Direct Digital Manufacturing (DDM) workflow for Printed Circuit Structures (PCS)

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Award winning 3D fabrication tools and solutions for next generation Smart Manufacturing with a wide range of materials

Electronic packaging
Life Science
3D Printing
Textiles

Vision: is to drive the next industrial revolution using direct digital manufacturing technology that will eliminate the need for retooling and one day lead to mass innovation by democratizing the Smart Manufacturing of complete products in multiple industries, ranging from fully functioning electronic devices to biological products.

No retooling
Precision
Proven
Fully smart
Minimal labor
Production speeds
Industrially hardened

will make mass, complicated manufacturing, personalized and simple
1st to print conformal antennas
1st to print 900MHz transmitter
1st to commercialize a bioprinter
1st to put linear motors on a 3D printer for superior prints
1st to print multi-layer, multi-material electrically functional structures
1st to combine 3D printing and printed electronics
1st to commercialize Z tracking for conformal printing
1st to use a paste to print metal 3D structures
1st to print a Phased Array Antenna
1st to add precision milling and pick and place on a single platform
1st and ONLY to print on a living ant
20 years of first
1st Bio Printer in ISS
Technology and Products

- Precision Microdispensing => SmartPump™
- Direct Digital Manufacturing => Multi-material printing, pick and place, and micro-milling

- 3Dn Series
- 3Dn-DDM Series
- BAT Series
- SVA Series
Automated Innovation = Digital to Physical

**Industrial Revolution**

1\textsuperscript{st} Mechanization, Waterpower, Steam Power

2\textsuperscript{nd} Mass Production, Assembly Line, Electricity

3\textsuperscript{rd} Computer and Automation

4\textsuperscript{th}

The age of purely mechanical industrialization is over. Welcome to the new data-driven electro-mechanical age.

“Welcome to the Cyber-Industrial Revolution”

* Digital Twin Engine

https://semiengineering.com/the-cyber-industrial-revolution/
The recent emergence of DDM in circuit technology has opened the third dimension and this is expected to be the next biggest evolution in circuit technology. This evolution will be two-fold.

First, circuits can be made truly three-dimensional (3D) and volumetric, not just a stack of planar circuits that is highly limited in how the vertical direction can be utilized.

Second, circuits can be designed into diverse shapes that integrate into higher level systems more conveniently and efficiently.

Such circuits can no longer be considered “boards” and are better called printed circuit structures (PCS) to include non-planar and volumetric topologies

The primary advantage of PCS is more functions per unit volume
DDM Workflow => 3D Manufacturing

- Thermoplastic print => Composites
- Laser process => Localized curing/sintering
- Print adhesive dots => time/thermal cure
- Pick and Place => Actives an/or passives
- Micro-dispense print => Conductive traces
- Micro-dispense print => Dielectric bridges
- Laser process => Localized curing/sintering
- UV => Curing
- Micro-dispense print => Conductive traces
- Thermoplastic print => Composites

This can be done today using a multi-head system. This is still a 2.5D approach.

Next generation is 2.5D Conformal

Next next generation is true 3D.
Siemens –nScrypt Relationship – Path for 3D Printed Electronics

Our portfolio of products for the design and development of electronic systems and integrated circuits (IC). Solutions include Electrical & Wire Harness Design and Electronic Systems Design as well as IC Design, Verification, Test and Manufacturing.
Optimized Tool Chain for 3D Printed Electro-Mechanical Structures

Goal: Optimized digital thread through design/verification & manufacturing

- Electro-mechanical co-design
- Multi-physics analysis of structure
- Design for additive manufacturing

- New machines & processes to integrate
- Tool-pathing algorithms for fabrication

Why:
Functional Integration & Functional Augmentation

SIEMENS
Siemens Software Solutions for Printed Electronics

Infill

Shifting

Xpedition
HyperLynx
Simcenter
Valor

High speed turning
3D/4D Printable Materials/Electronics on Large conformal surfaces

