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Bio-intelligent manufacturing cell for bio-hybrid machines fabrication

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Abstract

Biological Transformation in Manufacturing is a pioneering frontier of Industry 4.0, involving the integration of bio-intelligent structures, processes, organisms or materials into production engineering by systematically applying knowledge from biology. This should lead to a necessary convergence of biology and biotechnology with manufacturing processes, production systems and information technology offering the prospect of dramatic step changes for future innovation in manufacturing in order to enhance circularity and sustainability while advancing efficiency and competitiveness. In 2021, the first call topic on Biological Transformation “Development of technologies and devices for bio-intelligent manufacturing” was published in the Horizon Europe Programme Call HORIZON-CL4-2021-DIGITAL-EMERGING-01-27 where the project “A Modular Framework for Designing and Producing Bio-Hybrid Machines (BHM) - BioMeld” was approved and is introduced here.

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1. Introduction to the Biological Transformation in Manufacturing

Biological Transformation in Manufacturing (or in short Biologicalisation) is seen by [1] as a breaking new frontier of Industry 4.0. It is defined as the use and integration of biological and bio-inspired principles, materials, functions, structures and resources from living nature for intelligent and sustainable manufacturing technologies and systems with the aim of achieving their full potential [2].

In brief, Biologicalisation as the convergence of biology, engineering and information technology offers the prospect of dramatic step change scenarios for future innovation developments. Among its main aims, achieving the highest degree of autonomy in manufacturing systems is of utmost relevance.

A vision for the future of manufacturing in the framework of Biologicalisation was considered in [1] where it was proposed that the next generation of bio-inspired production processes could have self-learning and self-optimisation capabilities utilising real-time information from the production machines, making them highly efficient in terms of resources, energy and materials.

Moreover, future machines may have self-healing capabilities, be self-adapting, have the ability for self-calibration and possess higher levels of intelligence as a result of the extensive research into bio-inspired AI/ML techniques. Machine tools will have a high number of sensors, including bio-sensors, for the monitoring of different physical properties to provide full information about the actual machine tool behaviour and condition. The control systems with deeper intelligence will be capable of realising both model and

situation based smart control algorithms. Machines will have a greater degree of bio-intelligence due to the introduction of cognition with controls that are bio-inspired by the functioning of the human brain. Thus, it was concluded that the level of autonomy of equipment, machines and systems in manufacturing will increase enormously.

As one of the future scenarios and challenges, [1] reported that the design of machine tools inspired by mimicking ant colonies or bee hives in terms of work distribution, individualised operations and autonomy can highly extend autonomy in future manufacturing systems. With the increasing development of new sensors and control systems, highly autonomous machine tools should be in the spotlight for future advances. Just like an entity of a hive, colony or swarm is simultaneously independent and autonomous in its activities, a machine tool could also be simultaneously independent and autonomous in its manufacturing context. The machine tool or a swarm of machine tools could be called by the product like bees are drawn to pollen. The machine tools could then distribute and perform operations on the workpiece according to bio-mimetic algorithms or task distribution hierarchy [3].

In [4], the underlying hypothesis is that manufacturing machines, exemplified by selective laser melting (SLM) machines, can derive substantial advantages by attaining a high level of autonomy through the integration of bio-inspired AI, thereby achieving bio-intelligence in machine tools. The study successfully demonstrated that imbuing technical systems with elevated intelligence, approaching human levels, enhances the quality, robustness, and efficiency of additive manufacturing and other manufacturing processes (Fig. 1).

Adopting biological functionalities for machines increases their sustainability and optimises their behaviour within their operating and environmental conditions. The research work showed that manufacturing machines (e.g. SLM machines) equipped with bio-inspired AI are capable of permanently acquiring new knowledge, continually seeking self-optimisation and providing very high level of autonomy.

Careful estimation of the technological consequences raises the expectation of advancements in relation to:

- Fault reduction and increase in the strength of additively manufactured parts to the level of forged parts.
- Fault correction to reduce the scrap resulting from prematurely aborted jobs by a factor of 10 due to early in-situ counteraction after detection of process deviations.
- Reduction of average setup times in today's production mix in SLM by a factor of 2 to 4 due to the input of skilled operator's experience and newly generated knowledge made available by bio-inspired AI paradigms.

