Requirements for 3D Printed Applications using Novel Nanoparticle Enhanced Digital Materials

3D printed robotic and electronic applications

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***Abstract*— The DIMAP idea focuses on the development of innovative applications using additive manufacturing technologies. This paper describes the requirements for a 3D printed robotic arm and a luminaire application. In addition, the advances on novel ink materials for 3D multi-material printing by PolyJet technology are reported as well as advances on the printing equipment. The approach is application-driven and the first results of the project show advances in additive manufacturing technologies.**

Keywords: Digital Material, 3D Printing, Robotic, Electronic, Nanoparticule

I. INTRODUCTION ON DIMAP CONCEPT

The DIMAP (novel nanoparticle enhanced DIgital MAterials for 3D Printing) [1] project intends to implement an idea born among various industrial and research centres across Europe. DIMAP aims to develop applications not only limited to rapid prototyping but that address production processes. Two applications of high interest are being developed to demonstrate the printing feasibility of functional inks. The first application is a bio-inspired robotic arm developed by Festo [2] and Cirp [3], the second is a shape changing luminaire developed by Philips [4]. The challenges created by applications, materials and printing processes requirement interdependencies are numerous and complex. Namely, the development of novel ink systems with incorporated nanoparticles is especially challenging. In order to cope with these new material classes, the existing PolyJet technology is further developed and therefore improved.

The overall objective of the project is to enhance digital materials with novel nanoparticles for 3D Printing in order to increase design possibilities. Indeed, developing robots poses particular challenges in terms of design [5]. DIMAP proposes to learn from nature to create bio-inspired robotic joints and it appears that the additive manufacturing (AM) provides a suitable basis to mimic this approach [6]. As well, additive manufacturing enables a high-customized production. It has been demonstrated that customers perceive customized luminaires as high value products compare to standard products [7,8]. In order to develop those innovative added-value products, four different inks are investigated: electrically conductive inks, ceramic inks, high strength polymeric inks and lightweight polymeric inks. In parallel to the ink and process developments, safe by design and work place safety approaches are conducted in order to minimize the risk due to nanoparticles use. The

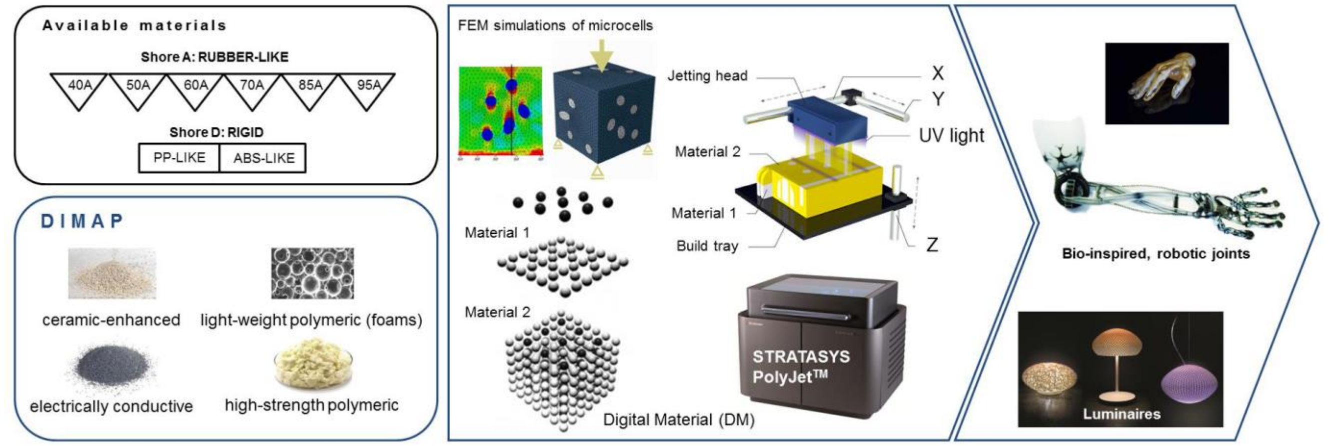

Figure 1. Concept for novel nanoparticle enhanced Digital Materials for 3D Printing and their application shown for the robotic and electronic industry

whole can be differentiated into 8 objectives [1,9]. Those objectives (four novel digital material developments, novel multi-material 3D printer, safe by design approach and two innovative demonstrators) are summarized in Figure 1. Within this paper, the requirements elaborated during the starting phase of the project and the challenges in material development are presented. The paper is structured as follows: In Section II, the designs and the concepts of the 3D printed robotic arm and luminaire are described. In Section III, the faced hurdles and the envisaged solutions are discussed. Section IV concludes the paper.

