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Three-Dimensional Printing and 3D Scanning: Emerging Technologies Exhibiting High Potential in the Field of Cultural Heritage

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Abstract: Three-dimensional scanning and 3D printing have become increasingly important tools in the field of cultural heritage. Three-dimensional scanning is used to create detailed digital models of cultural heritage sites, artifacts, and monuments, which can be used for research, restoration, and virtual display. Three-dimensional printing, on the other hand, allows for the creation of physical copies of cultural heritage objects, which can be used for education, exhibition, and preservation. The use of these technologies has many advantages, including the ability to document and preserve cultural heritage sites, artifacts, and monuments in a non-invasive manner, as well as the ability to create digital and physical replicas that can be used for education and exhibition purposes. However, there are also challenges, such as the need for specialized equipment and expertise, as well as concerns about the preservation of the original objects. Despite these challenges, 3D scanning and 3D printing have proven to be valuable tools in the field of cultural heritage preservation and their use is expected to continue to grow in the future.

Keywords: three-dimensional printing; 3D scanning; 3D design; cultural heritage; digitization

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1. Introduction

Three-Dimensional scanning is a process of collecting digital data on the shape and appearance of a real-world object or environment. These data can then be used to create a highly accurate and detailed digital replica, or 3D model, of the original object or environment. Three-dimensional scanning has a wide range of applications, from manufacturing and product design to entertainment, healthcare, and cultural heritage [1–8].

One of the key benefits of 3D scanning is the ability to quickly and accurately capture the geometry of real-world objects and environments, allowing for the creation of digital models that can be used for a variety of purposes. Three-dimensional scanning can be used in a variety of industries, including manufacturing, architecture, and film and game development, among others, to create detailed and accurate digital representations of objects, spaces, and people.

Another advantage of 3D scanning is its ability to automate and streamline various processes and workflows. For example, in manufacturing, 3D scanning can be used to quickly and accurately inspect and measure parts for quality control, reducing the need for manual inspection and improving efficiency. In the entertainment industry, 3D scanning can be used to create digital assets for films, games, and virtual and augmented reality experiences, allowing for more efficient and cost-effective production [9–11].

However, there are also some disadvantages to 3D scanning. One of the main limitations is the cost and complexity of the equipment and software required for 3D scanning, which can make it difficult for some individuals and small businesses to adopt the technology. In addition, the accuracy and quality of 3D scanning can be affected by factors such as the type of object being scanned, lighting conditions, and the environment. Moreover, there may also be privacy and security concerns associated with 3D scanning, particularly when scanning people, and it is important to be aware of and address these issues when using the technology [12,13].

Cultural heritage is an important area where 3D scanning is being used. Many museums and historical sites use 3D scanning to create digital replicas of valuable artifacts and historical structures. This can help to preserve these objects and make them more accessible to the public. Additionally, 3D scanning can be used to create virtual tours and interactive exhibits, which can be a valuable educational tool. The process provides a complete and immersive representation of heritage objects, allowing for virtual exploration, analysis, and preservation. It also enables sharing of cultural heritage with a wider audience, making it accessible for research, education, and promotion purposes. Furthermore, it serves as a valuable backup in case of natural disasters, theft, or degradation of physical artifacts [14–16].

Three-dimensional scanning technology has come a long way in recent years, and there are now many different types of scanners available on the market. Some of the most common types of scanners include structured light scanners and laser scanners. Each of these types of scanners has its own advantages and disadvantages, and the choice of scanner depends on the specific application and the type of object or environment being scanned. The recent introduction of portable, handheld, 3D scanners adds even more abilities to successfully utilizing these devices in field applications [17].

The benefits of portable 3D scanners include versatility, as they can be used in various settings and environments. They are also portable, allowing for easy transportation and use on-site. In addition, these scanners often provide high accuracy results, making them suitable for use in industries such as engineering, construction, and product design. They are also efficient, capturing detailed 3D data quickly and increasing productivity. Portable 3D scanners are often cost-effective, providing a good return on investment compared with traditional 3D scanning methods. Furthermore, they use non-contact scanning methods, reducing the risk of damage to the scanned object. Lastly, many portable 3D scanners are compatible with various software, making data processing and integration into other systems easier [18,19].

An alternative method to 3D Scanning is photogrammetry. This is a different technique that uses a series of photographs taken from different angles to create a 3D model and does not require the presence of a 3D scanner. The software then uses these photographs to create a 3D model by estimating the depth of the objects in the scene. This technique is well-suited for scanning outdoor environments and large structures, as well as for creating detailed 3D models of cultural heritage artifacts. One major disadvantage is the need for a large number of images to achieve high accuracy, which can be time-consuming to capture. Another issue is the difficulty in obtaining images with sufficient overlap and coverage, especially when trying to capture complex shapes or objects with reflective or transparent surfaces. Photogrammetry can also be sensitive to changes in lighting and shadows, leading to inaccuracies in the final 3D model. Additionally, the process of stitching images together and generating the 3D model can be computationally intensive and require powerful software and hardware. Overall, while photogrammetry can be a powerful tool for creating 3D models, its limitations and complexities must be considered in the planning and execution of a photogrammetry project [20–22].

Three-dimensional printing, commonly referred to as additive manufacturing, is a technique for producing three-dimensional items by layering material. This process is in contrast to traditional manufacturing methods, such as machining or molding, which involve cutting away or shaping material to create an object. Three-dimensional printing allows for the creation of complex and customized objects with a high degree of precision and at a relatively low cost. Three-dimensional printing works by depositing material layer by layer to build an object from a 3D model. There are several technologies used in 3D printing, including Fused Deposition Modeling (FDM), Stereolithography (SLA), and

Selective Laser Sintering (SLS). The process starts with creating a digital model, which is then sliced into layers and sent to the printer. The item is then constructed layer by layer by the printer until its completion. The material used in 3D printing can be plastic, metal, ceramics, or composites, among others, and is usually supplied in the form of filaments, resins, or powders. The type of material and technology used determines the final properties of the printed object, such as strength, flexibility, and surface finish [23–26].

The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have jointly developed a standardized terminology for additive manufacturing processes. This terminology defines terms and concepts related to 3D printing and additive manufacturing, including key process characteristics, types of materials used, and post-processing methods. The standardized terminology helps to ensure that professionals in the industry have a common language to communicate about additive manufacturing processes, reducing misunderstandings and errors. It also allows for clear and consistent documentation and reporting of additive manufacturing activities, enabling accurate comparisons and evaluations of different technologies and processes. The ISO/ASTM terminology for additive manufacturing processes is regularly updated to keep up with advancements in technology and industry trends, ensuring that the terminology remains relevant and useful to those in the industry [27–29].

One of the biggest advantages of 3D printing is its ability to create highly customized and unique objects quickly and efficiently. With traditional manufacturing methods, creating a one-off or customized product can be time-consuming and expensive. Three-dimensional printing allows for on-demand production, reducing the lead time and costs associated with traditional manufacturing. It also allows for fast prototyping and testing of designs, enabling businesses and individuals to quickly iterate and refine their ideas.