Direct Digital Manufacturing (DDM)

nFD – Filament Deposition
nMill – High-Speed Mill
nPnP – Pick & Place
nSP – Smart Pump

Compatible with Multiple Materials
Solder Paste, Conductive Ink, LTCC, Alumina, Superalloys/braze...
Line Widths as Small as 20µm

Page 8 Unrestricted © Siemens 2021.
Bluetooth – Flat Layout & Schematic

Workflow

Layout & Gerber
Workflow – Sciperio 3D Printed Electronics Demonstrator

TI CC2640R2F (4mm x 4mm 32pin VQFN) SoC Bluetooth Microcontroller (http://www.ti.com/product/CC2640R2F)

Sensor Suite:
• Acoustic
• Optical (light/no light)
• Gyroscope
• Magnetometer
• Accelerometer

I2C Based Sensor interface protocol
*Printed Circuit Structures
**Printed Circuit Cylinders

PCB
*PCS
Planar
Printed Antenna

Non - Planar
**PCC
DDM of Printed Circuit Structures (PCS)

Substrates & Pkgs

Interconnect & Vias

Components

Pre & Post Processing

Metrology

High Performance Materials

Micro-dispensing

Pick and Place

Milling/Lasers/photonic/Oven/magnetic

In Situ Measurement

AM 40MM Test Round
Siemens Accelerometer Circuit: Digital to Physical

Schematic and Layout

CAD Model

Printed Circuit Structure
Collaborative Case Studies - Siemens

NFC Circuits for Machine Qualification and Training

- Low-complexity
- Embedded NFC, links phone to website
- Printed inductor
- Multilayer
- Buried components

Flex Circuit Demonstrator

- Flexible Kapton substrate
- Flexible DuPont Conductive
- Integrated battery
- Simple LED circuit
Potential Multi-Material, Multifunction Solution \Rightarrow 3D Printing

Direct Digital Manufacturing (DDM)

3D Printing \Rightarrow It’s a lot about 3D printing, but not all
Integration Challenges

- Specifications of a device or a product establishes the material property requirements
- Material properties are more than just structural
  - Thermal conductivity
  - Electrical conductivity
  - Permeability
  - Permittivity
- Multi-material is a must => unless you’re making baby Yoda
- Nano ↔ Micro ↔ Macro scales matter and influence
- Contamination is an issue => clean matters
- Compatibility is an issue => some materials just don’t like each other
- Bulk properties do not equate to printed properties => don’t be fooled
- Sensor feedback during prints
- Sensor feedback during processing
- Real time in situ adjustments

Is it smart to put 3D Printing in Smart Manufacturing?

Is it smart to put Smart Manufacturing in 3D Printing?

Feedback
- Line scan using 100 sensors at 50 mm/s
- Millions of points analyzed
- Real time in situ adjustments...next

Printed Dogbone with defects

Layer by layer quantitative data
In-Situ Process Metrology

- Collect data per layer
- Isolate new layer data
- Compare data against model data
- Detect any errors
- Repair errors that can be corrected
Laser Line Scanning

- Real time kernel motion controller
- Runtime algorithm conducts scanning and defect detection

- Line laser based
  - Hardware synchronized laser scanning
  - 164 Mbps collection rate
Layer Analysis & Point Cloud Inspection

1 Layer
Inspection Area: 25mm x 65mm
Inspection Resolution: 20µm
Inspection Time: 48.7s
Points Collected: 4,076,491

<table>
<thead>
<tr>
<th>Layer Number</th>
<th>Expected Volume</th>
<th>Missing Volume</th>
<th>Missing %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer #2</td>
<td>108.518 mm³</td>
<td>7.196 mm³</td>
<td>6.6 %</td>
</tr>
<tr>
<td>Layer #3</td>
<td>108.518 mm³</td>
<td>7.152 mm³</td>
<td>6.6 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer</th>
<th>Expected Missing Volume</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer #2</td>
<td>7.55 mm³</td>
<td>4.69 %</td>
</tr>
<tr>
<td>Layer #3</td>
<td>7.55 mm³</td>
<td>5.27 %</td>
</tr>
</tbody>
</table>
- Any under extruded area within repair tolerance(pit/void) is reprinted using segments of the original printed paths, guaranteeing that the repair corresponds to the model.
- Scan data determines the areas to repair.