II. DESIGN SPECIFICATION AND MATERIAL REQUIREMENTS FOR ROBOTIC ARM AND LUMINAIRE DEMONSTRATOR

A. *Additive manufactured robotic arm*

DIMAP intends to 3D print bio inspired robotic joints. Man-machine interaction is a great challenge for mechanical devices and modern robot design. Low impedance and high force-to-weight ratio is currently seen as a key approach for bionics [10]. Flexibility and low weight are two *sine qua non* aspects of reducing impedance. 3D printing technologies offer freedom of design to manufacturing and therefore are predestined for the production of bio-inspired solutions. Nevertheless, each AM-technology currently available is limited within the available materials. Typically, only a limited number of polymer types are applicable when compared to other manufacturing techniques such as injection moulding or hot pressing. On the other hand, specialized technologies like selective laser sintering (SLS) or –melting (SLM) are capable of producing metal parts, but are heavily dependent on the quality and reproducibility of the base material/powder.

DIMAP application requirements create the basis to solve those technical limitations. The chosen solution is derived from Arthropod “jointed legs” and require development of functional materials (with high strength, light-weight, dielectric, magnetism or conductive properties), as well as technical improvements to the 3D-printer (combining thermal and Ultraviolet (UV) curing strategies).

The first draft of the joint (i.e., Figure 2) consists of two bellows surrounding the actual hinge, operated by compressed air. The current design features a material combination of a rubbery, flexible and deformable material on the one hand and a rigid material on the other hand. Mechanical properties mainly characterized the two materials. The second main part is the hinge, which is proposed to resemble to a human elbow joint. Therefore, a hard material is necessary to withstand the tribological stress generated by the movement of the connected elements without wearing out too fast. The last element is the arm structure; it should be made of a rigid, yet light material in order to reduce weight when compared with current designs being produced with other manufacturing techniques. Therefore, a combination of a hard shell filled with a porous (or foam-like) structure is considered. Finally, conductive tracts are intended to be printed on the structure to connect sensors (pressure, position, etc.). The length of the tracks is expected to be superior to 300 mm, which implies new challenges.

The development of such application to be 3D printed requires to conduct research activities on the material side as well as on the printer itself.

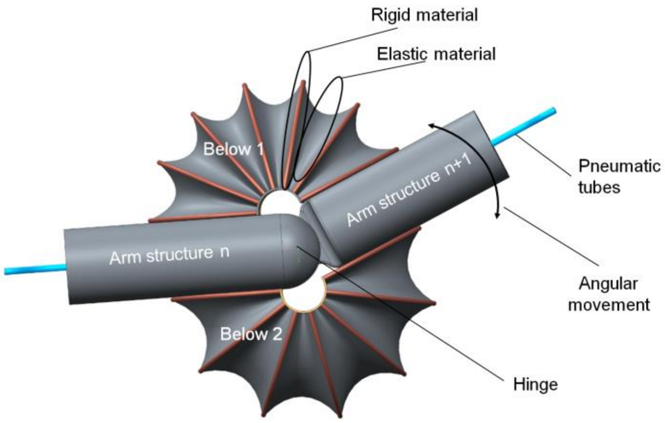

Figure 2: Conceptual drawing of robotic joint actuator

B. *Additive manufactured luminaires*

In lightning applications, the lead times from design to available finished products is long even for low volume productions (up to 6 months). This is based on the currently used injection moulding technique, which in addition is rather costly. Depending on the complexity of part and mould, the design and manufacturing of the mould can cost up to 1.5 million Euros. The implementation of AM is expected to increase the ability of companies to introduce new and improved products at accelerated rates. The profession retail lighting market is an interesting market for customization due to highly value added product diversity. There is a variety of different levels, on which one can customize parts and products using novel digital materials. Customization can happen at the material level, on the part level and finally on the modular level. In terms of mechanical strength and electrical conductivity, material requirements for this application have to be fulfilled, in order to accelerate the transition from mere prototyping towards production. DIMAP will show that the new developed ink systems lead the way to additive manufacturing of customized luminaires.

To that end, DIMAP will develop a luminaire demonstrator. Figure 3 shows a sketch of this demonstrator developed by Philips. It is a linear array of LED distant of 100 mm from each other. One pattern of the array is composed of one LED and of surrounding moveable elements, shaped as a V and dedicated to direct the light. The parts of the V facing the LED are reflective in order to minimize light losses. The movement is performed by pressurized air coming through a lower channel.

The approach chosen within DIMAP is to separate the development in two parts. The first one is the Printed Circuit Board (PCB) receiving the LED. The PCB part is made of a thermally conductive layer, used as a substrate for the rest of the structure and as a heat spreader. The second layer is made of a dielectric material to avoid sparking and electric bridging. On top of it, the electrical pattern is printed with conductive ink. A driver and an optical source (the LED itself) are mounted in further steps. Finally, a highly reflective layer (printed or coated) will cover the PCB.