Another advantage of 3D printing is its potential to revolutionize manufacturing and supply chains by enabling local production and reducing the need for global shipping. This can reduce transportation costs and emissions, as well as improve product delivery times for customers. In some cases, it may even be possible to produce parts and products in remote or off-grid locations, allowing for greater self-sufficiency and independence [30,31].

However, there are also some disadvantages to 3D printing. One of the main limitations is the limited variety of materials available for printing, which can limit the types of products that can be produced. In addition, the cost of 3D printers and materials can be high, making it difficult for some individuals and small businesses to adopt the technology. The quality and strength of 3D-printed products can also be lower than those produced by traditional manufacturing methods, although advancements in materials and printing technology are slowly addressing these issues. Finally, there are concerns about the environmental impact of 3D printing, as the production of some materials and the disposal of waste can have negative consequences [32,33].

In this context, 3D scanning and 3D printing are versatile and rapidly evolving technologies that have the potential to revolutionize the way we create and manufacture products. They both can be used to create complex and customized objects quickly and at a relatively low cost, and have the potential to change the way we think about manufacturing and design. In the field of cultural heritage, their contribution can be immense since they can be combined in a sequential workflow process where artifacts can be digitized and then fabricated in a vast number of relevant cases.

2. Materials and Methods

Both in 3D printing and 3D scanning processes, a vast number of different types of equipment are available. The variety of 3D printing and 3D scanning equipment available on the market has expanded the range of applications and benefits these technologies can provide [34–36]. Different types of 3D printers vary in terms of printing material, printing accuracy, printing speed, and cost, which makes them suitable for a wide range of projects and industries. For example, high-end 3D printers can produce intricate, detailed objects using advanced materials, while more economical options are better suited for large-scale production runs or simple projects.

In the same way, the diversity of 3D scanning equipment allows for different levels of precision, accuracy, and speed, making them suitable for a range of scanning applications. For instance, portable and lightweight scanning devices are ideal for capturing smaller objects, while stationary and more sophisticated equipment are better suited for capturing large-scale structures and complex geometries. The different options available make it possible to select the right equipment for a specific task, enabling the best results possible [37–39]. Figure 1 depicts a diagram of the combination of 3D scanning and 3D printing processes that leads to the final fabricated item, while Figure 2 depicts the use of portable 3D Scanner in scanning a glass artifact in the Laboratory of Non-Destructive Techniques, University of West Attica, Athens, Greece.

In this context, the vast number of different types of 3D printing and 3D scanning equipment available provides a great deal of versatility and flexibility, allowing for the deployment of these technologies in a wide range of applications and scenarios.

Regarding 3D scanners, structured light 3D scanners operate by projecting a pattern of light onto the object or environment being scanned. The 3D scanner then captures images of the object or environment as the light is distorted by the shape of the object or environment. These data are then used to create a highly detailed digital model. Structured light scanners are typically less expensive than other types of 3D scanners and are well-suited for scanning small objects or parts [40].

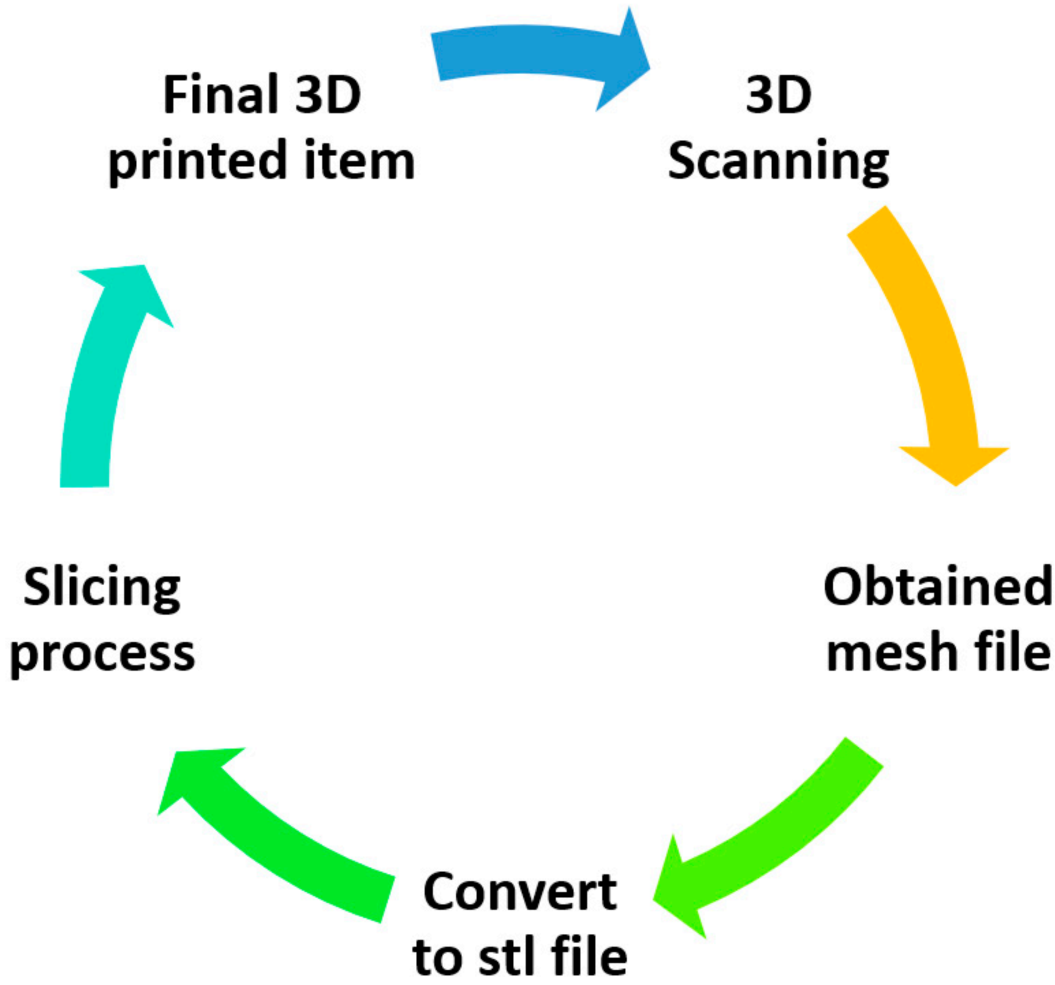

Figure 1. Combination of 3D scanning and 3D printing processes that leads to the final fabricated item.

Figure 2. Portable 3D Scanner scanning a glass artifact.

Laser 3D scanners, on the other hand, work by emitting a beam of laser light onto the object or environment being scanned. The 3D scanner then captures images of the object or environment as the laser light is reflected off it. These data are then used to create a highly detailed digital model. Laser 3D scanners are typically more expensive than structured light 3D scanners, but they are well-suited for scanning large objects or environments [41–43].

