The Applications of Additive Manufacturing Technologies in Cyber-Enabled Manufacturing Systems

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Abstract

The application of networked sensors and control in various areas, such as smart grids and infrastructures, has become a recent trend, called cyber-physical systems. The Cyber Enabled Manufacturing (CEM) environment is to apply these technologies in manufacturing systems to handle a significantly greater magnitude of manufacturing data. Additive manufacturing techniques print or place material layer by layer to form a part, thus have a great potential to help accelerate CEM process by printing or embedding sensors and actuators in the proper locations. This paper summarizes the roles of additive manufacturing technologies to help establish a CEM environment.

1. Introduction

1.1. Cyber-Enabled Manufacturing (CEM)

A CEM system is an offshoot of the generic Cyber Physical System (CPS) which consists of embedded and distributed sensors that are networked over a wide area to effectively gather information while being coupled with control systems that offer immediate response. Their applications are acknowledged to include electricity control grids, traffic management and accident reduction, disaster prediction and response, and preventive maintenance systems [1]. Their application in a manufacturing environment leads us to the concept of CEM.

A CEM system can be defined as an environment wherein intelligent use of networked sensors and process management is combined to efficiently utilize manufacturing information to increase awareness and connectivity [2]. An efficient CEM system would increase productivity, and safety standards while simultaneously driving down costs. A CEM environment enables remote access and control of manufacturing systems with the aid of visual, thermal and strain sensors to continuously monitor not just the end products being produced but also the health of the manufacturing machine. Such a networked environment is vital for sustainable quality control and timely and predictive maintenance of the manufacturing equipment. Such a network also ensures continuous connectivity of people in all levels of a factory, from the shop floor to upper management, [3] in the day to day activities of the plant.

The successful implementation of CEM systems in a factory requires the location of sensors in and around the equipment, and open-ended software architecture to utilize the information provided by the networked sensors. A significant amount of research has been conducted into the development of architectures for the command and control of the sensors [[2], [4]]. Locating of the sensors is performed by mechanical fastening or adhesion and in other cases by embedding the sensors into the body of the object in question. These sensors are then monitored using wireless sensing equipment [5] to obtain information on structural health, thermal signatures, stress and strain measurements, displacement, and other performance critical data [6]. The focus of this paper is to bring to light the use of additive manufacturing methods to embed sensors directly into the body of a part without adversely affecting its function and cost.

The use of CEM leads to smarter, more connected processes, for 1) agile and efficient production; 2) manufacturing robotics that work safely with people in shared spaces; 3) computer-guided printing or casting of composites and; 4) actively controlled buildings and structures to improve safety by avoiding or mitigating accidents.

1.2.Additive Manufacturing:

Additive manufacturing is the process of building complex three dimensional parts from their CAD models rapidly in a layer by layer manner. CAD models are sliced to obtain tool path and layer information which are used by the additive manufacturing equipment [7]. Material is deposited in a layer form one over the other and fused to the previous layer to form a cohesive bond. In the past, rapid prototyping technologies were primarily used to make parts to check for form, fit, and aesthetics but, with limited functional capabilities [8]. However in the recent past there has been a push to use these prototyping technologies to make end products with more functional applications in mind. Many researchers have successfully shown that additive manufacturing technologies can be used to manufacture end products and have termed them rapid manufacture and rapid tooling [[9], [10], [11]]. Rapid manufacturing exhibits significant advantages over conventional manufacturing processes including

- Reduced lead times
- Zero tooling costs
- Design and redesign flexibility
- Material flexibility
- Part complexity

The aim of this paper is to study the advantages of using additive manufacturing to develop CEM systems. These advantages enable their use in a multitude of direct manufacturing applications to produce parts used in aerospace, medicine, research, defense, and other sectors [12]. It is believed that many of the component items in a modern sonar transducer can be produced using these methods. The roles of additive manufacturing technologies include

