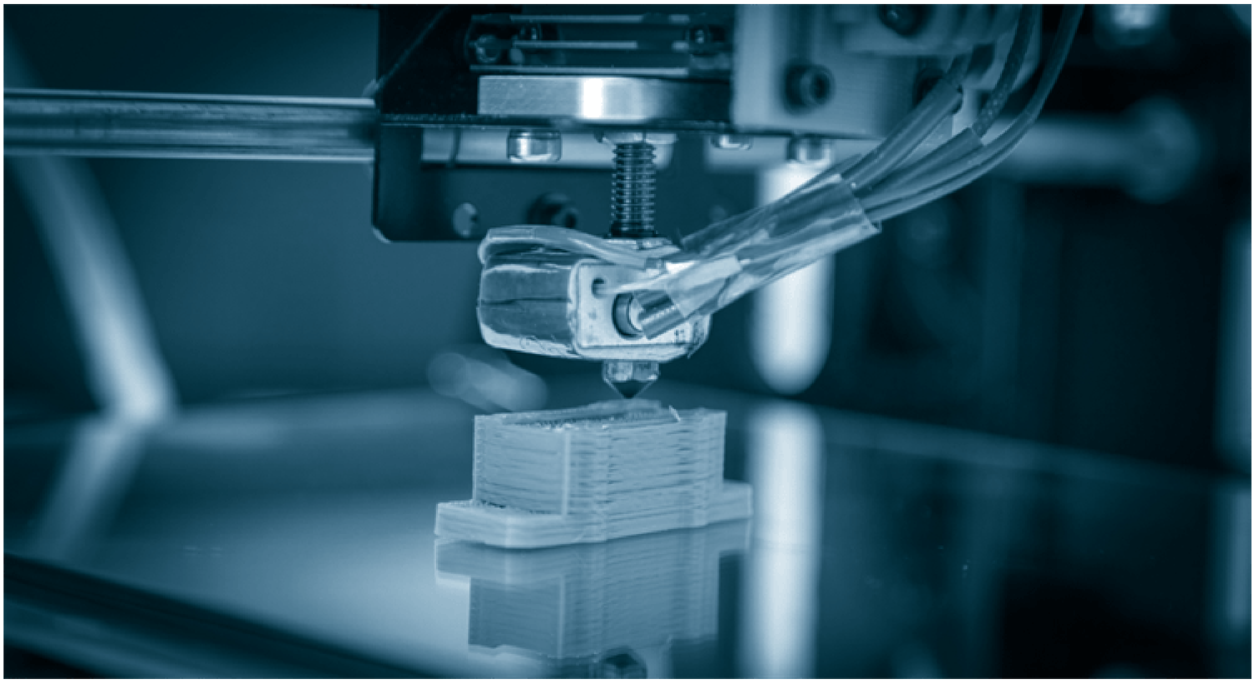
ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ
ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ & ΗΛΕΚΤΡΟΝΙΚΩΝ ΜΗΧΑΝΙΚΩΝ

Διπλωματική Εργασία

Διερεύνηση της ενσωμάτωσης αισθητήριων συστημάτων σε δομές μέσω τριsδιάστατης εκτύπωσης.



(Traksel, 2020)

Φοιτητής: Κριτσωτάκης Στέφανος
ΑΜ: 43689

Επιβλέπων Καθηγητής

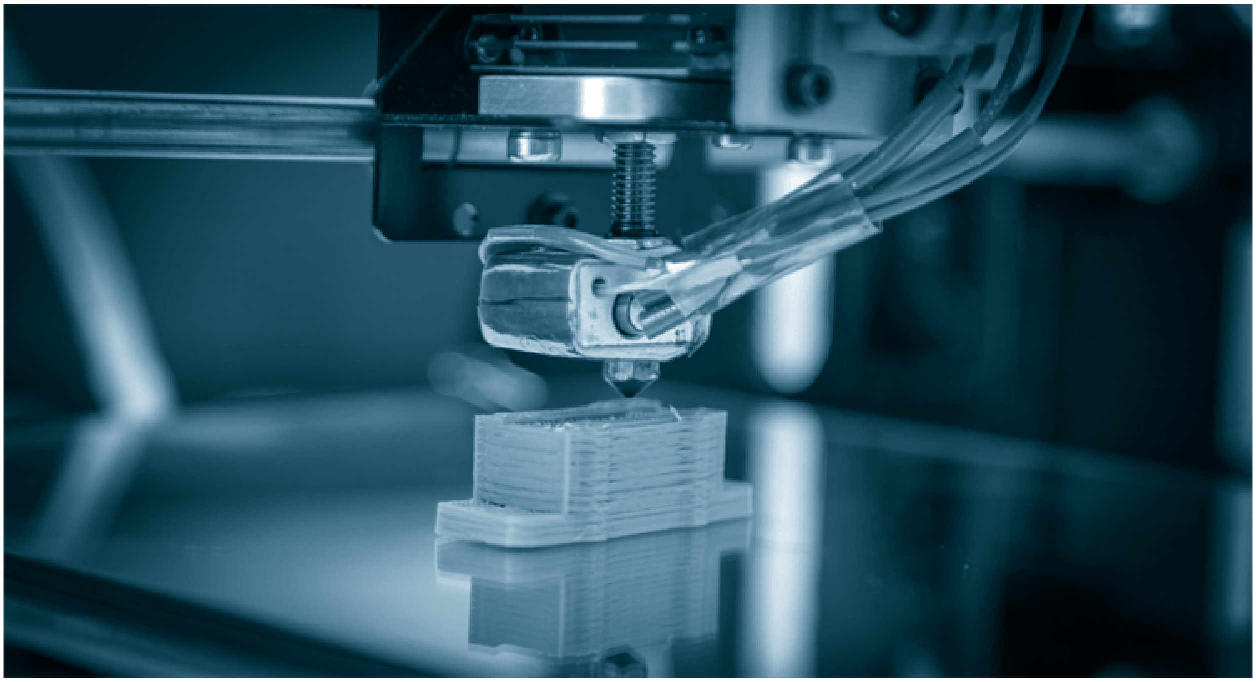
Κωσταντίνος Καλκάνης
Επίκουρος Καθηγητής

ΑΘΗΝΑ-ΑΙΓΑΛΕΩ, Οκτώβριος 2021

UNIVERSITY OF WEST ATTICA
FACULTY OF ENGINEERING
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Diploma Thesis

Investigation of Integration of Sensory Systems in Structures via Three-Dimensional Printing



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Student: Kritsotakis Stefanos
Registration Number: 43689

Supervisor

Konstantinos Kalkanis
Assistant Professor

ATHENS-EGALEO, October 2021

Η Διπλωματική Εργασία έγινε αποδεκτή και βαθμολογήθηκε από την εξής τριμελή επιτροπή:

(Ονοματεπώνυμο), (βαθμίδα)	(Ονοματεπώνυμο), (βαθμίδα)	(Ονοματεπώνυμο), (βαθμίδα)
Konstantinos Kalkanis Digitally signed by Konstantinos Kalkanis Date: 2021.10.14 13:08:35 +03'00' (Υπογραφή)	Stavros Kaminaris Digitally signed by Stavros Kaminaris Date: 2021.10.19 08:57:51 +03'00' (Υπογραφή)	Digitally signed by Konstantinos Psomopoulos Date: 2021.10.14 11:17:41 +03'00' (Υπογραφή)

ΔΗΛΩΣΗ ΣΥΓΓΡΑΦΕΑ ΔΙΠΛΩΜΑΤΙΚΗΣ ΕΡΓΑΣΙΑΣ

Ο κάτωθι υπογεγραμμένος Κριτσωτάκης Στέφανος, του Ευαγγέλου, με αριθμό μητρώου 43689 φοιτητής/τρια του Πανεπιστημίου Δυτικής Αττικής της Σχολής ΜΗΧΑΝΙΚΩΝ του Τμήματος ΗΛΕΚΤΡΟΛΟΓΩΝ ΚΑΙ ΗΛΕΚΤΡΟΝΙΚΩΝ ΜΗΧΑΝΙΚΩΝ,

δηλώνω υπεύθυνα ότι:

«Είμαι συγγραφέας αυτής της διπλωματικής εργασίας και ότι κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος.

Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου.

Επιθυμώ την απαγόρευση πρόσβασης στο πλήρες κείμενο της εργασίας μου μέχρι ……………………… και έπειτα από αίτησή μου στη Βιβλιοθήκη και έγκριση του επιβλέποντος/ουσας καθηγητή/ήτριας.»

Ο Δηλών
Στέφανος Κριτσωτάκης

(Υπογραφή φοιτητή/ήτριας)

This research paper would have been impossible to complete without the aid and supervision of Professor Kostantinos Kalkanis, as well as the incredible support of my friends and family in this endeavor.

Περίληψη

Η τρισδιάστατη εκτύπωση είναι μια τεχνολογία που υπάρχει εδώ και αρκετές δεκαετίες. Ενώ στην αρχή η χρήση της ήταν αρκετά περιορισμένη, στη σύγχρονη εποχή εξελίχθηκε δραστικά και εφαρμόστηκε σε διάφορους κλάδους λόγω των πλεονεκτημάτων της. Υπάρχουν πολλές διαφορετικές μέθοδοι για την τρισδιάστατη εκτύπωση, καθεμία από τις οποίες εξυπηρετεί καλύτερα μια ποικιλία εφαρμογών. Μια τέτοια εφαρμογή είναι η κατασκευή αισθητηριακών μονάδων. Οι αιθητήρες αποτελούν συσκευές οι οποίες είναι κατασκευασμένες για να εφαρμόζονται σε μια δομή ή περιβάλλον, προκειμένου να λαμβάνονται μετρήσεις ορισμένων παραμέτρων σχετικά με την κατάσταση του συγκεκριμένου στοιχείου. Αισθητήρες που παρακολουθούν τις παραμέτρους υγείας μιας δομής, όπως επιταχυνσιόμετρα και μετρητές καταπόνησης μεταξύ άλλων, μελετώνται με βάση τη σημασία της δομικής παρακολούθησης στην εποχή μας. Οι μέθοδοι και τα πλεονεκτήματα της τρισδιάστατης εκτύπωσης τέτοιων δομικών αισθητήρων μελετώνται προκειμένου να εφαρμοστούν σε δομικά αισθητήρια συστήματα. Περαιτέρω μελέτη περιλαμβάνει την ενσωμάτωση ασύρματων αισθητηριακών συστημάτων σε δομές, συμπεριλαμβανομένων τόσο των σύγχρονων κτιρίων όσο και των ιστορικών μνημειωδών κατασκευών.

Λέξεις – κλειδιά

Τρεισδιάστατη εκτύπωση, αισθητήρες, παρακολούθηση δομικής υγείας, συστήματα αισθητήρων, ασύραμτο δίκτυο αισθητήρων, δομικού αισθητήρες, παρακολούθηση μνημείων

Abstract

Three-dimensional printing is a technology that has been around for several decades. While in the beginning its usage was severely limited, in modern times it has evolved drastically and has been applied a number of different industries due to its advantages. There are a multitude of different methods that 3D printing may be used with, each better serving a variety of applications. One such application is the fabrication of sensory units. Sensor devices are built to be implemented onto a given structure or environment in order to take measurements of certain parameters regarding the target's status. Sensors that monitor a structure's health parameters, such as accelerometers and strain gauges among others, are being studied given the importance of structural health monitoring in our time. Methods and the advantages of 3D printing such structural sensors are being studied in order to be applied in structural sensory systems. Further study includes the integration of wireless sensory systems onto structures, including both modern buildings and historical monumental structures.

Keywords

3-D printing, sensors, structural health monitoring, sensory systems, wireless sensor network, structure sensors, monument monitoring

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Image Catalog

Introduction

With the ever rapid advancement of modern day technology and its increasingly accessible applications to people as a whole, 3D printing is nearing a time where it could become dominant in the production of goods in a myriad different cases. One idea worth investigating is that of building sensors and systems via 3D printing, and using said sensors for the monitoring and subsequent preservation of structures, including humanity's prized, yet fragile, historical and cultural monuments.

Subject of the diploma thesis

This paper presents the brief history and the fundamentals of 3D-printing while also presenting a study on how to create sensors with 3D-printing. The monitoring of a structure's health is of paramount importance nowadays given the increasing severity of natural phenomena such as earthquakes, as well as the ever-increasing design ambitions of modern engineering, therefore it could be worth looking into ways of building sensors cheaper, faster and with potentially optimal efficiency.

Purpose and objectives

The purpose of this paper is, firstly, to study the concept of 3D-printing, its applications in today's industries and the different technologies that have been developed. Secondly, it presents a study of the concept of sensors, their varying designs and target applications with greater emphasis on sensors that are built for monitoring structural parameters. Lastly, it explores potential methods of creating structure sensors via 3D-printing and integrating improved sensor systems for the monitoring of modern structures and historical monuments.

Methodology

This thesis was the result of an extensive literature review, which consists mostly of sourcing scientific journals, a selection of scientific books and presentation of a study comprising of a combination of ideas, theories, research and experimental investigation, supported by these sources.

Innovation

The concept of fabricating sensors via 3D printing in order to integrate them into improved sensory systems for more efficient monitoring of a structure's health.

Structure

The first chapter explores the history of 3D printing, followed by its applications in modern industries and explanations of individual printing technologies.

The second chapter covers the concept of sensory systems and how it has evolved, followed by a presentation of different types of sensors and structural sensors in particular.

The third chapter involves a study of the process of 3D printing sensors that could be used for structural monitoring, with individual sub-chapters for select cases of sensors, and the integration of improved wireless systems that attribute to better structural health monitoring.

1. CHAPTER 1: Introduction to 3D printing.

1.1. A brief history of 3D printers.

3D Printers have existed for the past few decades, a fact that might seem strange to the average person, given that only recently there has been an upsurge of 3D printer availability, usage and general hype (Horvath, 2014). With the current, relatively inexpensive 3D printers available on the markets, these marvelous machines show great promise in the sense that they could enable more dynamic and efficient development procedures of a wide range of products while granting the ability to distribute manufacturing in the process (Horvath, 2014). There are a lot of ways in which 3D printing can be utilized and change the way manufacturing is undertaken, particularly when designing and prototyping new products. That being said, the task of handling proper 3D printing procedures, such as three-dimensional modelling, material selection and machine programming among others, yet remains a daunting task for the average person (Horvath, 2014).

A brief explanation of the nature of 3D printing is due. As a broad definition, it involves the fabrication of any kind of object or structure by building it in a layer by layer manner by processing a material, instead of having a piece of material and cutting away parts of it in order to create said structure or object (Horvath, 2014). An object is being made manifest from nothing by adding layers of materials together, one at a time, until we have a completed object (Horvath, 2014). There are many natural examples of the process, with lower technological variations that have been used by other names for ages; such as making a wall made of bricks (Horvath, 2014). To be more specific, 3D printing is considered a type of additive manufacturing. By definition, additive manufacturing describes a process in which an object is being built from scratch by depositing material on a fabrication platform and having it processed layer by layer, until the object is ultimately complete (Horvath, 2014). Several forms of additive manufacturing involve the building an object by creating it from scratch, while most instead start with a piece of material and process it from top to bottom, leaving behind junk scraps (Horvath, 2014). Woodcarving and sculpting could be considered a form of additive manufacturing, since they start from a piece of wood or stone, and carve away bits and piece of the material to shape the desired object from said material. Both kinds of additive manufacturing also include the planning a built structures design regarding how it's going to be built, the steps of the procedure, the use of materials etc., all of which are also included in the process of 3D printing (Horvath, 2014). The added benefits of modern 3D printing machines and technologies are the utilization of robotic control and precision.

The current state of 3D printing is merely an evolution and convergence of technologies and techniques that have been around for some time (Horvath, 2014). Despite that, there have been some crucial technical and business environment innovations that came together to make consumer 3D printing considerably affordable (Horvath, 2014).

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Charles W. Hull is usually credited with the development of the first working robotic 3D printer in 1984, which was launched by 3D Systems in 1989 (Horvath, 2014). These machines utilized SLA systems (stereolithography), which uses ultraviolet light to solidify a resin with a laser) and many large commercial machines still use this technology. Several varying power-based technologies were patented later on during the early 90s (Horvath, 2014). These systems work by squirting a binder very precisely on the surface of a vat of power to create layers using platform that tends to move downwards (Horvath, 2014). S. Scott and Lisa Crump, in the meantime, patented fused deposition modeling (FDM) in 1989 and together founded the printer manufacturer Stratasys Ltd (Horvath, 2014). This technology (often referred to as FFF, which stands for fused filament fabrication) feeds a plastic filament into a heated extruder, followed by laying down the material with high precision (Horvath, 2014). Other 3D printing technologies are being developed

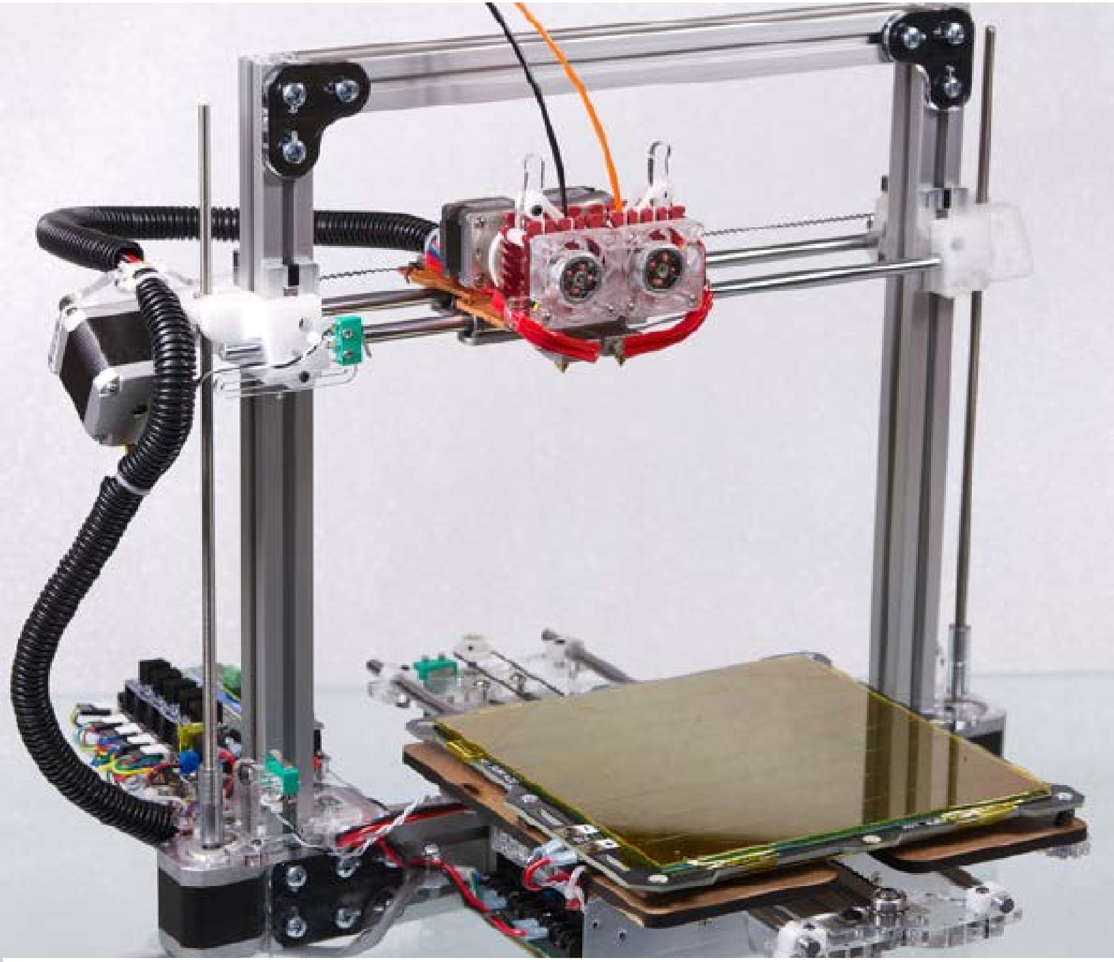

Figure 1. A typical Cartesian 3D printer (Horvath, 2014)

which can print at molecular levels, although they are currently still being tested and are not available for general and reliable use (Horvath, 2014). Other revolutionary applications include the fabrication of food and human body parts, or even the printing of large civilian structures (Horvath, 2014). Very recently in 2021, the world's first 3D printed steel bridge was installed over a canal in the city of Amsterdam (Horvath, 2014). Keeping the aforementioned examples in mind, it isn't difficult to see how far the ambitions of 3D printing have come, so much so that new ideas keep coming up and the question of whether or not it is possible is starting to diminish.

