Embedding passive electronic components into 3D printed structures using FDM technology

Dominik Bozsó[1] and Márk Tamás Baross[2]

[1] Óbuda University, Kando Kalman Faculty of Electrical Engineering, Tavaszmező utca 17., 1084, Budapest, Hungary; bozsodominik@stud.uni-obuda.hu

[2] Óbuda University, Doctoral School on Safety and Security Sciences, József körút 6. III., H-1088 Budapest, Hungary; baross.mark@uni-obuda.hu

Abstract: In today's rapidly evolving world, industries are constantly seeking innovative new solutions to improve the functionality of their products, while also trying to reduce manufacturing costs and optimize prototype production time. During my university years, I believe that this is the perfect time to research these technologies, as it will help my professional development and allow me to gain a wealth of experience that I can put to good use in the future. The primary goal of my research is to develop a technological basis within 3D printing technology for integrating basic passive electronic components into the 3D printing process using FDM technology. At the same time, and perhaps the next big challenge, is the integration of these 3D-printed elements and components with products from other industries. That is why I believe that combining 3D printing with electronic components, such as passive electronic components, and ICs into the carrier structure (rather than putting them in the traditional way) offers significant advantages, as it allows manufacturers to create more compact, durable, and aesthetically pleasing products. To this end, I need to conduct research in the field of material compatibility, as I need to examine the materials most commonly used in 3D printing, which include PLA, PETG, and conductive filament, and how these materials affect temperature changes, assembly difficulty, embedding techniques, and component integrity. For later practical implementation, my project focuses on comparing and testing different embedding methods. These include, for example, interrupting the printing process to insert components (pause and insert), designing assemblable elements, and using electrically conductor filaments. These methods not only focus on passive components (resistors, capacitors, LEDs), but also analyse embedding processes, which are an important part of developing this technology. Overall, the research involves a thorough comparison of component parameters (e.g., LED brightness, actual resistance value after embedding) to draw the appropriate conclusions. The results of the analysis may contribute to the manufacture of complex, intelligent, small-batch products for everyday use, with electronics integrated into their mechanical structure, bringing us closer to the future of fully printable electronic devices.

Keywords: 3D printing; electronics; embedding; FDM

1 Introduction

In today's rapidly evolving world, industries are constantly seeking innovative new solutions to improve the functionality of their products, while also striving to reduce manufacturing costs and optimize prototype production time. The primary goal of my research is to develop a technological basis within 3D printing technology for integrating basic passive electronic components during the 3D printing process within the framework of FDM (Fused Deposition Modeling) technology. Additive manufacturing, better known as 3D printing, especially the inexpensive and widely used FDM technology, has transformed product design and manufacturing, enabling the rapid creation of complex geometries in a cost-effective manner. At the same time, and perhaps the next big challenge, is the integration of these 3D-printed elements and components with products from other industries. That is why I believe that combining 3D printing with electronic components, such as passive electronic components, and ICs into the carrier structure (rather than fixing them in the traditional way) offers significant advantages, as it allows manufacturers to create more compact, durable, and aesthetically pleasing products. To this end, I need to conduct research in the field of material compatibility, as I need to examine the materials most commonly used in 3D printing, which are PLA, PETG, and a few other filaments, to see how these materials affect temperature changes, assembly difficulty, embedding techniques, and component integrity. For later practical implementation, my project focuses on comparing and testing different embedding methods. These include, for example, interrupting the printing process to insert components (pause and insert) and designing assembleable elements. These methods not only focus on passive elements (resistance, capacitor, LED), but also analyze embedding processes, which are an important part of developing this technology. Overall, the research involves a thorough comparison of component parameters (e.g., LED brightness, actual resistance value after embedding) to draw the appropriate conclusions. The results of the research may contribute to the manufacture of complex, intelligent, small-batch products for everyday use, with electronics integrated into their mechanical structure, bringing us closer to the future of fully printable electronic devices.