1. Embedded sensors
2. Print labels/EPCs
3. High performance temperature sensors
4. Fabricate on demand
5. Part DNA
6. Designing and producing conforming transducers
7. Tissue, organ production and other medical applications
8. Manufacture of assembled actuated mechanism
9. Manufacture of micro – sensors and micro - actuators

Additive manufacturing in CEM can also lead to sustainable mass production of smart fabrics and other wearables with applications in many areas, such as electronics to provide versatility without recourse to a silicon foundry, and the processing of emerging materials such as carbon fiber and polymers that offer the potential to combine capability for electrical and optical functionality with important physical properties including strength, durability, and disposability. In the forthcoming sections we will discuss the different rapid prototyping processes and their ability to aid CEM.

2. Discussion: The roles of Additive Manufacturing in CEM

As mentioned before additive manufacturing can be a boon to promote CEM. We will now discuss in detail the capabilities of additive manufacturing to aid CEM and their use in various applications and we will corroborate the same using research being conducted into the respective areas.

2.1. Embed sensors

One of the most critical aspects of Cyber Enabled Manufacturing is the embedding of wireless sensors into parts to accurately monitor changes in temperature and stress that the component is subjected to. Research conducted has shown that performance of wireless sensors does not deteriorate when embedded in materials [5]. Other types of sensors used include Fiber Bragg Grating, (FBG) which has shown promise for use in these applications [13]. The embedding is not restricted to the type and size of the sensors, and multiple additive manufacturing processes are available for this purpose, as discussed here. In some cases the sensors are directly inserted into the part, while in others, place holders are inserted that can be removed to include sensors after part manufacture.

2.1.1. Selective Laser Sintering (SLS):

Research conducted by Maier et al. has shown that selective laser sintering can be used to embed FBG strain gauges into sintered parts thereby encouraging CEM and remote sensing. Figure 1 and Figure 2 are used to explain the research. An ISO 3167 tensile test specimen was made with an embedded FBG sensor to measure strain change.

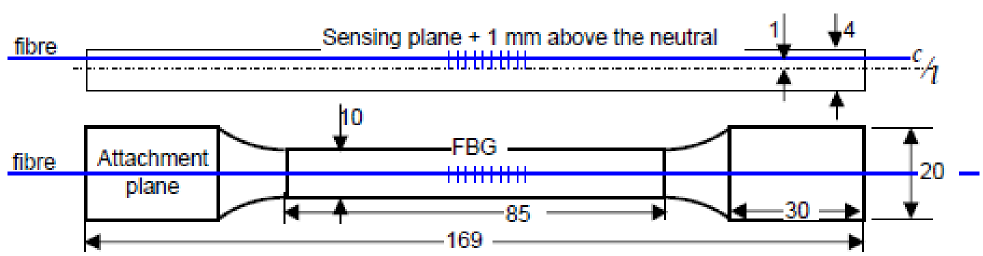

Figure 1: Schematic of an ISO 3167 specimen with the location of the installed fiber and FBG [14]

