capacitance low. (b) Eight electrodes and two axial end screens on the top and bottom side of the PCB, respectively, are used for the ECT system. (c) Picture of the measurement setup comprising the sensor plane attached on a pipe made of acrylic glass and the measurement hardware including the RF transmitter.

Γ_i, $i = 1 \ldots N_{\text{elec}}$. Using an electrostatic formulation of the Maxwell's equations, electric fields in Ω are governed by the potential equation $\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V) = 0$, where V is the electric scalar potential. ε_0 and ε_r are the absolute and the relative permittivity. The boundary conditions are of Dirichlet type and given by $V_{\partial\Omega} = 0$ on the screen, $V_{\Gamma_j} = V_0$ on the transmitter electrode and $V_{\Gamma_i} = 0$, $i \neq j$, on the remaining $(N_{\text{elec}} - 1)$ receiver electrodes. The inter electrode capacitances are computed by Gauss's law

$$c_{i,j} = \frac{1}{V_0} \int_{\Gamma_i} \vec{n} \cdot \varepsilon_0 \varepsilon_r \nabla V_j ds, \tag{4.3}$$

and stored in the matrix $\boldsymbol{C} = [c_{i,j}]$, where each column corresponds to one transmitter electrode and each line to one receiver electrode.

The computation of $\boldsymbol{C}$ given the permittivity distribution is referred to as forward map $F : \boldsymbol{x} \mapsto \boldsymbol{C}$. Hereby the state vector $\boldsymbol{x}$ denotes a parametric description of the material distribution in Ω_{ROI}. The numerical evaluation of F is done by means of the finite element method (FEM). $\boldsymbol{x}$ contains the relative permittivities inside of the corresponding finite elements. For the determination of $\boldsymbol{x}$, given the measurements $\tilde{\boldsymbol{d}}$ we use a nonlinear approach. Let $\boldsymbol{y}$ denote the components of $\boldsymbol{C}$ corresponding to the measurements collected in $\tilde{\boldsymbol{d}}$. Then $\boldsymbol{x}$ can be found by solving an optimization problem of form

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} ||\boldsymbol{y}(\boldsymbol{x}) - \tilde{\boldsymbol{d}}||_2^2 + \alpha ||\boldsymbol{L}\boldsymbol{x}||_2^2. \tag{4.4}$$

The first term minimizes the misfit between the model and the data. The second term is a so called regularization term, which is necessary achieve a numerical stable solution. This is required due to the ill-posed nature of the inverse problem. $\boldsymbol{L}$ is referred to as regularization matrix and α is the regularization parameter. For the solution of (4.4) a Gauss-Newton (GN) method is applied to find $\boldsymbol{x}^*$ in an iterative way by

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + s \left(\boldsymbol{J}\boldsymbol{J}^T + \alpha \boldsymbol{L}^T \boldsymbol{L} \right)^{-1} \left(\boldsymbol{J}\boldsymbol{r} + \alpha \boldsymbol{L}^T \boldsymbol{L} \boldsymbol{x}_k \right), \tag{4.5}$$

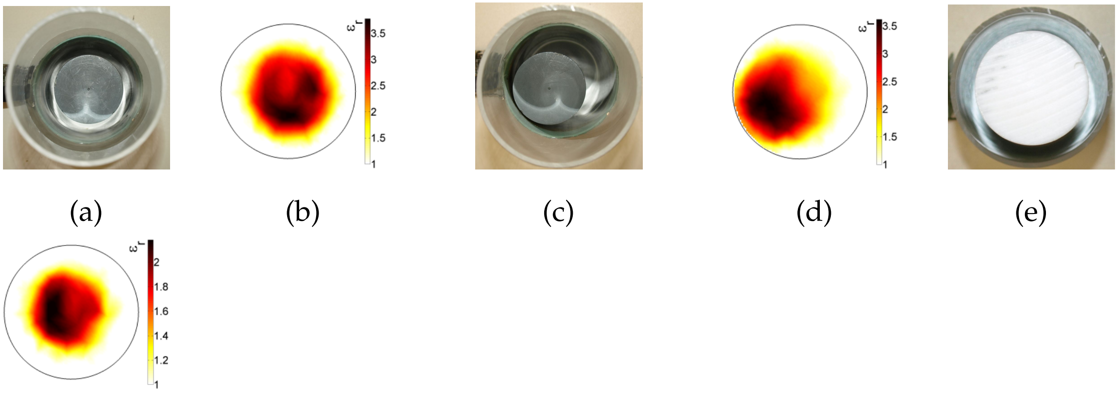
where $\boldsymbol{J}$ denotes the Jacobian and s is a step width parameter and $\boldsymbol{r} = \boldsymbol{y} - \tilde{\boldsymbol{d}}$ is the residual vector.

