The Sapienza approach to Additive Manufacturing. An ongoing multidisciplinary experience.

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*Dipartimento di Ingegneria Meccanica e Aerospaziale (DIMA)*

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Additive Manufacturing: a brief introduction

The Sapienza approach to Additive Manufacturing

Five projects conducted in 2018 or ongoing
“Additive on Earth, on orbit, on planet.
Space is the ideal environment to allow the scalability of a specific technology.
Because Space is a difficult environment where it is necessary to construct very complex multifunctional components that withstand very high temperatures, high mechanical strength, very low weight and with a very short supply chain.
In a few years we will print also human organs when on planet will be essential to face any emergency”. Tommaso Ghidini ESA ESTEC

"In the next decades, Additive Manufacturing will be the key enabling technology of new space missions, bringing humans on Moon and on Mars. But to this in necessary we must educate the future engineers to Additive-think, where Design for Manufacturing is replaced by Design for Performance (as Nature does). Then we can get the best from this disruptive technology."
No more a hype!

Innovative 4.0 Technologies

AM Technologies

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Additive Manufacturing (AM) summarizes manufacturing technologies which allows to create three-dimensional objects from a 3D geometry file by successively adding material.

In comparison to conventional manufacturing technologies (e.g. machining), where material is removed from a solid block in order to shape the part («subtractive manufacturing»).
From a 3D CAD model...

- Application of powder
- Exposure by Laser
- Lowering of platform
- Re-application of powder
- Exposure by Laser

... to complete parts

Works for plastics and metals
AM: a part of a bigger picture

- **PRODUCT INNOVATION**
  - Lightweight
  - Complex shapes
  - Multifunctionality
  - Performance
  - FGM (Functionally Graded Materials)

- **PROCESS INNOVATION**
  - time-to-market decrease
  - waste reduction
  - increase fly-to-buy ratio
  - increased flexible logistics
  - optimized supply chain
  - cost effective production of small lots

- **BUSINESS MANAGEMENT INNOVATION**
  - Industry 4.0, Logistics 4.0, Space 4.0
  - Open Innovation
  - NewSpace paradigm
Design for Additive Manufacturing (DFAM) is a design methodology enabling to consider AM-related aspects in the design phase.

It plays the same role of Design for Manufacturing (DFM) with respect to conventional manufacturing. Moreover, DFAM is an environment fostering the creation of designs taking advantage of the unique AM capabilities.

- Shape complexity
- Material nano, micro and meso structures
- Integration of several functions
- Spatial gradient of material properties

Main DFAM drivers:

☑ The AM is not only a process (systematic and systemic view is needed)

☑ The post-processing must be taken into account into design

☑ One material per machine (consistency of mechanical tests)

☑ If possible imitate the nature (biomimetic structures) → from DFAM to Design to Performance DFP
The Sapienza (DIMA) approach to Additive Manufacturing

1. Application driven
2. Multi-disciplinary
3. Oriented by system view, and to
4. life cycle (DFAM-DFP, MAIT, LOGISTICS)
Multidisciplinary Sapienza teams involved

Dept. of Mechanical and Aerospace Eng.  Dept. of Physics (Prof. Silvia Masi)

- **Aerospace Structures**
  - Prof. Paolo Gaudenzi
  - Prof. Luca Lampani
  - Dr. Marco Eugeni
  - Ing. Valerio Cardini
  - Ing. Luciano Pollice

- **Machine Design**
  - Prof. Francesca Campana
  - Ing. Michele Bici

- **Mechanical Technology**
  - Prof. Francesco Veniali
  - Prof. Alberto Boschietto
  - Dr. Luana Bottini

Dept. of Chemical Eng. and Materials  Dept. of Structural and Civil Eng. (Prof. Achille Paolone)

- **Science and Technology of Materials**
  - Prof. Teodoro Valente
  - Prof. Marco Valente
  - Prof. Jacopo Tirillò
  - Prof. Fabrizio Sarasini

