FACULTY OF TECHNOLOGY

SMART FLOORS: SENSORS AND APPLICATIONS

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Process technology
Bachelor’s thesis
March 2024

TIIVISTELMÄ

ÄLYLATTIAT: SENSORIT JA SOVELLUTUKSET

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Oulun yliopisto, Prosessitekniikan tutkinto-ohjelma

Kandidaatintyö 2024, 24 s

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Työn tarkoituksena oli tutkia, kuinka älylattioiden ja sensoreiden tekniikkaa ja materiaaleja pystytään mahdollisesti hyödyntämään lattiasovellutuksissa.

Työssä tutkittiin erilaisia älylattia ja sensori tyyppejä. Pääasiassa selvitettiin, että minkälaisia tekniikoita ja materiaaleja erilaiset älylattiat ja sensorit sisälsivät. Lisäksi työssä käsiteltiin, että minkälaisissa ympäristöissä älylattioita ja sensoreita pystytään käyttämään. Työn lopussa mietittiin ja vertailtiin, kuinka työssä läpi käydyt älylattia ja sensori tyypit eroavat toisistaan. Työ rajattiin siten, että siinä ei tutkittu lattiamateriaalien sopivuutta älylattioiden ja sensoreiden vaatimiin tekniikoihin. Työssä ei ole erillistä kokeellista osaa.

Työssä tutkittuja materiaalia ja menetelmiä voitaisiin hyödyntää tulevaisuuden tuotteissa. Tuotteita käytettäisiin mahdollisesti suurissa yleisötapahtumissa esim. urheilutapahtumissa, kuin myös pienimmissä tiloissa, kuten vanhainkodeissa.

ABSTRACT

SMART FLOORS: SENSORS AND APPLICATIONS

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University of Oulu, Degree programme of Process technology

Bachelor’s thesis 2024, 24 p

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The purpose of this thesis was to research how the technology and materials of smart floors and sensors can be utilized in floor applications.

Thesis examined various types of smart floors and sensors, primarily focusing on understanding the technologies and materials involved. Additionally, this thesis illustrates the environments in which smart floors and sensors can be utilized. A consideration and comparison were made regarding how the different types of smart floors and sensors studied differs from each other. The suitability of flooring materials for the technologies required by smart floors and sensors was not investigated. This thesis does not include a separate experimental section, and not all possible options for smart floor applications were covered.

The materials and methods researched in this thesis can be applied in future products. These products might be used in large public events such as sports events, as well as in smaller spaces, such as nursing homes.

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1 INTRODUCTION

In the constant development of modern technology and the expansion of digital solutions, new innovations are constantly made. Smart floors offer versatile possibilities across various domains. Smart floors can combine the practicality of traditional floor surfaces with the capabilities of intelligent sensors, opening new aspects in different fields such as healthcare and industrial applications.

The purpose of this thesis is to research various smart floor and sensor technologies and materials. Secondly, the goal is to clarify where smart floor sensors can be used and how they work in general. It is not studied in this thesis which floor types are suitable for different smart sensors.

2 SMART FLOORS AND SENSORS

Smart floor is an intelligent floor. Intelligent means the integration of technology and sensor system into flooring to enhance their functionality and efficiency. It is able to determine and measure people movements and activity. Smart floors are working with sensors. There are many sensors out there that can be used in different purposes. Smart floors can be used, for example, in nursing homes and large crowd venues such as sports stadiums.

2.1 Printed sensor electronics

Printed sensor electronics refers to the printing of functional materials on different kinds of substrates. It uses conventional printing methods, which are used for example in industries such as carpet industry. Additive methods are used when manufacturing of printed electronics. Using this method, material that is needed to achieve the targeted functionality is added layer by layer. The substrates, on which the printed electronics are manufactured, tend to be usually flexible, thin, and sometimes even stretchable. They are mostly made of fabric, plastic, or fiber-based materials such as paper. Components and structures that are used in printed electronics are easily integrated into a wide variety of devices. Diverse combination of printed electronics and substrates brings new different possibilities for the manufacturing and development of electronic applications. Figure 1 presents a few different sensors. (Määttä et al. 2022)