By 2009, 3D printer development had begun to split into two groups: those offering large, industrial printers (usually with some proprietary technology) and a large informal network of people working on open source filament-based printers for consumer use (Horvath, 2014).

On the 28th of April in 2009, the Kickstarter crowdfunding platform made its debut (Horvath, 2014). Kickstarter is a platform on the internet which allows people to deposit funds in order to fuel the development of an individual's project. This is followed up by the emergence of the RepRap project, which was an idea devised by Adrian Bowyer of the University of Bath that proposed open source development of open source 3D printer building (Horvath, 2014). Individual developers would attempt to design 3D printing machines and request funding in order to so. Crowdfunding websites have their own sets of rules, but all agree upon the fact that a project's goals and ambitions need to be made clear, therefore being an excellent way to support the open source creation of 3D printing machines (Horvath, 2014). After development of one such project was complete, the donors would more often than not be offered a resulting 3D printing unit as a reward for supporting the endeavor.

The convergence of expiring patents on core 3D printing technologies and the increasing interest in crowdfunding platforms have given rise to a favorable business environment, in which small inventors might bring 3D printers and other relevant products to a much wider audience, while requiring minimal capital (Horvath, 2014). Any sudden wave of innovation like the current one in 3D printing has multiple components, but the development of a couple of technologies, the Arduino and open source code repositories (like Github), have been a considerably large influence on the 3D printing field (Horvath, 2014)

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1.2. Applications of 3D printing.

As mentioned in the previous paragraphs, 3D printing has seen a rapid increase in usage by manufacturers in the past few years.

While manufacturers used to shy away from fully implementing 3D printing due to the particularly high entry costs, which would not allow profitable implementation to mass-manufacturing when compared to standard processes, recent market trends have shown that this is changing at long last. 3D printing has shown a rapid growth in the manufacturing industry, from food to medical utilities.

To be more precise, the industries that may now benefit from 3D printed manufacturing are:

- Food industry
- Fabric and fashion industry
- Electric and electronic industry
- Aerospace industry
- Automotive industry
- Architecture, building and construction industry
- Healthcare and medical industry

1.2.1. Food Industry

3D printing technology opens the doors for, surprisingly enough, the food industry.

Figure 2 A 3D-printed chocolate chip (Borison, 2014)

At present, there is a growing demand for the development of customized food for specialized dietary needs, particularly for athletes, children, pregnant women, hospitalized patients and possibly others, which require a variable amount and quality of nutrients by reducing the amount of unneeded ingredients and capitalizing on the presence of healthy (or rather, required) ingredients (Shahrubudin, Lee, & Ramlan, 2019).

That being said, it is no simple task to arrange the development of such intricate food. 3D printing provides the means to fabricate food in unique ways that are flexible and almost fully customizable (Shahrubudin, Lee, & Ramlan, 2019). Technologies such as ink jetting and binder jetting are being used for the production of 3D printed foods (Pitayachaval, Sanklong, & Thongrak, 2018).

The advantages brought by 3D printing in the food industry are highly efficient technology for its production while taking into account quality and preserving a low cost approach (Shahrubudin, Lee, & Ramlan, 2019). Creating new ways to produce and customize food products and adjusting them to the needs of any given case, 3D printing is proving to be both a beneficial and healthy approach (Shahrubudin, Lee, & Ramlan, 2019). By allowing food preparation and ingredients to be automatically adjusted to one consumer’s information, it might be possible to provide diets which enforce themselves without having the need to exercise (Shahrubudin, Lee, & Ramlan, 2019). It may not be a completely viable alternative to a balanced lifestyle when taking athleticism and diet into account, but it would be one step in the right the direction for people who might be unable or unwilling to exercise, as to not deprive themselves of the nutrients that their bodies require to stay healthy.

1.2.2. Fabric and Fashion Industry

Enter the retail industry, where 3D printed shoes, jewelry, consumer goods and clothing are slowly starting to make their way into the markets (Shahrubudin, Lee, & Ramlan, 2019). While it may not be the most natural assumption to think that the fabrication of clothing may be subject to being applied to by 3D printing, it is nevertheless becoming an option for companies around the globe, such as Adidas and New balance manufacturing custom made foot-ware specifically tailored to the measurements of athletes. (Shahrubudin, Lee, & Ramlan, 2019).

In particular, Nike made the 2012 Vapor Laser Talon football shoe and New Balance custom-fit shoes for athletes by using a 3D prototype. (Mpofu, Mawere, & Mukosera, 2014).

Figure 3 3D-printed Adidas shoes (Ice2Art, 2021)

Considering the nature of the 3D printing process, it stands to reason that it could be utilized for such purposes. 3D printing enables the fabrication of parts and objects that are designed to meet exact specifications as well as complex shapes and forms. Therefore, it is only to be expected that ways to use that technology for the creation of garments has been discovered. For example, it makes it possible to make shapes without molds (Shahrubudin, Lee, & Ramlan, 2019). Not only that, but by using 3D printing technology it becomes possible to design and produce clothing by using mesh systems and also print ornaments for traditional textile (Shahrubudin, Lee, & Ramlan, 2019). Moreover, the application of 3D printing technology is not limited to garments, but may also be used to print leather goods and accessories such as bags, watches and so much more (Shahrubudin, Lee, & Ramlan, 2019).

Most companies opt to not use 3D printing as a means to mass produce their wares, but instead to utilize it in order to design and try out new prototypes in a swift manner with little cost

(Shahrubudin, Lee, & Ramlan, 2019). That and the fact that 3D may easily create custom ordered apparel and design unique shapes, the 3D printing tech has seen a lot of use in recent years. As a recent example, the media of the fashion world was taken by surprised a 3D printed crimson colored dress was put on display, which bore a unique design based on fish scales that looked to be incredibly elegant and fashionable (McCormick, Zhang, Boardman, Jones, & Henniger, 2020).

1.2.3. Electrical and Electronics Industry

Manufacturers of electronics are looking into ways to take advantage of the possibilities offered by the technology of 3D printing as it continues to grow more accessible (Shahrubudin, Lee, & Ramlan, 2019). Structural electronic devices with complex designs and electrodes are being constructed by embedding conductors in the 3D printing process (Shahrubudin, Lee, & Ramlan, 2019).

Fused deposition modelling is a 3D technology, which will be explained in more detail in a later subchapter, that is often used for printing electrodes as it provides an economical, swift and high precision means of production (Shahrubudin, Lee, & Ramlan, 2019). The same cannot be said for typical industrial electrodes, which lack the customizability and flexible design present in printed electrodes in order to fit specific applications (Shahrubudin, Lee, & Ramlan, 2019). That being said, it should be obvious that printing is not limited to producing electrodes. Other active electronics are subject to fabrication by a 3D printing machine (Shahrubudin, Lee, & Ramlan, 2019). Transistors, diodes and other such active devices that play vital roles in circuitry. Their designs, by modern standards, are rather complex and require the usage of multi material printing tech in order to achieve manufacture (Shahrubudin, Lee, & Ramlan, 2019). In theory, being able to print active electronics would make a significant difference in the electronics manufacturing industry (Shahrubudin, Lee, & Ramlan, 2019). The development of environmentally friendly electronic devices with a low manufacturing cost, optimal safety and reliability as well as rapid production, is urgently in demand in order to address environmental concerns that plague our civilization currently (Shahrubudin, Lee, & Ramlan, 2019).

This thesis will expand on this particular topic in greater detail in chapter 3, focusing on the process of printing electronic components in order to create sensory devices.

1.2.4. Aerospace Industry

3D printing technologies are additionally finding their way into the aerospace industry, as it has altered the means by which components are being assembled (Attaran, 2017). The prospects of fabricating parts with reduced weight and complicated designs have led to the industry embracing 3D printing as a means of production (Shahrubudin, Lee, & Ramlan, 2019). Aerospace engines tend to be relatively easily damaged, therefore requiring maintenance through frequent part replacement (Shahrubudin, Lee, & Ramlan, 2019). It could even be possible to directly repair an aircraft's damaged component through selective laser melting. 3D printing technologies provide the means to fabricate spare parts quickly and efficiently. To emphasize this point, aircrafts manufactured by Airbus and Boeing are being built by adding in 3D printed components, of which there have been no reported deficiencies so far (Attaran, 2017).

Figure 4 3D-printed components of an Airbus Jet (3D-Printed 'Bionic' Parts Could Revolutionize Aerospace Design, 2017)

One interesting example that emphasizes on the excellence of 3D printing is the fact that parts may be created locally in remote locations (Attaran, 2017). To be more precise, it enables the use of 3D printing in space (Attaran, 2017). By having the ability to create component parts that are required for maintenance and repairs eliminates the need to deliver said parts from the earth to the international space station, therefore massively providing a massive reduction in total costs for the operation as far as funds and time are concerned (Attaran, 2017). Not only that, but by having the ability to fabricate components in space leads to much more forgiving inventory management, as there will be no provide additional storage for spare parts that are required for various operations (Attaran, 2017). This leads to space shuttles having even more space to carry other important inventory and the international space station also being more flexible in managing its inventory by having one less thing to worry about.

1.2.5. Automotive Industry

The use of 3D printing has been prominent in the automotive industry for some time now. It benefits from the same part production mentioned in the previous paragraph regarding the aerospace industry as far as complex and lightweight characteristics are concerned. The main application, however, is the rapid production of prototypes. Prototyping allows the fabrication of a completely functional vehicle straight from the design stage, while skipping the need to otherwise provide parts and components that would be required for the structure (Nichols, 2019). The lower costs and swift production are a couple of reason why General Motors has used additive manufacturing for at least two decades now (Attaran, 2017). That being said, 3D printing in the automotive industry is not limited to part production and rapid prototyping. The first automobile to include both interior and exterior parts built solely by 3D printing was presented by Kor Ecologic in 2011 (Attaran, 2017). The car is considerably lighter than its peers owing to its printed nature, yet it remains at the prototyping stage. The company has ambitions to release the vehicle to the markets at some point.

Figure 5 Complete 3-D printed car (Sheehan, 2018)

Another application of 3D printing in the industry, aside from prototyping and complete vehicle manufacturing, the fabrication of parts and tools is also possible and desirable (Attaran, 2017). Manufacture of parts and tools can, more often than not, take a rather long time under traditional methods, which would be undesirable, for example, when a vehicle calls for a swift faulty part replacement (Attaran, 2017). By utilizing 3D printing, said part could quickly and efficiently replace the faulty one, saving a great deal of time and money in the process. This can extend to a real world scenario where a customer returns a car, which suffers from one or more faulty components, back to its manufacturing company in order to have it repaired. The swift repair of said vehicle thanks to the rapid part production from a 3D printer will have a positive impact on the customer's opinion of the company, consequently boosting the company's long term reputation (Attaran, 2017). Moreover, being able to fabricate custom parts is a boon to classic car collectors (Attaran, 2017). Having possession of an automobile that is no longer in production or is unique is some way calls for spare parts that are specific to that vehicle. Companies can save a great deal of money from having to deploy or create specific tools that are required to build specialty parts, simply by designing them and then fabricating by 3D printing.

Lastly, by 3D printing whole vehicles or just using 3D printed components would reduce car emissions and fuel consumption in the long run. Manufactures have the ability to produce components that use aluminum alloy as their base, instead of being made from the same material in solid form, bringing its total weight to as low as 0.2 times the weight value of its solid counterpart (Attaran, 2017). Therefore, reducing weight leads to reduced fuel required to operate a vehicle in addition to the fact that, by 3D printing, there would be less waste out of the production process and smaller production and power costs (Attaran, 2017). All these ultimately attribute to reduced emissions and a step toward eco-friendliness.

1.2.6. Architecture and Construction Industry

3D printing is seeing extensive use in the architectural and construction industry for a number of reasons. First of all, following the theme of part manufacturing, the construction industry follows suit. The production of compartments and other structural elements via 3D printing has been a staple part of the industry for years now (Wu, Wang, & Wang, 2016). While the earliest uses of 3D printing in the industry saw the manufacturing of products by making use of ceramic material, modern printers may now fabricate components to be used for building projects (Wu, Wang, & Wang, 2016). Components that are being printed include, but are not limited to, window frame fixtures and plumbing fittings that are typically composed from nylon and plastic (Wu, Wang, & Wang, 2016). In addition to plastic and nylon, concrete is also being used as printing material by specialized printers in order to fabricate complex products made from said concrete (Wu, Wang, & Wang, 2016).

Moreover, 3D printing can be used for designing. While this was done mostly by simulating the structure with a computer software, 3D printing enables the observation and study of a 3D printed scale model of a given structure (Attaran, 2017). By converting a building design into a 3D model and then printing it into a tangible scale model, the improvement and detailed study of the building's structure may be achieved (Attaran, 2017). While the printed model may be complex and provide ample insight for the structure's characteristics, the durability of the print comes into question given its ambitious application. According to Gibson et al., a printed scale model built with a fused deposition modelling machine brought about its collapse, while a selective laser sintering machine provided a structure that possessed greater durability (Gibson, Kvan, & Ming, 2000).

Another point that is absolutely worth mentioning, is the potential construction of entire buildings or larger structures by making use of 3D printing technologies. In the past few years, the prospect of large scale 3D printing has brought about the respective development of large scale 3D printing machines (Wu, Wang, & Wang, 2016). Shanghai, China, saw the building of several medium sized houses by using a large printer (150m x 10m x 6.6m in dimensions), which used high-grade glass fiber and cement in order to fabricate these houses in a matter of hours (Wu, Wang, & Wang, 2016). Another very recent example of a 3D printed structure is a steel bridge in Amsterdam, the first one to be built in the world and opened to the public. A team of experts worked together for the design. It was built by using robotic arms and came equipped with the ability to be monitored internally thanks to an embedded sensor network, granting engineers the ability of real-time monitoring (Parkes, 2021). This project is a very positive example to the future of construction 3D printing.

Figure 6 World's First 3D-printed steel bridge in Amsterdam (Parkes, 2021)

1.2.7. Healthcare and Medical Industry

One of the most important edges of 3D printing technologies in medical applications is the design leeway provided for the fabrication of customized medical products (Ventola, 2014). The medical industry was revolutionized by the usage of 3D printing, by producing personalized implants in the range of prosthetics and hearing aids (Attaran, 2017). Printed customized implants and medicinal tools promote hastened procedures as far as surgery and the recovery rate of a patient are concerned (Ventola, 2014). The customization of drug dosages and the improvement of other custom medicinal equipment is another prospect feature of 3D printing (Ventola, 2014).

An additional benefit of great importance imposed by 3D printing technologies is the reduced costs required for the production of medical supplies (Ventola, 2014). While means of further reducing production costs are being explored, mass production of the abovementioned cases is still a more cost-effective way of producing them in the long run (Ventola, 2014). In addition, printing medical supplies has the potential to minimize manufacturing costs by means of reducing the utilization of unnecessary resources (Ventola, 2014).

1.3. The workings of a 3D printer.

Before an object can be 3d printed, it must first be created digitally as a 3D model. This can be achieved by using a 3d-space design software (such as SketchUp) to create the 3d model of an object, using a scanner to translate an already existing object into a digital 3d one or by scanning said object by photographing it from different angles. Once the 3d model is ready, it must be converted into an STL file. STL files are computer files that house the information required by a 3d printer in order to create the 3d object. Most, if not all, 3d printers are compatible with STL files. Once an STL file is loaded into a printer, it starts to dissect the object into a series of 2D layers, which is then printed layer by layer. (Xu, et al., 2017)

While this sums up the main principle of 3D printing, there are a multitude of different 3d printing methods, each with their own unique characteristics and advantages.

1.3.1 Fused Deposition Modeling

FDM (fused deposition modelling) was first invented by S. Scott Crump in 1989. This method involves the melting of material filament inside the machine, which then is pressed out through a small nozzle onto a fabrication platform in a specific manner depending on the 3d model, which is then left to cool down and becomes solid. The nozzle moves horizontally and vertically in order to "draw" the shape of the model's layer, while the platform moves on the z axis to change layers.

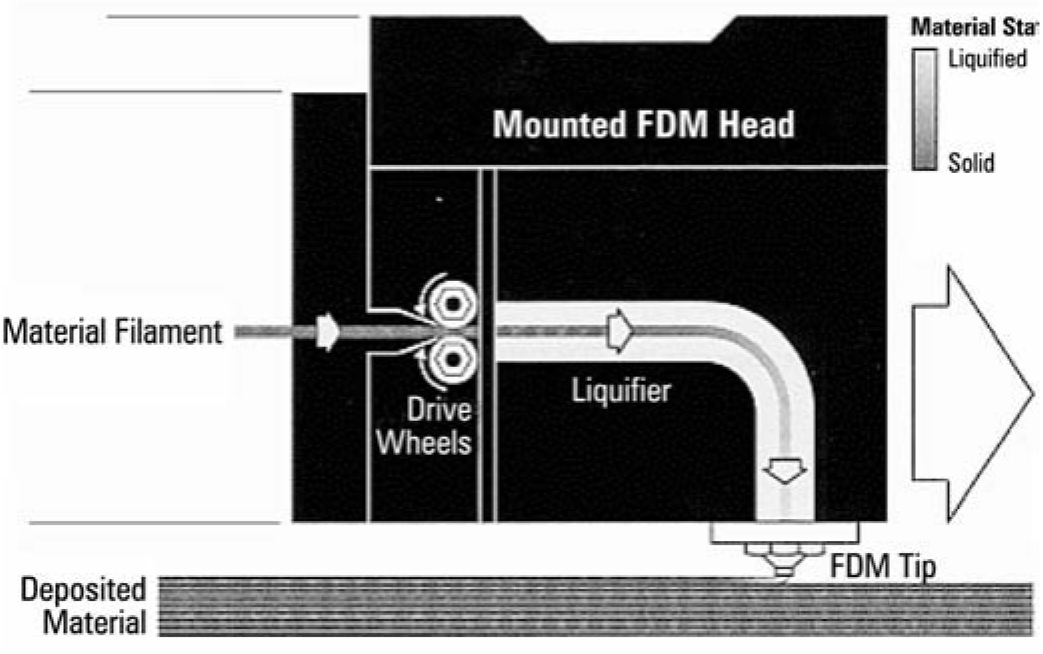


Figure 7 Fused deposition modeling process (Ahn, Montero, Odell, Roundy, & Wright, 2002)

The molten material of the layer fuses with the solidified material of the previous layer according to the model's geometry. This is repeated layer by layer until the 3d object is ultimately completed, a process that tends to take several hours. Materials used as filament include polyamide, polylactic acid, polycarbonate etc. The advantages of the FDM process is that it can produce parts with unique characteristics and cheap materials, although it suffers from poor model resolution and the time it takes to build an object leaves something to be desired. (Ahn, Montero, Odell, Roundy, & Wright, 2002)

1.3.2. Direct Ink Writing

Direct ink writing is similar to FDM in principle, in that a nozzle moves on a building platform while extruding material, but unlike FDM, which utilizes the melting of a material to produce a solid mass, direct ink writing instead uses all sorts of different materials. The materials range from ceramics and plastics to food substances and even cells. Direct ink printers are highly versatile due to their ability to support custom sized nozzles and grants the operator full control over the ejection speed, material density and other parameters depending on the object that the machine's operator wishes to create. (Xu, et al., 2017).

While FDM may be categorized as a sub-category of direct ink writing, there are other such methods depending on the filament used. In general, the filament used for the printing dictates the type and the complexity of the desired object. Colloidal gels, polymer melts, dilute colloidal fluids, waxes, concentrated polyelectrolyte complexes and other ink designs are being employed depending on the situation. (Lewis, 2006) Inks that become solid either through heating, or evaporating liquid, are generally being designed in order to meet the requirements to print said complex objects and structures.

