# The Material Turn in the Study of Form: From Bio-Inspired Robots to Robotics-Inspired Morphology

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*This paper investigates the mechanisms of knowledge production of twenty-first century robotics-inspired morphology. How robotics influences investigations into the structure, development, and change of organic forms? Which definition of form is presupposed by this new approach to the study of form? I answer these questions by investigating how robots are used to understand and generate new questions about the locomotion of extinct animals in the first case study and in high-performance fishes in the second case study. After having illustrated the landscape of twentieth-century morphology, I will reflect on the definition of form adopted in twenty-first century robotics-inspired morphology as well as on the differences between this approach to the study of form and the so-called nature-inspired disciplines, such as bionics or biomimetics. In the conclusion, I suggest that we are now in a material turn in morphology, characterized by the coexistence of the robotic, the virtual, and the real, which enables an understanding of how the structures and dynamics of shapes change over time.*

## Introduction

In the last decades, the implementation of robotics in diverse disciplines is radically changing how knowledge is produced, tested, and validated. Philosophers and historians of science and technology have started investigating the possible strengths and shortcomings of this implementation. Topics, such as the interrelation between robotics, AI, and the Internet of

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Things, and Human-Robot Interaction, are now part of mainstream philosophical research and debate (see, for example, Floridi 2008; Lacerda et al. 2019; Liggieri and Müller 2019; Müller 2020). These subjects have also been analyzed by relating robotic automation to broader social, economic, and ethical issues, such as the pros and cons of using robots in the workplace.

This paper situates itself within the technoscientific investigation of robotics. It does so by examining to what extent, if any, robotics[1] is changing the way in which scientists work with the notion of organic form. As the study of form and its changes through time, morphology has considerably transformed its knowledge claims and possibilities through the introduction of robotics. This application was first and foremost enabled by an economic shift. Due to the decreasing costs of the components and devices necessary to design and manufacture robots, several laboratories worldwide could either create their own robots to better understand morphogenetic processes or collaborate with engineers to develop joint projects (Gravish and Lauder 2018; Krause et al. 2011).

In this paper, I look at the epistemic repercussions of using robotics for producing morphological knowledge: how does robotics influence investigations of the structure, development, and change of organic forms? Which definition of form is presupposed by this new approach to form study? My answer to those questions is that robotics is changing the knowledge claims produced by and possibilities of morphological investigations. The design and production of concrete robots that interact with their environment through a feedback loop enables biologists to create and access an explanandum, the form-function complex that would be otherwise non-manipulable and non-researchable. Furthermore, the examination of robots' "behaviors consistent with biological observation" and the analyses of their "reactive behavior" helps biologists "generate new biological hypotheses of organic function," as engineer Nick Gravish and biologist George V. Lauder put it in a programmatic paper on the features of robotics-inspired biology (Gravish and Lauder 2018, p. 2).

This approach, though not entirely new, is rooted in a specific set of practices and notions of organic form that was developed throughout the twentieth century. With this statement, I am not playing the perverse game of showing that nothing is entirely new. I am not merely detecting a possible predecessor of current robotics-based morphology. Rather, I show that this approach to the study of form is based on a methodology that departed from biomimetics, another morphological and highly technological discipline. In other terms,

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[1] Following biologist Jens Krause and colleagues, I will use a minimal definition of robot. It can be defined "as a machine that is able to interact physically with its environment and perform some sequence of behaviors, either autonomously or by remote control" (Krause et al. 2011, p. 369).

the theoretical framework of robotics-inspired morphology, specifically, and biology in general, is different from that of bio-inspired robotics. Despite the similarity of seeing form changes through an engineer's lens and the continuous knowledge and practice exchange between these disciplines, the two approaches to the riddle of form should be kept divided in order to correctly understand their practices and knowledge claims. Therefore, in this paper, I will examine traits peculiar to robotics-inspired morphology.

To develop this point, I will investigate two emblematic case studies that came from two quite different biological disciplines and deal, therefore, with two diverse sets of data and specimens. The first case study is paleontological, focusing on the reconstruction of the morphology and locomotion of an extinct organism, the *Orobates pabsti*. It is an early example of tetrapods. It lived in the early Permian era, circa 290 million years ago. The fossils were unearthed close to Tambach-Dietharz, a small town in Germany, in 1998.