It has to be mentioned that a reconstruction of measured data requires a calibration strategy in order to minimize the difference between the physical process $P : \boldsymbol{x} \mapsto \tilde{\boldsymbol{d}}$ (the sensor) and the forward map F [Neu11]. For model based inversion techniques calibration has to be applied if the model error $e = P - F$ outweighs the measurement noise. For the presented ECT system a two point calibration is used with an air filled pipe and a solid polyvinyl chloride (PVC) block filling the entire pipe. Then, an affine transformation $\hat{c}_{i,j} = \rho_{i,j} c_{i,j} + c_{0,i,j}$ is applied to the output of F and $\hat{\boldsymbol{C}} = [\hat{c}_{i,j}]$ is used to assembly $\boldsymbol{y}$. Hereby, the gain $\rho_{i,j}$ and the offset $c_{0,i,j}$ are determined from the calibration measurements. This approach can also be applied to calibrate the measurements $\tilde{\boldsymbol{d}}$. Then $\boldsymbol{y}$ is obtained from $\boldsymbol{C}$.

Experimental Results

In the following experimental results are shown to give an idea of the capability of the proposed approach. Fig. 4.5 depicts the measurement setups and the corresponding simulation results.

In the first experiment shown in Fig. 4.5(a) a PVC block with a diameter of 65 mm was placed in the center of the pipe. The reconstruction result of the non invasive measurement is shown in Fig. 4.5(b). As can be seen, the relative permittivity distribution in the inside of the pipe can be reconstructed. According to the so called soft field nature [Bax97] of the capacitive measurement system a certain smoothness occurs to the reconstructed relative permittivity distribution in the inside of the pipe. Fig. 4.5(c) and (d) show the true position



(a) (b) (c) (d) (e)

(f)

Figure 4.5: Experimental results of the presented ECT system [SNZ12]. (a) and (b) PVC rod at the center of the pipe ($\varepsilon_r \approx 3.5$). (c) and (d) Same PVC rod positioned on the left side. (e) and (f) Teflon rod ($\varepsilon_r \approx 2.2$) positioned at the center (different scale).

and reconstruction result of the same PVC block at a different position inside the pipe. Again it is possible to reconstruct the position of the PVC rod in the inside. The third measurement in Fig. 4.5(e) and (f) a rod with a diameter of 50 mm made of polytetrafluoroethylene (PTFE or teflon) is positioned in the center of the pipe. It is possible to reconstruct the true relative permittivity $\varepsilon_r \approx 2.2$ of the rod. Also the position inside the pipe can be estimated.

4.5.2 From ECT to Open Environment Sensing

This section was already published in [SZ14]. Fig. 4.6 shows the idea of using an ECT approach for capacitive safety applications. The enclosed structure of the capacitive array is opened and attached to the surface of interest. The measurements obtained by the measurement circuitry are processed in an ECT manner. Compared to ECT the environment for such a safety device is very uncertain in most cases. Additional parasitic effects (shown in Fig. 4.1) can have a huge influence on the measurement results and also the measurement circuitry has to have the ability to deal with these effects (compare Table 5.1).

Recently in [Sch+13] it could be shown that such an ECT approach can be transferred to the open environment for e.g. safety applications. Although it showed promising results, limitations due to the measurement hardware and open environment effects (describe in Section 4.2) were found and are presented in the following.

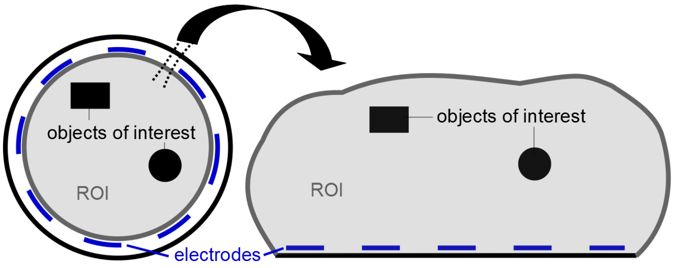


Figure 4.6: Sketch of the proposed idea to transfer the ECT approach to capacitive sensing for the open environment [SZ14]. The enclosed structure of an ECT system is opened and attached to the surface of interest. The ROI changes from the well known inside of e.g. a pipe to the uncertain open environment.