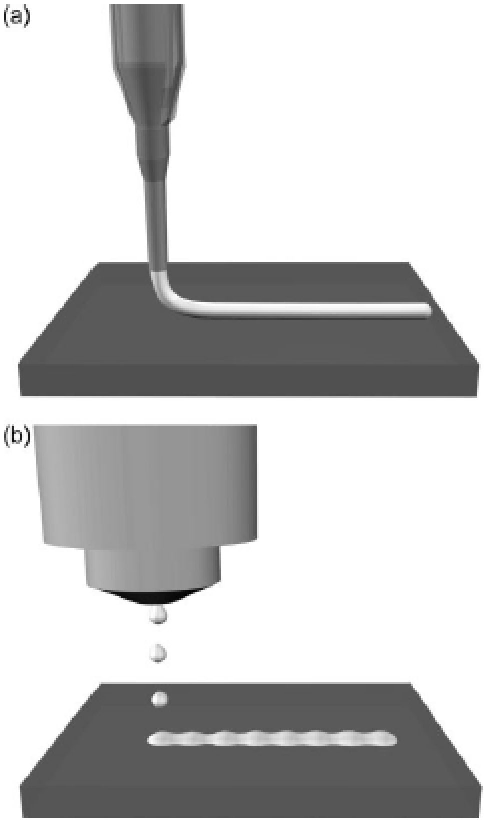


Figure 8 Illustration of direct ink writing with a) continuous filament and b) droplet jetting (Lewis, 2006)

The colloid volume fraction (φ) of the ink is held constant, while its mechanical properties are tuned by tailoring the strength of the interparticle attraction according to the scaling relationship given by

$$y = k\left(\frac{\phi}{\phi_{\mathrm{gel}}} - 1\right)^{x}$$

Where y is the mechanical property of interest (shear yield stress τy, or elastic shear modulus G'), k is a constant, φgel is the colloid volume fraction at the gel point and x is the scaling exponent. The equilibrium mechanical properties of a colloidal gel are governed by two parameters: φ, which is proportional to the interparticle bond density, and φgel, which scales inversely with bond strength. As the attractive forces between particles strengthen, colloidal gels experience a significant increase in both τy and G' (Lewis, 2006).

1.3.3. Photocuring

Photocuring is a 3d printing method that involves the building of a 3d object on platform by utilizing ultraviolet light, which cures liquid polymer materials in a layer by layer manner, similar to the previous methods mentioned. Photocuring is divided in two types: digital light processing (DLP) and stereolithography apparatus (SLA) (Quan, et al., 2020).

- SLA 3D Printing

SLA is a technique that was first realized by Charles Hull in 1986. Charles Hull is a leading figure in the 3D printing industry and co-founder of 3DSystems Inc. (Quan, et al., 2020). SLA is one of the first printing techniques and one of the most prominent still used to date. It is also the main method of photocuring, as most large industrial type machines are based on it.

It works by utilizing a laser beam that is based over a tank filled with resin, which becomes solid if traced by the beam (Quan, et al., 2020). In between is the printing platform, which descends into the resin tank to cover its surface with the substance, which the laser beam traces as a 2D layer which represents a cross section layer of the 3D model that is to be printed. Once the beam traces the boundaries and solidifies the inside of its area, the platform descends a very small distance under the first layer so that the beam can solidify the next layer of resin. The process is repeated until the final 3D object is completed. Given that the laser beam has ample space to move on, it can theoretically print larger sized models than the other printers.

The resin mentioned in this process is a special type of substance called photosensitive resin (Quan, et al., 2020). There are two types of mechanisms that SLA uses, depending on the laser lamp wavelength. These mechanisms are the hybrid photopolymerization and cationic photopolymerization. The wavelength of the beam is set to 355nm so that it allows both approaches to be viable. However, they have their differences. Hybrid polymerization uses hybrid photosensitive resin, which is quite cheap but often suffers from deformation during the printing process due to volume shrinkage, causing the end product to sometimes be printed slightly deformed due to reduced precision. On the other hand, cationic photosensitive resin suffers little to no volume shrinkage during the procedure, but is comparatively rather expensive.

Even though SLA is the first 3D printing tech to be used for quick prototyping thanks to its stable printing process and the ability to precisely print large models, it suffers from slow printing speeds and limited use of the expensive cationic photosensitive resin. (Quan, et al., 2020)

- DLP 3D Printing

Unlike SLA, DLP does not utilize a laser beam to create shapes on a material layer. Instead, it works in reverse. A projected light source is placed on the top, which projects the shape of a

model’s cross section layer onto the resin coated platform, which then descends to prepare the next layer until the object is complete, much like SLA (Quan, et al., 2020).

The key difference lies in the digital microscope device that acts as the projector. Dr. Larry Hornback was the one who invented this device back in 1997, who then proceeded to have it commercialized by Texas Instruments in 1996 (Quan, et al., 2020). Also called a DLP chip, this technological marvel is compromised by two million connected mini microscopes, about as small as a fifth of a hair. The chip receives input in order to project an image on any given surface (Quan, et al., 2020). The projection rate of the chip is extremely fast, allowing it to project grayscale shadows at a 1024 pixel resolution. Because of this, the DLP method is known for delivering high resolution prints. Of course, while it does deliver small objects at high resolution, it is consequently incapable of larger prints to due to reduced exposure area (Quan, et al., 2020).

Figure 9 A DLP 3D Printer (Creality, 2021)

DLP uses hybrid photosensitive resin. It cannot facilitate cationic resin due to the fact that that wavelength of the lamp in this case is 405nm, which the resin cannot work with because it is incapable of photopolymerization at 405nm irradiation (Quan, et al., 2020).

In conclusion, DLP offers the printing of small 3D objects at high resolution, unlike SLA which prints large objects at lower resolution.

1.3.4. Lamination

Laminated Object Manufacturing (LOM), differs considerably from the previously mentioned methods. It involves the slicing and sequential lamination of 2d cross-sections (Feygin & Hsieh, 1991). Sheet materials coated in adhesive are used for this process. Adhesive is used so that the sheet materials are attached to each other, either before the procedure or readied before it begins. The sheet material contains the adhesive injected inside it, or covering either of its sides (Figure 11) (Feygin & Hsieh, 1991). A three-dimensional object is built as the result of layers of sheet material are combined. Following input instructions from the information provided by the controlling software's model, a laser beam proceeds to cut the boundaries of a cross-section's layer after one is deposited. As per the norm, the process repeats until the 3D model is complete.

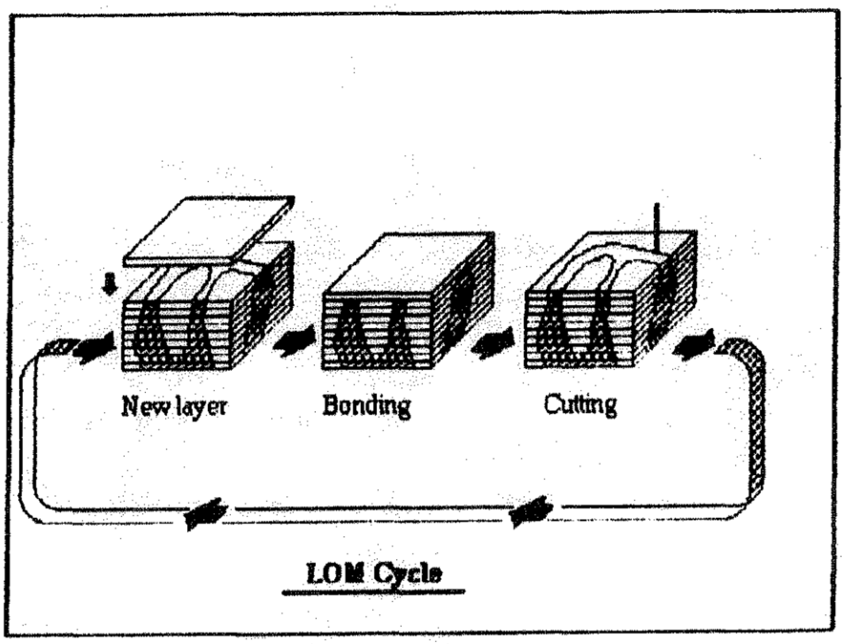


Figure 10 The LOM cycle (Feygin & Hsieh, 1991)

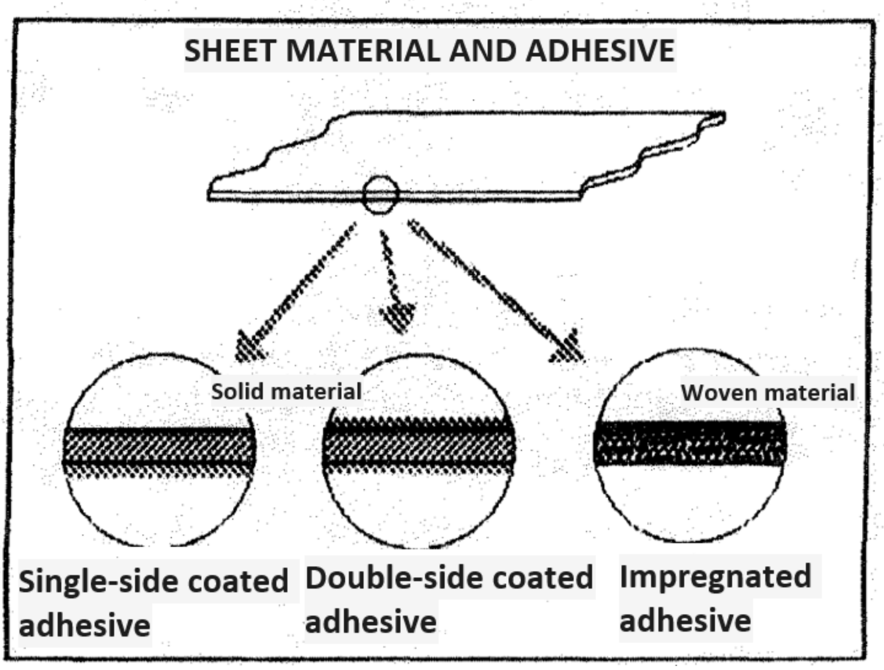


Figure 11 Material Combination (Feygin & Hsieh, 1991)

The basic structure of a LOM machine is depicted in Figure 12 (Feygin & Hsieh, 1991). A number of idler rollers are in charge of routing a length of sheet material that connects a rewinding and unwinding roll, which is responsible for the storage of the material. A vertically mobile platform, moved by a stepper rotor, is holding the laminated parts. A heated roller, that compresses and heats the ribbon between the lamination stack on the platform and itself, is located just above the platform (Feygin & Hsieh, 1991). The ribbon material is connected to the peak of the lamination stack thanks to the motion of the roller. A laser beam is projected by a horizontally and vertically moving pair of mirror that reflect it, and a lens to focus it. After the cut of the layer is done, the laser beam proceeds to slice and dice the leftover scraps into little squares that act as a makeshift support for the object, so as not to go to waste (Feygin & Hsieh, 1991).

While other techniques have set layer dimensions, Lamination allows user with the controlling software to dictate the thickness of each individual layer of the 3D model, which also directly affects the thickness of the material for each layer, and then generates the geometry of each layer (Feygin & Hsieh, 1991). The laser beam is guided to cut as deep as each layer is required, then proceeds to slice the leftovers into supporting squares. The platform then descends while the ribbon moves onto the rewinding roll. The platform ascends again, pushing the ribbon against the upper layer (Feygin & Hsieh, 1991). After the process repeats and ultimately the object is finished, it is received as a block with the finished object inside it. The material surrounding the object is actually the cubes that were sliced by the laser to be used as support and can be easily wiped off the 3D printed object.

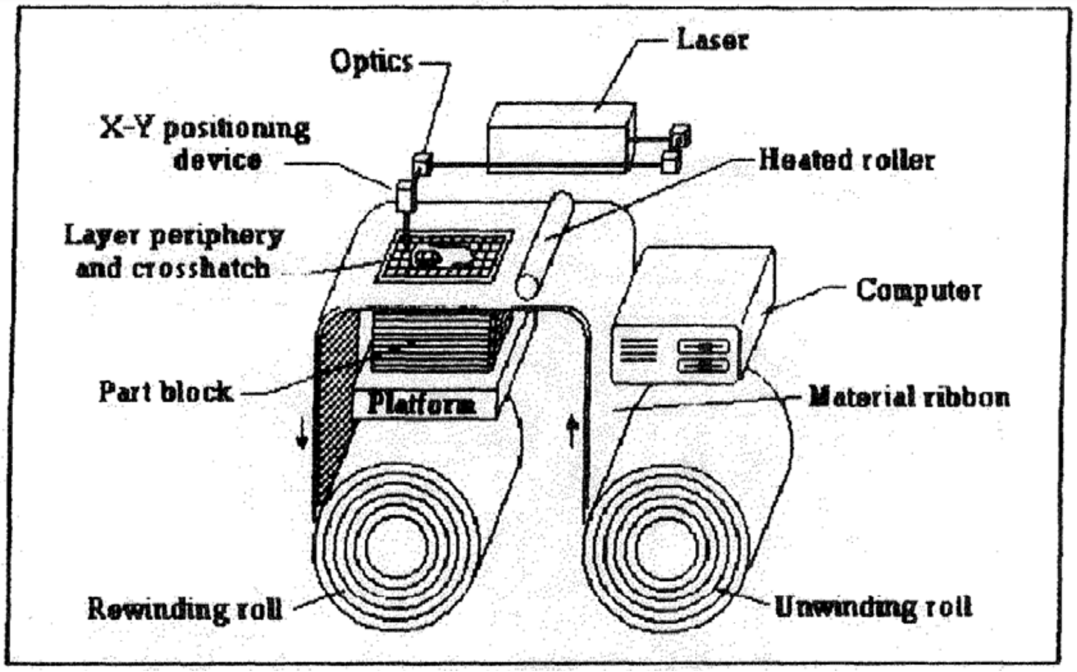


Figure 12 The LOM machine process (Feygin & Hsieh, 1991)

1.3.5. Selective Laser Sintering and Selective Laser Melting

SLS and SLM are two methods that involve the use of materials in powder form, such as metals and plastics. In a sense, their functionality is similar to that of lamination, in that a laser beam is in charge of shaping the required shape on a layer. Both methods are able to build objects that could be strong enough to meet the standards of military and aerospace applications. SLS in particular has been widely used for orthopedic and dental applications (Wimpenny, Pandey, & Kumar, 2017).

SLM works by taking, as per the norm, the data of the STL file input and translating it into laser movement (Chor Yen, et al., 2015). The process begins by spraying a layer of material powder upon the building platform. Once the platform layer is fully coated, a laser is being projected to heat, melt and fuse an area or shape on the layer according to the provided data instructions. Once the laser has finished the heating and the powder has become solid, the fabrication platform descends and a new layer of dust is placed upon it which the laser proceeds to process accordingly (Chor Yen, et al., 2015). The procedure is repeated until the 3D object is completed within layer of leftover powder, which can then be removed manually to reveal the finished object. In Figure 13, the procedure is illustrated from the starting point to the end product.

The parameters for the powder thickness of each layer and the parameters of the laser beam are adjusted before the procedure in order to achieve the desire object geometries (Chor Yen, et al., 2015). Other than that, the process itself is fully automated.

The building chamber of the SLM printer is usually filled with nitrogen gas in order to provide protection for the heated metal parts from oxidization (Chor Yen, et al., 2015). The range of a layer's thickness tends to be between 20 and 100 lm, as it strikes a balance point for delivering adequate resolution and proper powder flowability. The ability of the SLM laser to completely melt the powder material in order to deliver a solid object removes the need for any further post-processing procedure, other than retrieving the object itself. SLS, on the other hand, functions by binding power materials by sintering in solid state, which in turn results in structures with poor density and high porosity. Not only that, but SLS often requires additional post-processing procedures in order to deliver the final product in its proper condition, something that requires even more time on its end. Therefore, SLM is superior to SLS in this regard, given that it requires no extra steps in order to complete the product, saving time and generally being more reliable when it comes to manufacturing.

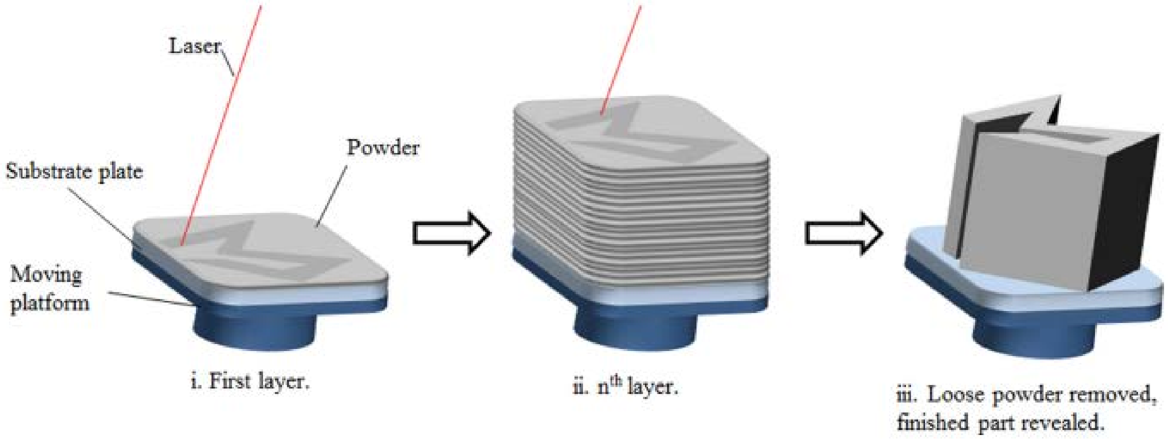


Figure 13 An illustration of the SLM process (Chor Yen, et al., 2015)

Not only that, SLM has been used as a means to repair damaged parts or components. The Direct Digital Manufacturing Lab at Georgia Tech has developed Scanning Laser Epitaxy (SLE) for additive repair of nickel-based alloys CMSX-4,5,6 Rene 80,7 and IN100.8 SLE requires a small amount of powder for repair, enough to cover the surface of the damaged part up to 2 mm in powder thickness (Chor Yen, et al., 2015). A high power Nd:YAG laser is then deployed to melt the powder material, covering cracks and holes in the damaged component. (Chor Yen, et al., 2015)

1.3.6. Photopolymer Jetting

Photopolymer Jetting is another form of fused deposition modeling, whose process is somewhat similar to that of photocuring, and is a relatively new form of rapid manufacturing. It was patented in 1994 by Sachs et al (Singh, 2011). Polyjet works by having a moving nozzle deposit a layer of photosensitive resin on the building platform, which is then heated and hardened by ultraviolet light bulbs (Singh, 2011). Once the resin material is hardened, the platforms descends slightly to repeat the process, as depicted in Figure 14. While a photosensitive resin is used as the main building material, there is another gel-like substance added as support for the object. After the process is complete, a stream of water gushes out to eject the support material in order to leave behind the printed structure (Singh, 2011).

Due to Polyjet's ability to quickly and precisely print structures without needing further procedures after the building, it is used today for rapid prototyping and manufacturing customized products. (Singh, 2011)

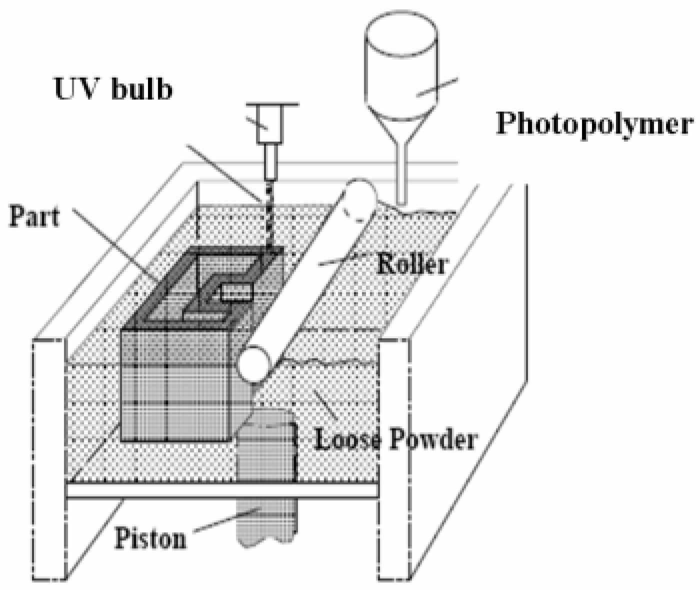


Figure 14 Schematic of the Polyjet Process (Singh, 2011)

1.3.7. Binder Jetting

Binder Jetting is a process that was developed in the early 90s at Massachusetts Institute of Technology, yet had not reached commercialization until 2010 (Gokuldoss, Kolla, & Eckert, 2017). While the printing procedure is quite similar to other technologies, BJ does in fact utilize two materials when printing instead of one, not unlike the gel substance of Polyjet. The process requires a liquid binder material, which is required the glue the printing material between layers, and the actual building material which is usually metal or ceramic.