2 Additive manufacturing and the basisc of FDM technology

Additive Manufacturing (AM) as a concept was already known in the 1980s and 1990s, as manufacturing processes in which the production of a given product or process took place layer by layer already followed this basic principle. Of course, this term was not used precisely at that time, as the concept of additive manufacturing only became a standard term in the 2000s, when the first industrial forms of 3D printing appeared, which became increasingly popular in the following years for both industrial and hobbyist use.

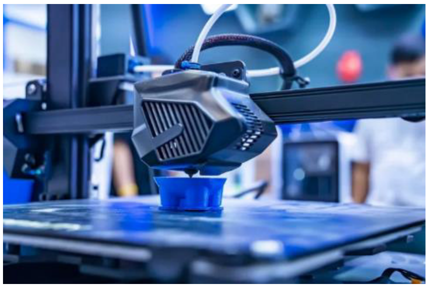

Figure 1. Additive manufacturing

Source: https://www.azom.com/article.aspx?ArticleID=23900

Compared to classic methods such as injection molding and CNC machining, it offers numerous advantages, from manufacturing costs to speed and quality. I would like to highlight the case of small-volume production, where the design and manufacture of molds used in the injection molding process is extremely costly, which is not a cost-effective solution for small batch production. This contrasts with 3D printing, where it is not necessary to manufacture the aforementioned molds, as the finished product can be produced layer by layer. Considering these aspects, it is easy to conclude that it is much more difficult to enter the market with a mass-produced product due to the favorable prices and online marketing of various East Asian companies. In contrast, 3D printing offers a significant advantage in rapid prototyping and customizable products, which makes it easy to enter the market. With the right digital platforms, 3D printing opens a new world for users, allowing them to obtain detailed, customized products, not to mention geometric shapes that cannot be achieved with other manufacturing methods. As part of this evolution, recent advances in functional 3D printing (such as multi-material printing, printed electronics, and printed optics) are the first steps toward the digital specification and manufacturing of fully interactive devices. These advances promise that interactive devices will eventually be highly customizable to the needs of the individual or task in a way that is not possible with traditional mass production techniques. Among the various additive manufacturing methods, powder bed fusion (PBF) processes, including laser processes, are essentially based on controlling solid-liquid and liquid-solid phase transitions in individual layers of the process. Powder bed fusion technology is a relatively expensive additive manufacturing technology. It is mostly used in industrial and commercial applications. In addition to rapid prototyping, metal- and polymer-based processes can also be used to manufacture end-use parts. To understand powder bed fusion processes, we need to know the characteristics of the powder, the changes in its liquid and solid phase transformations, and how it behaves to certain thermal cycle changes, which is why this is a much more complex and difficult topic to digest. In addition, as I mentioned, it is very costly and not necessarily suitable for small-scale prototype production, but rather for the manufacture of a final product, as we can produce samples at a much lower cost using FDM technology, and then, once we are satisfied with the functionality and design of the product, we can proceed to PBF printing if necessary. The other additive manufacturing process is FDM printing, an extrusion AM process that uses thermoplastics. Here, unlike in the powder bed process, the object is not placed in any other medium but is built up layer by layer on an object table using only the material currently in use. The filament itself can be purchased in roll form, and this thin filament is loaded into the 3D printer and softens when the preset temperature is reached, and the extruder head begins to build the object layer by layer thanks to its three-axis movement. To ensure that printing is smooth and continuous, the softened filament is cooled with fans so that the next layer can be built on top of a layer of the right hardness. The structure within the layer can be customized depending on the desired result. For example, if the external appearance of the printed object is important, the outer layer must be perfect. This can be achieved by first building the inner part of the layer and then the outer part. However, if we want to create a mold with precise dimensions, for example, then the precise dimensions are much more important, so building from the outside in is recommended. These steps are necessary because the soft filament extruded through the nozzle naturally has a physical diameter, even if it is very small, and during construction, this filament will be filled in with numerous layers. These steps are necessary because the soft filament extruded through the nozzle naturally has a physical diameter, even if it is very small. During construction, when filling in the numerous layers, these filament strands can push each other apart when hot and change the dimensions of the object. This is why it is very important to take this into account when designing a hole, for example, and to design them a few hundredths or tenths larger so that we actually get the hole with the designed diameter in reality. After learning the basics of FDM technology, it is clear that this solution is the most widespread, as it allows objects to be printed with the least amount of energy and with high precision, provided that the correct settings are used. In addition, when considering the post-processing work, this is also the most practical printing method, as there is no need to clean the object from dust in the case of powder printing, or from the large amount of resin residue in the case of resin printing, which not only concentrates on the object, but also on cleaning the printer. It is also important to mention the wide range of filaments available, as depending on the application, everything from easy-to-print, environmentally insensitive filaments to higher temperature resistant and flexible materials are available in a wide range of colors, so from this point of view, it is clearly the best choice in terms of convenience, cost-effectiveness, and knowledge for hobby and small industrial applications. Of course, like all technologies, it has its disadvantages compared to other solutions. These include resolution quality, which is due to the physical dimensions of the filament mentioned above, as well as the nozzle diameter. Due to these limitations, other 3D printing technologies, such as resin and powder printing, have much higher resolution capabilities, meaning that they can be used to print objects and parts with much greater detail and finer features. In addition, since it is built up in layers, the layer lines are visible to some extent, although current models are capable of printing with a layer thickness of 0.08, where this phenomenon is no longer visible at all, but regardless, they are still there, and our model is built up layer by layer. This leads to the last major disadvantage, which is weak resistance to mechanical stress due to the anisotropic arrangement. Of course, this can be improved by increasing the layer thickness and wall thickness, as well as by correctly determining the printing arrangement so that the layers are perpendicular to the forces acting on the larger areas, thus increasing the resistance of the given parts several times over.