5 Measurement System for Open Environment Applications

This section was already published in [SZ14].

5.1 Measurement Circuitries and Modes

There exist a huge variety of measurement circuitries for measuring electrical capacitances. A coarse classification presented in [Bax97] can be as follows

- Direct DC
- Oscillators
- Single-ended
- High-Z
- Low-Z
- Bridge

Table 5.1 gives an overview of the circuitries most commonly used for proximity sensing (i.e., direct DC and single-ended measurement systems are not taken into account). This work focuses on the effects arising when capacitive sensing gets into the open environment (which most often is the case in safety applications) rather than on the different properties of the circuitries. The interested reader can refer to [Bax97; Cui+11; Weg+05] and to the literature referenced there for more information on capacitance measurement circuitries.

It is also possible to distinguish the sensing system by the used measurement mode. The two different modes are often denoted as

- Mutual capacitance mode and
- Self capacitance mode.

The first mode utilizes measurements of the capacitance between two electrodes by applying a voltage on one electrode and measuring e.g. the displacement current on the other electrode (i.e., Low-Z circuitry). The second mode utilizes measurements of the displacement current originating from one electrode to the distance ground.

A difficulty associated with the self capacitance mode is the fact that the sensitivity is quite high at the edges of the electrodes in particular when conductive objects resides in the vicinity, e.g. as the carrier of the electrode. In this case moisture and contamination may significantly affect the measurement and no reliable proximity determination may be possible. A commonly used method to cope with this problem is active guarding where a guard is placed between the actual electrode and a metallic carrier. Thus, the sensitivity moves away from the edges of the electrodes. However, this also leads to a reduced sensitivity with respect to small objects in the vicinity of the electrodes. On the other side, the self capacitance mode usually offers a higher signal to noise ratio (SNR) compared to the mutual capacitance mode and, in conjunction with active guarding, a high robustness. The mutual capacitance mode usually has a worse SNR but has the capability to detect objects in situations where the self

Table 5.1: Comparison of different capacitive sensor front-end circuitry (adopted from [Zano5]). The lower part of the table indicates, whether a circuit is sensitive (-) or insensitive (+) to one of the parasitic effects shown in Fig. 4.1.

Class	Oscillators		High Z		Low Z		Bridge
Circuit	RC	SC	CF	DC	CA	CF	CF
Guarding	active	passive	active	active	passive	passive	passive
ADC required?	no	no	yes	yes	yes	yes	yes
BP filtering	no	no	difficult	diff.	possible	possible	possible
Complexity	low	low	high w. guarding	low	medium	high	high
Sens. to res. shunt	yes	minor	yes	yes	medium	minor	minor
Extended wire length?	minor	minor	no	no	minor	yes	yes
Long time stability	moderate	moderate	low to medium	low to medium	moderate	low to medium	medium/low
Short time stability	good	good	good	good	good	good	good
EMC emission	low	SR limit.	SR limit.	very low	SR limit.	SR limit.	SR limit.
EMC sensitivity	high	medium	low (freq. shifting)	high	medium	low (freq. shifting)	low (freq. shifting)
Spark discharge sens.	low	low	high	high	low	low	low
Measurement rate	low	low	medium	high	high	medium	medium
Matching	medium	good	medium	medium	good	good	good
Power consumption	low	low	moderate	low	low	moderate	medium
Suppression of:							
R_{1_GND}	+	+	+	+	+	+	+
C_{1_GND}	+	+	+	+	+	+	+
R_{1_2}	-	+	-	-	+	+	+
R_{2_GND}	+	+	-	-	+	+	+
C_{2_GND}	+	+	-	-	+	+	+
U_{D1}	-	+	+	+	+	+	+
U_{D2}	+	-	-	-	-	+	+
ESD 1	-	+	+	+	+	+	+
ESD 2	+	+	-	-	+	+	+

RC: Resistor/Capacitor, SC: Switched Capacitor, CF Carrier Frequency, CA Charge Amplifier, DC Direct Current, SR limit.: Slew rate limitation required.

capacitance mode is blind. Thus, a measurement circuitry which combines both measurement modes is preferable for applications where objects of different sizes and permittivities in different distances to the sensor surface have to be measured (e.g. in safety applications).