The building material is spread on the building platform as a layer while a layer of binder material is deposited in a specific manner on the layer, according to the 3D model instructions. The process is repeated until the final structure is completed as a result of the binder gluing specific parts over each layer. Unfortunately, BJ is plagued by a series of post-processing procedures that might often take longer to finish than the printing process itself. These procedures but are not limited to curing, sintering, de-powdering, annealing and finishing (Gokuldoss, Kolla, & Eckert, 2017). That said, despite the additional toll in terms of time and increased processing costs, the printed objects may be procured without needing support structures.

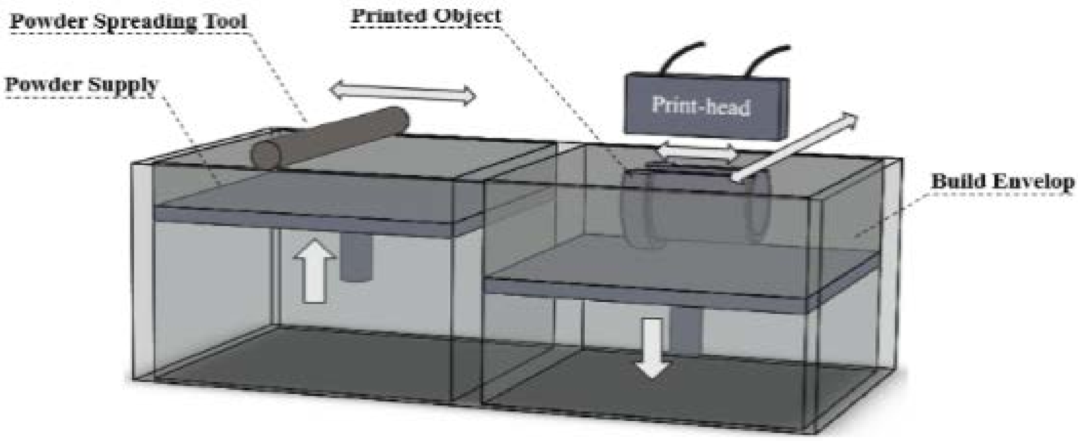


Figure 15 Binder jetting system schematic. (Gokuldoss, Kolla, & Eckert, 2017)

The printing process itself is considerably fast and may be hastened further by adding multiple nozzles to submit material on the layers. The method utilized by BJ does not include any kind of heating and therefore the resulting structured does not suffer from any additional pressure, even though this comes with the added drawback of printing objects that are of relatively weaker density and mechanical substance than other methods (Gokuldoss, Kolla, & Eckert, 2017). That being said, taking into account that cheaper coarse powder may be used in the process thanks to the secondary binder material, BJ remains a rather low cost AM (additive manufacturing) process with which complex parts and structures may be built.

2. CHAPTER 2: Sensory Systems

2.1. The evolution of sensors

Ever since technology became a mainstream tool for humans to use at their leisure, either for better living and the development of society as we know it to this day, then came the need to create sensors and other such devices. From the moment that sensors were conceived as a concept, humanity’s perception for security and comfort has been changed to become an everyday comfort for most.

The concept of sensors was first conceived as far back as the early 1800s, when a copper based temperature sensor was first built based on its electric resistance at varying temperatures (Wilson, 2004). That was only the beginning, seeing as, since then, there has been no shortage of new and peculiar ideas for building different types of sensors and make them available to the public. Such advancements that were made in various scientific fields have given rise to both complex and simplistic sensor systems that are still being used to this day, especially since science keeps discovering new ways to make sensors ever smaller and affordable, to the point where some are invisible to the naked eye. When there was a time where sensors were made to fit in one's hand and handled manually, today engineers have the means of embedding sensors onto clothing or even structures. One example is the aforementioned bridge in Amsterdam, which was fully 3D printed with sensors embedded within (Parkes, 2021). The amount of applications and different technological fields that sensors may be utilized can be truly astonishing.

A sensor, broadly speaking, is any device that has the functionality of detecting a change in its given field or application, by means of using an active material (usually referred to as a transducer). Said material tends to be the one responsible for receiving signals of change in its given application, and translates that signal into a form of output that will be recognized by a receptor, such as human sight or a computer system. Most sensors are shipped as complete packages when it comes to their core components, with some having built-in transmitters that send feedback wirelessly, or having physical components that connect it to an external system.

As mentioned earlier, sensor systems are constantly being designed to be smaller and discreet. This in turn allows them to be used in situations and applications where it would have been impossible for a person to manually apply it, such as complex structures or in mechanical complexes. In addition to that, miniaturized sensors found their way into other industries, such as aerospace and electronic engineering, but the most important might be in the medical industry. Sensors that can detect changes in one's heart rate or any kind of important physical condition have the potential to save countless lives. By taking into account the form of feedback that sensors work with as well as the application they are being used on, sensors are being classified based on these factors. Common sensor types include but are not limited to surveillance, monitoring and electromagnetics. One interesting application might be the monitoring of a structure's health, particularly a historical monument's such as the Parthenon, given that their designs are irregular and require intricate sensor systems to monitor.

As aforementioned, a simple fully packaged sensor can include connectors with which they may be fused with the connectors of other sensors or any kind of external interface. Regarding their internal components, a template sensor can include processing components, a power source and its sensing component (Wilson, 2004). Sometimes they also include communication devices or components for wireless feedback signals. Modern sensors tend to include all these and more, with the additional benefit of becoming ever smaller thanks to technological advancements

2.2. Types of Sensors

2.2.1. Biosensors

Biosensors are a type of sensor that was first conceived and built based on nature's example. To give an example, the enzymes of our bodies are a type of biosensor (Wilson, 2004). When we consume food and it is being digested, our body requires a way to differentiate the different qualities and types of nutrients it needs to sustain itself, be it proteins or other types of nutrients that we obtain from digesting food. Enzymes are part of the digestive procedure, as they are the ones responsible for identifying and categorizing said nutrients, which then signals our body to forward to its respective use. In that sense, enzymes act as a biosensor, as they are built to detect the different types of nutrients and then send feedback to the body.

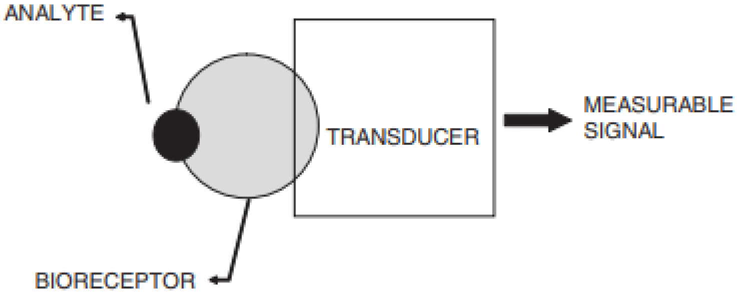


Figure 16 Biosensor configuration. (Wilson, 2004)

Modern day biosensors are being built based on this principle and their first concept came from Leland C. Clark Jr and co-workers in 1962 (Turner & Karube, 1987). They are small devices which come in contact with a sample by means of a bioreceptor. Once in contact, the biosensor recognizes the target sample and sends a feedback signal via a transducer (Wilson, 2004) N. For example, when taking in a sample of blood to measure a specific element of the substance, a biosensor with a bioreceptor built precisely for that type of element measurement (like glucose) is lowered into the substance sample, identifies the qualities or quantities of said element, then send a feedback signal via the transducer. The brightest qualities of the biosensors is the fact that both of its components are included in a single package and that the measurements are quick and easy, requiring no special preparation of the target substance and making the process considerable quick.

2.2.2. Capacitive and Inductive Displacement Sensors

Most sensors perform their functions by being in physical contact with their measurement target. As in the case of biosensors, which require their receptor to come in contact with the target analyte, sensors were at first built around the principle that in order to achieve proper measurements, the sensing device needs to be permanently in contact to its target (Wilson, 2004). However, there are some cases in which physical contact can damage or otherwise hinder the visibility of the measurement target. For example, placing a monitoring sensor on a sensitive and fragile component of an aircraft carries the small risk of damaging, however slightly, the like complex metal substance that coats the component (Wilson, 2004). Or in another case, placing a sensor that is visible to the naked eye onto a building's or monument's wall for whatever measurement or monitoring will no doubt disrupt its aesthetic.

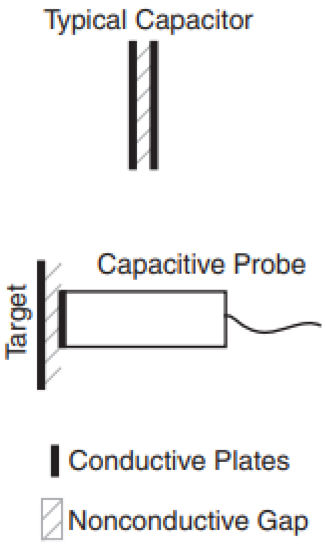


Figure 17 Illustration of the capacitance generated between probe and target surface (Wilson, 2004)

These are sample reasons why we conceived sensors that can take measurements without coming into direct contact with their target. In this category of contact-free sensors fall the inductive and capacitive displacement sensors (Wilson, 2004). The former is based on its utilization of electromagnetic fields, while the latter utilizes electric fields (Wilson, 2004).

Both sensors have their differences, but both follow the same structure in principle. These sensors generate their respective electric or electromagnetic field by means of a probe, which is attached onto a driver device (sometimes embedded into the probe itself) that contains the electronic setup which is responsible for guiding the probe and translating the measurement signals into voltage (Wilson, 2004).

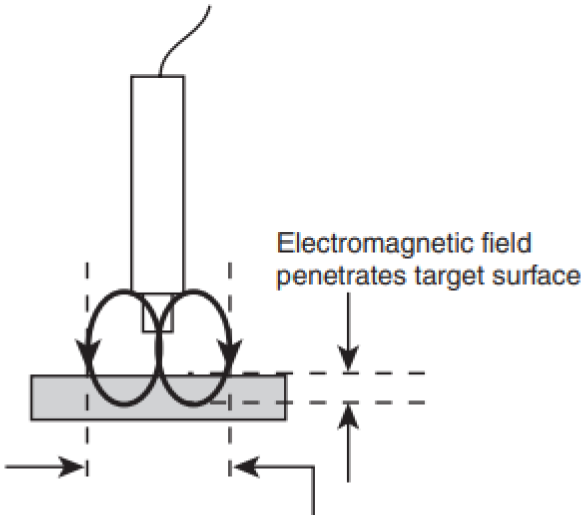


Figure 18Illustration of an inductive sensor's electromagnetic field generation (Wilson, 2004)

Capacitive sensors work by emitting an electric field near a measurement target. They rely on the fact that the capacitance between its probe and the target surface changes depending on their intermediate geometry and distance (Haitjema, 2020). The field senses the target's thickness by detecting its space within the electric field, no matter how small, by sensing its surfaces (Wilson, 2004). However, despite their ability to take accurate thickness measurement in different industry applications, their measurements can be easily disrupted. Since they detect changes in the space between the probe and the surface of an object, the gap between the probe and the material itself may sometimes be subjected to interjecting dust or other tiny material junk. Ideally, the gap between the probe and target needs to be as clean as possible, but that is rarely the case except for the unique case of vacuum. For that case, however, the probe needs to be specially built to prevent the disruption of said vacuum (Wilson, 2004).

Keeping that flaw in mind, inductive sensors come into play. Unlike capacitive sensors, they emit an electromagnetic field which inducts into the material, which sends back its own electromagnetic field, generating the sensor's response (Wilson, 2004). For that reason, inductive sensors are unaffected by debris in the gap between the probe and the target. They are in turn, however, affected by the type of material they are about to sense. Since metals have their own inductive properties, inductive sensors need to be calibrated depending on the target material (Wilson, 2004). Given their ability to ignore intruding junk, they are ideal for taking measurements while submerged in liquid.

2.2.3. Flow and Level Sensors

So far, we have researched the application of sensors when it comes to sensing solid materials. But there are often cases in other industries where there is the need to measure the other two states of matter, which is liquid and air. A multitude of flow sensor technologies have been designed to measure the flow rate or the substantial amount going through. For example, sensors are needed in order to provide insight into the flow of a river being handled by a facility or to measure the exhaust of a turbine.

Some flow sensors can perform the task of detecting measurements for both gas and liquid, while others are built specifically for either of those cases. Such sensors include thermal anemometers, differential pressure measurement sensors, turbine based flow sensors and more (Wilson, 2004). As a rule of thumb, flow sensors detect liquid or gas flowing rate by sizing up the velocity of the target by the means of a measurement point in the structure that the target is passing through, then apply a multiplicative calculation by taking into account the cross-sectional area from with the measurement is being made (Wilson, 2004).

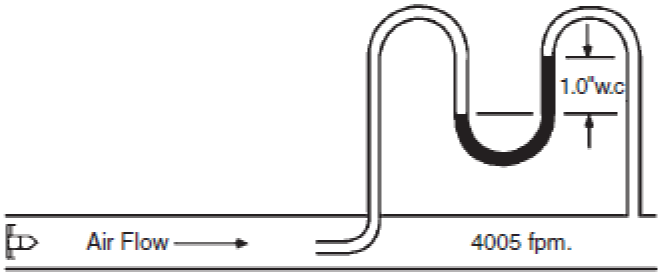


Figure 19 Measurement of air flow in a tube (Wilson, 2004)

2.2.4. Force, Load and Weight Sensors

Flowing away from the sensing of the immaterial back to the solid material, taking measurements of forces such as weight is typically one of the most common practices today by ordinary people. Going as far back as ancient times, the first weight scale that was used by merchants and bankers was a form of weight sensor. They would use a weight as a reference point on the one side, placing the measurement target on the other and making a measurement by comparing the difference of the scale's plate height. Some of the first weight scales used for measuring a human's body weight functioned by means of a strain gauge. That being said, these days most force sensors contain either piezoelectric quartz crystals or strain gauges, with variance depending on specific need (Wilson, 2004) s. Measuring and controlling applied forces is absolutely required in some scientific fields, such as when operating with medical robotics (Lebosse, Renaud, Bayle, & de Mathelin, 2011).

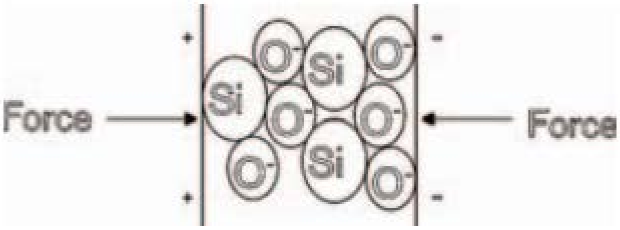


Figure 20 Piezoelectric effect. (Wilson, 2004)

As far as quartz force sensors are concerned, they are mostly utilized when the detection of tension, impact or compression forces is required. This type of sensors works by applying force or stressing the quartz crystal. When the crystal is subjected to external force, it generates an electrostatic charge on its surface, which the sensor module receives as a signal to compute measurements of said force (Wilson, 2004). The caveat is that, since the crystal generates its signal whenever force is applied or removed from it, it falls on a loop where if the applied force remains stable for some time, the signal generated will eventually fade away.

Taking into account the discharge time constant of the sensor, we can determine when the crystal's electrostatic charge returns to zero by calculating its rate. The sensor's discharge time constant (DTC) is the time that the sensor needs to reduce the power of its signal to 37% of the starting value of the measurement instant (Wilson, 2004).

By multiplying the lowest insulation resistance path (in Ohms) by the complete capacitance (in Farhads) of the system, we can determine the value of the DTC (Wilson, 2004). The relatively low frequency monitoring functions of this system is related to the discharge time constant, and it is for the crystal's somewhat quick discharge that it is not used for weighing measurements, but rather for measurements which involve interchangeable forces or quick force measurements.

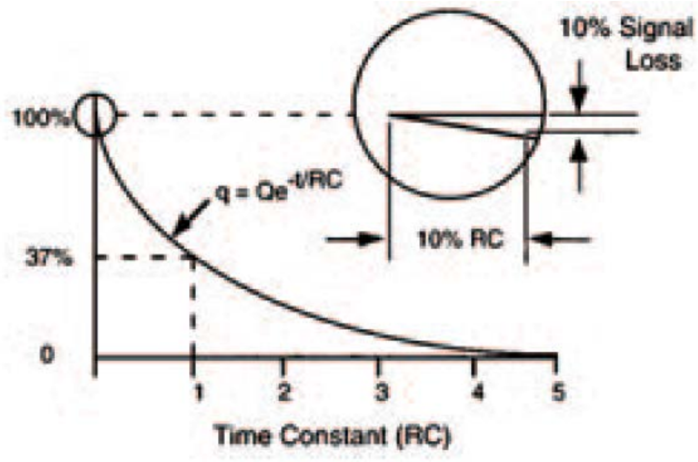


Figure 21 Decay due to discharge time constant (DTC) (Wilson, 2004).

The rate at which the quartz crystal discharges its signal is represented in Figure 21 and goes according to this equation:

$Q=Qe^\wedge(-t/(R*C))$

where:

- q = instantaneous charge (Coulomb)
- Q = initial quantity of charge (Coulomb)
- R = resistance prior to amplifier (Ohm)
- C = total capacitance prior to amplifier (Farad)
- e = base of natural log (2.718)
- t = time elapsed after time zero (Second)

From this equation and raw logic, we can assume that a quartz sensor with a higher DTC can detect the application of force for a longer amount of time. This chronic element can be altered by modifying the resistors inside the sensor's circuitry, changing the value of R in the equation and resulting in higher DTC if required, with some force sensors reaching time constants of half an hour, rather than mere seconds (Wilson, 2004). The manufacturer of the sensor is responsible for setting the DTC of a sensor. Some sensors require external amplifiers to set the time constant, while sensors with internal circuitry do so by altering the resistor value, as mention earlier (Wilson, 2004). Each come with their own manufacturing costs and are built, tweaked and shipped to suit the needs of their respective application.

2.2.5. Humidity Sensors

Humidity is a phenomenon that humans have attempted to measure for ages now. By definition, humidity is the presence of moisture in the air in a space, or in other words, to amount of vaporized water in the air. There are three points at which humidity is measured: absolute humidity, dew point and relative humidity (Wilson, 2004).

Dew point is the point which the vaporized water in the air begins to reach a liquid state. On the other end of the same spectrum is the frost point, which is the temperature below zero at which the vapor condenses into a solid state (ice) (Zhi & Lu, 2005). Dew and frost points are measured by thin film capacitive sensors (Wilson, 2004). In older times, people used to measure dew points by using chilled mirrors. Absolute humidity is measured with thermal conductivity sensors, while relative humidity (RH) is measured with resistive and capacitive sensors (Wilson, 2004). The development of these technologies did not begin until the mid-1900s.

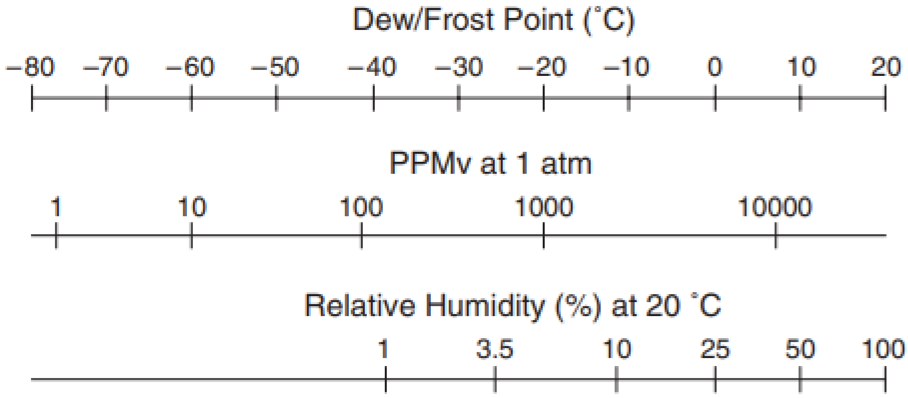


Figure 22 Correlation among humidity units (Zhi & Lu, 2005)

Sensors that measure absolute humidity do so by measuring the disparity of thermal conductivity between the real air and ideal, dry air. The dry air is simulated by a small tank of dry nitrogen. The sensor is arranged with two thermistors in a DC bridge circuit, with one element being held out to the environmental air while the other is submerged in said dry nitrogen (Wilson, 2004). By taking into account the difference of resistance between the two elements, the absolute humidity of the environment can be directly calculated (Wilson, 2004).