3 Passive components in 3D printed structures

With the advancement of 3D printing technology, the primary goal of being able to manufacture more complex 3D printed parts has already been achieved, and the next step is to further develop this technology. From a mechanical point of view, the integration of various reinforcements, stronger materials, and metals into the internal structures of plastic printed parts began to spread. I believe that the next step is to properly integrate electronic components into the printing process with a solution that replaces the concept of external covers, boxes, or caps as we know them today and creates a complex structure in both directions. However, achieving this process requires a great deal of research work to ensure that the electronic components and the plastic casing surrounding them can be properly combined to create the best possible combination of compact design, spatial integration, fast and convenient manufacturing, and maximum utilization of factors affecting electronics. After selecting, testing, and examining the appropriate components, the next largest and most important part of the project can begin: 3D printing and embedding. However, this process is preceded by an extremely long and, in terms of usability, manufacturability, quality, aesthetics, and functionality, extremely important 3D design of 3D printed forms, the housings of electrical components. This process is not as simple as it sounds at first, as it must comply with a great many factors and variables. In addition, several critical technological challenges complicate the process, both from the printer's point of view and from the point of view of the components. The first phase involves creating the approximate dimensions and shape of the part, which I do not create directly in the design software, but rather by designing a sketch of how I envisioned each given element. Once this is done, we can begin to determine the limits and accuracy of our own 3D printer, as each printer has a different level of accuracy. As I mentioned in chapter two, the molten filament flowing through the nozzle, among other things, naturally has a physical extent, and as we build the layers, the dimensions of the cavities and holes calculated in the design software may differ from the actual model. Therefore, it is worth printing smaller sample pieces first with the exact models of the given parts, then scaling them up and down with their offsets to achieve the perfect fit for our electronic component. Of course, we are not talking about centimeters here, but a few tenths or hundredths of a millimeter, but these size differences are also of significant importance for a precise fit. It is best if the fit is a little tight, so that the component almost must be snapped into place. Of course, this also depends on the design and casing of the component, which I will discuss in Chapter 4. The design part also includes the wiring within the 3D printed element and, as a result, the physical placement of the wires in the 3D designed component, as well as the design of the connections, which will allow us to connect two elements both physically and electronically. The printing and embedding phase are preceded by the slicing process, which is performed using the 3D printer software. This is where you need to configure all the important settings related to printing, which I will detail below. These settings include the selection of the printing material, print quality, layer thickness, printing of inner and outer walls, setting the thickness of the object wall, determining the fill rate, placing various printing aids (supports), print speed, and additional settings, mainly for preparing color printing with multiple filaments.