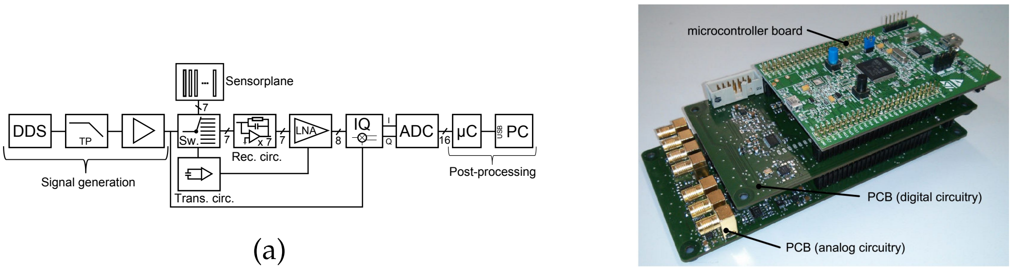
In the following section, the different types of measurement hardware used in the example applications are presented. Measurement results are shown where applicable and the different approaches for safety applications are compared.

5.2 Capacitance Measurement System

Taking into account the parasitic effects occurring in open environment measurements (presented in Section 4.2) and following the proposed ECT approach in Section 4.5 a new capacitance measurement hardware is presented in [Sch+ed]. It is shown how this measurement system is beneficial compared to the example applications. A comparison with two commercial available capacitance measurement systems highlights the performance of the presented system. Furthermore, the presented measurement system is tested in a robot application and its feasibility is demonstrated by means of experimental investigations.

5.2.1 Design of the Evaluation Circuitry

An overview of the presented measurement system is shown in Fig. 5.1(a). A sinusoidal signal, generated by a direct digital synthesizer (DDS), is applied to one or more electrodes through a switch circuitry. The displacement current originating the electrodes used as transmitters is measured by a transmitter circuitry [Sch+ed]. Each electrode is also connected to a receiver circuitry.



(a)

(b)

Figure 5.1: Proposed capacitance evaluation circuitry [SZ14]. (a) Overview of the different parts of the measurement system. (b) Picture of the three stacked PCBs of the evaluation circuitry.

If an electrode is not used as a transmitter, the receiver circuitry measures the displacement current entering this electrode. Since each electrode can be used as a transmitter or a receiver a total of $\frac{N_{elec}(N_{elec}-1)}{2}$ independent measurements, where N_{elec} is the number of electrodes, can be obtained with the mutual capacitance mode. With the additional self capacitance mode a total of $\frac{N_{elec}\,(N_{elec}-1)}{2} + N_{elec}$ independent measurements can be obtained. Additionally, the backside of the sensor can be connected to ground (mutual capacitance mode) or to the excitation signal (i.e., active guarding in self capacitance mode). This function is also possible with each electrode if the electrode is not used as transmitter or receiver. After amplification an IQ-Demodulator is used to get phase and amplitude information of the measured signals with respect to the excitation signal. The post processing consists of an ADC and a microcontroller (μC). The μC is used to control the measurement hardware (e.g. ADC, IQ-Demodulator, DDS, etc.), store the measurement signals and communicate with a host computer to do further post processing (e.g. reconstruction algorithms).

The proposed measurement system (shown in Fig. 5.1(b)) is able to work in the mutual capacitance mode and the self capacitance mode. It provides a high measurement rate ($> 1\,\text{kHz}$). The measurement frequency can be changed between 10 kHz and 1 MHz to any frequency value of interest. Thus, it is possible to obtain additional information about parasitic effects, due to their frequency dependency as shown in Fig. 4.1. This also gives additional information for material classification [Kir+08]. Furthermore, a change in the measurement frequency can be used to deal with EMC problems as shown in [Bra03].

As shown in Fig. 5.1(b) the measurement hardware consists of three stacked printed circuit boards (PCB). The top PCB is a commercial available microcontroller evaluation board. The PCB positioned central comprises all digital parts (e.g. clock generator, DDS, ADC, etc.). The bottom PCB comprises the analog circuitries such as transmitter and receiver circuitries and IQ-Demodulator.

Since each electrode can be used as transmitter and receiver the proposed measurement system can also be used for ECT applications. Thus, it is appropriate for the stated approach for capacitive safety applications in Section 4.5.