It was thus concluded that a very efficient and highly autonomous SLM machine can be designed with the bio-inspired AI methods and the computational power available today and that the underlying principles can be applied to other types of machines in advanced manufacturing systems.

In [2, 5], an automated stem cell production platform developed at the Fraunhofer Institute for Production Technologies (IPT), Aachen, Germany, is presented (Fig. 2). The primary focus of the research work for this realisation was on the bio-intelligence level of Biologicalisation, based on the

development and implementation of advanced bio-inspired algorithms such as reinforcement learning for control. The results achieved were optimised process parameters, better resource usage, higher throughput, increased quality, cost reduction, greater resilience, and higher autonomy of system operation. It was concluded that the automated production of biological materials, such as stem cells, represents perhaps the highest level of Biologicalisation in Manufacturing where a symbiotic co-existence and co-evolution of technical, ICT and biological sub-systems are manifested yielding a notable degree of autonomy in the production system.

An important advantage of biological systems over technical systems is the handling of unpredictable events that occur from the outside or internally [6]. Increasing the autonomy of technical systems is the driving force behind adopting bio-inspired procedures from nature. As flora and fauna have a huge portfolio of different strategies to regenerate their functionality, they represent a valuable blueprint for bio-inspiration in technical systems. However, just copying the strategies and mechanisms of nature is not useful as the time scales are completely different. This holds particularly true for evolution, growth, self-healing, self-repair and self-organisation although these capabilities are highly desirable to increase the production system autonomy.

Thus, the innovation process of Biologicalisation requires a continuous and systemic approach to find optimal solutions. Technologies such as wide sensor coverage, automatic decision making, AI/ML and modern ontology-based expert systems are currently used for developing highly autonomous manufacturing technologies and systems.

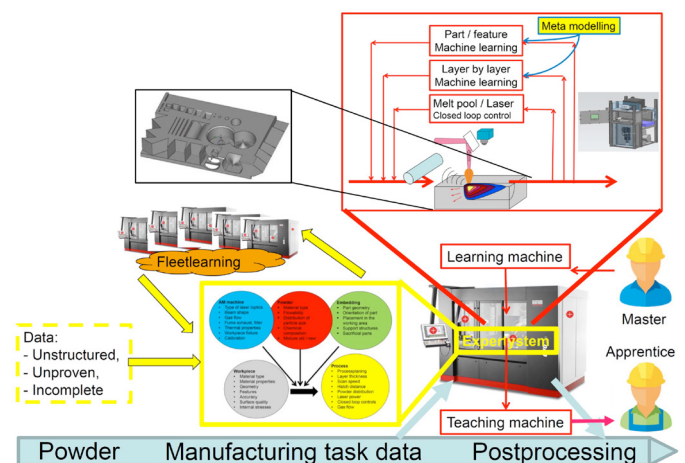


Fig. 1. Concept of bio-intelligent SLM machine [4].



Fig. 2. The StemCellDiscovery platform, Aachen IPT [2].

2. Bio-intelligent manufacturing cell (BIMC) for bio-hybrid machine (BHM) fabrication

In 2021, for the first time, an EC call topic on Biological Transformation in Manufacturing has been published within the call of the Horizon Europe Programme HORIZON-CL4-2021-DIGITAL-EMERGING-01 [7].

The topic title was “Development of technologies and devices for bio-intelligent manufacturing” and its description stated that “the use of biological elements as key enabling technology for manufacturing is an emerging trend that concurs with the pressing requirements of sustainability, and the biological transformation of industry can harness innovative and more efficient modes of production which can satisfy the needs of future generations”.

In response to this call, the project entitled “A Modular Framework for Designing and Producing Bio-Hybrid Machines (BHM) - BioMeld” was submitted and approved [8].

The BioMeld project aims to develop a modular modelling and simulation framework for the digital design of bio-hybrid machines (BHM) which combine living cell actuators and artificial materials with the main aim to achieve greater autonomy, flexibility and energy efficiency compared to current traditional solutions.

This framework entails the utilization of bio-inspired AI and ML paradigms in the early stages of the BHM manufacturing in order to find the most suitable and efficient product designs as well as scale-up the BHM fabrication by incorporating feedback from the analysis of the fabricated BHM into simulation scenarios, thus reducing the error-prone manual steps.