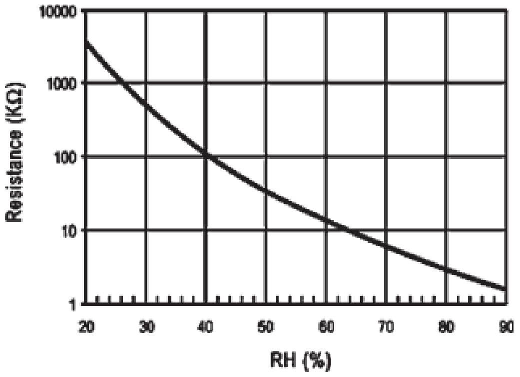


Figure 23 Relationship of impedance change to humidity (Wilson, 2004)

Resistive humidity sensors do not measure humidity per se. Instead, they measure impedance of a material, which is inversely exponential compared to humidity, as seen in Figure 23 (Wilson, 2004). The material used for today's resistive humidity sensors, which usually is conductive polymer or salt, are coated with ceramic and the sensor itself is covered by plastic (Wilson, 2004).

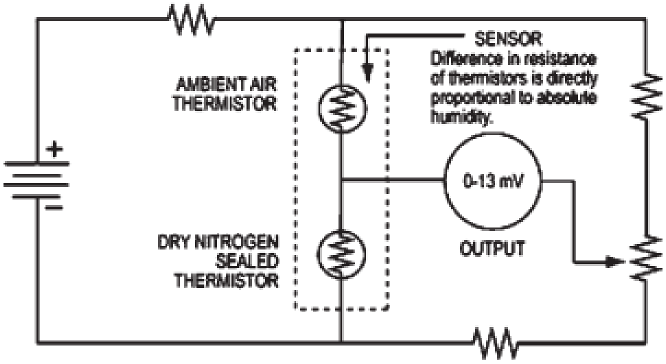


Figure 24 Thermal conductivity sensors (Wilson, 2004)

Sensors that measure relative humidity (RH) are the ones most predominantly used in most weather applications. To put it into perspective, these capacitive sensors can function in temperatures as high as 200 degrees Celsius and can accurately measure RH as low as 0% (Wilson, 2004). It is thanks to these characteristics that the capacitive sensors overshadow other humidity sensors, given their lack of drawbacks and great precision. These sensors work by measuring the change in the dielectric constant of the sensor, which is directly proportional to the air's RH, and can completely restore their form following their condensing (Wilson, 2004).

2.2.6. Temperature Sensors

Measuring the temperature of an environment has been a prominent task for ages. People use the measurements of a day's weather and consequently make their decisions with knowledge of the weather's temperature levels. Having knowledge of whether it is hot or cold outside or inside a space can vastly affect the decision making of our everyday lives for a number of different reasons. Thus, temperature sensors are critically important both for both society and in an environment where knowledge of a particular space's temperature is critical, such as the space in which a machine is contained and operates. Temperature affects all materials at a molecular level, thus being able to keep track of it is of great significance (Wilson, 2004).

Temperature is a type of measurement that we humans have conceived to express how cold or hot something is, or in other words, how much heat is contained inside an area or an object. There are materials that correspond to shifts in temperature, thus being used in temperature sensors as a way to detect changes (Wilson, 2004). There are sensors that work by having direct contact with the measurement target, be it in either state of matter, with a large temperature bandwidth (Wilson, 2004). Other sensors do not need to come into contact, instead they use infrared technology to measure temperature by detecting the energy emanating from various sources. The latter method is not compatible with the detection of heat coming from air and gas, due to the lack of any kind of solid frame, but works well with liquids and solids.

Temperature sensors using infrared technology work by detecting the infrared energy emanated by every object, and the amount of infrared energy is directly proportional to an object's temperature. Infrared sensors use lens to gather the radiated infrared energy onto a thermopile, which then provides a reading based on the amplified voltage output (Wilson, 2004). The amount of infrared energy that an object emits is not perfect, however, as the percentage of how reflective an object is (emissivity) is directly related to the amount of infrared energy that can escape from it (Wilson, 2004).

As for measuring temperature directly, the method is similar to the resistive sensors used to measure humidity, as mentioned in the previous paragraph. These devices are called thermistors, whose electrical resistance is shifted depending on the current temperature (Wilson, 2004). Most thermistors consist of two or more metal oxides which are covered in ceramic and contain wires connected to a semiconductor chip (Wilson, 2004). Thermistors are differentiated into two categories, depending on whether their temperature coefficient is negative or positive. In that sense, sensors with negative coefficient incur a negative shift in their electrical resistance while the temperature is increased, while sensors with positive coefficient display increased resistance as the temperature increases. Both types tend to wield the same results, while having only slight differences.

Negative coefficient sensors are placed in an advantageous position compared to positive, because of the fact that they are highly sensitive to temperature shifts and consequently deliver highly accurate measurement results. That is not to say that positive coefficient sensors would not be effective, however. An advantage unique to these sensors is the fact that they allow the usage of conductive polymer for the measurement, allowing for this stout material to be protected against extremely high temperatures and excessive current (Wilson, 2004).

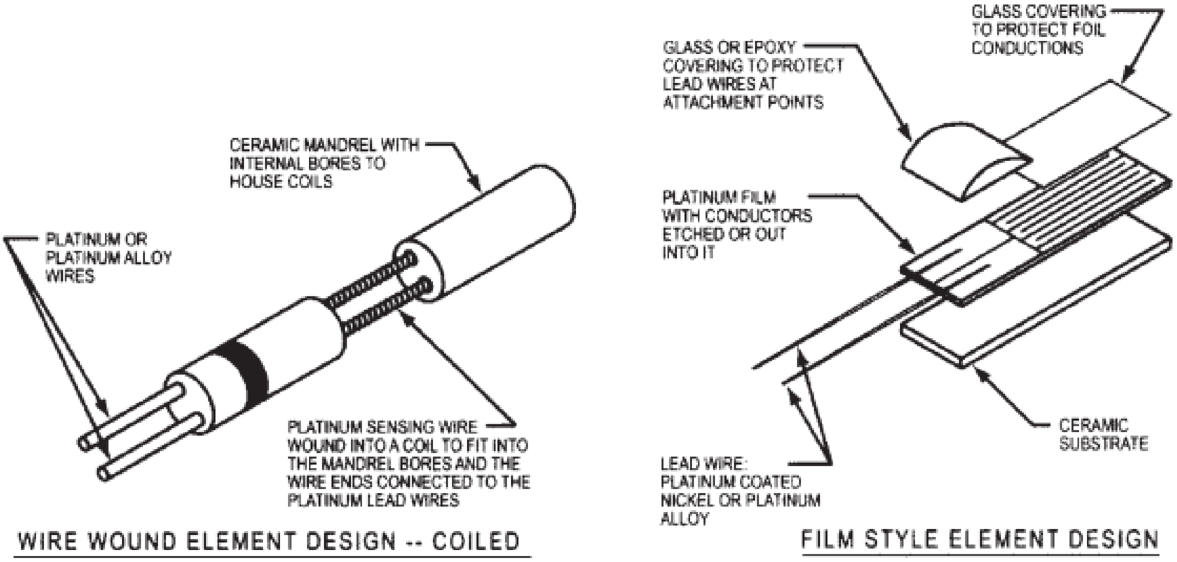


Figure 25 Sensing element designs (Wilson, 2004)

2.3. Sensors for Monitoring Structures

Structural sensors may be utilized to monitor structural movements, deformations, stresses and strains in buildings, engineered structures and even historical monuments. The wide range of sensors available through today’s technology gives us the leeway to configure monitoring solutions that can be customized to meet specific challenges and/or budgets.

It is becoming increasingly vital to be able to monitor structural integrity with sensors, for a couple of reason. First and foremost, modern buildings are being built with ever increasing ambition, with skyscrapers and other intricate buildings being designed around the globe. Having proper monitoring and maintaining of the foundations and other elements of these structures is critically important, as flaws that appear as a result of any kind of stress, or otherwise damage, could potentially spiral out of control and have destructive result if not properly managed and maintained in time. Second, as time passes, so does the health of historical monuments and structures deteriorate. In this case it is not a matter of safety, but rather a matter of historical and cultural preservation. Monuments stand as cornerstones of our pasts and must be preserved at all costs, by applying proper sensor systems to monitor their status and react accordingly when and if maintenance is required.

The following sensors may be used to successfully monitor the health of a structure: fissurometers, laser distance meters, accelerometers and strain gauges.

2.3.1. Fissurometers

Fissurometers, also known as jointmeters or deformeters, is a relatively rarely used term for instruments which are technically displacement gauges, used to measure and monitor the size and distance of cracks in a given structure (Fecker, 2007). While the application of such sensors is relatively outdated, they can still be applied as a viable means of detection and monitoring of cracks.

One easy to use, cheap and quick to set up fissurometer is the crack spy. The crack spy is similar to a ruler in its design. It consists of a pair of plastic plates that overlap, with one being acting as a distance calibrator and the other depicting a crosshair on the scale (Fecker, 2007). By placing and fixing the crack spy onto the point a wall's crack, it is able to measure any further horizontal openings in the crack by causing the bottom plate to move alongside the crack's opening. This allows the crack spy to measure the further opening of the crack, although the measurement is analog and is prone to human error.

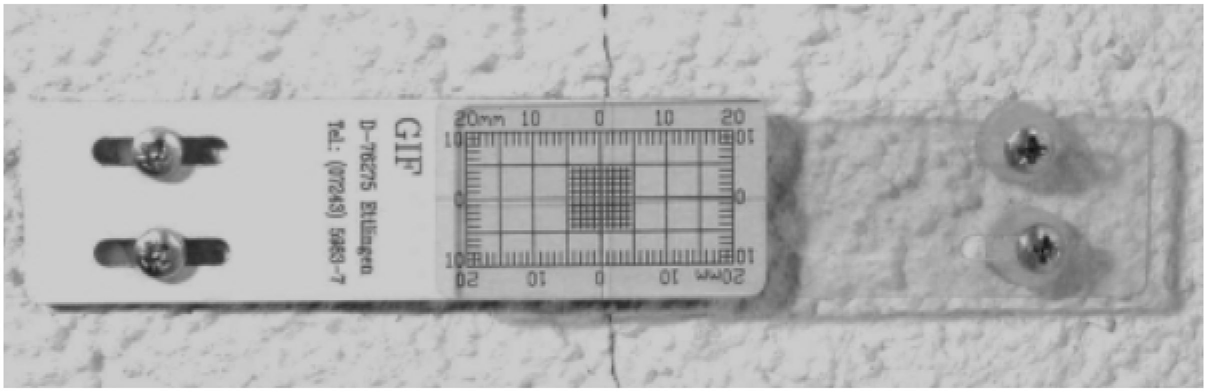
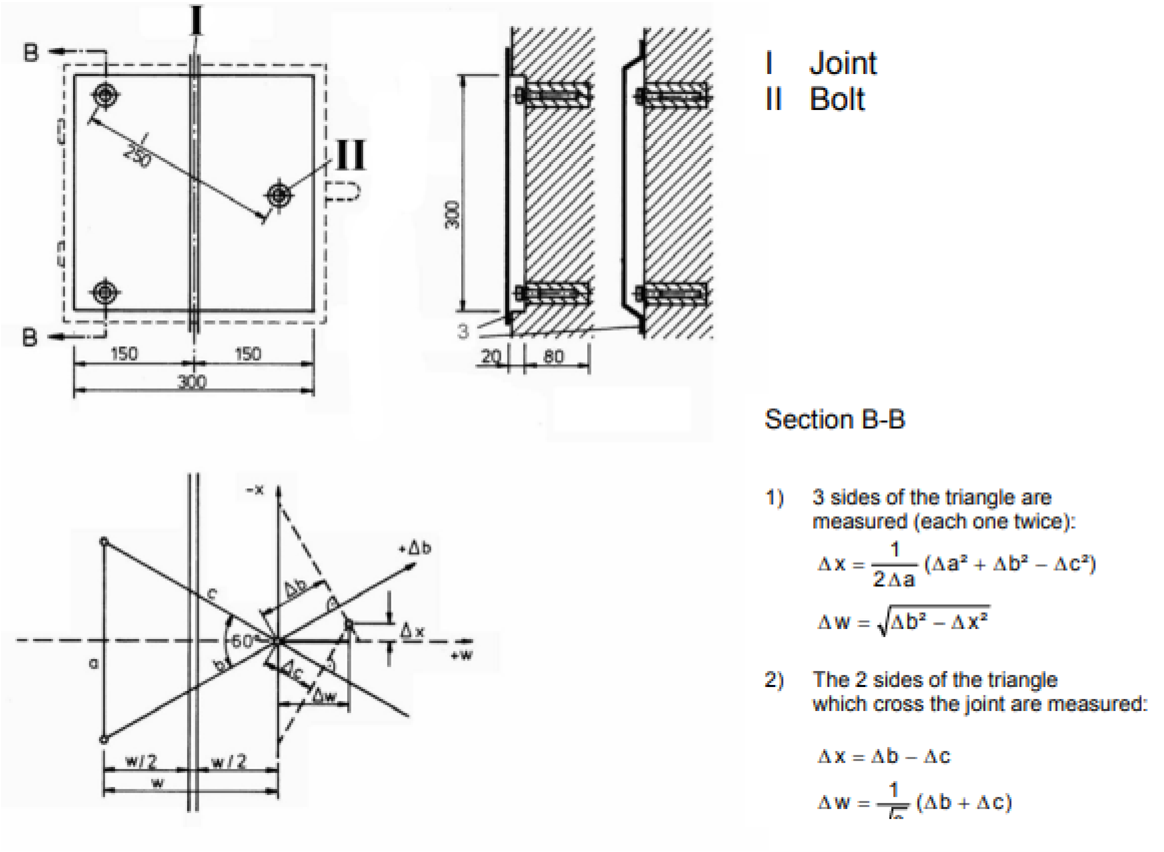


Figure 26 A crack spy (Fecker, 2007)

Another more reliable method is placing mechanical fissurometers that can keep track of crack measurements in different ways. Two methods may be utilized, one being to measure the displacement over a crack or over and parallel to it, as depicted in Figure 27 (Fecker, 2007). Taking measurements across a crack can be done with a mechanical fissurometer. A type FE fissurometer may be utilized by placing two measuring rods in an appropriate distance, drilling them ever so slightly into place. Displacement of the crack can be detected as the rods will be displaced at the same time. When that happens, an electrical signal is being transmitted via cable to a computer system (Fecker, 2007).



1) 3 sides of the triangle are measured (each one twice):

$$\Delta x = \frac{1}{2\Delta a}(\Delta a^2 + \Delta b^2 - \Delta c^2)$$

$$\Delta w = \sqrt{\Delta b^2 - \Delta x^2}$$

2) The 2 sides of the triangle which cross the joint are measured:

$$\Delta x = \Delta b - \Delta c$$

$$\Delta w = \frac{1}{\sqrt{\;}}(\Delta b + \Delta c)$$

Figure 27 Displacement measurements with three measurement rods (Fecker, 2007).

While these methods may accurately be able to monitor cracks, they leave a lot to be desired as their implementation requires the damaging of the structure, however minimal, and a cabled connection to send the signal. The cable is superseded by wireless systems which will be mentioned later.

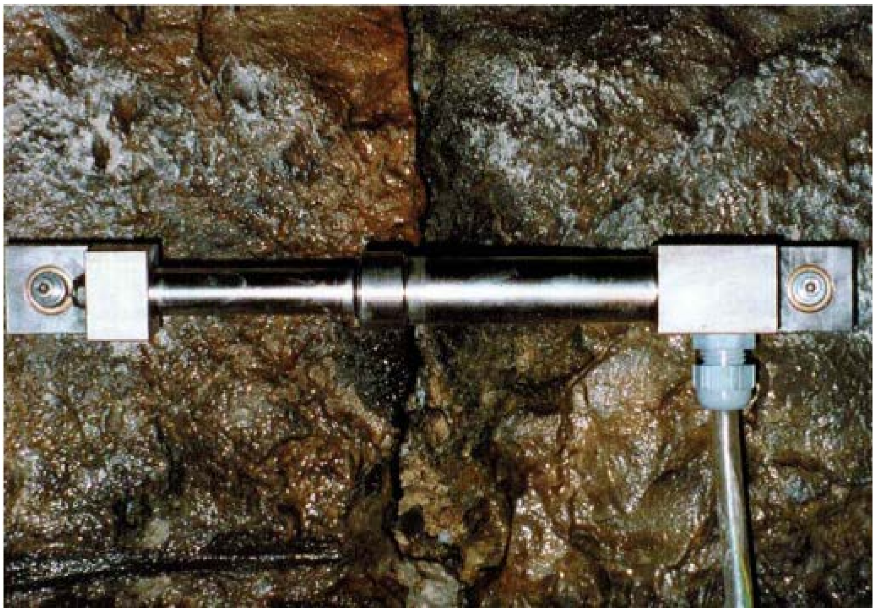


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Figure 28 Electric fissurometer FE with the measuring rods set 250 mm apart (Fecker, 2007).

2.3.2. Accelerometers

One type of sensor that is most commonly used today, not only in construction but in other cases in which we are involved in our everyday lives, is the accelerometer. It is a sensory device that specializes in providing feedback whenever it detects signs of vibration, displacement, applied force etc. (Wilson, 2004).

As far as structures are concerned, it is a well-known fact in the field of engineering that being able to monitor a structure's condition relative to applied forces such as wind, earthquakes or simply just material wear, makes a world of difference when designing a structure. By being able to take measurements of the acceleration caused by any and all damaging forces, engineers are able to better grasp the characteristics of a given structure, especially when it concerns an exceptionally tall or intricately designed building. Having the ability to monitor a structure's integrity at critical points and taking measurements of its condition in general can help prevent critical failures by performing maintenance when required, as well as providing insight when designing new structures in order to make them as safe and durable as possible. Building designs of newer structures has been improved because of the data and information provided by the dynamic response of accelerometers applied onto civil structures (Li, et al., 2006).

There are several types of accelerometer, but the two cases that stand out due to their popularity and usability in the case of buildings are the piezoresistive accelerometer and the capacitive accelerometer.

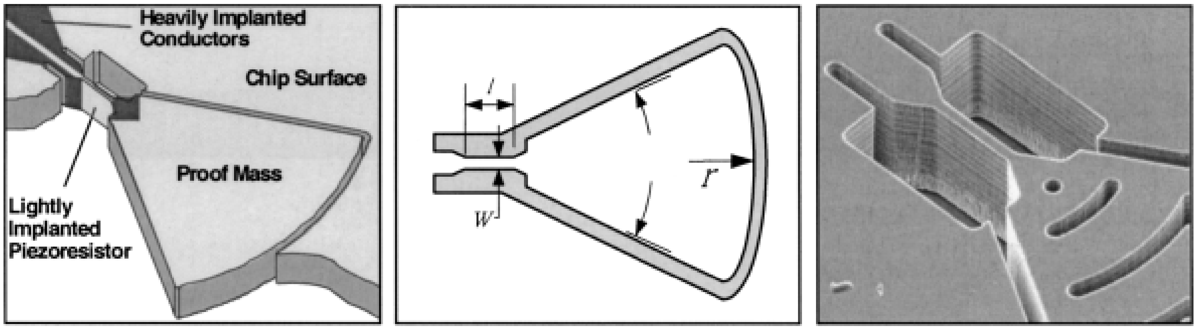


Figure 29I Illustration of design and dimensions of a piezoresistive accelerometer

The piezoresistive accelerometer is similar enough to the quartz crystal sensor’s piezoelectric nature, in that it measures applied force and stress by utilizing a piezoresistive crystal that possesses the property of undergoing deformation while being subject to external pressure. Likewise, the deformation is converted to a signal that is promoted to the sensor’s transducer in order to produce feedback. Building these sensors to be as effective and small as possible has been a challenge for years. The first sensors were built by containing the a proof mass material within a silicon case by means of a flexible element that has the piezoresistive material placed on top, which emits an electric signal when the experiencing external force and is then converted into voltage using a Wheatstone bridge around the piezoresistive material (Lynch, et al., 2003). By doing so, we are able to directly correlate the amount of acceleration experienced by the sensing element to the resulting voltage. Modern piezoresistive accelerometers are designed somewhat differently. As depicted in Figure 29, the proof mass that is connected to the sensor’s casing by an element which contains the piezoresistive material will start to budge whenever it experiences acceleration (Lynch, et al., 2003). The result of this movement will lead to the material between the sensor and the proof mass to become strained, resulting in the shifting resistance and emitting the electrical signal to the sensor. The dimensional parameters of the sensor unit can be customized to fit specific situations.

