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Embodied Intelligence in Additive Manufacturing

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Abstract. Embodied intelligence reflects the ability of an agent to interact with its environment through its body to gain intelligence and autonomy. Such a concept has become popular in recent years for the design of robotic systems. This paper generalises the embodied intelligence concept to Additive Manufacturing (AM) to provide a new understanding of the technology with inspirations from biological production processes including organism growth and animal construction. Morphology-based embodied intelligence is analysed on the design and manufacturing aspects for delivering intelligent products (including robots) while embodied artificial intelligence (AI) (foundation models) is discussed for the printer itself. The paper opens a new perspective for AM research.

1. Introduction

The creation of matters is the fundamental dynamics for the physical universe: atoms are synthesised to form molecules; organisms (e.g., animals, plants, etc.) emerge and grow in nature; and numerous products are manufactured daily to serve human society. No matter what a process of matter creation is, and whether it is happening on microscale or macroscale, it always follows a fundamental principle - being driven by and adapted to certain environments. Such adaptability reflects the intelligence of a system to be qualified and/or maintain its presence in a particular environment, which lies in the physical embodiment of this system. This in a sense corroborates Hegel's 'What is real is rational, and what is rational is real'.

The so-called 'embodied intelligence' broadly observed in nature such as fishes using fins to swim or birds using wings to fly, have been mimicked and applied to the design of innovative robot morphologies by roboticists [1, 2]. The intention is to enable the robot to perform a specific task or behaviour through learning and development in an unknown environment, which creates intelligence and autonomy [3]. If we consider that every artificial product (e.g., a desk, a car, a building, etc.) in human society is a robot (being able to react to external stimulus in certain ways and/or at certain levels, etc.), their embodied intelligence, despite being possibly too low-level to be called 'intelligent', allow them to fulfil expected functionalities for specific applications/scenarios which are their operational environments.

Additive Manufacturing (AM), also called 3D printing, has been a rapidly developed manufacturing technology across industries since its emergence in the 1980s [4]. It actualises the goal of matter creation through an automated, normally layerwise material-adding process with which any geometries can be theoretically attained without the need for moulds. With the advancement of materials, AM has been acknowledged as the game-changing manufacturing technology for the future society for its incomparable (with conventional methods as subtractive or formative processes [5]) capability to flexibly and economically deliver innovative functional geometries and bespoke customisations (e.g., artificial organs, etc.) [6]. Our vision for AM with embodied intelligence includes both the printed product and the printer aspects: 1) high-level morphologically intelligent products to create a highly efficient, sustainable and human-centred society, 2) intelligent 3D printers for autonomously planning and executing printing activities tailored/adaptive to their in-situ environment.

This paper aims to establish and clarify the embodied intelligence concept in AM for future society development by drawing lessons from biological production processes. Section 2 gives an overview of mapping biological production processes including organism growth and animal construction to AM to establish the understanding of the generation of embodied intelligence in nature. Section 3 discusses the definition of morphological intelligence of products and the pathway to attain high-level intelligent products from both the design and manufacturing aspects. Section 4 describes the embodied artificial intelligence (AI) for 3D printers to achieve autonomous printing planning and coding with an emphasis on construction-scale AM in remote harsh environments.

2. Mapping biological production processes to Additive Manufacturing

2.1. Organism growth: From genotype to phenotype

The most universal biological production process is the growth of a living organism itself, which changes the organism's morphology and dimensions. Through millions of years of evolution, the morphology of a living organism gains its intelligence, so-called 'morphological intelligence' - a form of embodied intelligence, to adapt to its living environment. Such morphological intelligence is represented by certain functions (e.g., strength, motion, etc.) tailored to the environment, taking effects from micro level (i.e., cells and tissues) to macro level (i.e., bodies and limbs)[7, 8].

The growth of a living organism can be seen as an additive production process primarily through cell proliferation: numerous cells exponentially create relevant tissues and then the macroscopic morphology of the organism [9]. The objective of this process is to generate the desired morphological intelligence (functions) which is 'designed' and 'optimised' by Natural Selection. If we were to analogize the AM process to organism growth, the objective of this AM process should be achieving the morphological intelligence for a product to adapt to/be qualified for specific applications.