Dept. General and Specialistic Surgery (Prof. F. Venuta)

Dept. of Planning, Design and Technology of Architecture (Prof. S. Lucibello)
Additive Manufacturing facilities of Sapienza

- On-demand laboratory (main campus)
- EOSINT M290
- Post-processing facility
- Metal and plastic additive manufacturing facilities
Five projects conducted in 2018
Main research areas covered

- **Design for Additive Manufacturing**
  - Re-design of a CubeSat

- **Multifunctional components realized by FDM**
  - Components with Embedded Electronic realized in AM

- **SE/CE tools for Design for Additive Manufacturing applied to Space systems**
  - Thermal control integrated into a structural components (a collaboration with RUAG Space)

- **Additive Manufacturing for logistics**
  - Realization of a secondary components by a direct geometrical acquisition (a collaboration with CSV of Italian Air Force)

- **Collaboration with Dept. of Physics**
  - 90GHz horns and tiltometer
1. Re-design of a CubeSat primary structure
NewSpace defines an emerging global industry of private companies and entrepreneurs who primarily target commercial customers, backed by risk capital seeking a return and profit from innovative products or services developed in or for space.

MORE FLEXIBILITY & RISK TOLERANCES FOR THE INTRODUCTION OF INNOVATIONS

NewSpace main featuring trends:

- Commercial customers
- Very large constellations of *small satellites*

The AM manufacturing of the structural sub-system of a NanoSat is considered...
Design for Manufacturing, Assembly, Integration (DFMAI)

*Designer should tailor their design to:

ELIMINATE manufacturing difficulties.

REDUCTION of cost of:
- Manufacturing
- Assembly
- Logistics

*according to: *Additive Manufacturing Technologies. 3D Printing, Rapid Prototyping and Direct Digital Manufacturing. Second edition* by Ian Gibson, David Rosen and Brent Stucker. Springer
CubeSat structure by EnduroSat. It is hard to envision a better mass distribution once mechanical interface requirements are taken into account.
Design path

DFAM for the reduction of the number of parts of a CubeSat 1U Structure

Fused Deposition Modelling Low-Fidelity Mock-ups to study form and function design strategies

Technology understanding for a functional prototype with metallic powder AM

Production of a Proof-of-Concept Mock-up in ALSi10Mg using DMLS
In order to move towards a Functional Prototype a change of material is necessary. Therefore a change of Manufacturing Technology and Design Approach is required.

**Low Fidelity Mock-Ups lessons learned**

**DMLS technology requirements**

**DFAM of Proof-of-Concept**

**Top level considerations:**
- Hinge design for DMLS
- Snap-Fit interlocking design for DMLS

**Second level considerations**
- Geometry design for DMLS
**Aim:** Development of a manufacturability map for non-assembly joints taking into account the clearance, the joint shape and the building orientation

**Problems:**
- Choice of the clearance
- Choice of the building orientation taking into account also the presence of support structures in non accessible zones
- Support structures removal
- Impossibility to perform finishing operation in non accessible zones to guarantee the functionality
- Measurement of the joint performance
Direct fabrication by SLM of non-assembly mechanisms

Fig. 2. Scheme of the clearance.

\[ \begin{align*}
M_1: & \quad \begin{cases}
    x(u, v) = \rho_1 \cdot \cos u \\
    y(u, v) = \rho_1 \cdot \sin u
  \end{cases} \quad u \in [0, 2\pi]; \quad v \in [0, H] \\
M_2: & \quad \begin{cases}
    x(u, v) = \rho_2 \cdot \cos u \\
    y(u, v) = \rho_2 \cdot \sin u
  \end{cases} \quad u \in [0, 2\pi]; \quad v \in [-H, 0] \\
C_1: & \quad \begin{cases}
    x = (\rho_1 + \chi) \cdot \cos u \\
    y = (\rho_1 + \chi) \cdot \sin u
  \end{cases} \quad u \in [0, 2\pi]; \quad v \in [0, H] \\
C_2: & \quad \begin{cases}
    x = (\rho_2 + \chi) \cdot \cos u \\
    y = (\rho_2 + \chi) \cdot \sin u
  \end{cases} \quad u \in [0, 2\pi]; \quad v \in [-H, 0]
\end{align*} \]
Direct fabrication by SLM of non-assembley mechanisms