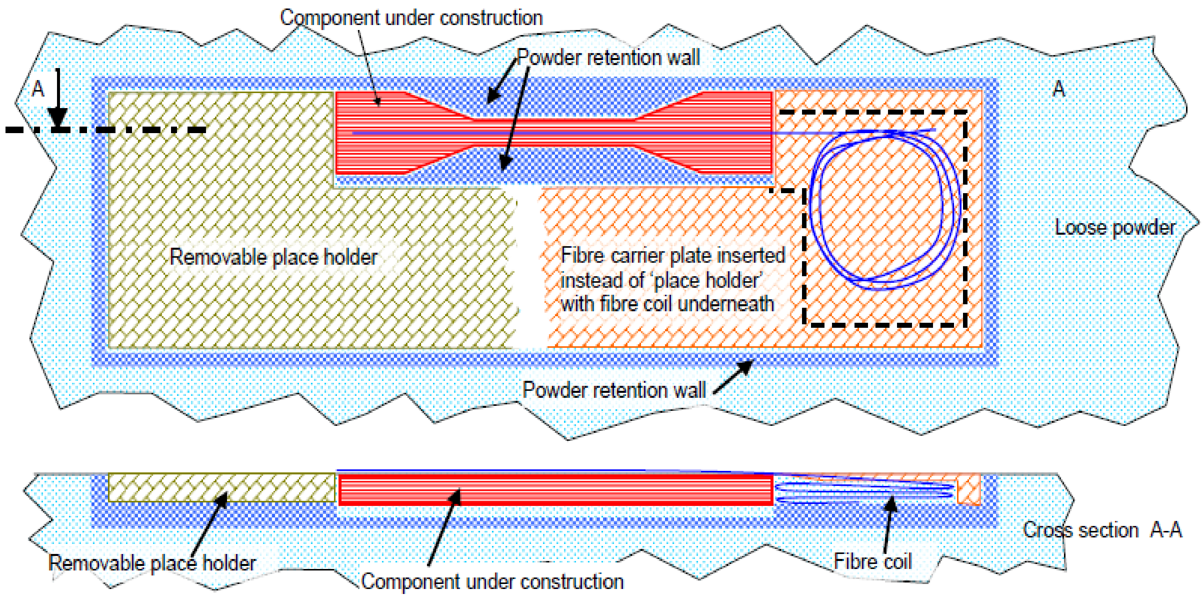

Figure 2: Top and side view of powder bed with component and fiber location [14]

The fiber and the component under construction are located on the powder bed using place holders as shown in Figure 2. The fibers are protected from the sintering process by the use of polyimide jackets to withstand the temperatures (220^{o}C) produced during the build. The research has led to successful construction of fiber embedded tensile test specimens that are stable, and creep free, using SLS.

2.1.2. Shape Deposition Manufacturing (SDM):

Shape deposition manufacturing is another additive manufacturing process that is showing applications in embedding sensors into parts. Cham et al. [15] conducted a feasibility study of using SDM to embed components and sensors into parts produced by this additive manufacturing method. Their conclusion was that SDM can be used to make mechatronics components with embedded sensors that would be difficult to make using conventional manufacturing processes. Their research is corroborated by work done [[16], [17]] at Stanford University into embedding fiber optic and thin film sensors into components at critical locations and measuring the sensory output.

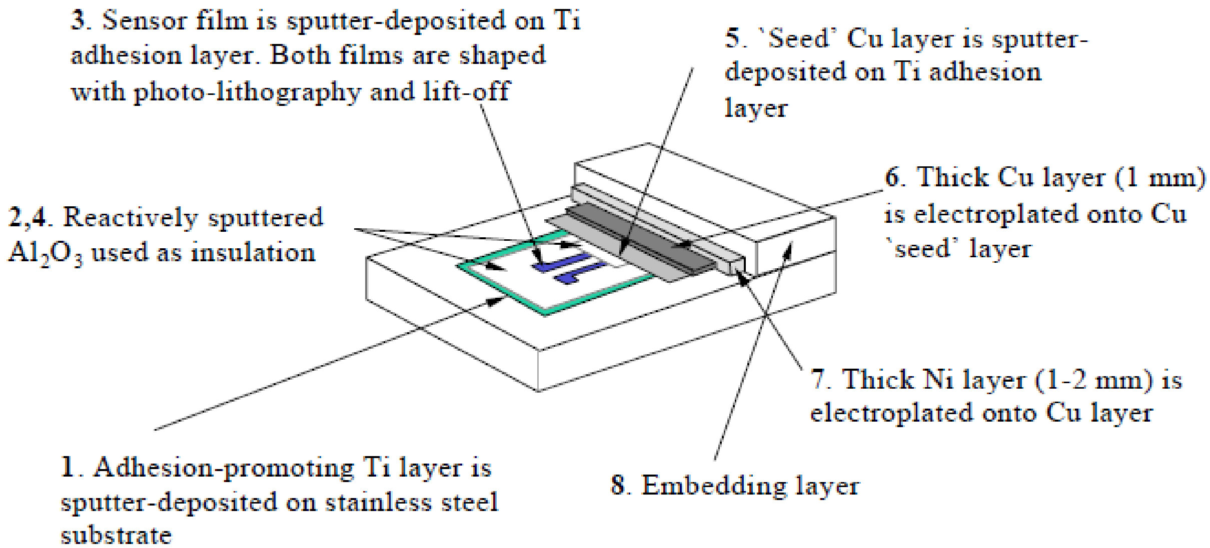

Figure 3: Procedure for embedding thermo-mechanical thin film sensors [16]