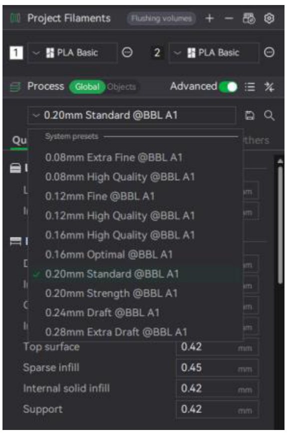

Figure 2. Bambu Studio settings

Source: Self-edited

When selecting printing materials, most slicer programs already have predefined profile presets, and this is also the case with Bambu Studio, which I will be using for this project, as the printer is also a Bambu Lab brand printer. Of course, these can be edited if one of the preset functions does not suit our needs, or if we want to adjust the printing temperature. We can also adjust the print quality and, with it, the layer thickness. If we want to print a more accurate, aesthetic, and detailed part, it is worth working with the smallest possible layer thickness, which in my case is 0.08 mm, because at this layer thickness, the lines found in the layers built on top of each other almost disappear, and we can also print a thin part in the Z direction completely, and the slicer will not skip it because it is basically not as thick as the layer thickness we are working with. The settings profiles are shown in Figure 2. The fill rate and wall thickness are also very important settings, as they allow us to directly change the resistance of our object, its tolerance to physical impacts, such as strength, protection against twisting, resistance to tensile and compressive forces, and transparency. Setting up support elements can also contribute significantly to achieving a printable form for individual parts, as the majority of printed parts do not lie completely flat on the printer bed due to their design. So, when printing not on the work sheet but "in the air," it is necessary to enable the support option, which automatically generates this support structure when the set threshold (x°) is exceeded, so that the filament can be printed onto a surface, as shown in Figure 3 below.

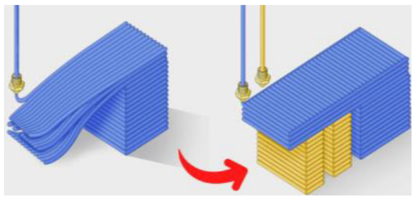

Figure 3. The importance of support
Source: https://tinyurl.com/yy8rcp3y

As a final step, I would like to mention an important setting option that edits the G-code, which is the format that the printer reads directly. This setting is none other than the Stop and Go function, which allows me to easily select the layer where I want to stop printing. During this process, it will be possible to insert electronic components, wiring, and connectors into the printed element that has been stopped. However, it is important to note that this step is not easy and requires great caution, as neither the printed object nor the work surface can be removed from the printer, otherwise the component would shift during insertion, causing a faulty continuation. In addition, with the stop and go function, the printer keeps the worktable warm so that the printed component does not separate from its surface, which is another reason why the otherwise replaceable work sheet cannot be removed. Printing is also complicated by other critical challenges. First, I would mention the problem where not only the part being printed can be damaged, but also the more expensive 3D printer, which is stopping printing at the correct layer. It is worth designing the inserted external part so that it does not rise above the remaining layers, as the printer continues printing based on the G-code and will not detect the extra part we have inserted, which can cause a nozzle collision accident, resulting in serious damage to both the print head and the control motors and their controls. Furthermore, it is also necessary to examine how much critical temperature change (thermal shock) the electronic components to be installed can withstand, since an embedding process cannot be considered successful if, although the result has been physically achieved externally, physically successful, but is not functional when tested, as the thermal shock has destroyed the electronic component.