On the other hand, it is worth noting the fact that errors and measurement problems might occur when scanning objects with the use of transparent materials in 3D printing. When scanning objects for 3D printing, one of the challenges that can arise is the accurate measurement of transparent materials. Transparent materials, such as glass, plastic, or resin, can be difficult to scan accurately due to their optical properties. The main issue with transparent materials is that light can refract or reflect off the surface, leading to errors and measurement problems in the scanned data. One common problem is that transparent materials can cause distortion in the 3D scanning process. This is because the light used in the scanning process can refract or bend as it passes through the material, resulting in an inaccurate representation of the object. This can result in the final 3D-printed object being inaccurate or distorted, leading to a loss of detail or fidelity in the final product. Another issue that arises with transparent materials is that they can cause reflections or shadows that can affect the accuracy of the scanned data. For example, if an object is scanned using a laser-based scanning system, reflections from the transparent material can create interference that leads to inaccurate data.

Similarly, if an object is scanned using a photogrammetry-based system, shadows created by the transparent material can result in missing or incomplete data. To overcome these challenges, there are several techniques and technologies that can be used when scanning transparent materials. One approach is to use specialized scanning systems that are designed to work with transparent materials. These systems may use specialized lighting, cameras, or sensors that can mitigate the effects of refraction, reflection, or shadows.

Another approach is to apply a coating or spray to the surface of the transparent material that can help to reduce reflections and refraction. This can help to improve the accuracy of the scanned data and reduce the likelihood of errors and measurement problems. In summary, scanning transparent materials for 3D printing can be challenging due to the optical properties of the materials. However, by using specialized scanning systems or applying coatings or sprays, it is possible to improve the accuracy of the scanned data and reduce errors and measurement problems in the final 3D-printed object.

Regarding 3D printers, there are several different types of 3D printing technologies available, each of which uses a different method to deposit layers of material to create an object. The most common types of 3D printing include Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) [34].

Fused Deposition Modeling (FDM) is the most prevalent 3D printing technique. It works by heating a filament of plastic or other material and extruding it through a nozzle to build up layers of material to create an object. FDM printers are relatively inexpensive and easy to use, making them a popular choice for home and hobby use. FDM technology works by depositing layers of material that are melted and hardened as it is printed. This process is widely used to create prototypes, manufacturing tools, and complex parts. It is a relatively inexpensive and accessible 3D printing technology that is used in industries such as manufacturing, aerospace, automotive, and medical. FDM technology is reliable, accurate, and easy to use, making it a popular choice for businesses and hobbyists alike. FDM printers are available in a wide range of sizes and materials, so they can be used to meet a variety of needs. One of the advantages of FDM 3D printing is that the material used is recyclable and can be used multiple times. FDM technology is also more precise than other 3D printing technologies, allowing for the creation of complex and precise parts [44,45]. Another advantage of FDM technology is that it can be used to construct very large objects with dimensions in meters. This is possible because FDM printers can be designed with a large build volume, allowing them to create objects of considerable size. Additionally, FDM technology is relatively low-cost compared with other manufacturing methods used to produce large objects, making it an attractive option for industries that require large-scale fabrication.

While FDM is an affordable and accessible technology, the surface of objects produced by FDM can sometimes appear rough or uneven. Fortunately, there are several methods available to improve the surface quality of FDM printed models. One method is to use chemical treatments to smooth out the surface of the printed model. Acetone is a commonly used chemical that can be applied to the surface of models made from materials such as ABS or PLA. The acetone vapors dissolve the outer layer of the model, smoothing out any visible lines or imperfections on the surface. Another chemical treatment involves using a mixture of isopropyl alcohol and water, which can have a similar smoothing effect. Thermal treatment is another method used to improve the surface of FDM printed models. This involves heating the surface of the printed model with a flame or heat gun, which melts the outer layer of the model and smooths out any visible imperfections. However, this technique requires care and caution as excessive heat can cause the model to warp or distort [46]. Figure 3 depicts a portable 3D printer, printing the result of the 3D scan depicted in Figure 1, scanning a glass artifact in the Laboratory of Non-Destructive Techniques, University of West Attica, Athens, Greece.

Figure 3. Portable 3D printer, printing a replica of a 3D scanned artifact.

SLA 3D printing is an additive manufacturing technique that uses photopolymerization to produce 3D objects layer by layer. It is one of the most precise and detailed 3D printing methods and is capable of producing extremely precise parts that are exceedingly difficult to produce using other techniques. SLA 3D printing is frequently used to create medical devices and prototype parts, in addition to jewelry, collectibles, and educational materials. SLA 3D printing begins with the transmission of a 3D model to a printer. The printer then uses a light source to solidify the poured-in liquid resin. The 3D object is constructed layer by layer as the light source hardens the resin. Following the completion of each layer, the printer advances to the next level until the entire object is printed [47].

Numerous advantages of SLA 3D printing exist, including its precision and ability to produce intricate parts that would be difficult to manufacture using other techniques. Moreover, SLA 3D printing is cost-effective and environmentally friendly, as it requires less material than conventional manufacturing processes. SLA 3D printing has revolutionized the manufacturing process and enabled the creation of intricate and complex parts with extreme precision. Its affordability and precision make it an attractive option for a variety of production and prototyping requirements. As the technology advances, we anticipate that SLA 3D printing will become more prevalent [47].

Selective Laser Sintering (SLS) 3D printing is a process that uses a laser to fuse together particles of plastic, metal, or ceramic powders into a solid object. The material is spread in thin layers on a build platform and the laser then precisely traces the cross-section of the design, fusing the particles together. The process continues, building layer upon layer, until the final object is complete. SLS 3D printing is known for its high precision and ability to produce complex geometries, making it a popular choice for prototyping and producing functional end-use parts. It is also suitable for producing parts in a variety of materials, including nylon, titanium, and aluminum. The SLS process is known for being fast and cost-effective, making it a popular choice for manufacturers looking to bring their products to market quickly and efficiently [48,49].

3. Applications

Three-dimensional printing and 3D scanning are two important technologies that have revolutionized the way physical objects are being fabricated. Three-dimensional printing operates under the principle of building an object layer by layer from a digital model. Three-dimensional scanning, on the other hand, is the process of capturing digital data from a physical object to create a 3D model.

Combining 3D scanning and 3D printing can have significant benefits for the field of cultural heritage. There is a number of ways in which these technologies can be combined and successfully used: Firstly, in the field of preservation, 3D scanning allows for the creation of a digital copy of an artifact or monument that can be used for preservation purposes. This digital copy can be used to create a physical replica through 3D printing, which can then be used for display or study purposes, without risking damage to the original artifact. Secondly, in the restoration field, 3D scanning can be used to create a detailed digital model of an artifact or monument that has been damaged or degraded over time. This model can then be used to recreate missing or damaged parts of the artifact using 3D printing, allowing for the restoration of the artifact to its original state. Regarding accessibility, 3D printing can be used to create replicas of artifacts that are otherwise inaccessible to the public. For example, replicas of ancient artifacts can be created and made available to people who might not have the opportunity to visit the original artifact. As far as education is concerned, 3D printing can be used to create physical replicas of artifacts for use in educational settings. Students can study the replicas up close, gaining a better understanding of the artifact and its historical significance. Lastly, in the greater research field, 3D scanning can be used to create detailed digital models of artifacts that can be studied in greater detail than would be possible with the original artifact. These digital models can be shared with researchers around the world, allowing for collaborative research projects.