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Fig. 17. Schematics of the joint sections for vertical (a) and inclined (b) fabrication. Polar plot of the clearance in mm for vertical (c) and inclined (d) fabrication of specimens with $\Phi = 30^\circ$ and $\chi = 0.05$ mm; section of the critical zone at different pin rotations (e).
Selective Laser Melting of non-assembled Hold Down mechanisms

6 parts  2 parts  1 part

Closure guides detail  Snap-fit detail

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Improving part quality of Selective Laser Melted parts

Surface modeling

Secondary finishing

New Strategies

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Remarks and Future Developments

- A CubeSat 1U structural subsystem has been studied and redesigned under a DFMAI approach and within a DFAM framework focusing on the consolidation of number of parts.

- Different structural configurations have been realized and Low-Fidelity plastic Mock-ups using Fused Deposition Modelling realized. It is to underline how having rapidly low-cost replicas, although low-fidelity ones, is invaluable.

- The possibility to realize a metallic proof-of-concept mock-up has been considered.

- The selected design successfully led to the manufacture of a single piece, metallic 1U CubeSat structure subsystem equipped with a hinge and snap fit mechanism.

As for future developments:

- Re-thinking of the entire design in order to reduce manufacture problems
- Geometry and surface accuracy evaluation and analysis in order to make it compliant with CubeSat standard.
- Consideration of off-the-shelf CubeSat components mechanical interfaces currently available in the market
2. Multifunctional components with embedded electronics realized by FDM
The possibility to **build smart (multifunctional & composite) components with embedded electronics using single extruder Fused Filament Fabrication (FFF) additive technology** is studied.

Open desktop technology: **total control over the process** (digital model and manufacturing process).

A methodology for production of **smart components with a low cost commercial technology and materials** is the main outcome.
Smart Components Realization in a AM framework

- Complexity of the component not related to its manufacturing cost
- Strong reduction of parts number for every realized component
- Possibility to delocalized manufacturing: long-term space-missions

Realizing Smart Components by means of AM technologies would drastically enlarge the horizons of applications of such elements

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The Additive Manufacturing Process

Pre-processing

**CAD modelling**
- Overall model design
- Parts subdivision design
  - Parts are manifold: No → No Assembly match → STL export → Yes
  - Parts are manifold: Yes → Parts assembly design

**CAM intervention**
- Print parameters selection
- Parts orientation and placement
  - Printing feasible: No
  - Printing feasible: Yes → Support structures management → Gcode export

Manufacturing

**Printing**
- Printer preparation
  - Printer ready: No
  - Printer ready: Yes → Gcode execution

Post-processing

**Operator intervention on printer**
- Resume printing / if printing stops
- Verify construction
- Parts removal from printer
  - Printing finished: No
  - Printing finished: Yes

**Operator intervention off printer**
- Support structures removal
- Surface treatment
  - Surface treatment: Yes
  - Surface treatment: No → Assembly test
  - Assembly test: No
  - Assembly test: Yes → Product final assembly
The Additive Manufacturing Process

Pre-processing

CAD modelling
- Overall model design
- Parts subdivision design
  - Parts are manifold: Yes → STL export
  - Parts are manifold: No → Parts assembly design
- No Assembly match → No
- Yes Assembly match → Parts orientation and placement

CAM intervention
- Print parameters selection
- Parts orientation and placement
  - Printing feasible: Yes → Support structures management
  - Printing feasible: No → Gcode export