5.2.2 Comparison with State of the art Capacitive Sensors

Table 5.2 gives an overview of the proposed measurement system [Sch+ed] and two commercial available systems [Ana13]. One of the commercial available measurement systems is working in the self capacitance mode (AD7148) and the other one is working in the mutual capacitance mode (AD7746). Although there exists a huge variety of capacitance measurement systems (compare Section 3.2), these systems are appropriate as state of the art systems by means of resolution and speed (i.e., measurement update rate).

Several experiments (Fig. 5.2(a) to 5.2(c)) were carried out in [Sch+ed] with the proposed measurement system and compared to the two commercial available

Table 5.2: Properties of the proposed measurement system compared to state of the art sensors [SZ14].

	Proposed sensor	AD7746	AD7148
Excitation signal	Sinusoidal signal	Square wave	Square wave
Frequency	Tunable from 10 kHz to 1000 kHz	32 kHz	250 kHz
Measurement rate	1.25 kHz (max. 6.25 kHz @ 1 MHz)	10 Hz to 90 Hz	40 Hz
Measurement method	Self cap. and mutual cap. mode	Mutual cap. mode	Self cap. mode
Shielding	Active guarding and Grounded shielding	Grounded shielding	Active guarding
Number of electrodes	$N_{elec} = 7$	$N_{elec} = 3$	$N_{elec} = 8$
Number of independent measurements	28 $\left(= \frac{N_{elec}\,(N_{elec}-1)}{2} + N_{elec}\right)$ for each frequency	2	8

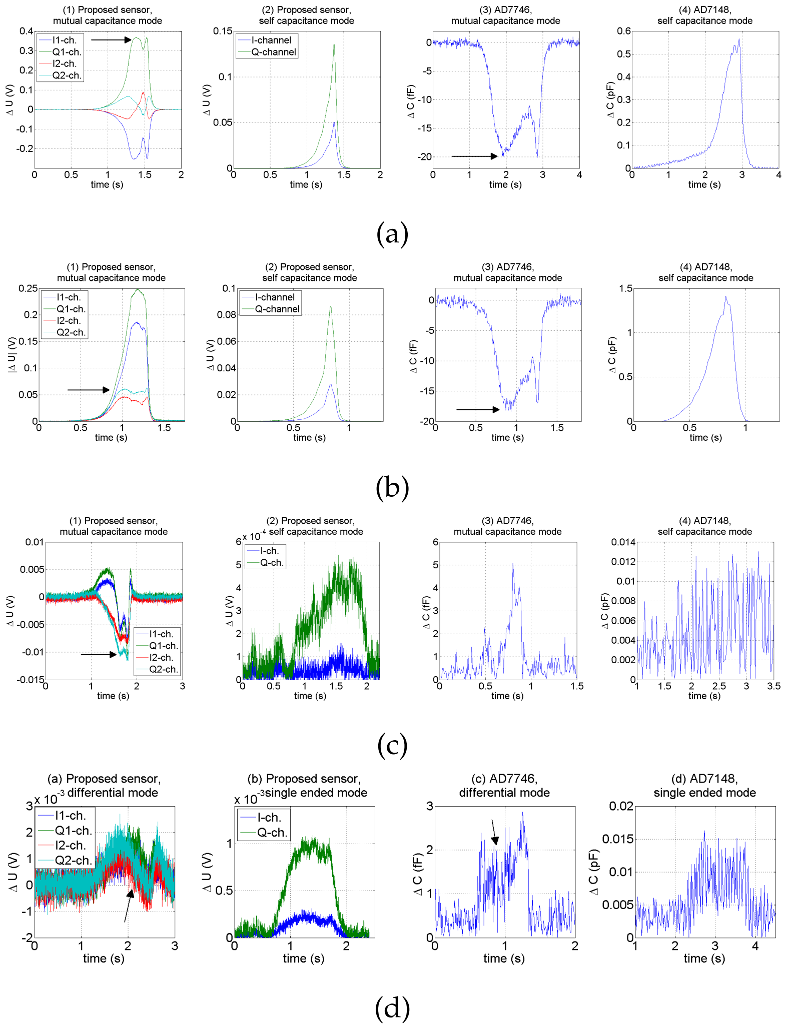
ones (Analog Devices AD7148 and AD7746 [Ana13]). In the first experiments shown in Fig. 5.2(a) a human hand approaches the sensor surface and leaves again. The human hand can be detected in self capacitance mode as well as in mutual capacitance mode with all three measurement systems (proposed sensor and commercial available ones). Although, due to shielding and coupling effects (described in Section 4.3) at a certain distance to the sensor surface the measured capacitance increases (marked with arrows in Fig. 5.2(a)). This effect can yield to ambiguities in proximity determination. An approaching metal rod shows similar signal to noise ratios as a human hand. It can be detected by all three measurement systems. Objects with low permittivity ε_r (i.e., close to 1) are difficult to detect with a self capacitance mode measurement system. As can be seen in Fig. 5.2(c) the plastic box can be detected by the proposed measurement system in the mutual capacitance mode and for close distances in the self capacitance mode. With the two commercial available measurement systems it is very difficult to detect this kind of objects (i.e., low permittivity and low volume).