Three-dimensional printing has numerous applications across various industries, including manufacturing, healthcare, fashion, and architecture [50–56]. For example, in the manufacturing industry, it can be used to quickly create prototypes, replace broken parts, and even produce end-use products. In the healthcare industry, 3D printing has been used to create custom prosthetics and implants, and to produce surgical models for planning procedures.

Three-dimensional scanning has a range of applications as well, including reverse engineering, quality control, and heritage preservation [57–61]. In reverse engineering, 3D scanning is used to capture the data from an existing physical object and create a digital model that can be modified or used for further analysis. In the heritage preservation field, 3D scanning is used to create accurate digital representations of historical artifacts, which can be used for research, preservation, and educational purposes.

Overall, 3D printing and 3D scanning have brought forth new capabilities, simplifying the processes for individuals and businesses to turn their concepts into reality. As these technologies continue to evolve, their applications are likely to become even more broad and have a greater impact in the future.

3.1. Three-Dimensional Scanning Applications in Cultural Heritage Field

Three-dimensional scanning is a powerful technology that has proven to be a valuable tool in the field of cultural heritage preservation. The ability to create highly accurate and detailed digital models of cultural heritage artifacts and structures has opened up new opportunities for their preservation, study, and dissemination. The use of 3D scanning in cultural heritage preservation is a growing field, and has the potential to revolutionize the modus operandi in preserving and sharing our cultural heritage.

One of the main applications of 3D scanning in cultural heritage field is the preservation of fragile or endangered artifacts. Traditional methods of preservation often involve physically handling and storing artifacts, which can lead to damage and deterioration over time. Three-dimensional scanning allows for the creation of digital replicas of artifacts that can be made available for study and research without the need for physical handling. This can significantly reduce the risk of damage to the original artifact and ensure its preservation for future generations [62]. Additionally, 3D scanning can be used to create detailed digital models of entire archaeological sites, allowing for the preservation of sites that may be at risk due to natural or human-fabricated causes [63].

Another important application of 3D scanning in cultural heritage preservation is the study and research of artifacts and sites. The ability to create detailed digital models of artifacts and structures allows for a greater level of analysis and study than would be possible with traditional methods. Three-dimensional scans can be used to create detailed digital models of artifacts, which can be analyzed and studied in great detail. This can provide valuable insights into the history, culture, and construction of artifacts and sites. Additionally, 3D scanning can be used to create digital restoration models, which can aid in the conservation and restoration of artifacts and structures [64].

Three-dimensional scanning also plays a significant role in the dissemination of cultural heritage. Digital models created by 3D scanning can be used to create virtual exhibitions, allowing people to view and interact with cultural heritage artifacts and sites from anywhere in the world. This can greatly expand the audience for cultural heritage and make it more accessible to a global audience. Additionally, 3D scanning can be used to create interactive educational tools and games, providing an engaging and immersive way to learn about cultural heritage.

In addition to the above applications, 3D scanning can also be used to create digital twins of heritage sites [65,66]. These digital twins are exact replicas of the heritage site, and can be used to simulate the potential impact of conservation work, development plans, or natural disasters on the heritage site. This can aid in the development of conservation and preservation strategies. It also allows for virtual visits for those who are unable to visit the site in person, or for those who want to see the site as it used to be in the past.

Furthermore, 3D scanning technology has the potential to democratize access to cultural heritage. With the help of 3D scanning and the internet, people all over the world can access and learn about cultural heritage that would otherwise be inaccessible to them. This is particularly important in developing countries and in regions affected by conflict, where cultural heritage is often endangered.

Numerous cases of relevant applications are being documented in published literature. More specific, one such case concerns the Parthenon temple in Athens, Greece where 3D scanning was used to create a detailed digital model of the Parthenon temple, which allowed for the analysis of the building's construction and the identification of previously unseen details. The Parthenon in Athens, Greece is a historic temple that has undergone extensive research and analysis over the years. Recently, 3D scanning technology was utilized to create a detailed digital model of the Parthenon. This allowed for an in-depth analysis of the building's construction and the identification of previously unseen details. The 3D scanning operations provided a precise and accurate representation of the temple, which offered valuable information for architectural, historical, and cultural studies. The use of 3D scanning in this case has significantly contributed to a deepened understanding of the Parthenon and its place in history. Figure 4 depicts the relevant operations [67].

Another relevant case concerned the Nefertari tomb in Egypt, where 3D scanning was used to document the tomb of the ancient Egyptian queen Nefertari, which was closed to the public for many years due to preservation concerns. The digital model of the tomb allowed for virtual tours to be created, allowing people to explore the tomb from anywhere in the world. The Nefertari tomb, located in the Valley of the Queens in Egypt, is an unprecedented testament to ancient Egyptian royalty and the rich history of the region. However, the tomb was closed to the public for many years due to concerns over preservation and conservation. In order to document this unique and important site, 3D scanning technology was used to create a digital model of the tomb's interior. With the help of this technology, researchers and preservationists were able to document the intricate details of the tomb's murals, decorations, and architecture, providing valuable information for future generations. The digital model of the tomb also enabled virtual tours to be created, allowing people from all over the world to explore this amazing site from the comfort of their own homes.

Figure 4. Three-dimensional scanning operations in Parthenon artifacts [67].

In this way, the use of 3D scanning technology has played a crucial role in preserving the legacy of the Nefertari tomb and ensuring that its story is not lost to time. The virtual tours allow for a greater understanding of the tomb's rich cultural and historical significance, and provide a new way for people to explore and appreciate this important site. The 3D scanning of the Nefertari tomb was performed by a team of experts, including archaeologists, conservators, and technology specialists. Figure 5 depicts the relevant work conducted in Nefertari tomb [68,69].

In addition, the Bamiyan Buddhas in Afghanistan is also a relevant case where 3D scanning was used to document the statues of Bamiyan Buddhas. The Bamiyan Buddhas in Afghanistan were two massive ancient statues of the Buddha carved into the cliff face of Bamiyan Valley. Sadly, they were destroyed by the Taliban in 2001. Recently, however, there has been a resurgence of interest in preserving and reconstructing the site. One of the methods being used is 3D scanning. By using lasers to scan the remaining structures, a digital model of the Bamiyan Buddhas can be created, allowing for detailed analysis and potential reconstruction in the future. This innovative technique is helping to keep the memory of the Bamiyan Buddhas alive and ensure that their cultural significance will be preserved. Figure 6 depicts the relevant 3D scanning operations in Bamiyan Buddhas, Afghanistan [70].

Figure 5. Three-dimensional scanning operations in Nefertari tomb [69].

Figure 6. Three-dimensional scanning operations in Bamiyan Buddhas, Afghanistan [71].