The second part is the LED array; its function is to control the light effect, changing the angle of the V. The main challenge in this part is to print simultaneously hard and soft material. Indeed the reflective part has to maintain its shape and therefore high-strength ink should be used.

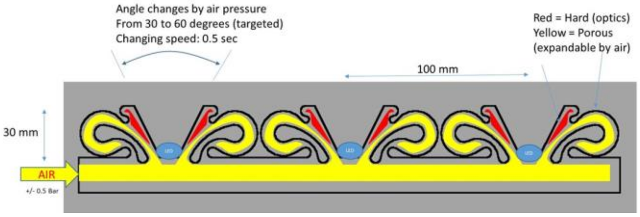

Figure 3: Concept sketch of hard/soft combination activated by pressurized air

III. HURDLES AND SOLUTIONS

Additive manufacturing techniques offer an unchallenged design freedom. Nevertheless, the material variety is limited. One of the main challenge faced by DIMAP concerns the ceramic inks being researched in Karlsruhe Institute of Technology in the group of Prof. Thomas Hanemann [11]. The ceramic inks developed in DIMAP are partially dedicated to the Printed Circuit Board on which the Light-Emitting Diode is printed. One of the main challenges for PCBs is to dissipate the heat generated by electrical current and to limit the material deformation induced by this heat. Therefore the ceramic part has to perform high heat dissipation (10 – 50 $W.mK^{-1}$) and small linear thermal expansion coefficient (inferior to 10-6 K^{-1}). If expansion is too high, it can lead to solder fatigue and cracks in conductive tracks.

Ceramic inks developed by DIMAP are actually based on polymer ink. Within a certain range, the physical properties of resins and polymer can be adjusted by the addition of organic or inorganic nano-sized fillers [12-14]. The addition of spherical ceramic particles with average particle size larger than several micrometres normally deteriorates the resulting mechanical properties, while ceramic fibres enhance them. The addition of ceramic nanoparticles causes an enhancement of the thermomechanical properties due the particle’s very large surface area generating an interfacial layer with pronounced attractive forces [15-17].

As explained in the previous paragraph, the addition of nanofiller can be used to tune thermomechanical properties of polymer-based ink. The specifications given by Philips and Festo imply a high load that will increase the ink viscosity significantly. Now, the ink viscosity at jetting temperature (60-90°C) excides the 20 mPas recommended by Stratasys to use the actual PolyJet technology. The solutions to overcome this problem heads towards a new generation printhead accepting higher viscosity or a hybrid solution including existing technologies (i.e advanced ink-jet (e.g., SIJ Technology), air pressure-based multi-nozzle dispenser, Aerosol-type (e.g., Optomec) [18], syringe-type dispenser). Due to their high hardness, ceramic materials are also considered for printing the hard-shelve structure of the robotic arm hinge. Since materials like ZrO_2 and Al_2O_3 are also brittle and relatively heavy, DIMAP proposes to fill the ceramic hard-shelve with a foam-like material. The purpose of a foam-like material is to reinforce the ceramic structure and maintain an overall low-weight. For example, solid PS has a density of 1050 kg m-3, but expanded PS can have a density as low as 15 kg m-3 [19-21]. The development of such inks is challenging and therefore different approaches are envisaged. The first approach developed by the University Johannes Kepler of Linz [22], is to include in polymer based inks Microspheres. The microspheres are made of a shell-polymer and of a core blowing agent. Under heat or UV exposure, the core material blows, resulting in expanded microspheres with thinner polymer shell. To maximize the chance of developing foam-like ink, an open-cell foam approach is also considered. Unlike the microsphere approach, this does not require synthesis of polymeric material. The blowing agent is ground down to an acceptable size and uniformly dispersed in the matrix ink. Depending if the compound is organic or inorganic, the agent will be blown using heat or UV exposure. During the expansion process, the bubbles can freely merge creating a porous foam and gas permeable structure.

IV. CONCLUSION

New printing techniques allow the creation of so-called digital materials with which multiple material combinations and novel composites with predictable physical properties can be produced. As explained in the previous parts, DIMAP intends to use the design freedom given by AM and the PolyJet technology to produce demonstrators with innovative design and exceptional mechanical properties. Different material properties can be achieved and used to implement functional materials to the portfolio of printable materials, either by adding nanoparticles or by adjusting the polymeric ink composition and the curing processes;.

In the upcoming months the main focus of the project will be on the development of suitable ink formulations with incorporated nanoparticles. In addition, the ink stability and curing strategies will be developed and first printing tests will be performed.