5.3 Realisation Example - Robot Collision Avoidance

This section was already published in [Sch+ed]. As stated in [Sch+13] special precautions are required to avoid injuries when robots and humans share the same environment. In the future we can expect that more and more autonomous systems and robots will become a part of our lives. This also means that robots will operate in fairly undefined environments, where little prior knowledge is available. It is therefore important that these systems also gather information about the environment in a similar fashion as humans explore an unknown environment. Vision will be quite important for this task. However, it will also require other senses. It is also quite attractive to add sensing capabilities that are beyond the abilities of humans [Sch+13]. Thus, in the presented application a robot arm (Kuka LWR 4) is attached with the presented capacitance measurement system to avoid a human-robot collision. Fig. 5.3 shows a picture of the setup comprising the robot arm and the sensing electrodes.

5.3.1 Highly Reactive Robot Motion Generation and Control

The capacitance measurement hardware was already described. To combine the presented sensor with a robot, the measurement data has to be observed from the robot motion control. In the following a short description of the used motion generation and control is given. It describes one out of many possibilities. It is intended to keep the control scheme very simple. The discrete control scheme



(a)

(b)

(c)

(d)

Figure 5.2: Measurement results for four different objects obtained with the proposed capacitance measurement system and two commercial available systems [Sch+ed]. (a) A human hand approaching and leaving the sensor surface. Black arrows indicate the transition from shielding to coupling mode (refer to Section 4.3). (b) A metal rod approaching and leaving the sensor surface. (c) An empty plastic box approaches and leaves the sensor surface. With the self capacitance mode it is difficult to detect the approaching box. However, the proposed measurement system working in mutual capacitance mode is able to detect even objects which have such a low permittivity and small volume. (d) Only the self capacitance mode of the proposed measurement system is able to detect a foam material approaching the sensor surface.

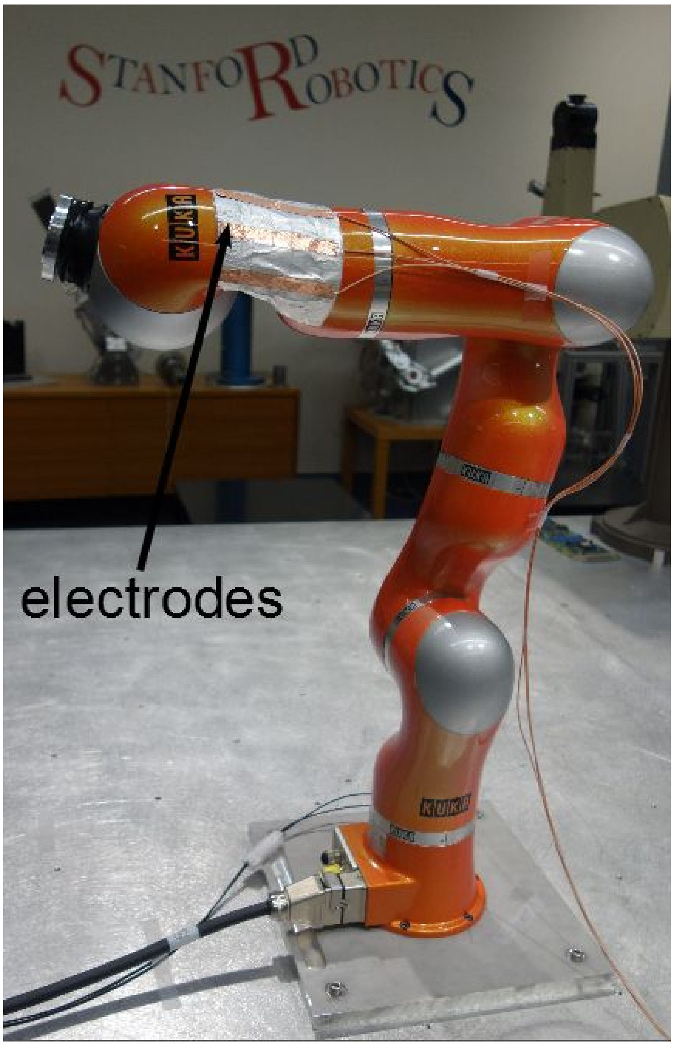


Figure 5.3: Proposed capacitance measurement system mounted on the 7 doF robot arm (Kuka LWR 4).