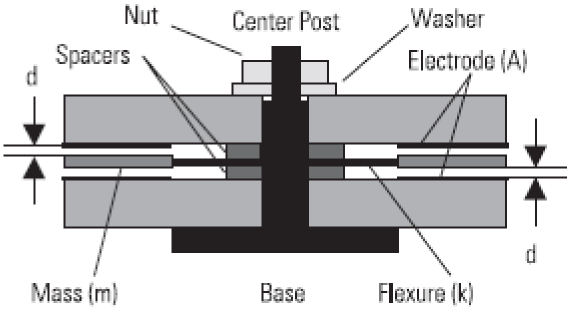


Figure 30 Structure of a capacitive accelerometer (Wilson, 2004)

Capacitive accelerometers function is a similar way to the piezoelectric accelerometers by sensing developments across the surface of a material. However, the key difference lies in the fact that they assess shifts in capacitance instead of resistance. By placing two plate capacitors, being set to function in opposite mode, in parallel formation facing each other we have essentially built a basic capacitive accelerometer sensor. The capacitor plates mentioned are able to provide a voltage output, which is proportional to the amount of accelerating force that the sensor is being subject to, by engaging in a bridge formation and being reliant on the sensor's carrier demodulator circuit (Wilson, 2004). The capacitance of the plate formation can be expressed with this equation:

$$C_0 = \epsilon_0 \epsilon \frac{A}{d} = \epsilon_A \frac{1}{d},$$

where $\varepsilon_A = \varepsilon_0 \varepsilon A$ and A marks the area of the electrodes, d expresses the distance that separates the plates and ε the permittivity of the material that is separating them (Andrejašic, 2008). Different types of capacitive elements may be used depending of the given task. An example is using a set of aluminum plates and a metal sensing diaphragm which is placed between the two plates, consequently devising two capacitors with their unique respective capacities depending on the distance from the interjecting diaphragm, as seen in Figure 30 (Wilson, 2004). That being said, in order for the sensor to function properly, an internal electronic circuit is mandatory so that it can translate the shifts in capacitance into a signal that can be used as feedback. As depicted in Figure 31, the circuit is being passed through by a stable direct current thanks to a voltage regulator between the circuit and the power supply, which is usually a battery. The signal passes through the capacitance bridge, which is set to divide the oscillator signal depending directly on the amount of capacitance that has been changed in the two capacitor plates (Wilson, 2004)

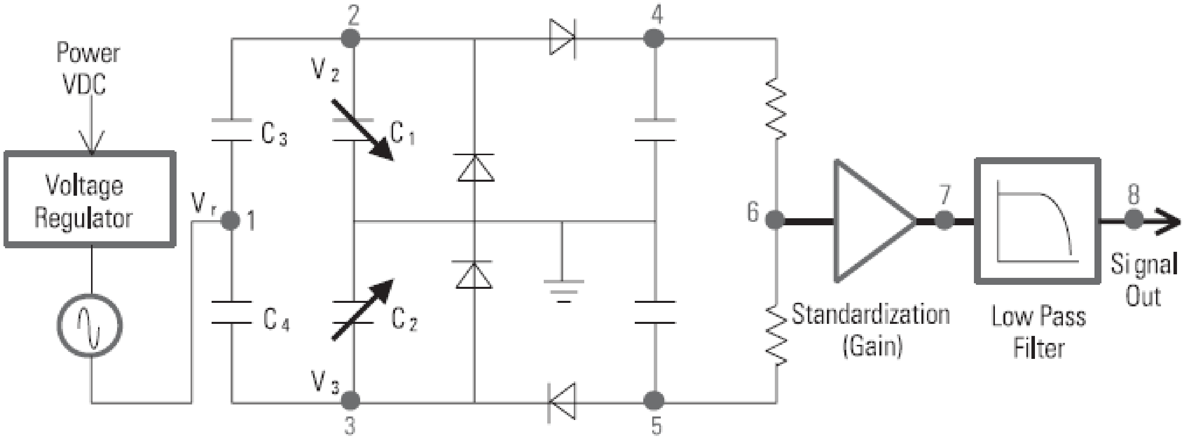


Figure 31 inner circuitry of a capacitive accelerometer (Wilson, 2004)

. The signals are then simplified as they go through rectification and end up re-engaging with each other, ultimately creating an electrical signal which is proportional to the external force that caused the capacitor elements to shift in capacitance (Wilson, 2004). A notable advantage of the capacitive accelerometer is its ability to express high durability when exposed to great shocks, although tend to suffer from limited high frequencies (Wilson, 2004).

2.3.3. Laser Distance Meter

The laser distance meter, often referred to as laser telemeter or rangefinder, is a sensory device that utilizes a laser beam to measure distance. These kinds of sensors are manually handled and are not used for automated monitoring in structures, but they are finding use whenever a measurement needs to be taken at a distance. Other fields of use include but are not limited to military applications, home improvement projects and storage management due to the ability of these sensory devices to swiftly measure distance at range.

That being said, it not possible to take measurements when the subjected material is less than 75 millimeters long and possess a thickness less than 2 centimeters because of how the laser meter works (Finlayson & Sinclair, 1999). These devices function by firing a laser beam at the speed of light over a certain distance to the target object, which is then reflected back. The sensor measures the distance from the firing point to the target by calculating the time it took for the beam to be reflected back relevant to the speed of light. Measurements of small distances, such as cracks, would likely be inaccurate if taken by a laser meter due to the incredibly fast speed of light. Other methods would better suited for taking smaller measurements. It should be noted that the two towers of Bologna possess an integrated static structural monitoring system which includes laser displacement sensors (Baraccani, et al., 2017).

Figure 32 A laser rangefinder (LASER RANGEFINDERS – HOW DO THEY WORK? WHICH ONE SHOULD YOU CHOOSE?, 2019)

2.3.4. Strain Gages and Piezoresistance

A lot of sensors used in structural health monitoring are built around the fundamentals of strain gauge and piezoresistance technology. It involves the principle of converting the strain suffered by a material into an electrical signal. If that sounds familiar, look no further than the aforementioned quartz crystals and piezoresistive accelerometer, which all utilize piezoelectric effects to provide signals that act as feedback for calculating measurements of force and stress on a given area. When the resistance of the gauge is altered by means of enduring strain, that shift in resistance is translated into a voltage signal by means of attaching the gauge element to a Wheatstone bridge setup. Several kinds of materials have proven to act as better strain gauges compared to other ones, such as semiconductor silicon, but the fact stands that the strain gauge can consist of nearly any kind of material (Wilson, 2004). In addition, strain sensors differ based on their number of fixed resistors and gauges. While some are employing a single strain gauge, there have been newer arrangements which employ two resistors and gauges or even just four gauges (Wilson, 2004). The applied load on the strain gauge can be indicated by the composition of the sensor's transducer as well as the significance of the gauge's deformation indicated by the change in its resistive property.

A Wheatstone bridge setup is required to be joined to a strain gauge in order to counteract parasitic signals and other forces that might interfere with the configuration. A head signal of 5 to 20 volt DC is applied at points A and D in the bridge formation, as seen in Figure 33. This setup is necessary so that, whenever the transducer structure is being subjected to external force, a voltage output is the result of the bridge falling into imbalance that goes between points B and C. This voltage output is corresponding to the force load being applied (Wilson, 2004).

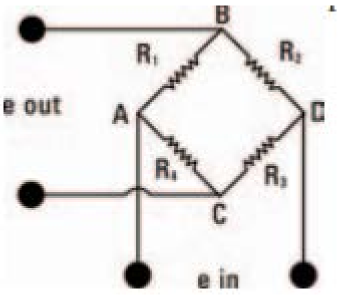
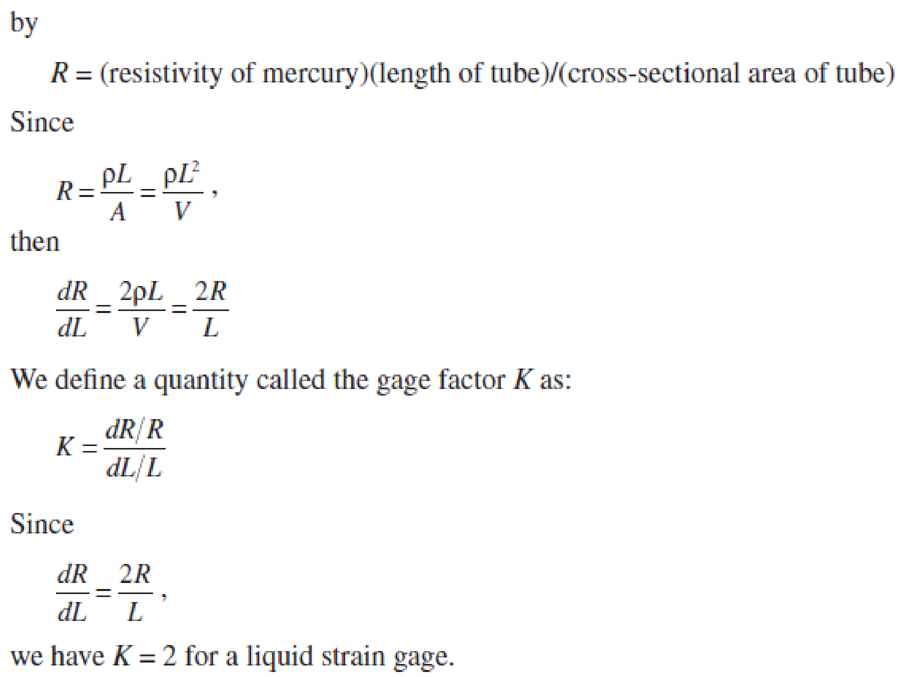


Figure 33 Typical Wheatstone bridge configuration.

Piezoresistive sensor technology defines a device that demonstrates a shift in its resistance as long as it placed under stress (Wilson, 2004). Such devices are most commonly used in accelerometers. Piezoresistivity relies largely on the sensor's geometrical placement on a given application, given that in order to achieve precise measurements the sensor need to be placed in locations with the highest and most likely instances of strain before it can deliver optimal measurements (French, 1998). One of the two elements that constitute a piezoresistive material is the geometrical component, which is necessary in its case so that the other component, the strained element that is, may go through its dimensional change (Wilson, 2004).
Examples of piezoresistive sensors that were used a long time ago are the liquid mercury tubes, metal wires and thin film strain gauges.
Mercury tubes were placed as strain gauges, the resistance of the liquid was able to be measured by means of electrodes at both ends of the tube (Wilson, 2004). Applied forces at both ends of the tube would cause the tube to stretch and fluctuate its diameter, while the liquid itself remained unable to be compressed given its nature. The resistance of the gauge in this gauge can be calculated as:



by

R = (resistivity of mercury)(length of tube)/(cross-sectional area of tube)

Since

$$R = \frac{\rho L}{A} = \frac{\rho L^2}{V},$$

then

$$\frac{dR}{dL} = \frac{2\rho L}{V} = \frac{2R}{L}$$

We define a quantity called the gage factor K as:

$$K = \frac{dR/R}{dL/L}$$

Since

$$\frac{dR}{dL} = \frac{2R}{L},$$

we have $K = 2$ for a liquid strain gage.

Therefore, the resistance may be calculated as a fraction of twice the fractional change of the tube's length (Wilson, 2004).

The precision of the measurement of the resistance is one additional issue when it comes to strain gauges, but it may be improved by creating larger shifts in the voltage and utilizing greater currents. That being said, the reduction of power inside the resistive element indicates the amount of current that can go through. In order to capitalize on the thermal conduction from the thin film to the substrate, methods for optimized bonding of thin film gauges. Better accuracy is achieved by boosting the amount of current going through for the measurement as a result of optimizing thermal conductivity (Wilson, 2004).

3. CHAPTER 3: 3D-Printed Structure Sensors & Integration

3.1. Building Sensors via 3D-Printer

In the first chapter the thesis focused on the different types of 3D printing technologies available today, such as binder jetting, photopolymerization, lamination and so on. It cannot be overstated how much potential freedom these technologies provide us when our goal is to create or build onto complex structures, being able to utilize a plethora of different materials in the process. Therefore, we turn our attention to sensors, devices that are rather complex in their design as stated in the previous chapter.

The idea of being able to 3D print electronics in general is considerably older than one might initially believe, dating as far back as the 1990s (Xu, et al., 2017). The first printed field-effect transistor was built by Francis Garnier back in 1994, followed by the production of another transistor by handling screen printing technology in 1995 and the fabrication of an organic transistor in 1999 by Jacobson and co. (Xu, et al., 2017). Last but not least, Sirringhaus and co. presented the capability to print electronic circuits with ink jetting technology in the year 2000 (Xu, et al., 2017). These examples may be what sparked the modern approach to building sensing devices using 3D printing instead of conventional methods.

With sensors seeing increasingly high rates of use in all kinds of industries, so develops a drive to design and create sensors faster and being able to design and test prototypes with as few resources and wasted time as possible. Producing structures at high resolutions, being slow at manufacturing, prototyping and generally proving tedious to construct are the most significant difficulties we encounter when utilizing manufacturing methods that remain conventional (Ni, et al., 2017). It is for that reason that, when it comes to manufacturing sensors, there has been an increasing interest in leaning towards using 3D printing methods for building sensors. The current goal of printing sensors is to try and erase the difficulties that traditional building methods present, such as cheaper fabrication materials and shorter fabrication times. Unlike traditional methods, 3D printing provides the opportunity to halt or begin the process at any point during fabrication to make modifications or to integrate

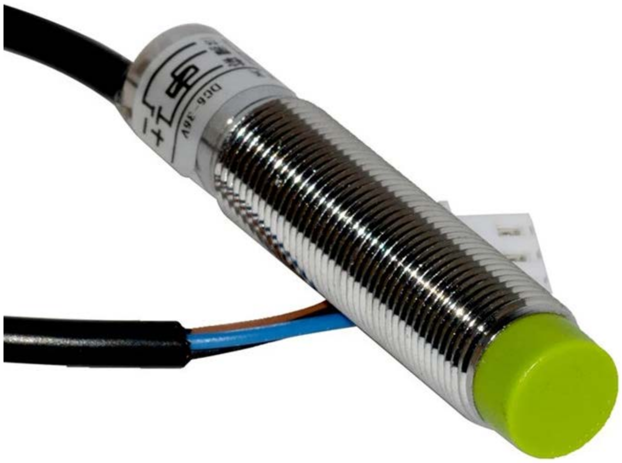


Figure 34 A 3D printed capacitive sensor (AliExpress, 2021)

supplementary parts and components onto another structure (Xu, et al., 2017). In addition, the traditional method to create sensors also includes the post-processing procedures as part of their time tax, including ultraviolet exposure and photo-resistant coating. While most 3D printers deliver objects that are ready for use, there are some 3D printing technologies that also require post-processing, although the time required remains low even in these cases (Manzanares & Pumera, 2018). As far as manufacturing costs are concerned, an example is presented by comparing polydimethlsiloxane soft lithography and stereolithography, where the former procedure costs 215 US dollars while the latter would cost 200 US dollars at worst (Ni, et al., 2017). Therefore, printing complete sensors or integrating sensors onto printed components is a process that may can be achieved with minimum hassle and with lesser financial cost. However, despite all the advantages that 3D printing has presented over time when it comes to building sensors, there are still some cases where traditional methods may be cheaper in the long run. More specifically, methods that are being used for mass production like dipping liquid sensing layers onto a substrate could still prove to be more economic (Ni, et al., 2017). Therefore, printing sensors is better suited when crafting, prototyping or modifying individual pieces in small batches. Conventional manufacturing remains the most economic choice when it comes to industrial production, at least for now.

Most sensors used today require embedded complex electronic devices and circuitry. With 3D printing, it is possible to both design the electronics into the complete package and print it out directly. Given the freedom granted by three-dimensional design, the process allows printed sensors to include important components. Not only that, but printed sensor devices have the advantage of being built with increased sensitivity when it comes to taking measurements via sensing (Ni, et al., 2017). By taking advantage of the printer’s full capabilities, we are granted the flexibility of either directly printing sensor devices, building molds for casting sensors or fabricating research platforms ready to me merged with commercial sensors (Ni, et al., 2017). Moreover, having the freedom to design a sensor in a three-dimensional environment grants the ability to create or prototype sensors that are customized to suit the needs of specific applications, such as modifying a sensor’s geometry to better fit electrodes or a surface about to be placed on, or any at all product as long as its dimensions are not unknown.

3.2. Embedded Sensors and Systems

3D printing has presented engineers with numerous new, cheap and innovative ways to construct sensors. Being able to fabricate standalone pieces with little cost and wasted time is no doubt a boon in and of itself. Therefore, 3D printing technologies have given leeway to the discoveries of new methods in which sensors might be embedded onto structures and objects as a result of the desire for personalization and customization. Thanks to the wide array of materials available in the 3D printing process and the ability to configure complex shapes and mechanisms, this endeavor might now be achievable. Conductive materials are required for the fabrication of electronic sensors, such as liquid metals that can be utilized by direct ink writing. The presence of these metals is required as they act as conductors, antennas and capacitors (Ota, et al., 2016).

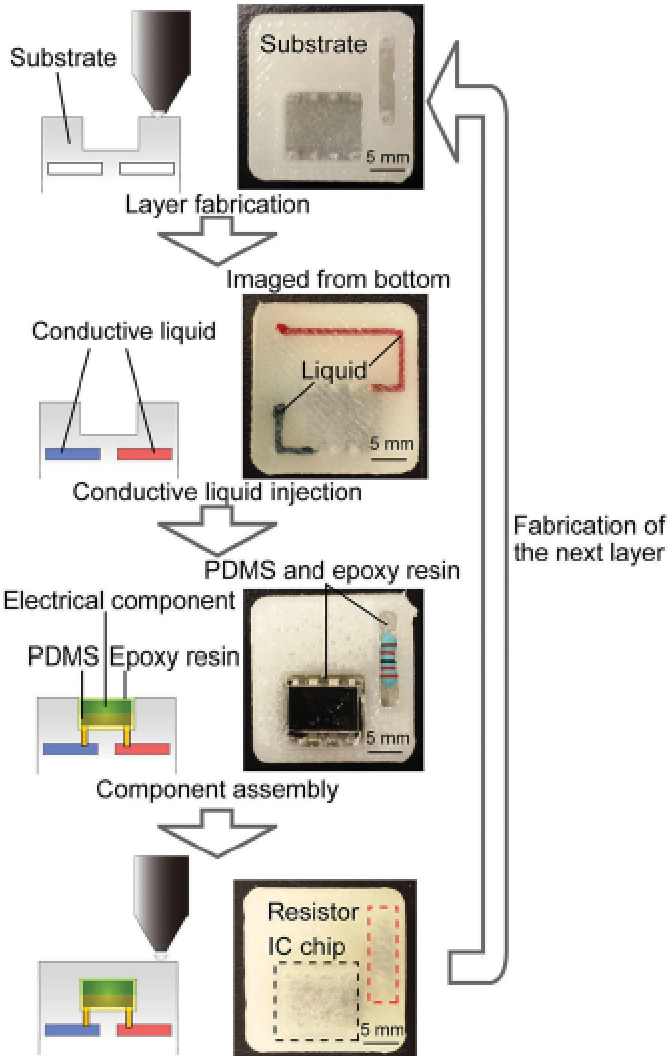


Figure 35 Process of 3D printed embedding of circuitry (Ota, et al., 2016)

Considering the possibilities, 3D printing enables the development of printed structures with integrated electronic systems. The bridge that was 3D printed in Amsterdam is a testament to this achievement, as it was built with embedded sensors (Parkes, 2021).

As presented by (Ota, et al., 2016), it is possible to utilize 3D printing electronics of either rigid or flexible nature, particularly when it comes to printing circuit boards required for sensing onto structures (Ota, et al., 2016). In order to fabricate circuitry elements, conductive pathways need to be printed inside an object or structure, while configured accordingly depending on the desired design. If the design calls rigid condition in order to perform its function, it needs to be printed with equally rigid substrates. This is respectively true for stretchable applications. To deliver complete systems embedded inside an object, the aforementioned channels will additionally be utilized as interconnecting pathways to be integrated with silicon chips (Ota, et al., 2016). These silicon IC chips are necessary in order to deliver advanced circuitry which would be otherwise difficult to achieve using nothing but liquid components in the printing process (Ota, et al., 2016).