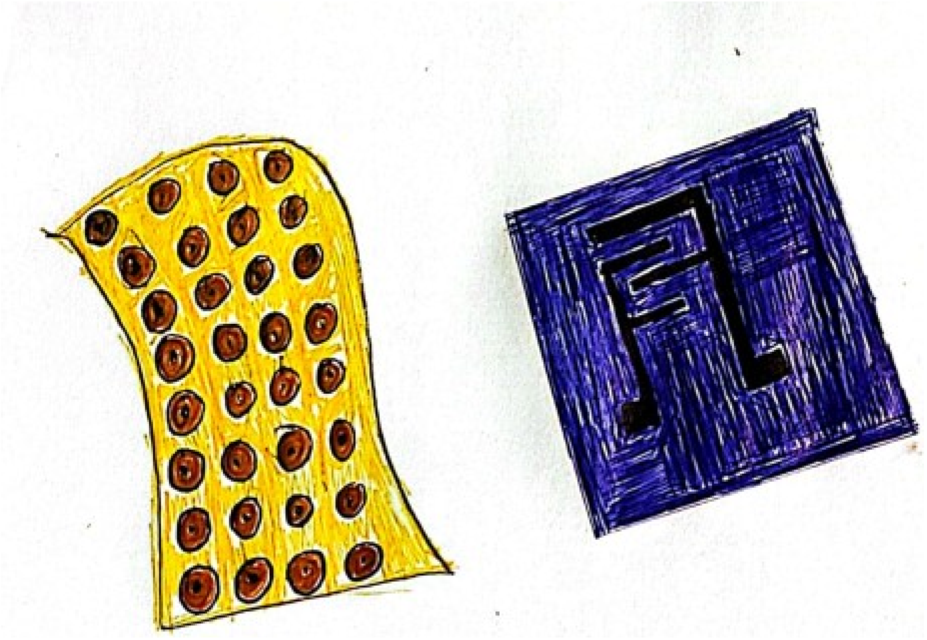

Figure 1. Different printed sensors (retelling Määttä et al. 2022, Wang et al. 2020)

Printed sensor electronics is sustainable because there are several possibilities to use a wide selection of substrate materials including bio-based, compostable, and recyclable materials. Printing process occurs at room temperature and in normal atmosphere, which decreases process energy consumption. The manufacturing process is chosen based on requirements. For example, it is cost-effective to print large areas or large quantities. The industry is continuously looking for new ways to cost-efficiently produce products which have properties that meet the demand of its user. Using printed electronics, it is possible to create products that are both complex and difficult to manufacture. (Määttä et al. 2022)

2.2 Roll-to-roll printed flexible sensors

Materials that can be used for R2R (roll-to-roll) must possess the sensing functionality as printed on a flexible carrier foil. They also need to have process compatibility. Printed electronic and optoelectronic components such as resistors, capacitors, inductors, antennas, light venting devices like LEC (light emitting capacitor) and OLED (organic light emitting diodes) and biosensing devices are using R2R processing technology. There are materials, such as PEDOT:PSS (Poly((3,4-ethylenedioxythiophene) polystyrene sulfonate) dispersions and certain nanoparticle inks, already possess the required characteristics. However, commonly materials in printable form need to be blended in a solvent system. This system includes a carrier that also provides binding functionality, a sensor material, and a set of suitable additives. When mixing binders and other additives, there may be some advantages such as increased stability and surface. Typically, additives tend to have a negative effect to the sensor material characteristics as they may influence sensitivity when coated on a particle. In the worst case, additives may react with the sensing material hence negating the sensor functionality. (Hast et al. 2014)

Carrier and additives in a R2R printable ink are essential despite their possible disadvantages. Suitable rheology is the first thing that ink needs. Generally, this is directly related to viscosity. Suitable viscosity range for gravure and flexo inks is between 50 cP and 500 cP (mPa*s). Viscosity at this range disables the ink flow in a printing cylinder. It also prevents ink spreading in a nip, hence resulting in better line and pattern definition. (Hast et al. 2014)