- If the scan determines an area out of tolerance (specified by the user), the tool will initiate the respective repair.

- Repairing over extrusions

- Milling the bounds of the print layer

- Milling the entire surface as required
Correction Repair

Defect layer before repair

Defect layer after repair

Defects
Applications

Process Gizmos – End Effectors

Many Feedstock formats

- Inks, Pastes, Elastomers
- Thermoplastics
  - Filament
  - Pellets
- Thermosets
  - Conductive
  - Dielectric
- Metals and Ceramics
- Energetics
- Electronic Components
  - SMT
  - Packaged
  - Bare Die

Process Precision Control Materials
Printing Circuits

Phased Array Antenna

WiFi Sensor Devices

Timing Circuits

Embedded micro-controller

Non Planar Devices

RF Dish

Sciperio Experience Printing Many Electronic Devices
Novacentrix HPS-FG57B silver ink (conductivity similar to CB028) MMIC phase shifter QFN package is embedded into support & cavity substrates

Printed Circuit Structure (PCS)

Printed from bottom to top

- 0.2 mm 100% ABS
- 3 mm 50% ABS
- Ground
- 0.25 mm 100% ABS, feed sub.
- 1.25 mm 100% ABS, cavity
- 0.5 mm 100% ABS, support sub.

Phase Shifter Ground Connection

Unit cell footprint fits in $15 \times 15 \text{ mm}^2$

2x2 Unit Cell in the same form factor
Applications

Structural RF electronics - PAA

- World’s first 3D Printed Phased Array Antenna
- 4 Elements
- Estimated 10x cost reduction

- Printed Quadcopter
- Integrated payload and quadcopter

Air Force Flight Demonstration
Bioprinter configuration:
- biologics
- non-biologics

Forward-deployed prints:
- scalpel handle and hemostat
- bioactive bandages (hydrogel layer with antibiotics over a flexible structural layer)
- T9 vertebrae surgical model
- bioprinted meniscus (mesenchymal stem/stromal cells and a hydrogel scaffold)
NASA ScienceCasts: Cutting-edge Biomanufacturing Aboard the International S...
Direct Digital Manufacturing

Factory in a Tool (FiT) will provide a forward deployed capability for printing electronics and tissue engineered products for the warfighter.

Factory in a boX (FiX) for Austere Deployment

Modular Mobile Direct Digital (M2D2) Manufacturing Systems
Industry 4.0 - Smart Manufacturing

ISS MAY 2019

Brick and Mortar Manufacturing

Cyber Network

In Space Manufacturing

Modular Manufacturing
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Abstract Title: Direct Digital Manufacturing (DDM) workflow for Printed Circuit Structures (PCS)

Digitally based manufacturing has been around for years and has been the basis of turnkey lights out manufacturing processes and systems. Moving forward is the concept of Direct Digital Manufacturing (DDM) which brings together conceptualizing the electronic device, developing a digital twin of the product, and digitally merging workflow with the manufacturing process. This would further extend through to physical product. This paper will illustrate DDM is the basis of developing the capability of conceptualizing, designing, and digitally manufacturing electronic devices and more specifically printed circuit structures or PCS and printed circuit cylinders, PCC. Unlike tradition PCB’s or multichip module technology, the goal is fully printed electronic devices that can merge structure with electronic functionality. This paper will explore the current state of practice in manufacturing workflow and extend to the emerging factory in a Box concept of multi-material printing of next generation electronic controller and packaging technology. This will also include exploring design tools that provide the capability of codesign mechanical function with electronic function and modeling the manufacturing process and electronic device using digital twin concepts and workflow enabling smart manufacturing of printed electronic devices and precision of DDM technology.