The organism growth process reflects a genotype-to-phenotype ('GtP') chain through which a set of genetic information is translated into a physical manifestation [10] (see Figure 1). The genotype refers to the genetic makeup of DNA that stores the information of the target morphology (phenotype). In AM, the genotype corresponds to the digital design parameters that define the characteristics of the desired output. These parameters could include information about material composition, microstructure geometry, macrostructural geometry, density distribution, and other relevant attributes. Essentially, the genotype in AM is a comprehensive dataset that encodes all potential variations and configurations of the product being designed.

The translation from genotype to phenotype is the process where the encoded design parameters are converted into cell proliferation instructions to create a tangible morphology. In AM, this translation process is carried out by professional processing software (e.g., slicers) embedded in AM machines (printers). The outcome is the specified building instructions (e.g., toolpaths) for guiding the material placement to create the object with all its physical and functional characteristics (the phenotype). Learning the lessons from organism growth to create morphologically intelligent AM products is discussed in Section 3.

2.2. Animal construction: From genotype to extended phenotype

Another interesting biological production process is the animal construction (manufacturing) behaviour. This has many forms in nature, for example, spiders weave webs, corals make reefs, and ants and birds build nests (Figure 1). Animal construction behaviour is considered as a type of extended phenotype for certain animals which is encoded in their genotype and generates changes to their living environment when it happens [11].

The genotype-to-extended phenotype ('GtEP') chain describes the extra process by which a set of genetic information is translated into a physical form outside of the organism's body. The traditional phenotype refers to the observable traits of the organism itself while the concept of the extended phenotype goes further to encompass the organism's influence on the environment. One of such influences refers to structures or changes an organism creates in its surroundings, which is why animal construction behaviours are commonly observed.

Mapping the animal to a 3D printer or printing robot out of an AM process, the genotype-to-extended phenotype chain defines how the design parameters of the printer itself dictate its physical products that can make a difference to their operational environment. Particularly, printers or printing robots can manufacture objects in the field at the construction scale, well known as 'construction 3D printing', which has been extensively explored and applied over the last decade [12, 13]. Learning from animal construction methods to inform the planning and implementation of construction-scale AM has elicited some interest from researchers [14], leading to process-oriented biomimetics research. This is further discussed in Section 4.

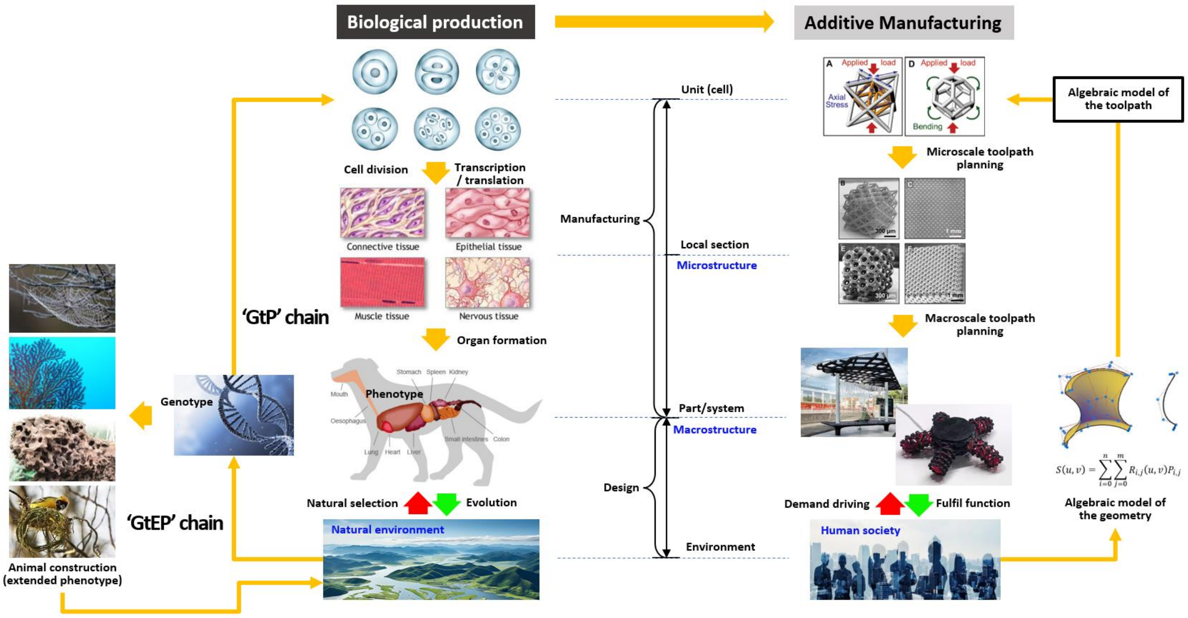

Figure 1. Mapping organism growth to Additive Manufacturing (images: [15] and google.com).