A fabrication scheme is demonstrated in the Figure 35. To begin with, the printer fabricates the base substrate of the sensors, which is enclosing the vacant spaces and microchannels that are required to hold the integrated elements. Following that, circuit components and interconnects are being shaped by injecting appropriate liquid metal, and then the substrate slots are being occupied by embedded silicon chips or other electronics, as required (Ota, et al., 2016). They are being placed in such a way that the liquid metal channels create connections with the electronics. The final step involves the spraying of the layer with epoxy resin, in order to provide a level surface. Should the design of the built sensor in question require further modification or additions, the process may be repeated in the same way until the task is complete (Ota, et al., 2016). The software being used, as well as the injected material for the electric channels, allows for the designing of the creation of components with varying electrical properties or dimensions, depending on the application.

This general approach may be adopted in order to allow printed electronic systems to be embedded inside objects. In the following example, an embedded photodetector system was integrated within a structure that resembles the Sather Tower of the University of California, by means of a photoresistor delivering output to completely embedded sensor circuitry through external connection (Ota, et al., 2016). Intertwined circuits where applied onto three different layers in order to fabricate a photodetection platform. The first layer embeds a microcontroller unit which acts as a digital output. The second layer includes a low pass filter which is needed to diminish interference and noise. The third layer implements a transimpendance amplifier, whose function is to convert the output signal of the phototransistor into voltage (Ota, et al., 2016). The following figure demonstrates the procedure as well as the implementation of this design, particularly in a right angle, which goes to show that such implementation can involve the freedom of geometrical placement in any given situation (Ota, et al., 2016).

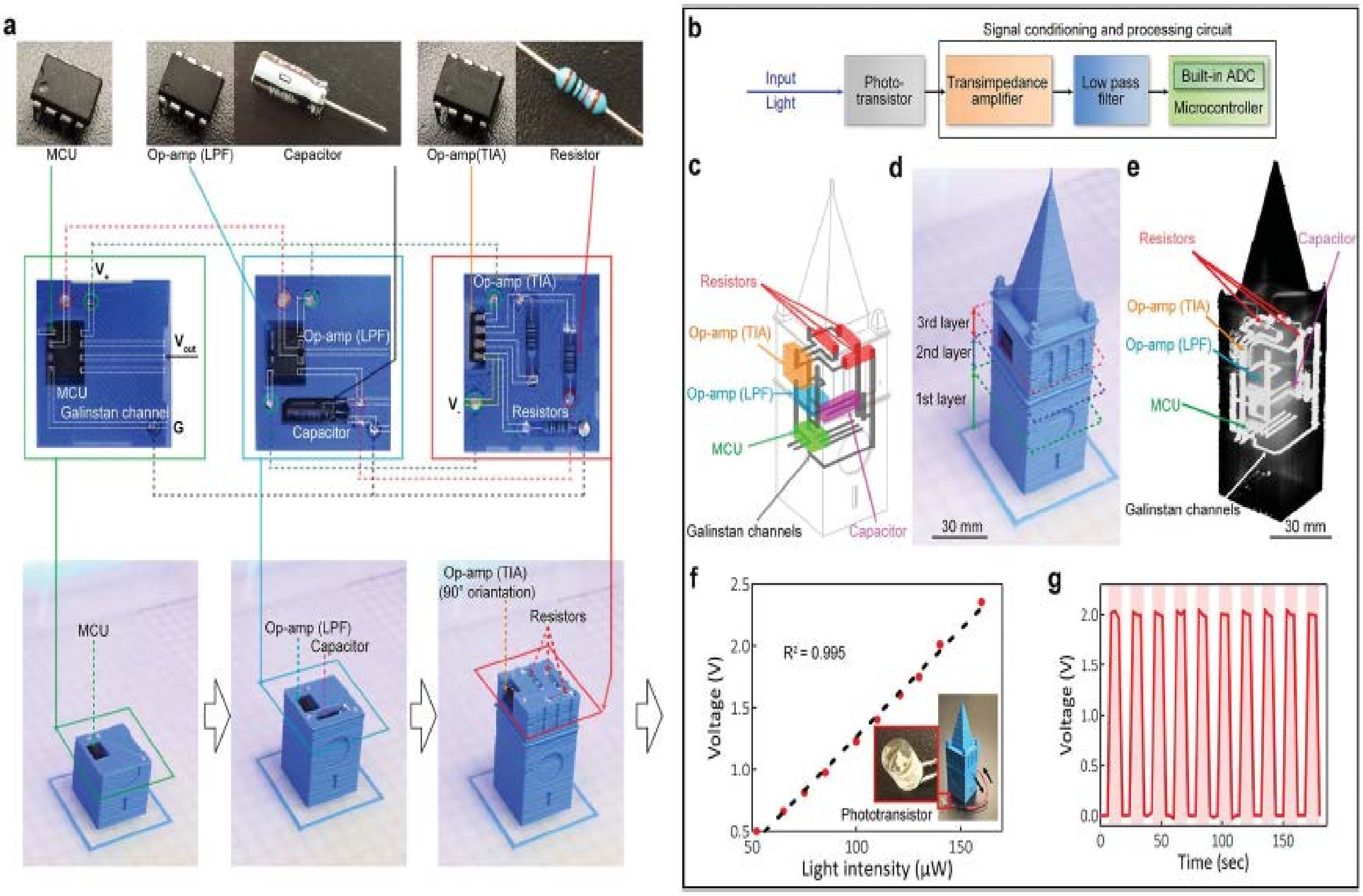


Figure 36 Illustrated example of embedded sensor system within a printed structure (Ota, et al., 2016)

The illustrated procedures provide but a sample of the possibilities provided by 3D printing technologies when it comes to embedding sensors onto structures and objects. By making use of this technology it might also be possible for engineering researchers to study structure design by printing miniatures of bigger structures and studying the implementation of sensory systems by embedding samples onto the printed structure.

3.3. Printing Strain Sensors

Strain sensors are being used in a very wide array of applications and can be integrated onto already existing objects with relative ease. Aside from their use in medicine and such, they may also be used as sensors for irregular placements due to their potential flexibility. That being said, it seems to be relatively hard to embed electronic devices with flexible matrices due to the differences in mechanical properties between typical rigid electronic devices and soft objects (Muth, et al., 2014). Basically, a deformable conducting material needs to be fused in some way with an inactive flexible material in order to produce an elastic sensor. Among others, 3D printing technologies such as lamination and direct ink deposition are being used to this day in order to manufacture the coveted sensing geometry. (Muth, et al., 2014). However, despite the fact that sensors may be fabricated in this manner it is unfortunately a costly endeavor for the materials required, not to mention that the resulting sensors are not as durable nor as quickly manufactured en masse, resulting in a lack of widespread use (Muth, et al., 2014)

Muth and co have presented a new method to manufacture strain gauges called embedded 3D printing, or e-3DP for short. It involves the utilization of direct ink deposition to create highly flexible strain sensors. A viscoelastic ink is used as the material deposited through the printer’s nozzle straight into an elastomeric reservoir (Muth, et al., 2014). The reservoir acts as matrix material while the deposited ink fabricates the resistive sensing element, while creating a blank space which needs to be supplied with a layer of filler fluid. Once the printing process is finished, the filler fluid and the reservoir are cured together in order to form a single rigid piece, with the conductive ink staying in fluid form in the process (Muth, et al., 2014). Therefore, it is proven that by utilizing the embedded 3D printing technology it is possible to fabricate flexible sensors seamlessly and precisely. Irregular sensor geometries in three-dimensional environments can be printed thanks to the precision pathing of the ink deposition and the supporting reservoir (Muth, et al., 2014).

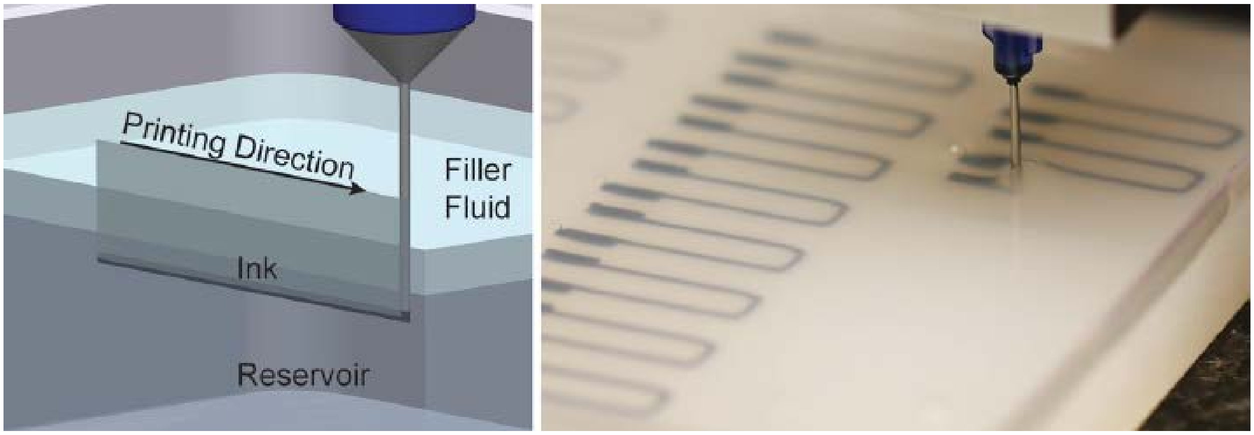


Figure 37 Illustration the e-3DP process. Conductive ink is printed into the elastometric reservoir while being capped by the filler fluid. (Muth, et al., 2014)

Before printing strain gauges in this manner, however, several precautions need to be taken. The filler fluid and the supporting reservoir need to meet certain criteria before being built. (Muth, et al., 2014) First of all, the patterning of the chosen ink filaments needs to be facilitated by the supporting reservoir. Following that, the filler fluid needs to be incorporated immediately should any defects become present while the ink nozzle does its job, so that they are taken care of. Once the embedded sensing elements are done being printed, the filler fluid portion of the reservoir needs to be condensed into an extensible elastomer matrix (Muth, et al., 2014).

In order to be able to meet these requirements, Muth et al modified a silicone elastomer in order to create both the filler fluid and reservoir by adding thickening or thinning agents onto the elastomer to produce the required material properties (Muth, et al., 2014). The resulting reservoir wields properties that allows the nozzle to proceed unhindered provide support for the patterned ink filaments while being able to do so without distorting their geometry. As for the thinning agent for the filler fluid, is seems to flow smoothly into the voids that are presented as the nozzles goes through.

The materials used for the procedure need to meet a pair of certain criteria in regards to their compatibility, before being able to successfully print soft sensors (Muth, et al., 2014) Firstly, the filler fluid and the reservoir ought to exhibit identical chemical qualities in order to prevent esoteric interfaces inside the elastomeric matrix following the post-process curing procedure. Secondly, both after the printing process is done as well as while it is being processed, the conductive ink needs to minimally diffuse within the reservoir in order to keep its fidelity (Muth, et al., 2014). The filler fluid and reservoir made from modified ecoflex retain their properties only before the curing post-process. The sensor comes out after curing as expected; rigid yet highly extensible (Muth, et al., 2014). The cured elastomeric matrix shows great levels of flexibility, up to 900% stretchability, and malleability proving ideal for soft and flexible sensors. The performance of soft sensors in general can be attributed to recent advances in the manufacturing process of materials, making them as strong as rigid sensors (Tang, Jia, Zhou, & Li, 2020).

3.4. Printing Accelerometers

Accelerometers are a vital part of monitoring machinery and other intricate structures, such as wind turbines. Therefore, the construction of accelerometers with high sensitivity is a subject that is being tackled by utilizing 3D printing technology.

The fabrication procedure of suspended structures that could function as capacitive accelerometers has been illustrated by Palma and co. (Rivadeneyra, et al., 2015). Firstly, a Serfix III screen printing machine was used for the fabrication of the cantilever on a polyethylene terephthalate substrate. Moreover, a direct metal printing machine, which is based on inkjet printing tech, was used for the printing of electrodes. The electrodes were composed of silver nanoparticles and they act as the electrical contact required in order to measure capacitance (Rivadeneyra, et al., 2015). Inkjet technology can be used for the fabrication of both the electrodes and the cantilever structure. The procedure then involves the alignment of the printed pillar and beam and subsequent layering of adhesive epoxy on top of the pillar, then the printing of the silver ink onto a polyethylene terephthalate substrate in order to create the electrodes (Rivadeneyra, et al., 2015). After that, both substrates are aligned and pasted

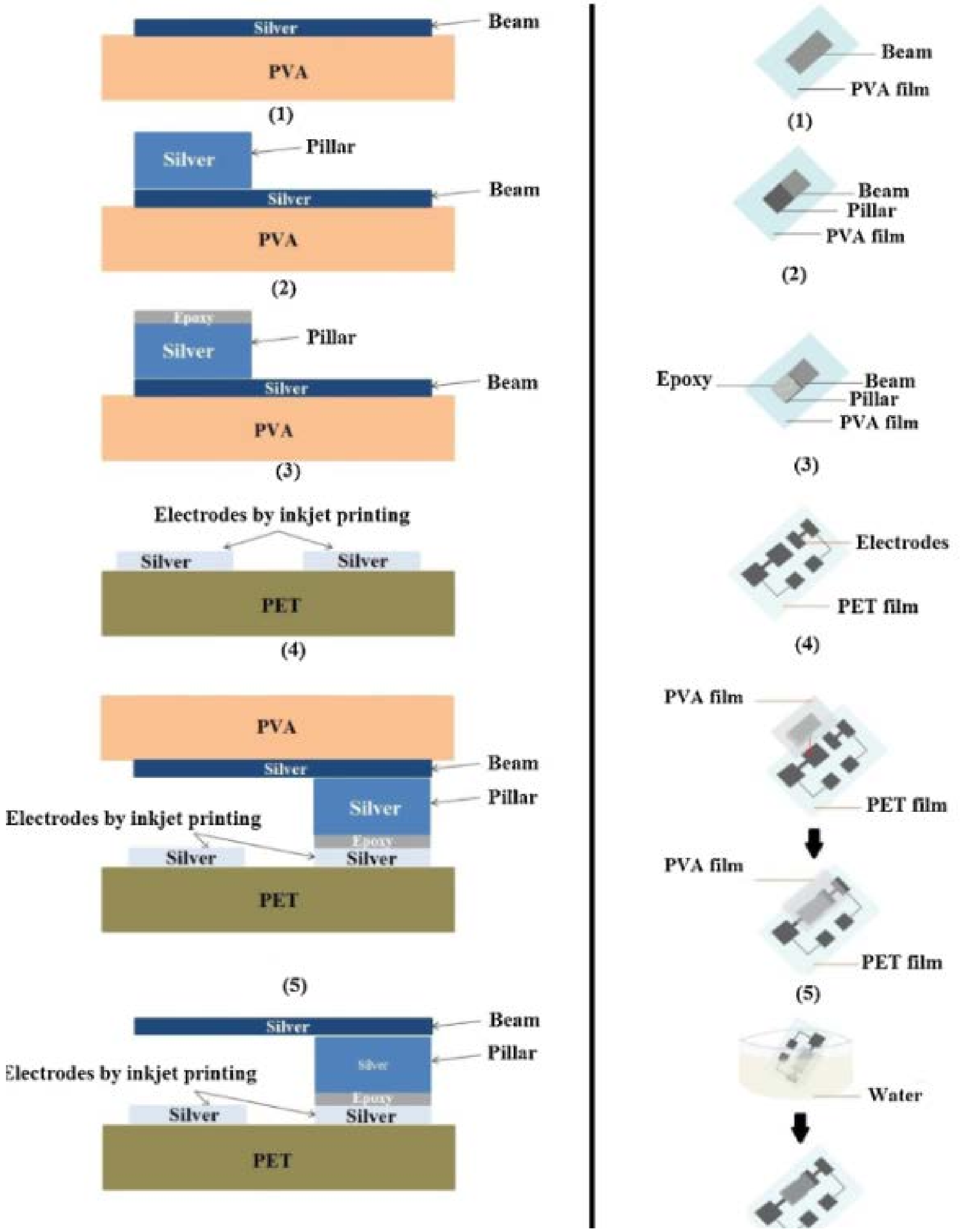


Figure 38 Illustration of the fabrication procedure of a capacitive cantilever accelerometer (Rivadeneyra, et al., 2015)

together via the layered epoxy, followed by the removal of the sacrificial substrates by flowing water.

As far as the materials for the printing are concerned, the cantilevers utilized conductive silver ink and epoxy in order for the printed components to stick together and provide electrical conductivity (Rivadeneyra, et al., 2015). A commercial polyvinyl alcohol film was used as the removable substrate in order to construct a cantilever, which relies on P.E.T. screen printing in order to provide greater resilience to the resulting sensor (Xu, et al., 2017). The PVA film may be easily cleared away by flowing water. Increased performance during the substrate removal was shown when providing silver paste for the structural material, compared to acetone (Xu, et al., 2017). The cantilever's loose end's peak to peak displacement was calculated from different frequencies of acceleration as a function of them (Xu, et al., 2017).

It should be noted that 3D printing also provides an ecologically friendly process when printing such a type of accelerometer, since polyvinyl alcohol tends to be biodegradable. In addition, the accelerometer cantilever's dimensions may be altered and customized to fit different applications, simply by altering the parameters of the printing process (Xu, et al., 2017).

3.5. Structural Health Monitoring

3.5.1 The Significance of SHM

The integration of sensors onto built structures is critically important in order for engineers to have access to information provided by the sensors regarding the condition of a given structure. Strain gauges and accelerometers are typically used in order to provide strain and vibration measurements at varying points around or inside a structure (Li, et al., 2006). The information provided by such sensors is typically relayed to a central processing unit, usually a computer, by means of cable connections (Mechitov, Kim, Nagayama, & Nagayama, 2004). The data provided by integrated sensor systems have helped further studies of building design by capitalizing on improved structural designs (Li, et al., 2006).

Having the ability to manufacture sensor units via 3D printing additionally provides the opportunity to obtain structural measurement information with reduced costs, potentially improved efficiency and with less time spent on the manufacturing procedure.

3.5.2 Measuring Improvement

However, while strain gauges and especially accelerometers provide reliable data based on damaging events, such as the acceleration caused as a result of an earthquake, we seem to be unable to note the static displacement brought by said acceleration (Li, et al., 2006). When it comes to structural health monitoring, it is crucial that engineers are supplied with as much information as possible and in close to optimal quality. It is for that reason why Li and coworkers have suggested the integration of accelerometers with GPS technology (Li, et al., 2006).

When a structure is subject to displacement, and therefore acceleration, its position is displaced ever so slightly. This information may be measured by GPS by taking into account the structure's position coordinates and provides the opportunity to monitor the dynamic status of the given structure (Spilker Jr., Axelrad, Parkinson, & Enge, 1996). As the years passed, there has been important improvements in the designing of technologies which allow for greatly accurate measurements being taken in real time (Li, et al., 2006). The systems being developed thanks to these technological advancements is known as RTK, which stands for real time kinematic systems (Li, et al., 2006). The systems utilized real time kinematic GPS modules for application in structural monitoring. GPS tech has its own drawbacks, despite its real time measuring prowess, in that it cannot take measurements at a degree of more than 20 Hz (Li, et al., 2006). That being said, that was true for older GPS equipment, while at present that are ways to achieve increased sample rates. A prominent problem still remains; the calculation of coordinates is largely affected by the geometry of a given satellite, while the accuracy of measurements may be altered by multipath (Li, et al., 2006). The measurement data provided by an accelerometer and a GPS device tends to be evaluated independently, setting aside the fact that both techs are related due to the fact that they rely on motion to provide feedback and consequently complement one another. Sensor noise remains an issue that studies are trying to tackle, as it prevents the direct separation and analysis of the measurements without additional procedures (Li, et al., 2006). Dynamic structural deformation is often caused by natural causes such as earthquakes and powerful winds, and there have been studies that have proven that the integration of GPS and accelerometer sensors is looking to be a viable method to monitor the abovementioned effect.