Another important physical composer is related to ink settling, e.g. how fast internal structure in ink is formed. If the formation of this structure takes too much time ink is heavily spreading and if it is too low ink is facing poor levelling. This kind of factors can be affected by a suitable solvent system, binder or carrier material or by using suitable levelling agents or surface-active materials. In addition, these are also affecting to a surface tension of an ink. It is good to remember that surface tension of the ink has to be lower than surface free energy of a surface where ink is to be printed on. (Hast et al. 2014)

Moreover, the sensing structures need to be applicable also in a system to printability reformation with numerous of additives. Therefore, additives which enhance mechanical properties are required in some cases. It is possible to use waxes to strengthen abrasion resistance and some carboxylic acids to modify surface chemistry in a way that next layer is more easily printable on it. (Hast et al. 2014)

For the sensor material itself, there are a multidisciplinary material portfolio that consist of commercially available and so-called homemade materials. All the material families that are suitable for R2R printed sensor structures include nearly all convectional materials used for sensing applications. Among those are conductive, metallic and nanoparticulate inks, organic and inorganic semiconductors, and biomaterials such as enzymes and antibodies. (Hast et al. 2014)

2.3 Capacitive, resistive, triboelectric and piezoelectric technologies

Literature explores different sensing mechanisms for smart floor sensor units, including capacitive, resistive, triboelectric, and piezoelectric technologies. Each approach has its advantages and disadvantages in terms of leakage, circuit complexity, power requirements, and self-powering capabilities. Ongoing research continues to advance these technologies for improved performance and expanded applications in smart floor systems. (Rueda et al. 2023).

Capacitive sensors detect changes in applied force by measuring variations in capacitance between two electrodes, which occur due to changes in the distance between them. Commercial capacitive floor sensors have been used to study gait patterns. However, leakiness can be a concern with capacitive sensors, and addressing this issue may require complex circuit designs. (Rueda et al. 2023)

Triboelectric transducers present several challenges due to their specific movement requirements, which involve contact-seperation or sliding motion. Additionally, these transducers typically exhibit high impedance and generate open circuit voltages in the hundreds of volts range. Moreover, their output signal is generally in the form of alternating current (AC), necessitating specialized electronics to process the signal appropriately. Triboelectric sensors can be utilized for various sensing applications and have the added advantage of generating electrical energy from mechanical motion. (Rueda et al. 2023)

Piezoresistive strain gauges offer an inexpensive and reliable method for strain measurement. Chen et al. introduced a flexible matrix of strain gauges that enables directional strain measurement while conforming to the surface on which the gauges are placed. They discussed potential applications for damage detection in machinery and structures. One drawback of this approach is that the sensor units require external power, as strain gauges measure strain through changes in internal resistance. In contrast, triboelectric transducer units offer a self-powered solution, serving both as sensors and energy harvesters. Figure 2 presents flexible sensor array beneath the floor tile.

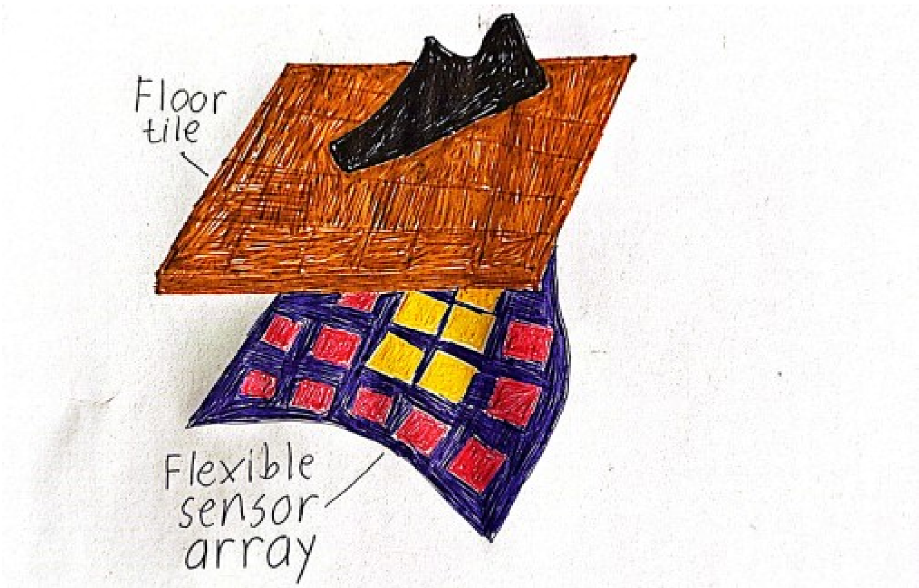

Figure 2. Floor tile and flexible sensor array (retelling Rueda et al. 2023)