Figure 3 shows the procedure for embedding a thin film thermo–mechanical sensor into metallic components. One of the advantages of using SDM is its usability with metallic materials [18]. Thin film sensors were characterized using four-point bend tests which compared favorably with commercially available strain gauges and theoretical models.

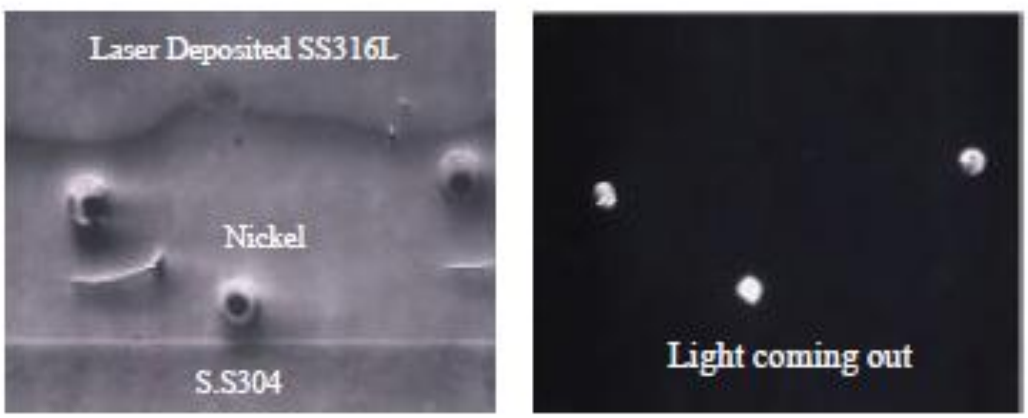

Figure 4: Embedded fiber optic sensors [16]

Figure 4 shows the embedding of optical sensors into metal matrices. They were used to accurately measure temperature and strain values measured on their parent components.

2.1.3. Ultrasonic Consolidation (UC):

Ultrasonic consolidation is a more recent addition to the additive manufacturing list. It creates metallurgical bonds between its layers through the use of ultrasonic energy to weld thin sheets of metal onto the preceding material. It is coupled to a CNC mill that removes and shapes excess material as and when necessary. This leads to the production of highly dense parts that can be made of metal. Siggard et al. [[19]] have successfully demonstrated the use of UC to embed sensors into dense metallic parts.

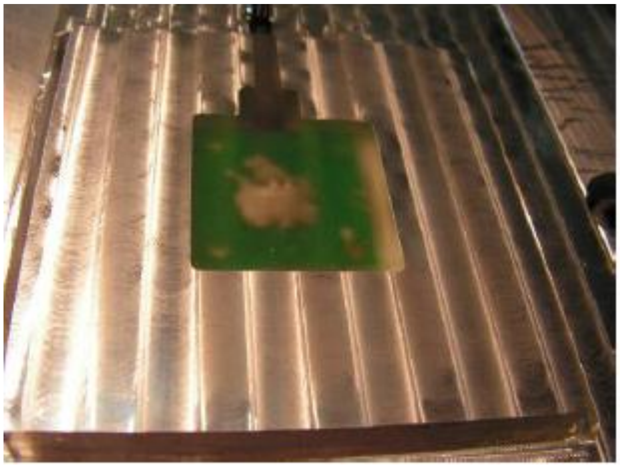

Figure 5: Sensor embedded using alumina filled potting epoxy [19]