In this context, another relevant case documented in published literature is that of the Great Wall of China where 3D scanning was used to create a detailed digital model of the Great Wall of China, which allows for the analysis of the wall's construction and the identification of areas in need of preservation. The Great Wall of China is one of the most iconic and recognizable structures in the world, and was recently subject to 3D scanning technology in order to better understand its history and preservation. Three-dimensional scanning involved capturing detailed digital data of a physical object, which can then be used to create a virtual model. This technology was used to scan the Great Wall, providing a precise representation of its current state and allowing for a better understanding of the wall's deterioration over time. This information can be used to provide in-depth data for restoration and conservation efforts, providing an important technological tool in this direction. Figure 7, depicts the relevant 3D scanned model that is publicly available for downloading in "MyMiniFactory" online platform [72–75].

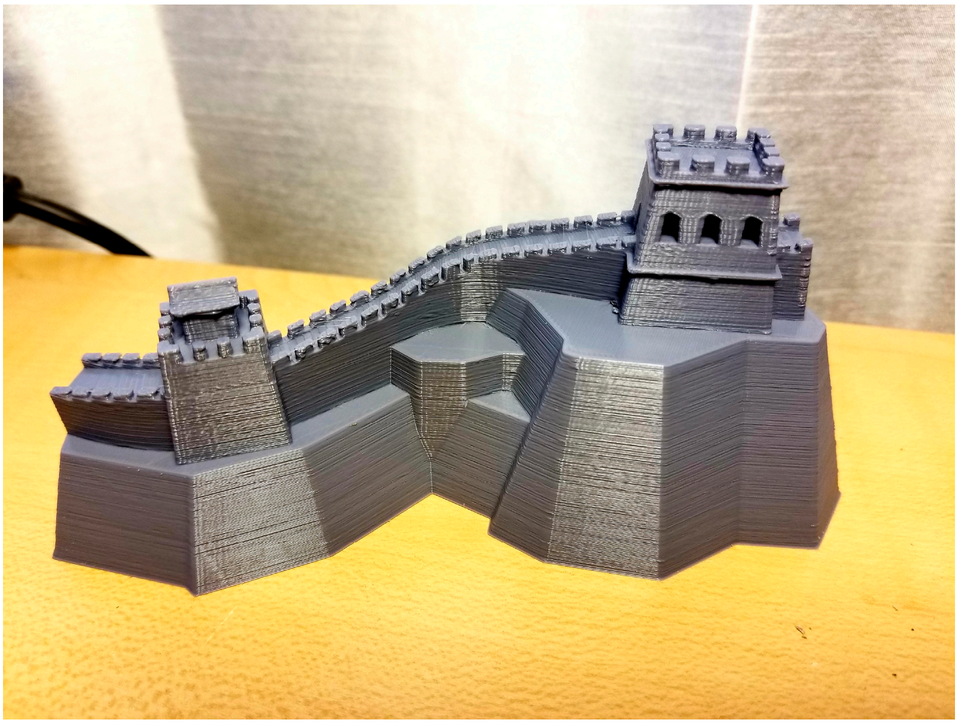

Figure 7. Three-dimensional scanned model, publicly available for downloading in "MyMiniFactory" online platform [72].

The Sistine Chapel in Vatican City is another documented case where 3D scanning was used to create a detailed digital model of the Sistine Chapel's ceiling fresco, which allowed for the analysis of the painting's technique and the identification of previously unseen details. The Sistine Chapel in Vatican City is one of the most famous and well-preserved works of Renaissance art, and was recently the subject of 3D scanning technology. The 3D scanning process involves capturing detailed digital data of the physical structure and artwork, which can then be used to create a virtual model. This technology was used to scan the Sistine Chapel, providing a precise representation of the artwork and allowing for a better understanding of its preservation over time. This information can be used to inform conservation efforts, helping to ensure that this magnificent work of art will continue to be enjoyed by generations to come. Additionally, the 3D scans provide an opportunity for scholars and researchers to study the artwork in great detail, leading to a deeper understanding of Michelangelo's techniques and vision [76,77].

In another documented case, in the Mayan Temples of Tikal, Guatemala, 3D scanning was used to create detailed digital models of the Mayan temples of Tikal, which allowed for the analysis of the temples' construction and the identification of previously unseen details. The digital models also allow for virtual exploration of the temples, providing an immersive educational experience for people who may not be able to visit the site in person. The Mayan Temples of Tikal in Guatemala are some of the most impressive ancient structures in the Americas, and were recently the subject of 3D scanning technology. Three-dimensional scanning involves capturing detailed digital data of the physical structures, which can then be used to create a virtual model. This technology was used to scan the temples at Tikal, providing a precise representation of their current state and allowing for a better understanding of their history and preservation over time. This information can be used to inform restoration and conservation efforts, helping to ensure that these ancient wonders will continue to stand for generations to come. Additionally, the 3D scans provide an opportunity for scholars and researchers to study the temples in great detail, leading to a deeper understanding of the Mayan civilization and its architectural achievements [78,79].

In this context, another documented case concerns the Terracotta Army of Xi'an, China, where 3D scanning was used to create detailed digital models of the Terracotta Army, a collection of thousands of life-size terracotta figures that were buried with the first emperor of China. The digital models allow for the analysis of the figures' construction and the identification of previously unseen details. The Terracotta Army of Xi'an in China is one of the most famous collections of ancient sculptures in the world, and was recently the subject of 3D scanning technology. The 3D scanning process involves capturing detailed digital data of the physical sculptures, which can then be used to create a virtual model. This technology was used to scan the Terracotta Army, providing a precise representation of the sculptures and allowing for a better understanding of their preservation over time. This information can be used to inform conservation efforts, helping to ensure that these valuable works of art will be preserved for generations to come. Additionally, the 3D scans provide an opportunity for scholars and researchers to study the sculptures in great detail, leading to a deeper understanding of the art and technology of ancient China. Figure 8 depicts the relevant 3D scanning operations [80,81].

Figure 8. Three-dimensional scanning operations in Terracotta Army of Xi'an, China [82].

Similarly, the Tower of London is another documented case where 3D scanning was used to create a detailed digital model of the Tower of London, which allows for the analysis of the building's construction and the identification of areas in need of preservation. The digital model also allows for virtual exploration of the tower, providing an immersive educational experience for people who may not be able to visit the site in person. The Tower of London is one of the most iconic and historically significant structures in England, and was recently the subject of 3D scanning technology. The 3D scanning process involves capturing detailed digital data of the physical structure, which can then be used to create a virtual model. This technology was used to scan the Tower of London, providing a precise representation of its current state and allowing for a better understanding of its history and preservation over time. In addition, the 3D scans allow scholars and researchers to examine the tower in great detail, thereby enhancing their understanding of its history and significance [83,84].