On the other hand, piezoelectric transducers offer a more traditional approach to developing self-powered sensors. Unlike triboelectric transducers, even small deflections can generate sufficiently high signals with good linearity in piezoelectric transducers. The energy harvested from these transducers can be utilized without the need for complex impedance matching circuit. (Rueda et al. 2023)

The utilization of piezoceramic materials, like lead zirconate titanate (PZT), in smart floor environments for sensing or energy harvesting has been a subject of study for some time. However, piezoelectric polymers, such as polyvinylidene fluoride (PVDF) and its copolymer poly(vinylidene-trifluoroethylene) (P(VDF:TrFE)), have gained particular interest in this field. Unlike piezoelectric ceramics, piezoelectric polymers offer high flexibility and can be printed onto foil substrates in various shapes using solution-based techniques. Moreover, these polymers require relatively low processing temperatures, typically around 135 ºC. Printing methods like screen printing enable the creation of large sensor areas with intricate pixel array designs. (Rueda et al. 2023)

By gaining a better understanding of how mechanical stimuli translate into sensor output signals, it becomes possible to design more efficient and effective smart floor systems. Such advancements would not only save resources but also enable the reliable resolution of specific events at the sensor level. This knowledge can pave the way for further innovation and improvement in the field of smart floor sensors and their applications. (Rueda et al. 2023)

To implement different sensor configurations and designs in smart floor applications, several models have been developed to interpret the sensor data. However, there is a lack of systematic research investigating the relationship between mechanical stimuli on the floor surface (pressure distribution) and the output signals of the sensor elements. Understanding this relationship is crucial for optimizing the density and arrangement of sensor elements. This optimization aims to reduce costs, minimize material usage, and ensure that events of interest can be accurately detected at the sensor unit level. (Rueda et al. 2023)

2.4 EMFi floor

ElectroMechanical Film (EMFi) is a thin, flexible, inexpensive material. It forms of cellural, biaxially oriented polypropylene film coated with metal electrodes. Many commercial applications, such as keyboards, microphones, and loudspeakers, are using EMFi material. The base material is low priced so it is suitable for large area applications, such as in surveillance sensor systems installed on the floor. (Paajanen et al. 2000 s.95-102)

When using EMFi as a sensor, an external force affecting its surface causes a change in the film thickness, resulting in a change between the metal layers. This charge can be perceived as a voltage. There have been studies, where researchers have used EMFi material as a wide area floor sensor, which is installed in research laboratory as a part of smart living room covering a 100 square meter area. EMFi floor contains 34 horizontal and 30 vertical stripes, which are 30 cm wide. The sensor material is placed under the normal floor, where it makess up a 34x30 matrix with a cell size of 30x30 cm.

It is more advantageous to use long stripes instead of small squares because there are small number of wires and a small number of channels to process. Using this setting, there are only 64 channels to process. Small squares 30x30 cm in size would result in over a thousand pieces. Anyway, using of a sensor stripe matrix, poses challenges in signal processing. For example, when several persons are being simultaneously tracked on the floor, pressure events overlap, although the people are far from each other. In addition, it is complicated to get ”high-quality” footsteps for identification, when the person is walking freely around the room. Given footstep impact may fall on multiple sensor stripes.