4 Testing of electronic components and methods of their embedding

I would like to mention an important electronic component and examine it separately in advance for my future project, which would be the LED, as this component will certainly play a role and I would like to integrate it into my 3D printed elements as a module. The LED has two important parameters that are key characteristics for me to ensure that it is suitable. The first is heat dissipation, as, like resistors and most electronic components, they generate heat that needs to be dissipated. Usually, these components dissipate this heat through their surface into the surrounding medium, However, in my case, in striving for the most precise, stable, and premium solution, there will not be an air medium at a level where heat dissipation can occur properly, so it is important for me to examine how they behave in different temperature ranges, whether for a short or long period of time. To this end, I took measurements where I designed and printed various elements into which I installed the LEDs and examined over a longer period of time how their temperature and other important parameters change, which in my case are light scattering and color modification. Therefore, to measure the latter property, I designed the 3D-printed sockets to be either completely closed or open in terms of installation, so that I could examine both heat dissipation and light scattering and color change. The Figure 4 shows the difference between the two sockets, which illustrate two different thermal management solutions. The one on the left is an open-construction socket, allowing the LED to dissipate heat directly into the ambient air, while the one on the right is a completely closed structure, where heat dissipation is achieved by conduction through the PLA cover, heating it up, which allows for slower heat dissipation due to the high thermal resistance of PLA, which can increase the operating temperature of the LED, leading to a reduction in its service life. In the open design, the LED shines brightly in its own range, while heat dissipation is also more efficient than in the closed solution on the right, where color and intensity changes are clearly visible. I performed the test with white PLA and closed the socket with a 0.16 mm layer thickness surface in the enclosed structure, which is still well within the range that can be illuminated.

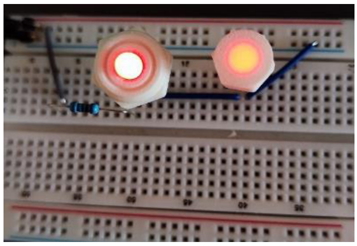

Figure 4. Printed LED socket - light diffusion and color change
Source: Own image

5 Material compatibility from the point of view of electronic components

Successful integration means not only embedding electronic components, but also creating a unified, cohesive structure. To achieve this goal, this chapter focuses on comparing different 3D-printed support structures, thereby facilitating the selection of the appropriate filament and improving the quality of adhesion between the polymer matrix material and the electronic components. First, I will describe PLA (polylactic acid) and its properties in detail. PLA is the most widely used filament in 3D printing, particularly in extrusion-based printing. It is biodegradable and has a negligible impact on the environment. However, there are limitations to its use that need to be considered. These include its impact resistance, mechanical weakness, and heat resistance, which is one of its most defining characteristics and a key factor in choosing it for a project. PLA is a compostable material made from plant starch, making it excellent for recycling. However, it is not only this parameter that makes it so popular, as in terms of printability, it is by far one of the best and easiest filaments to work with. This is due to its low-temperature printing capability and, as a result, its low warping tendency. Of course, the material also has its shortcomings, such as the low heat resistance mentioned above, which can be a decisive factor in the outcome of most projects. In addition, the material has a rigid structure and is therefore not capable of plastic deformation. Overall, this filament is therefore the perfect choice for producing prototype models, as it allows parts to be created cost-effectively with perfect printing and scaling, which can then be used as the basis for the final product. The next material to be examined is PETG (Polyethylene Terephthalate Glycol), whose name may be familiar from PET bottles. The name is not a coincidence, as it is a modified PET material, which is strong and tough, so it is not as brittle as the PLA, and is therefore capable of minor deformation, but will naturally break after a certain amount of stress. It has better heat resistance parameters than PLA but is not outstanding among the filaments used for 3D printing. Based on its properties so far, it may be a very good choice from an embedding point of view, but when compared to this project, the more sustained high printing temperature is not advantageous for various electronic components. In addition, PETG filament requires complicated preparation, as it must be stored in a dry place with low humidity, otherwise it will not print properly with this raw material. At this point, it begins to fray, as shown in Figure 5, and if the moisture content is high, we get a component with an impure layer structure, as shown in Figure 6, which visibly forms a single unit, but the layers separate much more easily due to the high humidity.