Likewise, the Notre-Dame Cathedral in Paris is another example where 3D scanning was used to create detailed digital models of the Notre-Dame Cathedral after the fire in 2019, which allowed for the analysis of the building's construction and the identification of areas in need of preservation. The digital models also allow for virtual exploration of the cathedral, providing an immersive educational experience for people who may not be able to visit the site in person. The Notre-Dame Cathedral in Paris is a historical and architectural treasure that was captured in a new light through the use of 3D scanning technology. The scanning process involved capturing millions of data points and images of the structure, which were then used to create a highly detailed and accurate digital model of the cathedral. This technology allows for a deeper understanding of the cathedral's design and construction, as well as a way to preserve its history and beauty for future generations. The 3D scanning also proved valuable in the aftermath of the 2019 fire, as it aided in the restoration efforts by providing a precise record of the building's original features. The case of the Notre-Dame Cathedral exemplifies the ability of technology to protect and promote cultural heritage [85,86].

Lastly, the Lascaux Caves in France is another paradigm where 3D scanning was used to document the prehistoric paintings in the Lascaux Caves, which have been closed to the public since the 1960s to protect the fragile artwork. The digital models allow for virtual tours to be created, allowing people to explore the caves from anywhere in the world. The Lascaux Caves in France, renowned for their Paleolithic cave paintings, have been captured in a new way through 3D scanning technology. The scans have allowed for the creation of a detailed digital model of the caves, preserving their beauty and history for future generations. The technology also provides researchers with a valuable tool for studying the caves, as the 3D scans allow for a closer examination of the art and the cave's geology. The digital replica of the Lascaux Caves has also enabled visitors from all over the world to enjoy the splendor of the cave paintings without having to travel to the site. The 3D scanning of the Lascaux Caves is thus not just a means of preserving cultural heritage, but also of promoting it globally [87,88].

3.2. Three-Dimensional Printing Applications in Cultural Heritage Field

Three-dimensional printing is considered as a rapidly evolving technology that has the potential to revolutionize the field of cultural heritage. The ability to create highly accurate and detailed physical replicas of cultural heritage artifacts and structures using 3D printing technology has opened up new opportunities for their preservation, study, and dissemination.

One of the main applications of 3D printing in a cultural heritage field is the preservation of fragile or endangered artifacts. Traditional methods of preservation often involve physically handling and storing artifacts, which can lead to damage and deterioration over time. Three-dimensional printing allows for the creation of physical replicas of artifacts that can be made available for study and research without the need for physical handling. This can significantly reduce the risk of damage to the original artifact and ensure its preservation for future generations. Additionally, 3D printing can be used to create detailed replicas of entire archaeological sites, allowing for the preservation of sites that may be at risk due to natural or human-fabricated causes.

Another important application of 3D printing in cultural heritage is the study and research of artifacts and structures. Three-dimensional printing allows for the creation of highly accurate and detailed physical replicas of artifacts, which can be analyzed and studied in great detail. This can provide valuable insights into the history, culture, and construction of artifacts and structures. Additionally, 3D printing can be used to create physical models for use in conservation and restoration efforts, allowing for the testing and development of new techniques and materials.

Three-dimensional printing also plays a significant role in the dissemination of cultural heritage. Physical replicas created using 3D printing technology can be used to create exhibitions and displays, allowing people to view and interact with cultural heritage artifacts and structures in a tangible way. This can greatly expand the audience for cultural heritage and make it more accessible to a wider range of people. Additionally, 3D printing can be used to create educational tools and games, providing an engaging and immersive way to learn about cultural heritage.

In addition to the aforementioned applications, 3D printing can also be used to create physical models of heritage sites for use in conservation and preservation planning. These models can be used to simulate the potential impact of conservation work, development plans, or natural disasters on the heritage site. This can aid in the development of conservation and preservation strategies, and in providing a better understanding of the site's condition and its evolution over time.

One of the main advantages of 3D printing in the field of cultural heritage is its ability to create highly accurate and detailed replicas of artifacts and structures. This is particularly important in the case of artifacts that are difficult or impossible to preserve using traditional methods, such as organic materials or fragile artifacts. Additionally, 3D printing allows for the creation of replicas that are highly detailed and accurate, making them valuable for research and study.

Numerous cases of relevant applications are being documented in published literature. More specific, one such case concerning the British Museum in London used 3D printing to create a replica of the Rosetta Stone, which was made available for public viewing. This allowed visitors to view and interact with the artifact in a tangible way without handling the original, which is fragile and sensitive to light exposure. The British Museum has utilised 3D printing technology as a means of preserving and promoting cultural heritage. The museum has used 3D printing to create detailed replicas of artifacts and artworks, allowing visitors to get a close-up look at these important objects. The technology has also been used to create interactive displays, allowing visitors to see and touch 3D-printed models of objects from the museum's collection. Additionally, the British Museum has used 3D printing to create research tools, such as replica bones for scientists studying human evolution, and to create educational resources, such as hands-on models for school groups. The British Museum's use of 3D printing enhances the visitor experience and further assists in promoting cultural heritage. Figure 9 depicts a 3D-printed replica of a part of its collection, derived from a 3D scan [89,90].

In a similar documented case in Italy, a team of researchers used 3D printing to create a replica of a 2500-year-old Etruscan chariot, which was found buried in a tomb in the ancient city of Tarquinia. The replica was used for educational purposes and is currently on display at the National Etruscan Museum in Rome. The discovery of an Etruscan chariot buried in a tomb in the ancient city of Tarquinia in Italy has been made even more exciting through the use of 3D printing technology. Using the data collected from scans of the chariot, a highly detailed and accurate 3D-printed model was created, providing researchers with a new tool for studying the ancient artifact. The 3D-printed chariot also offers a unique educational opportunity, allowing students and visitors to see and touch a replica of the chariot without having to handle the fragile original artifact. The 3D printing of the Etruscan chariot has helped to bring this piece of history to life and has added to our understanding of the culture and technology of the ancient Etruscans [91,92].

Moreover, in Egypt, the Ministry of Antiquities used 3D printing to create a replica of a 3500-year-old statue of Ramses II, which was found in the temple of Aten in Luxor. The replica was made available for public viewing and educational purposes. Ramses II Aten Luxor is a statue that was created using 3D printing technology. This method of production allows for intricate details and precision in the design, resulting in a highly accurate representation of the ancient Egyptian pharaoh. The statue stands at a remarkable height, capturing the regal presence of Ramses II. The use of 3D printing made it possible to recreate this piece of history in a way that was previously impossible using traditional manufacturing methods [93,94].

Figure 9. Three-dimensional-printed replica of a part of British Museum's collection, with its original design data derived from a 3D scan [90].

In addition, the Smithsonian Institution's Digitization Program Office used 3D printing to create a replica of the Wright Brothers 1903 Flyer, the first successful powered aircraft. The replica was used for research, exhibition, and educational purposes. The Wright Brothers, Orville and Wilbur, are widely recognized as the pioneers of powered flight. On 17 December 1903, the brothers took to the skies in their Flyer, making history with the first successful manned flight. This flight lasted just 12 s and covered a distance of 120 feet, but it was a monumental moment that changed the course of human history. Over the following years, the Wright Brothers continued to refine their design, eventually leading to the development of practical, usable aircraft.