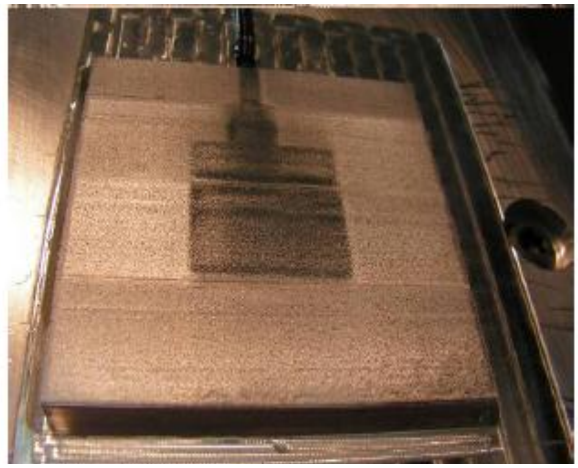

Figure 6: Ultrasonic consolidation of aluminum onto embedded sensor [19]

They use alumina filled potting epoxy to embed sensors into pre-milled slots in metallic parts as shown in Figure 5. Any excess material is milled off to produce a flat surface onto which thin sheets of metal are ultrasonically welded as shown in Figure 6. Room temperature and high temperature 300^{o}F embedding was studied with the high temperature embedding exhibiting favorable results without any loss in the sensor's performance characteristics.

2.2.Direct manufacture of assembled actuated mechanisms

Conventional manufacturing processes are incapable of creating linkages, making additive manufacturing an important tool in the quick creation of mechatronics assemblies that can be actuated.

2.2.1. PolyJet 3D Printing

Unlike conventional manufacturing processes, some additive manufacturing processes provide the flexibility to use multiple materials for part generation using the same process during a single run. One such process is the PolyJet 3D Printing process that contains multiple jets, each depositing different materials, to generate integrated assemblies featuring stiff components and flexible joints and gaskets. Researchers at Virginia Polytechnic Institute and State University have taken this a step further to include fibers to the existing process to create jointed and actuated mechanisms [20].

Figure 7: Actuated finger created using Objet PolyJet 3D Printing Machine [20]

The build process is halted to include the fibers and then continued to create an assembly of a finger that has both rigidity and dexterity without the need to change processes. The fibers are placed into pre-designed channels and the build process resumes creating an assembly capable of actuation as shown in Figure 7.

2.2.2. Stereo Lithography (SL)

Stereo Lithography is the process of curing photo-curable polymers contained in vats in a layer by layer manner to form 3D shapes. Significant research has been conducted into SL for its use to embed sensors and actuators. In this case, inert inserts are placed into the vat of photo-polymer before or during the build of the 3D part [21]. These inserts are later removed to be replaced by the sensors or actuators that were pre-determined to be placed. Work conducted by Tse et al. indicates its application includes micro-sensor packaging [22]. De Laurentis et al. created complex working mechanisms in a single run SL process without the need for external assembly. Experimentally determined clearance values, and support structure generation, were used to make mechanical assemblies. Figure 8 and Figure 9 show the results they produced.

Figure 8: Universal joint built using SL [23]

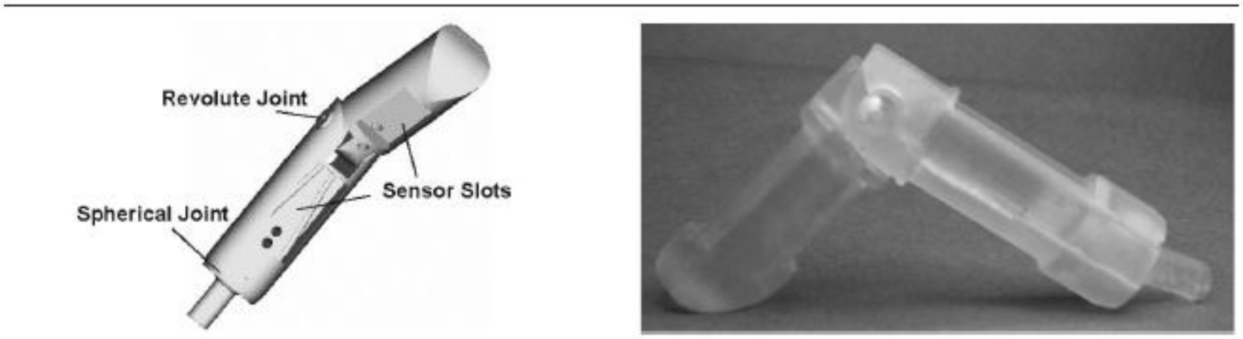

Figure 9: Robotic thumb built using SL [23]