In the BioMeld project, this framework is used to develop a BHM consisting of a bio-hybrid catheter as an innovative medical device capable to release drugs in hard-to-reach regions of the human body.

The main project objectives are:

(A) *Achieving high autonomy, flexibility and evolvability of the BHM through a discrete manufacturing process that combines bio-inspired and bio-integrated approaches.*

The BHM is a flexible, reconfigurable and modular soft catheter, the controllable flexion of which depends on the force generated by muscle cell contractions (Fig. 3).

The catheter body incorporates magnetic-responsive fillers for magnetic control whereas the catheter tip is equipped with (Fig. 4): (i) a muscle cell-based motor, (ii) an electronic platform to trigger its activation and provide real time feedback on its motion via organic transistor-based strain sensors (Fig. 5), (iii) a bioreactor to keep it functional in the long term.

The fabrication of muscle cell-based bio-actuators is carried out by bio-printing technologies such as mold casting, extrusion-based bio-printing as well as light-based bio-printing (Fig. 6).

(B) *Developing a modelling and simulation framework for the digital design of BHMs.*

The modelling framework adopts a multiscale, modular structure for generating and gradually refining BHM designs, through several modules with varying levels of abstraction.

Beginning with the most abstract module, a 3D voxel-based simulator, it incorporates simple soft-body dynamics parameters (geometry, gravity, materials physical properties).

To bridge the sim-to-real gap, additional physics-oriented simulations include real-world aspects such as fluid dynamics and the dynamics of electric-stimulus response.

To automate the generation of virtual morphologies, a combination of Compositional Pattern Producing Networks (CPPNs) and Neuroevolution of Augmenting Topologies (NEAT) evolutionary optimization is employed.

(C) *Developing a bio-intelligent manufacturing cell (BIMC) for BHM fabrication.*

The BIMC, comprising workstations, material handling, storage resources and control systems, is set up and tested in view of performing the manufacturing processes and assembly operations to realize the BHM catheter with an as high a degree of autonomy as possible.

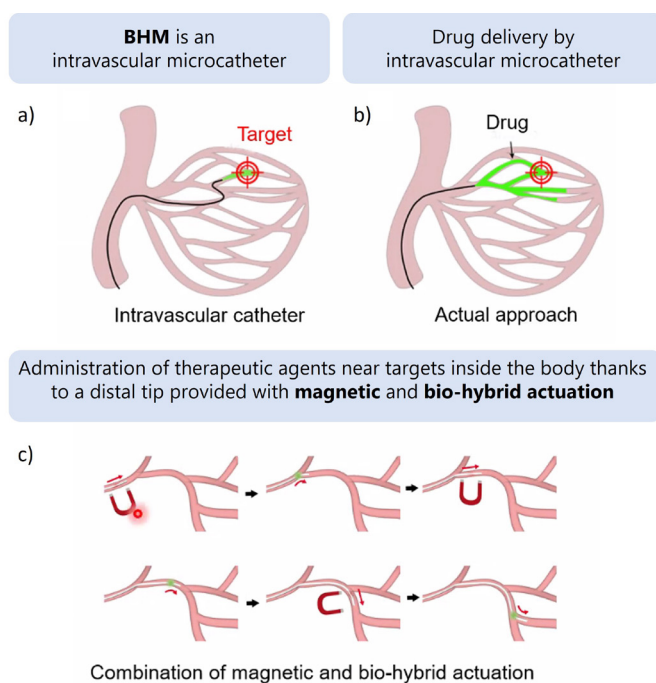


Fig. 3. BHM consisting in a bio-hybrid autonomous and flexible catheter capable of motion and flexion due to muscle cell-based bio-hybrid motor: (a) intravascular catheter for (b) drug deliver via (c) bio-hybrid actuation of muscle cells combined with magnetic particles [8].

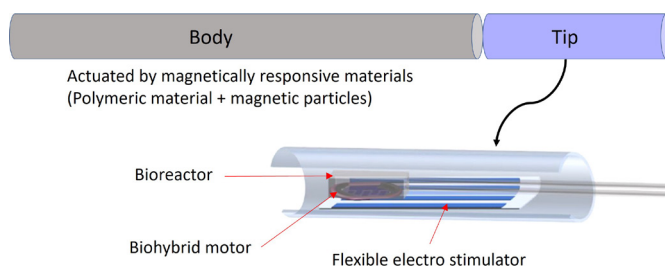


Fig. 4. Catheter body incorporating magnetic-responsive fillers to be controlled magnetically, and catheter tip equipped with a muscle cell-based motor, an electronic platform to trigger its activation and real time feedback on its motion via flexible strain sensors, and a bioreactor to keep it functional in the long-term [8].