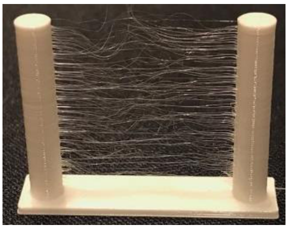

Figure 5. PETG stringing example
Source: https://shorturl.at/OGjep

Figure 6. PETG high humidity
Source: https://shorturl.at/nGpS5

The next filament worth mentioning is ABS (Acrylonitrile Butadiene Styrene), which may be familiar from the plastic injection molding industry, whether in the world of building blocks or car parts. The raw materials are naturally compatible with each other, but ABS filament is optimized with additives for 3D printing, while ABS granules used for injection molding are optimized with additives necessary for mold filling. A significant advantage over the previous two filament types is its high heat resistance, which can reach up to 80°C with proper handling. In contrast to the two filaments mentioned above, however, it is much more challenging to print with, as it is highly prone to warping, which can cause serious problems in precise embedding processes, and toxic gases are also produced during printing, which is why it is necessary to print in a closed printing space, also in order to maintain a higher temperature range. This characteristic and the enclosed space are also not favorable factors from the point of view of electronic components.

The importance of different temperatures has already been mentioned in relation to different filament types, both from the point of view of printing, embeddability, and the use of the end product. Using the filaments mentioned in the previous chapter, I have created a summary table showing their heat distortion temperatures, which indicate the temperature at which the material softens under a given load to such an extent that it leads to deformation or deflection. The table is shown in Figure 11, which shows that PLA becomes plastic at around 55 °C, while ASA filament, which has the highest heat resistance, only begins to deform at around 90 °C. In terms of mechanical load capacity, PLA has the most rigid properties, so it can withstand high forces, but it is not capable of deformation, so it breaks easily. In contrast, ASA and ABS are much more durable and capable of some deformation without breaking immediately, but even a smaller force than with PLA is sufficient to cause breakage. I would classify PETG filament between the two limits, as this material is capable of much greater deformation, so it ranks below ASA and ABS in this respect, but the layers do not separate immediately, they stretch. The load-bearing test results are shown in Figure 8, where PLA was able to withstand a load of 70 kg horizontally, which means perpendicular to the print layers. So here I did not test the adhesion of the layers, but the toughness of the material itself.

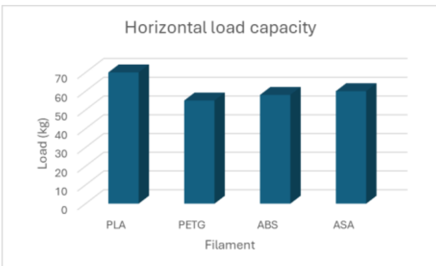

Figure 7. Thermal distortion diagram

Source: Own editing

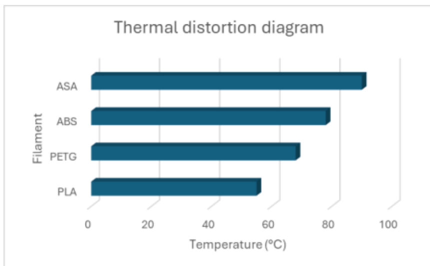

Figure 8. Horizontal load capacity diagram

Source: Own editing

Conclusions

Starting with the basics of FDM printing, I traced the development of 3D printing from its beginnings to the present day. In the next chapter, I continued with an examination of electronic components, detailing their operation and emphasizing their importance. Continuing this chapter, I discussed the embeddability of electronic components in 3D printed elements from all angles, crossing the two industries. In structuring this chapter, I naturally tried to cover the points that will form an important part of my project. When embedding electronic devices, I not only conducted research, but also carried out my own measurements so that I could examine the results I had measured myself. At the end of my research, I also conducted material research and comparisons, again using measurements, so that I could make decisions based on the most accurate data possible.

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