Manufacturing

Printing
- Printer preparation
  - Printer ready: Yes → Gcode execution
  - Printer ready: No → No

Post-processing

Operator intervention on printer
- Resume printing / if printing stops
  - Printing finished: No
  - Printing finished: Yes → Verify construction → Parts removal from printer

Operator intervention off printer
- Support structures removal
  - Surface treatment: Yes → Assembly test
  - Surface treatment: No → Product final assembly
The Additive Manufacturing Process

**Inclusion of electronic components and realization of circuits**

**Pre-processing**
- **CAD modelling**
  - Overall model design
  - Parts subdivision design
  - Parts assembly design
- **CAM intervention**
  - Print parameters selection
  - Parts orientation and placement
  - Support structures management
  - Gcode export

**Manufacturing**
- **Printing**
  - Printer preparation
  - Printer ready
  - Gcode execution

**Post-processing**
- **Operator intervention on printer**
  - Resume printing / if printing stops
  - Verify construction
  - Parts removal from printer
- **Operator intervention off printer**
  - Support structures removal
  - Assembly test
  - Surface treatment
  - Product final assembly
The machine used is a **Sharebot42** single extruder. In the following table the basic characteristics of the machine are enlisted.

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Printing volume</td>
<td>250 mm x 220 mm x 200 mm</td>
</tr>
<tr>
<td>Maximum extrusion flow</td>
<td>24 mm³/sec</td>
</tr>
<tr>
<td>Heated printing plate max temperature</td>
<td>90°C</td>
</tr>
<tr>
<td>Minimum layer thickness</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.4 mm (interchangeable)</td>
</tr>
<tr>
<td>Compatible filaments (1.75 mm diameter)</td>
<td>PLA-S, Nylon-Carbon, Thermoplastic Polyurethane (TPU), ABS-HF, Poly</td>
</tr>
</tbody>
</table>
In order to propose a realization workflow it is necessary to:

- **Choose the conductive material** and evaluate its conductive properties
  - Evaluation of the resistance behavior with respect the geometrical properties of the circuits
  - **Evaluation of the repeatability** of the chosen value of the resistance
  - **Evaluation of the stability of the** obtained resistance with respect the time
  - Printing of demonstrators

- **Evaluate the inclusion strategies** of the electronic components (once the material is choosen)
  - Inclusion test
  - Printing of demonstrators
Experimental Campaign

Test Goals

- Printing conductive traces
- Printing of interfaces with electronics component
- Analysis of resistance behavior wrt section of traces
The inclusion of electronic components stress the key aspect in the design and manufacturing processes:

- Placement of the components
- Pausing of the AM machine

- Design of the placement of the components (CAD)
  - Creation of cavities and tracks
  - Distribution and interconnections design
  - Identification and design of thermal protection

- Pausing the printer (CAM and Manufacturing)
  - Precise layer identification
  - Components placement
  - Temperature control
  - Change of filament if single extruder
• **Layers are identified** during the slicing
• **Gcode is the edited** to define the manufacturing pausing

---

**Experimental Campaign**

```
G1 E0.20533 F5000.00000
G92 E0
G1 Z1.000 F5000.000 // CAM individuated layer for pause
G01 Z1.000 F5000.000 // Set to relative positioning
G90
G01 X0.000 M0 // Lower bed by 50 mm
G91
G01 Z-50.000 // Pause and wait for user
G90
G01 X-25.000 Y-50.000 // Set to relative positioning
G90
G92 E0
G1 X125.000 Y145.666 \* F5000.000
```

---

1. **Printing start. Raft layers**
2. **First interruption. Filament change 1**
3. **Second interruption. Filament change 2**
4. **Third interruption. Resistor Inclusion**
5. **Fourth interruption. Microcontroller, LED and photosensor inclusion**
6. **Final interruption. Printing finish**