Since the filler materials raise the viscosity of the inks, an adaptation of the printing technology will be mandatory. Upgraded print heads that are able to cope with the new materials are one way this will be achieved during the runtime of DIMAP. A different approach could be a combination of different dispensing techniques. Depending on the final ink properties a appropriate solution will be implemented.

With regards to the safe-by-design approach and safety aspects, each material will be evaluated and a Safety Data Sheet (SDS) will be developed. Personal monitoring devices will be used during the material preparation and printing steps to analyze exposure to nanoparticles in these stages of the whole process. Also, a life cycle assessment will be carried out to determine the impact of the printed product throughout the whole production, usage and disposal span.

REFERENCES

[1] http://www.dimap-project.eu/ [accessed June 2016]

[2] www.festo.com [accessed June 2016]

[3] www.cirp.de [accessed June 2016]

[4] www.philips.com [accessed June 2016]

[5] R. Neumann, A. Hildebrandt and E. M. Knubben (Eds.) “Fluid Power in Motion”, 2008.

[6] K. Liu and L. Jiang, “Multifunctional Integration: From Biological to Bio-Inspired Materials”, ACS nano 2011, 5(9), pp. 6786–6790.

[7] B. Soars, “Driving sales through shoppers’ sense of sound, sight, smell and touch”, Intl J of Retail & Distrib Mgt 2009, 37(3), pp. 286–298

[8] D. Hinks and R. Shamey, “Review of Retail Store Lighting: Implications for Colour Control of Products”, Coloration Technology, 2011, 127, pp. 121–128.

[9] S. Scholz, A. Brunet., T. Müller and A. Fuchsbauer, “Novel Nanoparticle Enhanced Digital Materials for 3D Printing and their Application Shown for the Robotic and Electronic Industry”, proceding of the CENICS 2016 conference.

[10] S.P. Buerger, Stable, high-force, “low-impedance robotic actuator for human-interactive machines”, Ph.D. Thesis, Massachusetts Institute of Technology, Dept. of Mechanical Engineering, 2005.

[11] T. Hanemann, W. Bauer, R. Knitter and P. Woias, “Rapid Prototyping and Rapid Tooling Techniques for the Manufacturing of Silicon, Polymer, Metal and Ceramic Microdevices”, in: “MEMS/NEMS” (Ed.: C. Leondes), Springer US, 2006, pp. 801-869, ISBN: 978-0-387-25786-0

[12] T. Hanemann and D.V. Szabó, “Polymer-Nanoparticle Composites: From Synthesis to Modern Applications”, Materials, 2010, 3, pp. 3468-3517, doi: 10.3390/ma3063468.

[13] S. Schlabach, R. Ochs and T. Hanemann, D.V. Szabo, “Nanoparticles in polymer-matrix composites”, Microsystem Technologies, 2011, 17, 183-193, doi: 10.1007/s00542-010-1176-8.

[14] D.V. Szabó and T. Hanemann, “Polymer nanocomposites for optical applications”, In Advances in Polymer Nanocomposites: Types and Applications; Ed. F. Gao, Woodhead Publ., Oxford, 2012, pp. 567-604, ISBN 978-1-8456-9940-6

[15] L.S. Schadler, L. Brinson and W. Sawyer, “Polymer nanocomposites: A small part of the story”, JOM Journal of the Minerals, Metals and Materials Society, 2007, 3, pp. 53-60, http://dx.doi.org/10.1007/s11837-007-0040-5.

[16] L.S. Schadler, S.K. Kumar, B.C. Benicewicz, S.L. Lewis and S. E. Harton, “Designed Interfaces in Polymer Nanocomposites: A Fundamental Viewpoin”t, MRS Bulletin, 2007, 32, pp. 335-340.

[17] W.R. Caseri, “Nanocomposites of polymers and inorganic particles: preparation, structure and properties”, Materials Science and Technology, 2006, 22(7), pp. 807-817.

[18] http://www.optomec.com/ [accessed June 2016]

[19] H. Weber, I. Grave, E. Röhrl, “Foamed Plastics”, in: Ullmann's encyclopedia of industrial chemistry, 2010, Wiley, Chichester.

[20] Handbook of polymer foams, Ed.: Eaves, D., 2004, Rapra Technology, Shawbury, Shrewsbury, Shropshire, U.K.

[21] J. Maul, B. G. Frushour, J. R. Kontoff, H. Eichenauer, K.-H. Ott, C. Schade, “Polystyrene and Styrene Copolymers”, In: Ullmann's encyclopedia of industrial chemistry, 2010, Wiley, Chichester.

[22] http://www.jku.at/ [accessed June 2016]