The Smithsonian Institution made it possible for people to experience the 1903 Flyer in a new way, through the use of 3D printing technology. This technology allows for the creation of highly detailed, accurate replicas of the Flyer, providing a unique opportunity to study and appreciate this historic machine. The 3D-printed model is a testament to the ingenuity of the Wright Brothers and the transformative power of technological innovation.

By making the 1903 Flyer available as a 3D print, the Smithsonian is preserving this important piece of history for future generations. It also allows people who might not have the opportunity to visit the original Flyer, which is housed at the Smithsonian's National Air and Space Museum, to have a tangible, three-dimensional representation of this remarkable machine. Figure 10 depicts the 3D-printed replica of the Wright Brothers 1903 Flyer, derived from a 3D scan [95,96].

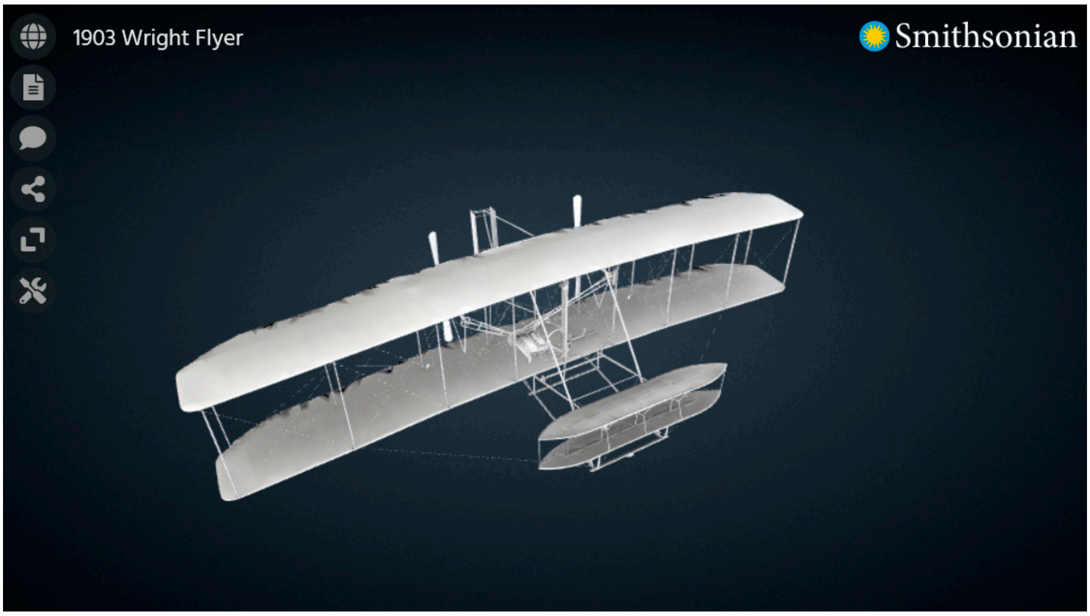

Figure 10. Three-dimensional-printed replica of the Wright Brothers 1903 Flyer, derived from a 3D scan [97].

In another relevant documented case in Peru, researchers used 3D printing to create a replica of a pre-Columbian vessel in the form of a human head. The replica was used to study the original artifact which was fabricated of fragile materials and is too delicate to be handled. A 3D printing replica of a pre-Columbian vessel in the form of a human head was created in Peru, offering a unique look into the art and culture of this ancient civilization. The original vessel, believed to have been created between 800 and 1500 AD, was found among the ruins of the Moche culture, an advanced civilization that flourished in northern Peru for several centuries. The 3D printing replica provides a detailed, accurate representation of the original vessel, including its intricate designs and symbolic features. This replica offers a new way to study and appreciate the artistry and cultural significance of this artifact, beliefs, customs, and traditions of the Moche people. The 3D printing replica of this pre-Columbian vessel is an important step in preserving and sharing the rich cultural heritage of Peru for future generations [98].

Likewise, in the United Kingdom, the Royal Institute for Cultural Heritage (KIK-IRPA) used 3D printing to create a replica of a 15th-century sculpture of Saint George and the Dragon, which was located in the Church of Saint George in Bruges, Belgium. The replica was used for research and conservation purposes, as the original sculpture underwent significant damage over the years. Three-dimensional printing technology has made it possible to create highly detailed replicas of historic structures such as the Saint George Dragon Church in Bruges, Belgium. By using laser scanning and computer modeling techniques, experts are able to accurately capture the intricate details and proportions of the church's architecture, including its iconic towers, stained glass windows, and intricate sculptures. The 3D printing process then creates the physical model using materials such as plastic or resin, layer by layer, to produce a highly accurate and durable replica. This not only provides a way for people to learn about and appreciate the history of the church, but also offers an interesting new perspective on how technology and tradition can intersect [99].

Furthermore, in the United States, the Getty Conservation Institute used 3D printing to create a replica of a Roman marble statue of a youth, which is in the collection of the J. Paul Getty Museum in Los Angeles. The replica was used for research and educational purposes, as well as to study the original statue's condition, which was in need of conservation. The Getty Conservation Institute (GCI) employed 3D printing technology to create a replica of a Roman marble statue of a youth in the collection of the J. Paul Getty Museum in Los Angeles. This statue, which is considered a masterpiece of ancient art, is one of the museum's prized possessions. Using digital scanning techniques, the GCI was able to capture the intricate details and exact measurements of the original statue, including its textures, shapes, and patterns. The resulting 3D-printed replica offers a unique opportunity to study the ancient work up close, as well as to showcase the statue to a wider audience. In addition, the replica serves as a valuable tool for conservators and researchers, allowing them to study the original statue without risking damage. The GCI's use of 3D printing technology demonstrates how this cutting-edge technique can be used in the conservation and preservation of cultural heritage [100,101].

Lastly, in Japan, the National Museum of Emerging Science and Innovation used 3D printing to create a replica of a 12th-century Buddha statue which is on display in the museum. The replica was used for research and educational purposes, and to study the original statue's condition, which was fragile and needed conservation. The National Museum of Emerging Science and Innovation in Japan used 3D printing technology to create a replica of a 12th-century Buddha statue. This statue, which is considered a valuable cultural artifact, is one of the museum's most prized possessions. By using digital scanning techniques, the museum was able to accurately capture the intricate details and exact measurements of the original statue, including its textures, shapes, and patterns. The resulting 3D-printed replica offers visitors a unique opportunity to view the statue up close and appreciate its beauty and cultural significance. Moreover, the replica serves as a valuable tool for conservators and researchers, allowing them to study the original statue without risking damage. The museum's use of 3D printing technology demonstrates how this innovative technique can be used in the preservation and sharing of cultural heritage with wider audiences [102].

4. Discussion

Three-dimensional scanning technology is expected to continue to grow and advance in the future, with many exciting possibilities on the horizon. One of the main areas of growth is expected to be in the field of augmented and virtual reality, where 3D scanning will play a critical role in capturing real-world objects and environments for use in immersive experiences.