2.5 Integrated triboelectric nanogenerator

In smart floors, it is possible to use integrated square-frame triboelectric nanogenerator (SF-TENG) as energy harvester and motion sensor. This kind of smart floor has two working modes based on two pairs of triboelectric materials: first one is purposely chosen polytetrafluoroethylene films and aluminium (Al) balls, and the other is the floor itself and the objects such as basketball and shoe soles. When bouncing basketball, repeatedly on the floor, 87 serially connected light-emitting diodes can be lit up simultaneously. In addition, the friction between the triboelectrically chargeable objects and the floor can conduct an alternating current output in the external circuit without the vibration of the AL balls. (He et al. 2017)

Triboelectric nanogenerator (TENG) is a strong candidate when compering other energy harvesting devices. In general, it is working with two dissimilar triboelectric materials, preferably of opposite tribopolarity, to generate electrostatic charges on their respective surface. After that, through periodic motion, such as seperating and contacting or sliding, between the materials, a potential difference can be created periodically between two electrodes that are attached to the materials. Thus, it generates an alternating current (AC) output in the external circuit. On the basis of the triboelectric effect and electrostatic induction, TENGs of dissimilar structures have been utilized to harvest low-frequency mechanical energy such as wind, human motion, wind, vibration and water waves. TENG has also been widely applied as touch and pressure sensors, motion sensors and acceleration sensors because it is sensitive to mechanical agitations. Either way, triboelectric effect demands intimate contact between the materials that might result in frictional heating and material abrasion. (He et al. 2017)

2.6 DLES-mats for position sensing and activity monitoring

Deep learning enabled smart mats (DLES-mats) based on the triboelectric mechanism are developed to realize an low-cost, intelligent and highly scalable floor monitoring system. This monitoring system is achieved through the integration of a minimal-electrode output triboelectric floor at array with advanced deep learning (DL)-based data analytics. The DLES-mats are fabricated by screen printing, high scalability, presenting the merits of cost effectiveness and self-sustainability in large area applications. A separable electrode pattern with variant coverage rate is designed for each DLES-mat, imitating identification of the QR (quick response) code system. Therefore, after the collateral in an interval scheme, minimal two-electrode outputs with separable and stable characteristics for the whole DLES-mat array can be achieved. The differentiation of the collateral-connected DLES-mats is based on the relative magnitude output signals, allowing indoor positioning and activity monitoring. Moreover, with the integrated DL-based data analytics, identity information related with walking gait patterns can be extracted from the output signals using the convolutional neutral network (CNN) model. Huge data processing information can be saved compared to the original image. Minimal two-electrode outputs enables faster data analytics for real-time applications in smart buildings and homes. (Shi et al. 2020)

3 POTENTIAL APPLICATION ENVIRONMENT

There are numerous amounts of different sensors. Also number of variables that can be measured is huge. With sensors that are in floors or mats, It is possible to measure, for example, where people are gathered. Smart floor sensors can be used almost everywhere, home, office or even sports stadiums. Floors can be carried out with built-in sensors to acquire the substantial sensory information for example from human walking, human activity status or individual identity. In addition, in the aspect of elderly people, the detected sensory information is great importance because sensors can detect if a person falls by monitoring the irregular output signals in the time domain. (Shi et al. 2020)

In the current technology trends, there is a growing demand for the integration of pressure sensors into various environments. These trends aims to enhance automation capabilities and enable condition monitoring across different domains. Pressure sensors have become widely prevalent in medical applications, industrial settings, positional tracking systems, and other fields. Their versatility has made them indispensable. (Rueda et al. 2023)

In the area of smart buildings and homes, pressure-sensitive floor tiles offers exciting possibilities for movement tracking, occupancy detection, and event monitoring. These tiles provide a means to gather valuable data without relying on privacy-violating video surveillance, which is especially important in non-public areas where such surveillance is prohibited. These functionalized floor tiles, when combined, form a “smart surface” that typically includes a data collection and wireless transmission unit for analysis. (Rueda et al. 2023)

3.1 Nursing home applications

In nursing homes, smart floor is a technological aid in nursing care. It can detect a person’s movements and location within the apartment using a sensor film installed beneath the floor (Elsi smart floor). This kind of smart floor automatically monitors residents, eliminating the need for the person to carry devices such as wristbands. Sensors placed beneath the floor send data to a program, which generates alerts, information, recording and statistics. (Rannikko et al. 2018)

The smart floor allows nurses to anticipate accidents and the need for assistance. It also enables the initiation of care promptly when an elderly person falls in their room. It enhances safety, dignity and cost-effectiveness. The floor signals when person gets out of bed, enters the restroom, and if person falls in room. There are also some additional features that are possible to install, such as emergency calls and fire alarms. (Rannikko et al. 2018)