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When the printer is paused, a manual operation is performed to place the components in the respective positions.
Proposed Fabrication Process

Fabrication timeline

- First pause - Circuitry Wiring inclusion or filament change
- Second pause - Component inclusion
- Third pause - Component thermal Protection inclusion
- Fourth pause - Filament change
- End Print

Section details

- Conductive material
  - Conventional material (copper wires)
  - Conductive filament
- Circuitry chamber layers PLA grooved
- PLA grooves
- Outer bottom layers PLA
- Electronic component to include
- Component chambers layers PLA
- Thermal seals layers PLA
- Thermal seals PLA
- Outer top layers PLA
- Sensor layers PLA based Graphene
- Graphene filament strategy
- PLA based graphene
- PLA grooved

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A new step in the Additive Manufacturing Process

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A new step in the Additive Manufacturing Process

Pre-processing

- CAD modelling
  - Overall model design
  - Overall circuit design
    - Merge designs
      - No Parts are manifold
      - Yes Parts assembly design
        - No Assembly match
        - Yes STL export

- CAM intervention
  - Print parameters selection
  - Parts orientation and placement
    - No Printing feasible
    - Yes Support structures management
      - Gcode export
      - Gcode edit
  - Z levels individuation

Manufacturing

- Printing
  - Printer preparation
    - No Printer ready
    - Yes Gcode execution

- Elements Inclusion
  - Printer automatic interruption
    - Resume printing
  - Print finished
    - No
    - Yes
      - Z level verification
        - Deposition of corresponding component

- Operator intervention on printer
  - Resume printing / if printing Stops
  - Verify construction
  - Parts removal from printer

- Operator intervention off printer
  - Support structures removal
  - Surface treatment
    - Yes Assembly test
    - No Product final assembly
The possibility to build **smart sensorised components with embedded electronics** using a low cost additive technique without the intervention of any other manufacturing machine has been studied.

A **methodology for the inclusion of electronic components in the manufacturing process** has been presented and discussed.

The presented new methodology of **design and manufacturing** allows the **production of a smart component without the need of any hardware modification to the manufacturing machine or the implementation of additional manufacturing technologies**.

The methodology enables the FDM technology to embedded circuits and sensors which **can adapt to the structures geometry**.

The obtained results pave the way for further developments in the **production of smart components with low cost commercial technology**.
3. SE/CE design for AM technologies for Space systems

A Sapienza and RUAG collaboration
Research motivations

- **AM**: a new manufacturing paradigm
- **DFAM**: an innovative design thinking
- **Advanced Systems and Concurrent Engineering**

Maximization of AM benefits in Space systems design and manufacturing → **Design to performance**

**INNOVATIVE SATELLITE ARCHITECTURES**
TRADITIONAL WORKFLOW

STARTING POINT

PRELIMINARY SCREENING

DFAM

SYSTEM

SINGLE EQUIPMENT

SINGLE EQUIPMENT IMPROVED

SYSTEM IMPROVEMENT FOR WATERFALL EFFECT
SE/CE design for AM methodologies for Space systems
A Sapienza and RUAG collaboration

PROPOSED WORKFLOW

STARTING POINT

SYSTEMS ENGINEERING + DFAM

SYSTEM

SINGLE EQUIPMENT

DFAM

SINGLE EQUIPMENT IMPROVED

DIRECT SYSTEM IMPROVEMENT AS PROJECT GOAL
SE/CE design for AM methodologies for Space systems
A Sapienza and RUAG collaboration