2.3. Manufacture of micro sensors and actuators

The need of the hour is the manufacture of sensors that do not adversely affect the functioning of the entity that they are mounted on. If the act of sensing affects the applicability and basic functions of the part, it is detrimental to the system the part is used on and increases cost. Therefore the need to manufacture sensors that are small enough to be included in the component is great. Additive manufacturing plays a vital role in enabling the direct manufacture of micro–sensors and micro–actuators. Micro-Stereo lithography (MSL) is an additive manufacturing process that enables the fabrication of sensors of small size.

2.3.1. Micro–StereoLithography (MSL):

Research conducted by Leigh et al. has highlighted the use of MSL in the fabrication of flow sensors of small dimensions. Since resins used in MSL are required to provide more functionality than regular structural strength they have used an MSL resin, embedded with magnetite (Fe_3O_4) nanoparticles, to fabricate a flow sensor device. The device fabricated is shown in Figure 10.

Figure 10: Flow sensor device fabricated using MSL [24]

The advantages of MSL include small size and easy dimensional and functional adaptability to suit situational needs. The electronics for the device are not altered in the case of a redesign and hence the costs incurred during redesign are minimal. Additive manufacturing techniques like MSL enable the rapid and cost effective manufacture of such small devices even on a small scale. Research conducted in South Korea [25] furthers the use of MSL in the manufacture of microscopic bellow and micro–grippers. These micro-actuators can be used in various applications including biotechnology, biochemistry, and micro-sensing. Figure 11 shows microscopic images of the bellows manufactured using the MSL process.

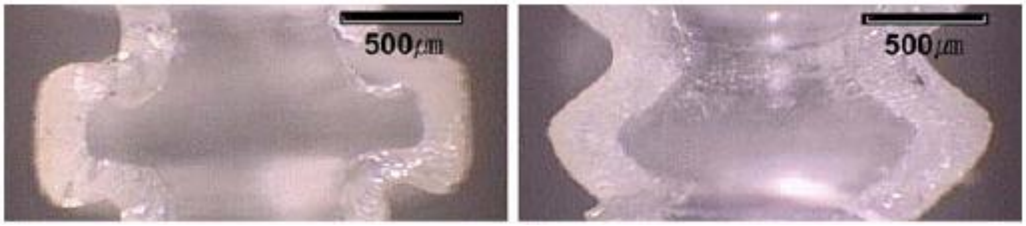

Figure 11: Microscope images of micro bellows developed using MSL [25]

To further test this capability they manufactured two–grip micro-grippers shown in Figure 12, and three–grip micro-grippers shown in Figure 13. The micro-grippers were successfully tested to show their bendability.

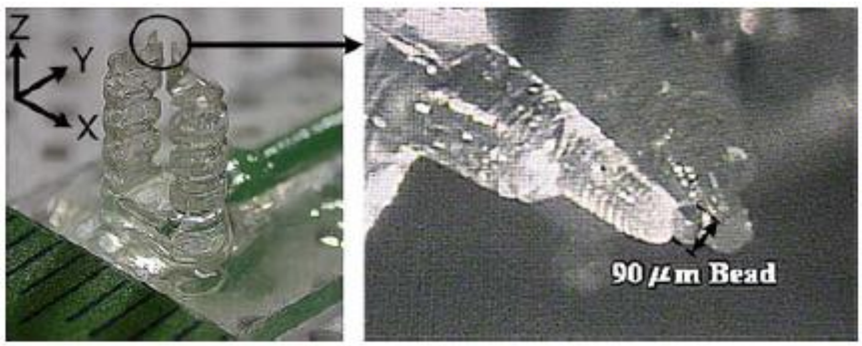

Figure 12: Fabrication and testing of two-grip micro-gripper [25]