shown in Fig. 5.4 works on a sampling period of T^{cycle}. A state of motion at an instant T_i is represented by the robots position $\vec{P}_i$, its velocity $\vec{V}_i$, and its acceleration $\vec{A}_i$. Taking into account kinematic motion constraints $\mathbf{B}_i$ that contain maximum values for the velocity, acceleration, and jerk vectors, the online trajectory generation algorithms [Krö10] of the Reflexxes Motion Libraries [Krö11] compute a time-optimal, jerk-limited, and synchronized trajectory that transfers the robot system from its current state $\left(\vec{P}_i, \vec{V}_i, \vec{A}_i\right)$ a desired target position $\vec{P}_i^{trgt}$ and velocity $\vec{V}_i^{trgt}$. These algorithms are executed at every control cycle, so that the system can always react instantaneously in a deterministic way. The output of the algorithms $\left(\vec{P}_{i+1}, \vec{V}_{i+1}, \vec{A}_{i+1}\right)$ is forwarded to the underlying robot motion controller.

The underlying controller can be a position controller, a trajectory following controller, an impedance controller, or any other controller that is capable of following a trajectory. As long as no object is detected in the proximity of the virtual whiskers, the task-dependent input values $\vec{P}_i^{trgt,task}$, $\vec{V}_i^{trgt,task}$, and $\mathbf{B}_i^{trgt,task}$ are used. At the moment an object is detected, the value of the switching variable σ_i changes, and a different set of input values $\vec{P}_i^{trgt,react}$, $\vec{V}_i^{trgt,react}$, and $\mathbf{B}_i^{trgt,react}$ are used so that the robot can react immediately and try to avoid the potential collision.

5.3.2 Experiments and Results

An experiment and measurement results are shown in Fig. 5.5. The robot arm is moving in his workspace. As soon as an object (e.g. human hand) is detected by the capacitance measurement system, the robot arm reacts instantaneously to the measurements and tries to avoid contact with the object [Krö10] (shown

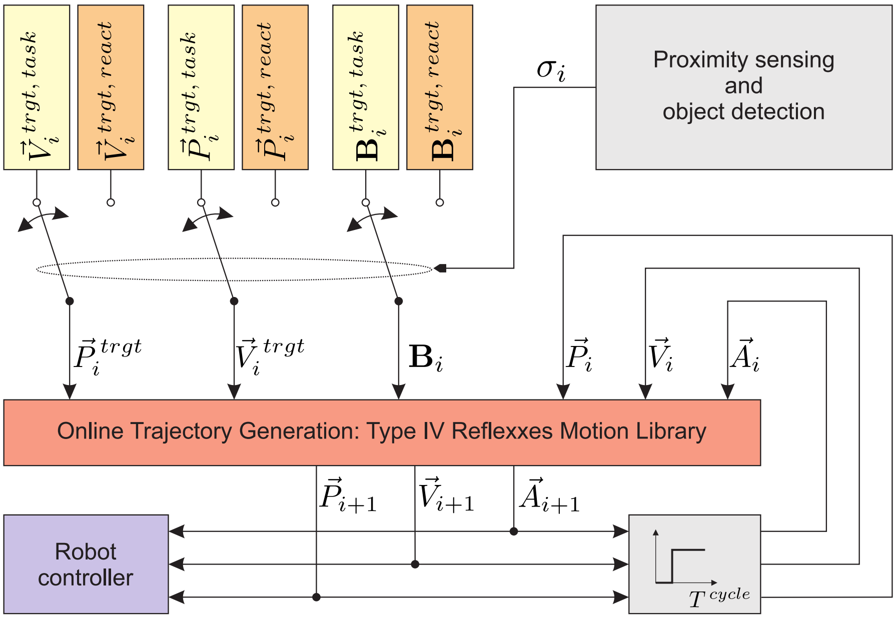


Figure 5.4: Overview of one of the simplest possible robot motion generation architectures. The two sets of motion parameters *task* and *react* can be changed from one control cycle to another using the switching signal σ_i. The online trajectory generation algorithms [Krö10] of the Reflexxes Motion Library [Krö11] let robots react to the input signals from the proximity sensor within the same control cycle they occur.

in Fig. 5.5). Fig. 5.5 shows the measurements of the proposed measurement system for an approaching human hand.