The BIMC is designed to be flexible in order to cope with a certain level of variation in part or product styles.

According to the concept of bio-intelligent manufacturing as defined by [2] the BIMC will be established as an integrated manufacturing cell merging AI and ML with bio-inspired and/or bio-integrated manufacturing solutions, incorporating information channels, sensors and actuators systems.

The BIMC is expected to assess the process conditions and autonomously apply corrective actions using data coming from all process chain steps, including machine and process monitoring data detected by sensors during the BHM catheter fabrication.

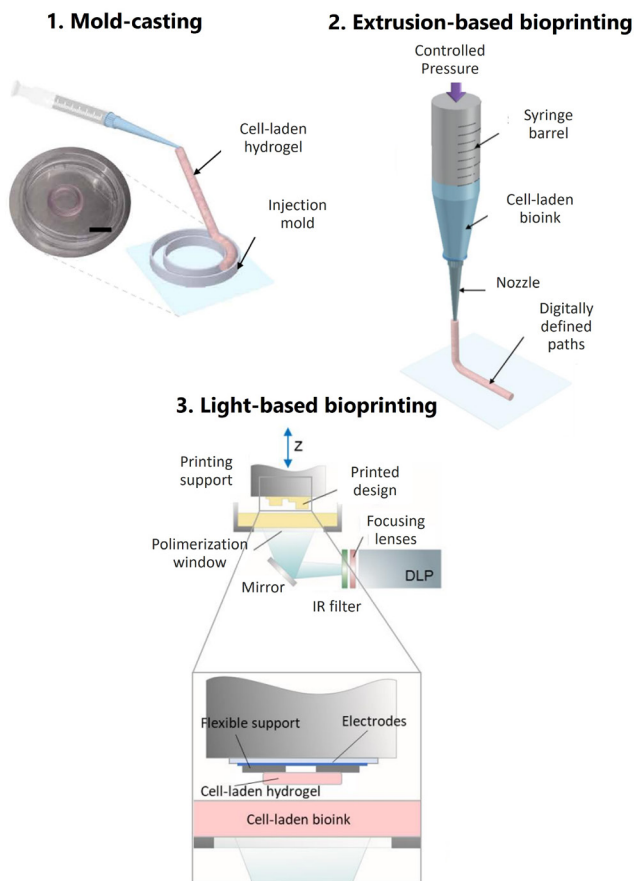


Fig. 5. Fabrication of muscle-based bio-actuators: (1) mold casting; (2) extrusion-based bioprinting; (3) light-based bioprinting [8].

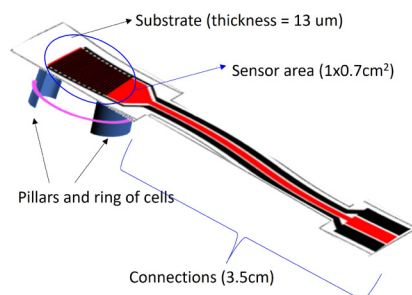


Fig. 6. Electronic platform for real-time direct monitoring of muscle cells by means of organic transistor-based strain sensors [8].

3. Conclusions

In this paper, the Biological Transformation in Manufacturing, or in short Biologicalisation, has been introduced as an emerging new frontier of Industry 4.0, involving the integration of bio-intelligent structures, processes, organisms or materials into production engineering by systematical application of knowledge from biology.

In the framework of Biologicalisation, the Horizon Europe project “BioMeld - A Modular Framework for Designing and Producing Bio-Hybrid Machines”, approved within the HORIZON-CL4-2021-DIGITAL-EMERGING-01-27 Call Topic “Development of technologies and devices for bio-intelligent manufacturing”, has been presented.

The BioMeld project’s aim is to develop a bio-hybrid catheter as an innovative medical device to release drugs in hard-to-reach regions of the human body where living cell actuators and artificial materials are combined to achieve greater autonomy, flexibility and energy efficiency in comparison with the current traditional solutions.

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