3.2 Sport application

In sports, an increasing amount of information technology and sensors are used, providing more precise and reliable results in sports than what humans can achieve. The EMFi sensor is suitable for boundary sensing when the goal is to enhance the usability of indoor sports fields, such as volleyball and basketball. This is possible because EMFi sensors are highly useful for precision-demanding measurement applications. The sensor should be installed beneath the surface of the field by taping it securely, but for one-time use, surface installation under the tape is also possible. Boundary sensing requires, in addition to the EMFi sensor, a computer for signal processing, data analysis software, and possibly a signal amplifier along with wires. Separate studies should be conducted to assess its suitability for competitive use. (Huttunen et al. 2017)

3.3 Indoor positioning

Smart floor monitoring system has been developed for indoor positioning, activity monitoring, and individual recognition in smart building/home applications. It is realized through the system integration of self-powered triboelectric DLES-mats and advanced DL -based data analytics. There are several benefits in screen printing manufacturing and triboelectric sensing mechanism. The DLES-mats possess the grand advantages of low cost, high scalability, and self-sustainability, which are ideally suitable for large-area floor monitoring such as sports venues. In addition, the design of a distinct electrode pattern enables the interval parallel connection of different DLES-mats. This results in minimal two-electrode outputs with clear and stable differentiation for a 3x4 DLES-mat array. This kind of smart floor monitoring system can be achieved for real-time position sensing and identity recognition. The positions sensing information from each step is adopted to control the lights in corresponding positions. At the same time, the full walking signal is analyzed by the CNN model to predict whether the person is a valid user of the room so as to auto-control the door access. Comparing with camera and smart tag-based individual recognition, smart floor monitoring system is based on the dynamic gait-induced output signals which provides a video-privacy-protected, highly convenient, and highly secure recognition approach. (Shi et al. 2020).

4 DISCUSSION

4.1 Use in future products

There are several different versions of smart floors and sensors. Finding the right smart floor solution for different spaces depends largely on where and what kind of products are wanted to use.

Printed sensor electronics take advantage of flexible, thin and stretchable materials. These materials can be, for example, plastic, fabric or fiber-based products like paper. The use of bio-based and recyclable materials is also possible, which is a positive aspect for the future. Using printed sensor electronics in flooring would be most suitable for large public events where the information transmitted by sensors can be utilized. Also, from a cost-effective perspective, printing large areas at once is advantageous.

Another viable smart floor option is the EMFI floor. Since EMFI material is thin, it is well-suitable as a smart floor material. The sensor material is placed under the normal floor. EMFI material is suitable for various purposes because it is inexpensive to produce and many sensors with different stiffness can made from it. One potential application is implementing boundary sensing in indoor sports such as tennis and volleyball. If EMFI is compared to other sensors, EMFI is slightly more challenging to install and there is a greater need for pre-processing to collect data.

If the goal of using a smart floor is to obtain information about for example, people’s location or activity, DLES smart mats are well-suited for this purpose. These mats have high scalability and are durable. DLES-mats can be used for individual identification, localization, and general activity monitoring. An inexpensive triboelectric sensing mechanism is used as the material. Combining the triboelectric sensing mechanism with, for example, the roll-to-roll printing method offers great potential to achieve affordable, extensive and self-sufficient floor sensing technology. The design of separate electrode patterns allows parallel connection between different DLES-mats. DLES-mats are suitable for large spaces, such as sports events.

The application of various smart floors and sensors in floor products requires careful investigation and testing. Floor materials need to be thin enough and installable as a floating installation (not glued). A floating floor consists of floor elements that are connected to each other. This allows for controlled integration of sensors into the floor materials. Through testing, it must be determined whether data transfer can be implemented wired or wirelessly. Sensor technologies applicable to floors are already so advanced that their breakthrough into broader use in the near future is likely. Examples of applications include nursing homes, sports fields, and monitoring large crowds, such as sports events.

4.2 Different technologies

Printed sensors electronics and roll-to-roll printed flexible sensors are using printing techniques such as inkjet or screen printing to deposit conductive materials onto flexible substrates. These technologies enables the creation of electronic sensors and gives multiple advantages compared to other technologies such as cost-effectiveness, lightweight properties and suitability for large-area and flexible applications.