3. Towards morphologically intelligent AM products

3.1. Morphological intelligence in products

The nature of a physical product is to satisfy the desire or need of a customer [16]. We consider morphological intelligence as a measure of a product's functional performance based on its morphology for the satisfaction of human needs. In this context, every product has a certain morphological intelligence, e.g., the intelligence of a desk refers to it having several legs to stand on and bearing some loads. However, we usually don't recognise such morphological intelligence as it is too low-level to meet our common understanding of intelligence. Therefore, high-level morphological intelligence can be defined as innovative and superb functions or features that are not commonly seen or never exist in the current market. The generation of such high-level morphological intelligence can be expensive or impossible for conventional manufacturing processes while AM has the potential to deliver this goal economically and efficiently.

The desired highly intelligent morphology can refer to both macro and micro scales. Recent advances have shown the benefits of manipulating morphologies in micro [15] and macro [17] scales separately. Much microscopic intelligent morphology aims to create functional materials (e.g., graded functional materials) using bio-inspired structures. A comprehensive summary of such biological material structures is shown in Figure 2. Hereinto, one cellular/lattice structure called Triply Periodic Minimal Surface (TPMS), has been the focus [18]. Similarly, the macroscopic intelligent morphology refers to topology-optimised functional or material-saving geometries - examples of these can be seen in Figure 3.

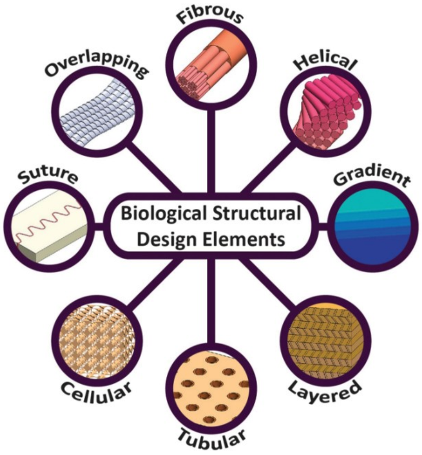

Figure 2. Common biological material structures [19].

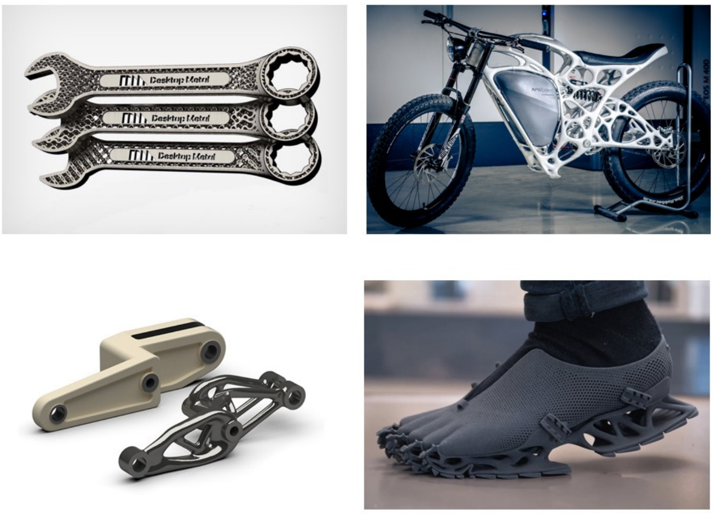

Figure 3. Examples of the macroscopic intelligent morphology [20].

It should be noted that the macro and micro scales here are defined as per the manufacturing resolution/precision for the sake of practicality, and are relative concepts with the actual values varying according to the dimensions of the product itself. For instance, the micro scale of a protective helmet is on the order of microns up to submillimetres, while the micro scale of a building refers to millimetres up to centimetres, which represents the macro scale for the helmet. Due to their distinct performances, biological material structures are commonly used for designing both the micro and macro morphology of a product.

When the produced object can autonomously change its morphology according to the ambient environment, it reflects an even higher level of intelligence. This is how 4D printing enables a printed product to interact with the environment, often through biomimetic morphology-changing behaviours [21]. Currently, some materials have been engineered to become 4D printable and more are expected in the future [22].