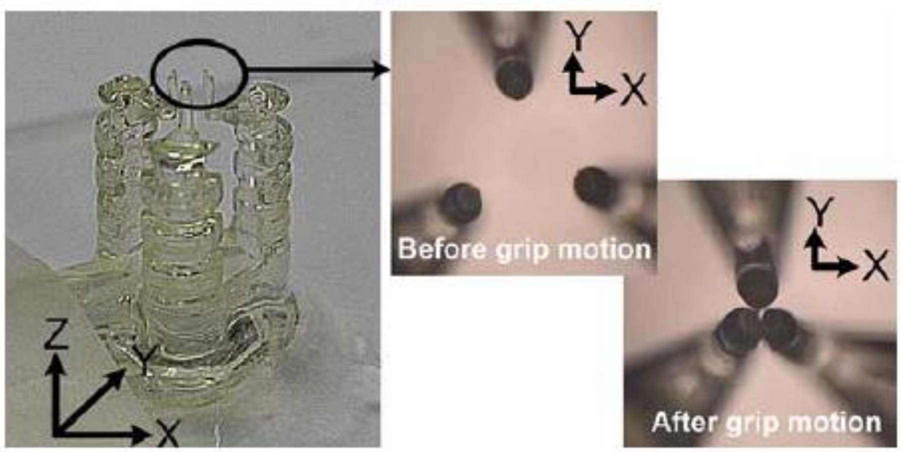

Figure 13: Fabrication and testing of three-grip micro-gripper [25]

2.4.Printed circuits/Embedded Passive Component's (EPC)

In recent times it has been widely acknowledged that the use of EPC's in electronics produces a 30% reduction in space requirements, better signal integrity and significant cost savings over discrete surface mount devices. For the manufacture of EPC's, use of additive manufacturing provides much higher flexibility with respect to material composition and layer thickness as compared to traditional manufacturing processes [26]. Inkjet printing is thought of to be a promising additive manufacturing technology in this regard.

2.4.1. Inkjet printing

Irrespective of the manufacturing process involved, tolerances of embedded resistors after manufacturing exceed 15%, bringing into the equation post process laser trimming which, in turn, increases costs. Embedded sensors based on polyimide were developed by Dupont as ink material. With the use of ink jet printing the tolerance variation of the embedded sensors was expected to be reduced to 1%, thereby eliminating the need for laser trimming. This research was further corroborated by work done at Nokia [27]. In comparison to etching and thin-film technologies, ink jet printing offers the added advantage of using multiple materials on different print heads during the same cycle reducing the number of processes required during the printing of EPC's. The authors, while acknowledging the advantages of using inkjet printing, have used six sigma methodologies to further improve the process and making it more attractive for commercialization.

2.5.In vivo surgery

2.5.1. Bio Laser Printing (BioLP)

Computer Assisted Medical Intervention (CAMI) is the process of providing tools and data to the clinician to aid in the performance of diagnostic and therapeutic actions like surgery and local injection of drugs in an accurate and safe manner. Once perfected, this system will be a major advancement in the field of medicine and will lead to increased use of robots and automation in surgery. As proof of concept, researchers in France [28]have successfully performed the first in vivo bio-printing in mice. BioLP as an additive manufacturing process was chosen to aid in bone repair. BioLP, like other additive manufacturing processes, has rapid production rates and the ability to easily customize based on immediate need. Figure 14 shows the equipment and setup for in vivo bio printing.