The comparison with other capacitance measurement systems and the example application on the robot arm shows promising performances of the presented measurement system. With this kind of capacitance measurement system it should further be possible to realize a complete ECT sensor system for the open environment. Additional information due to both, self capacitance and mutual capacitance measurements will allow an object classification. Furthermore, possible calibration techniques and the available frequency hopping of the excitation signal will allow to handle parasitic effects and improve capacitive sensing for safety applications.

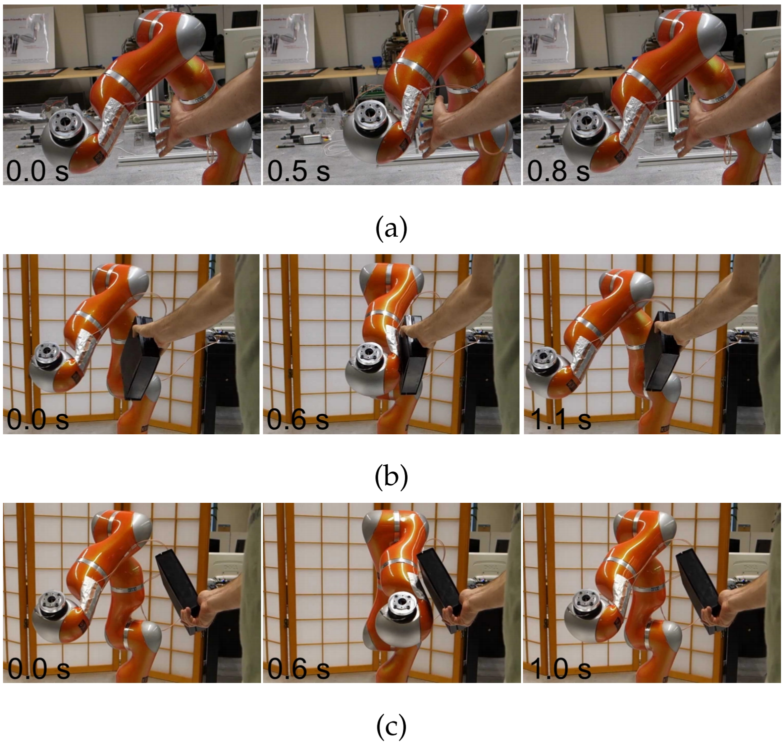


Figure 5.5: Experiments with the proposed measurement system on a robot arm (KUKA LWR 4) from [Sch+ed]. (a) A robot arm reacts instantaneously to the measurement data of the presented capacitive sensor. Capacitive sensing allows the robot to avoid collision with a human hand, maintaining a minimum distance of approximately 50 mm. (b) In the self capacitance mode an empty pastic (PVC) box cannot be detected early enough. Thus, the robot arm touches the box before it reacts and the arm moves back. (c) Using the capacitive sensor in the mutual capacitance mode enables the system to detect the empty plastic box early enough and to avoid a collision.

6 Conclusion and Outlook

"In the last years research in the field of capacitive sensing has more and more addressed collision avoidance in order to protect humans, animals and objects. The technology offers complementary features compared to other technology that makes it particularly interesting for fusion concepts. The strength of capacitive sensing is the capability to perform well for short distances without requiring a free line of sight. Furthermore, it is also capable to provide classifications of objects." [SZ14]

The thesis started in with an introduction to "safety" in terms of standards. State of the art technology for safety applications and an introduction to capacitance measurement were presented afterwards. The physics behind capacitance measurement were shown, example applications were presented and the problems when it comes to open environment measurements were shown. Additionally the presented state of the art measurement circuitries which were also used in the example applications were shown. Furthermore, we proposed a new approach using capacitive sensing for safety applications in an ECT manner. [SZ14]

"Finally, a measurement system was presented and it has been shown that evaluation circuitry is now capable to comply with the short response times as are needed in many safety applications. In particular, the technology addresses the need for such sensors in human robot interaction. Current research focuses on the application of the devices in open environments, i.e. environments that have almost no constraints with respect to object types or environmental conditions.” [SZ14]

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