To provide an example, a case study was made by Li X. and co in which they studied the deployment of a combined GPS and accelerometer system (Li, et al., 2006). The subject of study was a steel tower in Tokyo owned by the Japan Urban Development Corporation, which had the sensor system installed in order to take continuous measurements of the tower's deformation during a typhoon on the first of October 2002 and an earthquake on May 2003 (Li, et al., 2006). It is a well-known fact that a country such as Japan suffers greatly from natural forces, given its location, and is therefore critically important that the structural health of its buildings is monitored as optimally as possible. The end result of the study is that the measurements of the accelerometer sensor generate noise at high frequencies, while the GPS shows the same behavior but on low frequencies this time around (Li, et al., 2006). This arrives to the conclusion that the two measurements counteract each other, and by converting their measurements in an appropriate manner into readable data the study comes at the conclusion that the results were in agreement with one another, therefore proving that integration of accelerometers with GPS tech is indeed a viable option for application in structural health monitoring.

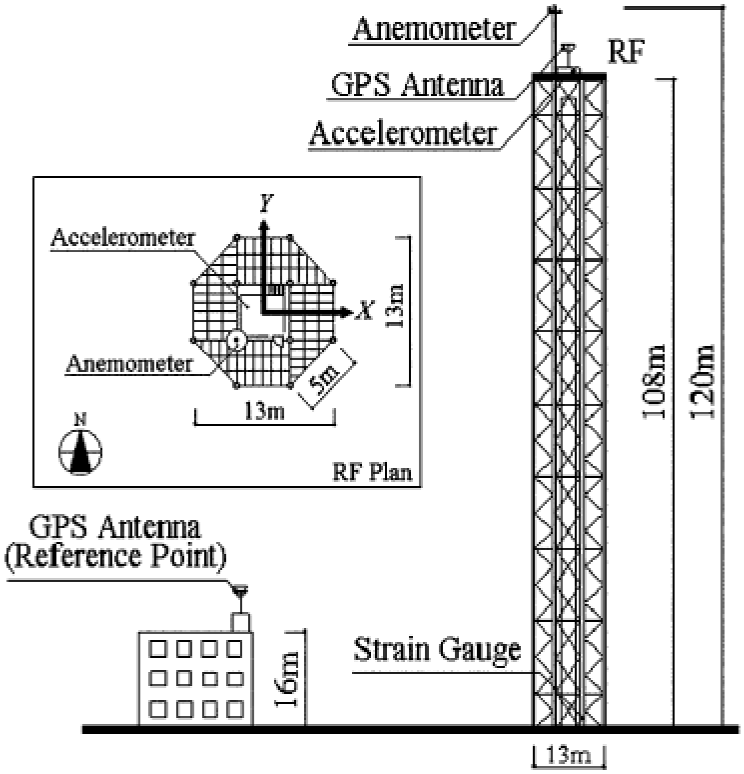


Figure 39 Setup of GPS assisted measurements (Li, et al., 2006)

3.5.3 Implementation of Wireless Sensor Networks

Integrating sensors on structures requires the transfer of their measurement data into a central control and observation computer unit. As mentioned earlier, this tends to be done by means of cable connections, interconnecting the sensor units to a central unit. However, that application comes at a significant disadvantage. Cable connections run the risk of being compromised by wear or external damages, not to mention the fact that they take time, planning and additional costs in order to be implemented. Durable and flexible wiring is especially costly, sometimes adding up to cost more than the sensors themselves (Mechitov, Kim, Nagayama, & Nagayama, 2004).

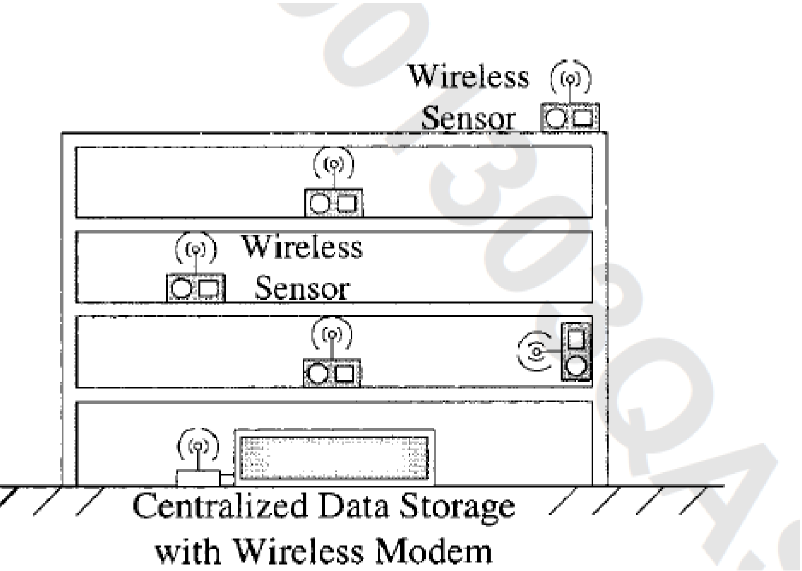


Figure 40 WSN illustration (Mechitov, Kim, Nagayama, & Nagayama, 2004)

Technological advancements in recent years have given leeway for the removal of cabled connections by means of wireless technology. Wireless sensor networks (WSNs) are the result of years of technological advancements in networking and sensor design (Attaran, 2017). These advancements are the result of the industry’s desire to develop cheaper and potentially more effective alternatives to structural monitoring system designs (Lynch, et al., 2003). Embedded system technologies provide an additional means to proceed with the approach of integrating WSNs onto a given structure.

Lynch et al conducted a study which demonstrates the assembly and usage of wireless sensors (Lynch, et al., 2003). A wireless sensing unit is composed of a sensing interface, a computational core and wireless communication elements (Lynch, et al., 2003). The sensing interface is designed by taking into account the fact that it needs to be able to handle multiple channels and operating modes while also being responsible for the interfacing of strain gauges, accelerometers, displacement or other such transducers (Lynch, et al., 2003). The core is a single channel analog-to-digital converter with sampling rates up to 100kHz and a 16bit conversion resolution (Lynch, et al., 2003). The entire wireless sensing unit is handled and given instructions to by the core. The core obtains sensor measurements by starting up the sensing interface by means of an establishment of the desired data acquisition sampling rate (Lynch, et al., 2003). Before the measurements are stored into the board’s memory after being identified by the computational core, they need to first be collected by triggering the sensor interface through the core right after initializing (Lynch, et al., 2003). The core possesses the liberty of choosing to transfer the data though the network’s modem, which is central for the network of sensors in the structure. That should happen after the core has computed the data by filtering it if necessary after it has been stored (Lynch, et al., 2003). It should be noted that, in theory based on what has been discussed so far in this paper, it would be possible to provide a 3D printed sensor unit packed with the required sensors, circuitry and antenna. Inkjet printing techniques provide the ability to develop fully integrated, packaged and cheap wireless sensors (Farooqui, Karimi, Salama, & Shamim, 2017). Farooqui et al have made a study on a proposed

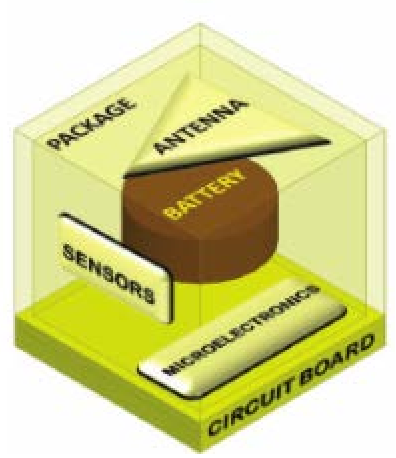


Figure 41 The design of a packaged cubic sensor node, with 3D printed sensors, antenna and circuit board (Farooqui, Karimi, Salama, & Shamim, 2017)

packaged design of one such sensor unit, which includes embedded sensors, antenna, battery and circuit board (Farooqui, Karimi, Salama, & Shamim, 2017).

The advantages of wireless monitoring are proven further by taking into account potential damages to the system due to natural catastrophes, like typhoons or earthquakes as mentioned earlier (Mechitov, Kim, Nagayama, & Nagayama, 2004). Should a system or material failure occur at a sensor that is part of a cabled system, the whole system's functionality would potentially come crashing down. That is not the case with a wireless sensor network as it guarantees the system's functionality as long as the central unit is intact, even should individual sensors become damaged. In addition, the processing of the sensing measurement data could occur at a sensor locally, therefore decreasing the control turnabout time and optimizing the general responsiveness of the system (Mechitov, Kim, Nagayama, & Nagayama, 2004).

Mechitov and coworkers have developed a high-frequency distributed sensing system for application on structural monitoring by utilizing a wireless sensor network platform which consists of Mica sensor boards and Mica-2 (Mechitov, Kim, Nagayama, & Nagayama, 2004). It delivers a WSN-based system which brings durability and lower cost while emulating the functionalities of centralized sensing systems (Mechitov, Kim, Nagayama, & Nagayama, 2004). The network controls and processes data on its own thanks to the wireless sensing network system and is built to be extensively customizable. Its systems provide options for varying sensing modalities, data processing and aggregation (Mechitov, Kim, Nagayama, & Nagayama, 2004). Structural health monitoring computations are being processed following the gathering of the coveted data size that is being generated by the sensors and sampled by a central data acquisition unit (Mechitov, Kim, Nagayama, & Nagayama, 2004).

The current issue with basic wireless sensor network technology is the fact that the measurements of the sensors and the data being delivered over the network is being desynchronized (Mechitov, Kim, Nagayama, & Nagayama, 2004). This has been tackled by Mechitov and coworkers' further study. First of all, sensor data is being stored in flash memory so that the peak duration of continuous sensing is limited and thus less prone to interrupts. Secondly, a routing service is being established in order to maintain connectivity with the sensor network by means of each sensor node emitting heartbeat messages (Mechitov, Kim, Nagayama, & Nagayama, 2004). This method enables fast network recovery in case of individual sensor failure, efficient memory storage and optimal bandwidth control (Mechitov, Kim, Nagayama, & Nagayama, 2004). Last but not least, the clocks of the sensors ought to be synchronized as closely as possible. By merging timed sync messages to the heartbeat messages of a node, it is possible to sync the sensors while disallowing the additional usage of bandwidth. Proper synchronization is highly important in order to deliver accurate sensor readings at precise moments in time, and this system can maintain synchronization as tight as 1 millisecond (Mechitov, Kim, Nagayama, & Nagayama, 2004).

These methods combined provide the ability to apply structural health monitoring techniques to structures of larger scale while enabling the construction of a distributed sensing and control platform (Mechitov, Kim, Nagayama, & Nagayama, 2004). Responsiveness as a whole and reduced reaction time is brought by utilizing individually local actuation.

The performance of the aforementioned wireless network distributed sensor system was studied by Mechitov and coworkers by demonstrating its viability in a simulated real world scenario. Their experiment took place on the model of an 18-story building. Their goal was to verify sensor precision by using accelerometer and strain gauge measurements and examine synchronization and stability by performing networking tests. They used Mica-2 motes from Crossbow Inc. that were equipped with sensor boards and taking measurements by being placed on each floor of the model building that is being placed on a shaking platform that is producing white noises frequenting 1 and 100Hz (Mechitov, Kim, Nagayama, & Nagayama, 2004). Drawing a parallel to a real world situation, a tower structure up to 300 meters tall may require at least one sensor per one to five floors, although more intricate structural health monitoring applications would likely need the integrating of a multitude of sensor units per floor. The end results of the experiments may be seen in the graphs, which show that the accelerometer and strain gauge display accuracy that is comparable to respective wired analog devices (Mechitov, Kim, Nagayama, & Nagayama, 2004). Mechitov's team displayed that it is possible to integrate a system of sensors that is wireless instead of wired, bringing with it additional benefits while sacrificing very little in terms of precision.

3.5.4 Monitoring Historical Monuments with WSNs.

The practices for efficient structural health monitoring are not being limited to modern buildings. The safety assessment of historical structures is a concern that affects cultural civilizations around the globe, especially since history marked the destruction of the San Marco bell tower in Venice in 1902, and more recently the Civic Tower in Pavia in 1989 (Abruzzese, et al., 2009).

We mentioned earlier in the paper that earthquakes and strong winds leave elements of a structure prone to damage. This is especially true for historical structures, as it affects them even more given the fact that they are additionally required to withstand the test of time as they are prone to wear and tear. Their foundations and varying masonry jobs as well as their archaic geometries leave them vulnerable to the forces they are being subject to. Most historical monuments are built from natural stone, therefore are sensitive to environmental and temporal decay (Winkler, 1997).

The aforementioned examples sparked the urge to conceive of ways to adequately monitor the health of historical structures. It is extremely important that we are making use of the means available to modern engineering in order to reliably monitor such structures, so that they are punctually maintained and the rates and cause of their decay measured and analyzed properly.

The previously mentioned method of using wireless sensor network systems to monitor the health of structureσ could potentially also be applied to the case of historical structures. In order to impede the potential destruction of a historical building or structure, real time measurements of the structure's status of damage and decay are necessary to acknowledge. A WSN system should be able to provide the data required to achieve the abovementioned goals (Abruzzese, et al., 2009).

The research on historical and monumental structures has evolved extensively in the past few decades, with increasingly enhanced method for conservation and diagnosis (Abruzzese, et al., 2009). The mechanical properties of the masonry material involved in most historical monuments have posed a roadblock in understanding the behavior of their respective monument. By utilizing measurements of static and dynamic forces, researchers are able to gather data regarding the decay rate and durability of a given element of masonry (Abruzzese, et al., 2009).

We mentioned earlier that accelerometers are a great sensing tool especially when it comes to low frequency detection. Therefore they are suitable devices for monitoring the acceleration rates of a monument at different points, as their data provides us with the means to realize the natural frequencies that affect the structural behavior of the structure (Abruzzese, et al., 2009). By taking into account the fact the required accelerometers could be 3D printed and integrated wirelessly into a network system of sensors, this particular endeavor is proving to be considerably cheaper and easier than by using manufactured sensors linked together via cable connections. Not only that, but the lack of wired connections means no interference from external electromagnetic fields and most importantly, no extra maintenance costs due to the lack of cables (Abruzzese, et al., 2009). Adding to these benefits, a wireless system of sensors provides additional improvements in the sense that they are going to be more discreet and invasive. While in most buildings wiring and other such elements are being tolerated, that is not the case for historical monuments. Taking account tourism and the fact that historical monuments stand as a testament to a culture's legacy, it is of great importance that monuments are well kept not only in their substance but in their appearance as well. Having wiring connections placed around a monument would make for a pitiful sight, whereas a wireless network of sensors may be placed discreetly and without wirings, laying bare the sight that is meant to be displayed. A wireless system, in addition, provides the benefit of concentrating the gathered data into a central unit, therefore eliminating the need to manually check the measurements (Abruzzese, et al., 2009).

As it stands, wireless sensor networks may be operated in a couple of different ways. Namely, applications in which the network is designed to take low profile measurements over an extended period of time, and applications where the target goal is taking greatly precise and swiftly repeating measurements over a short period of time (Abruzzese, et al., 2009). Monuments require special treatment, therefore the use of a WSN system which provides adequate measurements over a long period of time is required, while optimally utilizing a software that has the capability of detecting and consolidating overall damages at key points where the measurements spike.

Abruzzese et al hypothesize the integration of a WSN system on a hypothetical Italian historical building (Abruzzese, et al., 2009). In this paper we will hypothesize the placement on a monument such as the Parthenon of Athens. In order to integrate a WSN system, the sensors would need to be placed at key points around the structure. These sensors can range from accelerometers to measure vibration, strain gages to measure to measure the displacement of foundations or 3D printed soft and flexible gauges that can be customized to fit inside cracks or other potential delicate points of the structure, or any other sensor that might be required. According to Michetov et al as mentioned earlier, in order to take proper and synchronized measurements across all the sensors that are entwined in the network, the data collected from the measurements will need to be stored in flash memory before it can be properly transmitted to a central unit. The central unit then ought to concentrate the data into a database that defines the dynamic parameters of the monument (Abruzzese, et al., 2009). Should a number of different measurements show a certain level of disparity between them, an alert function may be deployed which will prompt the overseeing authority to take notice. The threshold of said variance is dependent on each given case. It may be set by running calculations through a FEM simulation of a building's structural behavior on a damaged element and an undamaged element respectively (Abruzzese, et al., 2009).

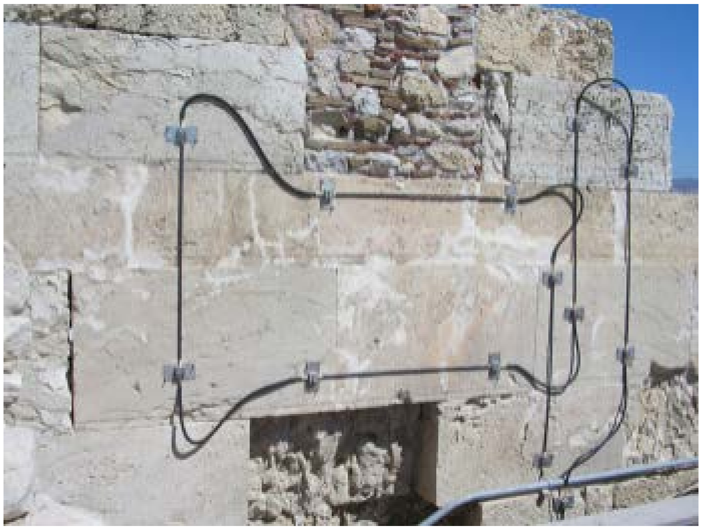


Figure 42 Wired sensors on the northern wall of the Parthenon (Lobell, 2015)

Accelerometers and strain gauges, that tend to make up the majority of a WSN, typically provide adequate information regarding the material decay or the structural damage that a monument undergoes under long periods of time (Abruzzese, et al., 2009). As explained by Lynch et al, the wireless sensor nodes can accommodate their own processors which can process the measured data before transmitting it to the central unit, while conserving battery power by turning the sensor's processing unit on and off whenever data interrogation is required (Lynch, et al., 2003). By filtering the measured data of each individual sensor node in the network by limiting transmitted data only to notable vibrations or anomalies, the size of the data transmission is reduced, therefore reducing the amount of time required for its analysis and hastening the process of data evaluation (Abruzzese, et al., 2009).

The presented methods of structural health monitoring could provide a possible notable example of the possibilities presented by wireless sensor networking systems when it comes to the preservation of our revered historical monuments and structures.

Conclusion

This thesis went over a fraction of the possibilities that 3D printing is potentially capable of. 3D printing has had an undeniable impact on the industries that govern the life of the average person, as well as industries whose technologies keep advancing for the perseverance of mankind. A wide variety of 3D printing technologies have been discussed, each with their own unique properties and applications. Taking advantage of the leverages brought by 3D printing, such as quicker and cheaper manufacturing and rapid prototyping, industrial development has the potential to advance with superior speed and efficiency.

The electronics industry might be of distinct importance, particularly due to the significance of sensory systems. Sensors have been a critical part of people's lives in the past decades, and will continue to be due to the ever growing ambition in creating complex structures. There are a myriad of sensors available that may be used for varying tasks, while sensors that monitor structural integrity are relatively limited. Sensors such as accelerometers and strain gauges have been the subject of this study, in regards to their viability to be manufactured by 3D printing. Indeed, we have witnessed that 3D printing is a viable option for the fabrication of structural sensors while keeping in mind the benefits that they bring, such as low fabrication cost, internal embedding options, reduced production time and flexibility of design. These are all highly contributing factors when investigating the health monitoring of a structure. That being said, even though such methods have been studied and researched, they may still require some polish and iterating before they can become the new norm in the place of mass production.

As far as the monitoring of a structure's health is concerned, including the delicate historical monuments, this thesis has gone through methods and systems with which the monitoring of their foundations and imperfect designs may yet be preserved by observing them through wireless sensory systems. By utilizing WSNs, we are able to monitor a structure with little maintenance requirements in regards to the sensors themselves when compared to a cabled system. In addition, 3D printing allows for the construction of flexible or irregularly shaped sensors, granting us the ability to utilize them even in the delicate standing condition of said monuments, while being discreet enough to preserve their form and image. In our age, natural phenomena, such as earthquakes and strong winds, are becoming increasingly potent due to changes in our planet's climate, therefore the importance of efficient sensory systems for our structures cannot be overstated. Historical monuments, in particular, are prone to damage from the aforementioned factors, while factoring in the passage of time itself. Cheap and efficient structural health monitoring, made possible due to the utility and integration of 3D printed sensors and wireless sensory systems, constitutes a critically important factor for the preservation of historical monuments and the safety of modern structures. In practice, however, new issues could arise as a result of such implementation, such as battery dependence of wireless sensor units. Of course, there could be solutions or workarounds for such issues (such as batteries recharging as a result of exposure to sunlight) and could prove to be potential subjects for future studies.

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