3.2. Robots with morphological intelligence

Robots are a special category of products. In robotics, morphology, which includes a robot's physical form and its functional adaptation to tasks and environments, plays a critical role in determining its capabilities and efficiency. Iida et al. [23] offers an integrative perspective on perception from a biologically inspired robotics standpoint, stressing the critical role of sensor morphology in robotic systems. This insight underscores the relevance of physical form in robotics, demonstrating how structural design can impact a robot's functionality and interaction with its environment.

AM significantly releases the freedom of robotic design, particularly in morphological innovation. AM enables the creation of complex geometries and structures, previously unfeasible, leading to a new era in robotic morphology customization. Vujovic et al. [1] highlight this in their study on evolutionary developmental robotics, demonstrating how AM techniques improve robot physical structures, emphasizing the importance of AM in innovative robotic design. Further research could delve deeper into this area, perhaps exploring specific case studies or new materials.

The integration of adaptive sensory systems into a robot's morphology marks a leap in embodied intelligence. These systems, ranging from tactile sensors to advanced vision systems, are crucial for effective environmental interaction. The challenge is integrating these sensors into the robot's body to enhance functional capabilities without disrupting its overall morphology. Nurzaman et al. [24] explore this in their study on active sensing systems with adjustable sensor morphology, providing practical examples of how sensory adaptation can be integrated into robotic design, furthering the narrative of morphological adaptation enhancing functionality.

3.3. Design: Evolution-based cross-scale morphology optimisation

On the topic of morphology design and optimisation of AM products, topology optimization [25] are usually employed in product design to enhance performance and efficiency. Among the most renowned topology optimisation algorithms are the Bi-directional Evolutionary Structural Optimization (BESO) [26] and the Solid Isotropic Modeling with Penalization (SIMP) [27], both of which are integral to achieving sophisticated and functionally enhanced design outcomes. Within this context, evolutionary algorithms [28, 29] have been utilised to find forms that yield desired intelligence. Such optimisation strategies usually closely resemble the natural selection processes that govern the growth of organisms. These strategies translate genetic design information into tangible physical forms, enabling the genotype-to-phenotype chain. This translation process continuously refines the digital design parameters of an AM product through the iterative application of evolutionary algorithms, leading to the optimisation of either micro or macro-structural designs.

Our vision is to combine the evolution-based optimisation of microstructure and macrostructure (simultaneous computation) to achieve co-evolution [30, 31]. The results of this cross-scale evolutionary design are concurrently optimised morphology both in micro (local) and macro (global) levels [32, 33]. Fast and effective testing and validation of the resultant cross-scale optimised morphology through simulation (e.g., finite element analysis) will still remain a challenge for design automation.

3.4. Manufacturing: Non-layerwise volumetric forming strategies

The nature of AM lies in the material-adding mechanism. As the cross-scale intelligent morphology generally refers to discrete and non-dense material placement at the micro scale related to the ordered cavity and void generation, the printing resolution must be able to formulate the microscopic material structures with both accepted accuracy and speed. This leads to the elimination of the conventional layerwise processes utilising a fixed higher printing resolution to form the microscopic material structures (e.g., 1-micron printing resolution for a 100-micron micro structure) as it will be extremely time-consuming for forming the macro structure (the whole body) of the product. Improved layerwise slicing methods such as varying-thickness / multi-directional parallel slicing or non-parallel slicing [34] can provide better performance but the effectiveness is still limited.

A possible solution will be non-layerwise volumetric additive forming. Instead of layerwise fixed-resolution material accumulation, this forming strategy aims to create local geometries through one-time adaptive material placement with on-demand dynamically varying printing resolution at the target locations to form a specific geometry. Examples of such forming strategy can be seen in [35, 36]. The planned toolpaths (e.g., medial axes) can directly follow/capture the topology (skeleton) of the target object, enabling varying-cross-section voxels as material units to mathematically represent the volumetric forming process. Such forming strategy allows the printing toolpaths to be directly designed or together designed with the object morphology in a parametric way, leading to a much simplified and efficient Design for Manufacturing (DfM) workflow for creating intelligent morphology at both micro and macro scales.

4. Can a 3D printer have embodied intelligence?

Considering a 3D printer to gain embodied intelligence, it should be able to interact with the environment like the organism. For all the stationary 3D printers (either desktop or industrial classes), such an environment is mostly a built (artificial) environment of the human society (Figure 1). The embodied intelligence of these 3D printers would be enabled by foundational AI models such as the Large Language Model to allow the automatic generation and comprehension of toolpaths, machine codes and material application of any forms given by humans as environmental inputs [37, 38]. This will help to eliminate the barrier of demanding expert knowledge in planning and coding for executing printing activities (behaviours), significantly contributing to the efficiency and universality of AM processes.