PROPOSED WORKFLOW

STARTING POINT

SYSTEMS ENGINEERING + DFAM

SINGLE EQUIPMENT

DIRECT SYSTEM IMPROVEMENT AS PROJECT GOAL

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**CASE-STUDY**

**MULTIFUNCTIONAL INTEGRATED S/C LATERAL PANEL**

**DESIGN APPROACH**

- **QUANTITATIVE THERMAL ANALYSIS**
- **QUANTITATIVE STRUCTURAL ANALYSIS (TOPOLOGY OPTIMIZATION)**
- **EQUIPMENT DEFINITION (TRADITIONAL HEAT PIPE)**
- **CUSTOMIZED TOPOLOGY CONFIGURATION**
- **CONVERGENCE VERSUS A HEAT PIPES CUSTOMIZED CONFIGURATION (AS COMPROMISE OF BOTH ANALYSIS, only minor compromises were necessary)**

**AM BIOMIMETIC RADIATIVE-STRUCTURAL PANEL**

- Heat pipes
- V-shape boundary connections
- Heat pipe crosssection
- Structural grooves
- Harness accommodation

**Thickness FEM (nominal)**
- $T = 100$
- $T = 144\%$

**Potential real heatpipe geometry**
- $I_{H_2}T_3 = 100\%$
- $I_{H_2}T_3 = 300\%$
- $I_{H_2}T_3 = ???\%$

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CASE-STUDY
MULTIFUNCTIONAL INTEGRATED S/C LATERAL PANEL

I PROTOTYPE
10% scaled
Full representation
Material: PLA
Technology: FFF

II PROTOTYPE
25% scaled
Full representation
Material: PLA
Technology: FFF

III PROTOTYPE
50% scaled
Cutted representation
Material: AlSi10Mg
Technology: DMLS
Through some specific test cases of industrial relevance new methods, processes and tools implementing innovative design strategies and MAIT logics & techniques for the development of new space systems characterized by enhanced performance have been proposed.

Specific technological issues aiming to reduce the traditional schedule and cost of space missions have been considered:

- integration of functions within the same equipment improving the traditional MAIT logics
- design and manufacturing logics of harnessing smart embedded sensors
- novel techniques for the connection points by using advanced manufacturing technologies and materials
- new product life-cycle design methodologies by applying and improving the actual Systems and Concurrent Engineering approaches

The systemic and systematic Systems Engineering (SE) approach has been stressed as the enabling environment for the development of the design for additive manufacturing.
4. Additive Manufacturing for logistics: a cooperation with the Italian Air Force
Research motivations

- Development of a logical workflow from the geometrical acquisition to the validation and certification
- Additive Manufacturing as a new possibility for logistics: obsolescence management and remote manufacturing
- Understanding of the limitations of the available documentation

Stand-by-compass MB-339: components objective of the study
Methodological Workflow

1. Geometrical acquisition
   - Design documentation
   - Reverse Engineering
   - Measurements

2. Digital Model
   - Prototyping (FDM)
   - Realization (SLM)

3. Numerical Modelling
   - Validation (FEM)

4. Flight Test
Selective Laser Melting fabrication of a FT-339C compass case

3D model reconstruction through Reverse Engineering

Dynamic simulation

Flight test

Customized SLM process flow

Computerized tomography for defect control
Functional flight test

- Functional verification (assembling)
- Operative functional verification
- A sensorised flight is scheduled in 2019
The role of Additive Manufacturing in a logistic chain has been explored.

The whole workflow from geometrical acquisition to production has been investigated.

All the limitations of the actual technical documentation have been stressed.

The realized components has been tested by a functional operative flight.

Further sensorised flights have been scheduled.
Collaborations with the Dept. of Physics of Sapienza
AM SLM manufacturing of a tiltometer (spring) (Prof. F. Ricci)

Fabrication of a deformable component for the measurement of damping properties

Specialized fabrication for thin wall component

Special support structures generation, novel process parameter set for improvement of surface properties

Checking and simulation
The multidisciplinary environment fosters all the research activities

Collaboration with important players in aerospace sector: RUAG Space, Italian Air Force, Italian Space Agency

All the projects are based on a system and systemic approach to the design for additive manufacturing

Sapienza has shown an important capability in design and realization of components from different applications

And an extra on bio-engineering...