Triboelectric and piezoelectric sensing mechanism offers possibilities such as movement tracking, occupancy detection, and event monitoring. Triboelectric- and piezoelectric sensing mechanisms has its advantages and disadvantages. Triboelectric sensors have challenges for movement requirements, which involve contact-seperation or sliding motion. Piezoelectric sensor are more traditional when developing self-powered sensors. Compared to triboelectric sensors, in piezoelectric sensors even small deflections can generate high signals with good linearity.

Triboelectric nanogenerator (TENG) has a possibility to convert distributed energy such as motion, vibration or pressure into electrical energy. This kind of smart floor has two working modes based on two pairs of triboelectric materials.

EMFi floor forms of cellular, biaxially oriented film coated with metal electrodes. EMFi is metallized on both sized. External force affecting its surfaces causes a changes in the film thickness, resulting in a change between the metal layers. EMFi has a capability to measure pressure and force changes offering large application in technology field. Its advantages over other polymer electrets is based on its flexibility. Also, EMFi has strong permanent charge which makes it very sensitive to dynamic forces exerted normal to its surfaces. (Paajanen et al. 2000 s.95-102)

DLES-mats are based on triboelectric mechanism. It uses technology where the smart floor monitoring system is achieved with deep learning data analytics. This technology saves resources and enables faster data analytics for real-time applications in smart buildings. Table 1 illustrates differences in smart floor technologies.

Table 1. Smart floor technologies

Smart floor applications	Differences in technologies
Roll-to-roll printed flexible sensor	- Electronic components are printed onto flexible substrates in a continuous roll - uses printing technologies, such as inkjet or screen printing, to create electronic components on various substrates.
Triboelectric and piezoelectric sensing mechanisms	- Triboelectric Sensing: Involves the generation of electrical charges through friction between two dissimilar materials. - Piezoelectric Sensing: Involves the generation of electrical charges in response to mechanical stress or pressure applied to certain materials (piezoelectric materials).
EMFi floor	- forms of cellural, biaxially oriented polypropylene film coated with metal electrodes. - an external force affecting its surface causes a change in the film thickness, resulting in a change between the metal layers
Integrated Triboelectric Nanogenerator	- This kind of smart floor has two working modes based on two pairs of triboelectric materials - first one is purposely chosen polytetrafluoroethylene films and aluminium (Al) balls other is the floor itself and the objects that can be triboelectrically charged such as basketball and shoe soles
DLES-mat	- A separable electrode pattern with variant coverage rate is designed for each DLES-mat, imitating identification of the QR (quick response) code system. - monitoring system is achieved through the integration of a minimal-electrode output triboelectric floor at array with advanced deep learning (DL)-based data analytics

5 CONCLUSION

There are many different possibilities for smart flooring. In this work, not all possible options for smart floor applications were covered. The choice of the right smart floor and sensor depends mainly on where it is intended to be used, and what information is wanted. Possible use environments would be such as nursing homes and sports events. For large public spaces like sports events, smart floors with cost-effective materials and sensor types, such as printed sensors and EMFi floor are best suited. It is also cost-effective to print large areas at once.

The investigated floor applications in this thesis should be experimentally tested to determine which smart floor application is suitable for each specific purpose. Additionally, it would be possible to see whether they work in practice and what is the best solution. Through experimental research, it could also be examined which types of flooring materials are suitable for the aforementioned floor applications. Another related topic for further research would be data transmission in smart floor applications, either wirelessly or through wired connections.

6 SUMMARY

The purpose of this thesis was to investigated different smart floors and sensors and compare them. Smart floor is an intelligent floor and it is working with sensors. It integrates intelligent systems into flooring solutions.

Smart floor sensors can detect and analyse factors, such as movement, pressure, temperature, and even environmental conditions. Data transfer can be implemented wired or wirelessly depending on technology and future testing.

Smart floor applications investigated in this thesis, can be utilize various places and events. However, experimental testing is required when utilizing these applications in future products. Experimental testing is often necessary to optimize and validate the performance of these smart floor applications, ensuring their reliability and effectiveness in different environments.

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