The embodied AI can be even more essential for mobile 3D printers which usually undertake large-scale AM processes for construction purposes. Inspired by animal construction, a construction 3D printer is a mobile 3D printing robot acting like an animal to construct structures in the natural environment. Preliminary lab-based examples can be seen in the University of Stuttgart ICD/ITKE research pavilions where spider webs [39] and moth webs [40] are mimicked for robotic additive construction of pavilions. The vision is for such 3D printing robots to interact with / take in information (of limitations) from their surroundings and perform construction using in-situ material resources with printing toolpaths and manufacturing strategies adaptive to the local landscape[41]. The latest example can be seen in [42] where a robot is autonomously selecting and placing local stones to additively construct large-scale walls.

The above-mentioned mobile 3D printers with embodied AI are particularly needed for construction activities in a remote location which is hard or impossible for human beings to access (see Figure 4). Such locations can mainly include three types:

- Extreme environments which are harsh or dangerous for human beings such as polar areas [43], deep sea [44] and extraterrestrial spaces (e.g., Moon and Mars [45, 46]) for potential human habitats in the future - it should be noted that lunar construction has been a promising research and application area for large-scale AM using lunar regolith [47];
- Natural disaster sites often with risk of potential continuous damages where emergency shelters and blindages are needed for saving human lives and protecting properties [48];
- Battlefields or battlefronts where military facilities need to be rapidly constructed for the purposes of crossing gullies or shielding enlisted men and weapons [49].

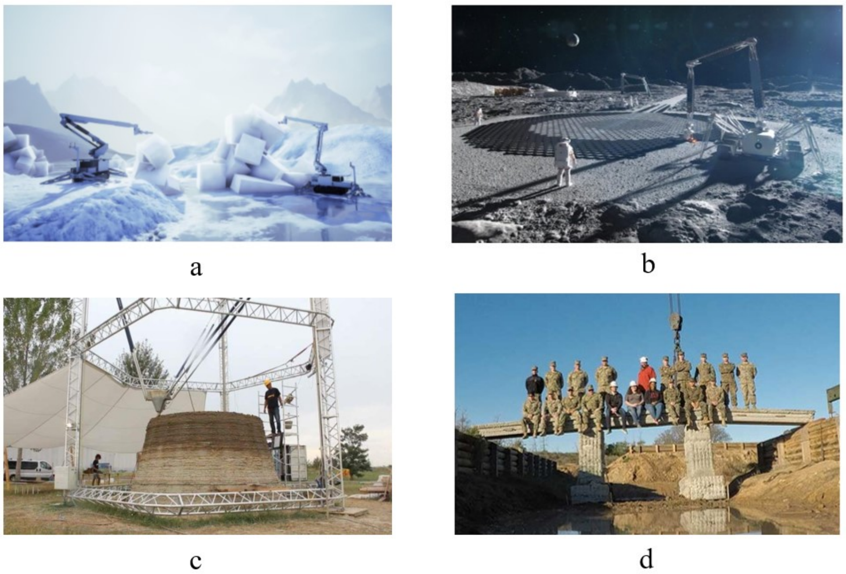

Figure 4. Examples of large-scale mobile 3D printing in a remote location: a) printing at polar areas [43], b) moon base printing [50], c) emergency shelter printing [48], and d) military bridge printing [49].

5. Conclusions

Additive Manufacturing has been rapidly developing since its birth creating innovative products for modern society and will continue to grow with expanding materials and scales. This paper opens a new perspective on evaluating the performance of AM products, morphology-based embodied intelligence taking inspiration from robotics. Learning from organism growth, the paper defines high-level morphological intelligence as superb functions for AM products and discusses evolution-based cross-scale morphology optimisation (design aspect) and non-layerwise volumetric forming strategies (manufacturing aspect) for achieving such intelligence. Besides the products, 3D printers, both stationary ones and mobile ones (field printing robots) also need to be equipped with embodied intelligence (foundational AI models) to conduct autonomous environment-driven planning and coding for AM tasks. Animal construction behaviours can be learned for mobile 3D printers. The authors believe that embodied intelligence provides a promising direction for the future development of AM. One of the most important next steps is establishing metrics for measuring and benchmarking the embodied intelligence in AM to drive performance comparison and improvement.

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