Additionally, there is growing interest in using 3D scanning for monitoring and tracking objects and people in real-time, which can have applications in fields such as logistics, security, and sports. With the advent of more advanced sensors and algorithms, it is also likely that 3D scanning will become more accessible and affordable, making it possible for a wider range of individuals and organizations to use.

Overall, the future of 3D scanning technology is bright, with many exciting opportunities to enhance the way we interact with the physical world and gather information about it. As the technology continues to evolve, it will likely have a profound impact on the way we live and work.

Likewise, 3D printing technology is expected to have a major impact on various industries in the future. In manufacturing, it is predicted to play a larger role in mass production of complex and customized products. In healthcare, 3D printing is expected to play a bigger role in producing custom prosthetics, implants, and surgical models, and it is also likely to contribute to the advancement of personalized medicine and tissue engineering. The construction industry is also expected to be impacted by 3D printing technology, as it has the potential to revolutionize building construction processes by allowing the printing of entire buildings and houses, leading to faster and more efficient construction methods. Moreover, 3D printing has the ability to reduce waste and contribute to a more sustainable future by producing only what is needed, when it is needed [103–110]. Consumer goods production is also expected to change as a result of 3D printing, which can enable the production of items at home, tailored to specific needs and preferences, and on demand.

Three-dimensional printing technology has advanced significantly over the years and is constantly evolving. The next frontier in 3D printing is 4D and 5D printing. Four-dimensional printing refers to the addition of a time dimension to 3D printing, allowing for the creation of objects that change over time. For example, 4D-printed materials can respond to environmental factors such as heat, light, or moisture, and change their shape or properties accordingly. Five-dimensional printing, on the other hand, involves the integration of multiple functionalities into 3D-printed objects, such as sensors, electronics, and other materials. This opens new possibilities for creating smart and interactive products with unique capabilities, from wearable devices to self-assembling structures. As 4D and 5D printing continue to evolve, they have the potential to revolutionize the way products are designed and manufactured, leading to new and innovative solutions to a wide range of challenges [111,112].

In the field of cultural heritage, both 3D printing and 3D scanning are poised to play a critical role in preserving and studying the past. With 3D scanning, it is possible to create highly accurate digital representations of artifacts and cultural sites, which can be used for research, preservation, and educational purposes. Three-dimensional scanning can also be used to monitor the condition of objects over time, helping to identify and address potential problems before they become more serious. Additionally, 3D scanning can be used to create virtual exhibits and educational resources, making it possible for people around the world to learn about cultural heritage without having to travel.

Three-dimensional printing, on the other hand, has the potential to create highly detailed replicas of cultural artifacts and sites. This can be useful for research, education, and even for creating new exhibits, without the need to handle delicate and fragile original artifacts. Three-dimensional printing can also be used to repair damaged artifacts, as well as for creating casts for molding and reproduction purposes.

While 3D scanning and printing have significant potential to improve the preservation and study of cultural heritage, there are limitations that need to be addressed. Firstly, the factor of cost. Both 3D scanning and printing can be expensive, and the cost of equipment and materials may limit the availability of these technologies for cultural heritage institutions with limited budgets. Secondly, the parameter of accuracy. The accuracy of 3D scanning and printing technologies can vary depending on the equipment and methods used. The accuracy of the scanned data can also be affected by the condition and complexity of the object being scanned. This can impact the quality of the final 3D-printed replica, particularly in cases where fine details are important. Thirdly, material limitations. While 3D printing has come a long way in terms of the range of materials that can be used, some materials used in cultural heritage preservation and restoration may not be compatible with current 3D printing technologies. For example, certain types of stone or metal may be difficult to 3D print. Moreover, intellectual property concerns arise by creating digital copies of artifacts and monuments. In some cases, institutions may not have the legal right to create a digital copy of an artifact or monument, or to use the digital copy for commercial purposes. In addition, there may be ethical considerations when creating replicas of cultural heritage objects, particularly if the replicas are intended to be displayed in public. Some people may argue that replicas can diminish the value and significance of the original artifact. Overall, these limitations may impact the effectiveness of combining 3D scanning and printing technologies in the field of cultural heritage. However, as the technology continues to develop, it is likely that many of these limitations will be addressed, making these technologies even more useful for preserving and studying cultural heritage.

Another issue can be that large-format 3D scanning and 3D printing can certainly impact the resolution of replicated objects. When scanning or printing large objects, the resolution of the equipment can be a limiting factor in the level of detail that can be captured or reproduced. For 3D scanning, larger objects may require the use of lower resolution settings to capture the entire object. This can result in a loss of detail and fidelity in the scanned data, which can affect the accuracy of the final 3D-printed object. Additionally, the scanning process may take longer and require more resources to capture the larger object, increasing the likelihood of errors or distortions in the data. Similarly, when 3D printing large objects, the resolution of the equipment can impact the quality of the final product. Larger objects may require the use of thicker layers, which can result in a lower resolution print with less detail. Additionally, printing larger objects may require more time and resources, which can increase the likelihood of errors or defects in the final product. To overcome these challenges, it is important to use high-quality equipment with high resolution settings when working with large objects. Additionally, it may be necessary to use specialized software or techniques to optimize the scanning or printing process for larger objects, such as adjusting the lighting or angle of the scanner or printer. By carefully considering the equipment and processes used, it is possible to minimize the impact of resolution limitations and achieve high-quality results when working with large-format 3D scanning and printing.

In conclusion, the future potential of both 3D printing and 3D scanning in the field of cultural heritage is immense. These technologies can help preserve and protect the past for future generations, while also making cultural heritage more accessible and understandable to a wider audience.

5. Conclusions

In conclusion, the significance of 3D printing and 3D scanning as emerging technologies in the field of cultural heritage cannot be overstated. These cutting-edge technologies hold immense potential for preserving, studying, and showcasing the cultural heritage of our world.

Three-dimensional printing has proven to be an incredibly valuable tool in the preservation of cultural heritage, offering the ability to produce intricate and delicate artifacts with remarkable accuracy. This not only helps to preserve the cultural heritage for future generations, but it also provides an opportunity to make these artifacts more accessible to people around the world. Additionally, the use of 3D printing in the creation of replicas and models can help to minimize the handling and exposure of fragile and delicate artifacts, helping to reduce the risk of damage and deterioration.

Three-dimensional scanning, on the other hand, provides an efficient and non-invasive method for capturing and preserving the geometry and details of heritage sites and artifacts. This technology allows for the creation of high-precision digital models, providing a wealth of information for researchers and historians. Furthermore, the use of 3D scanning in heritage documentation and conservation can help to support decision making and provide important information for future restoration and preservation efforts.

Combined, 3D printing and 3D scanning have the potential to revolutionize the way we preserve, study, and showcase our cultural heritage. By making it more accessible and engaging, these technologies have the potential to inspire and educate future generations, helping to ensure that our cultural heritage is never lost. As these technologies continue to evolve, we can expect to see even more innovative and impactful applications in the field of cultural heritage in the future.

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