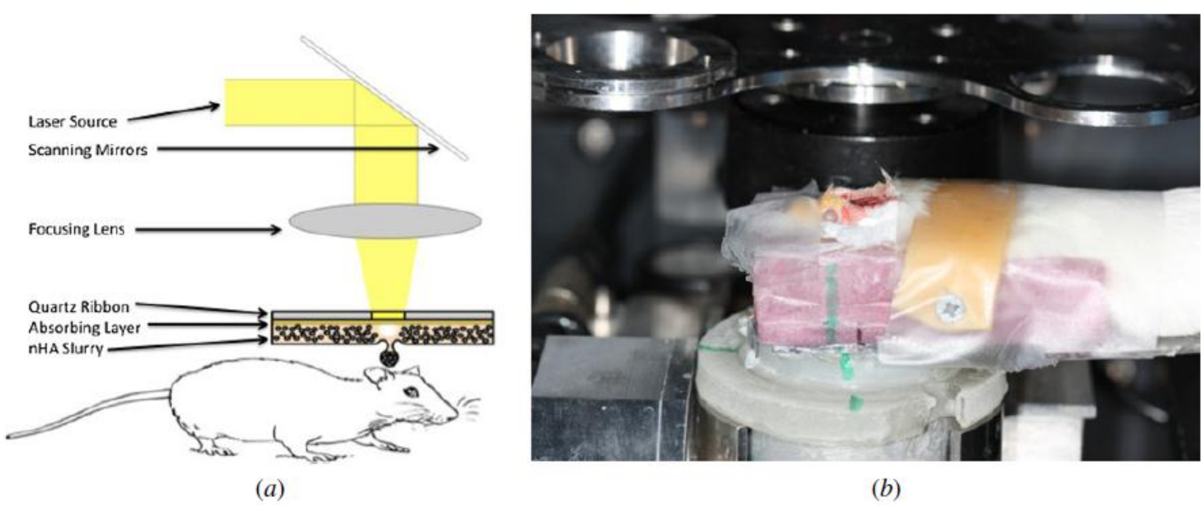

Figure 14: a) Schematic of setup for in vivo laser printing b) Specific holder for in vivo printing in mouse calvaria defects [28]

The researchers successfully completed the surgery and post process MRI scans revealed good tissue regeneration and lack of any necrosis. Although the application was only in bone surgery, the success achieved is significant in the implementation of CAMI.

2.6.Organ printing and labeling

One of the major challenges in today's world of medicine is human casualty associated with organ failure. The reasons for this are innumerous including lack of organs available for transplant, time constraints involved in organ processing, incompatibility between donor and patient, etc. The advent of additive manufacturing has led to its widespread use in medicine, especially in the areas of organ printing [[29], [30]]. But a system to accurately monitor the condition of the organs and ensure their timely and safe usage is as yet unavailable. Researchers at the University of Nebraska–Lincoln have proposed the use of RFID tags embedded in the organs to monitor their vital signs and guard against tissue necrosis [31]. Additive manufacturing systems are currently available in the market for bio-printing and for Radio Frequency Identification (RFID) printing. It is theorized that a hybrid system could be designed and built that could perform both the task of printing the organ and also non-invasively printing the RFID tag.

2.7.Ultrasound transducers

Transducers are components that convert electrical energy into ultrasound and vice versa. They are used widely in ultrasound imaging devices but are, as yet, difficult to manufacture, owing to the intricate nature of the design and the ceramic materials used in construction. Additive manufacturing in the form of digital micro printing provides an easier solution to the manufacture of transducers. Researchers at General Electric [[32], [33]] have successfully created transducer components out of additive manufacturing and are working towards improving the process to make it even more cost effective.

3. Conclusion

This paper is aimed at bringing to light the use of additive manufacturing in enabling cyber enabled manufacturing. Various additive manufacturing processes were investigated and their applications in the fields of sensor embedding, micro-sensor manufacturing, transducer manufacturing, actuator and assembly manufacturing, micro-actuator manufacturing and computer assisted medical intervention were studied. It is found that additive manufacturing, owing to its advantages of low manufacture time, easy customizability, material flexibility, and greater tolerance of part design complexity, is a viable option for use in cyber physical systems to bring about cyber enabled manufacturing.

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