The second case study is about the form-function complex, which enables tunas' high-performance swimming. Thus, it is taken from a so-called neontological discipline. In biological and philosophical literature, "neontologists" are biologists who deal with living organisms (e.g., Currie 2019, Depew and Simpson 2006, Sepkoski 2012, Gould 1980). Conversely, paleontologists work and investigate extinct and fossilized plants and animals. Besides marking an important difference regarding two different temporal dimensions in biology, namely deep and shallow time, this distinction emphasizes the different features of data available to these biologists. Unlike neontologists, paleontologists always deal with incomplete and imperfect data and cannot perform investigations in vivo. By choosing to focus on both the morphology of recent and extinct organisms, I will be therefore able to provide a quite satisfactory overview of the possibilities and limits of robotics-inspired morphology.

However, tempting as it might be, I would neither develop nor support the thesis that robotics is closing the gap between experimental and non-experimental sciences – in this case, between paleontology and neontology (Turner 2007). Rather, I argue that robotics is emblematically calling attention to how knowledge production relies on a technological setting. Hence, in delineating and historicizing some pillars of the twenty-first century study of form, this paper is intended to broadening historians' and philosophers' of science focus on how (morphological) knowledge production and technology are deeply entangled. It signposts the concrete entwinement between technology and theory to visualize and study morphological explananda. By doing so, it contributes to the broader history and philosophy of the study of form during the last two centuries, a history and philosophy which is still being written.[2]

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[2] On the broader history of twentieth-century morphology see, for example, Love 2003, 2006; Tamborini 2020b, 2020c, under contract.

First, I will portray the landscape of twentieth-century morphology to detect different notions of organic forms. Second, I move to the two emblematic case studies. Then, I will examine the broader theoretical payoff and structures of twenty-first century robotics-inspired morphology. In the conclusion, I will reflect on what I name the material turn in the study of form.

## 1. Twentieth-Century Morphology

During the first half of the twentieth century, evolutionary morphology gradually lost its central disciplinary importance. It transformed itself from being "the first evolutionary science" (Bowler 1996, p. 17) to a discipline that, according to biologist Ernst Mayr, one of the main architects of the modern synthesis of evolution, i.e., the merging of Darwinian theory with Mendel's genetics during the 1930s, did not contribute at all to the advancement of evolutionary thought (Mayr 1980, 1982). Despite Mayr's quite biased judgment and disciplinary morphology breakdown, a "desire for morphology" transversally permeated the entire twentieth century (Tamborini 2020d). Within this strong desire for investigating form's structures and the mechanisms of their possible changes through time, at least four different and conflicting definitions of organic forms and corresponding methodologies could be identified.

First, the organic form was equated with a classical machine. The champion of this view was German-born American biologist Jacques Loeb (1859–1924). In *The Dynamics of Living Matter*, Loeb stated that "living organisms may be called chemical machines, inasmuch as the energy for their work and functions is derived from chemical processes, and inasmuch as the material from which the living machines are built must be formed through chemical processes" (Loeb 1906, p. 1). The recognition of the identity between organisms and chemical machines put to the foreground the old issue of the organism's intrinsic purpose as a stronghold for the form's autonomy over its possible reduction to mechanical principles. Unlike machines, organisms seemed to maintain a sort of self-preservation and purposeful behavior. Loeb replied to this objection that "the fact that the machines which can be created by man do not possess the power of automatic development, self-preservation, and reproduction constitutes for the present a fundamental difference between living machines and artificial machines. We must, however, admit that nothing contradicts the possibility that the artificial production of living matter may one day be accomplished" (Loeb 1906, p. 1). Hence, the first approach to the form problem was rooted in a purely mechanistic conception of life, as one of Loeb's books was titled. This view was bolstered by an optimistic trust in technology progress towards the development of automatic machines—as did, in fact, happen over the course of the twentieth century.

Second, in open contrast with Loeb and other biologists, a vitalist definition of form was advanced. German biologist Hans Driesch (1867–1941) was one of its main supporters. After having supported mechanistic theories, he oriented himself towards neo-vitalism after a series of experiments on sea urchins. He shook sea urchin embryos at two- and four-cell stage, thus separating them into a single cell. He discovered, then, that every separated cell was able to develop itself into a complete sea urchin. Driesch interpreted these results as a powerful smoking gun for an anti-mechanistic and vitalist theory of morphogenesis (e.g., Driesch 1892, 1898, 1919). Every cell had an intrinsic power to form an entire organism. As the Baltic biologist Johann von Uexküll (1864–1944) cogently summarized the theoretical payoff of Driesch's experiments: "Driesch had succeeded in demonstrating there was no trace of any machine-structure in the germ cell, and that it consisted rather of equivalent parts. This explodes the dogma that the organism is only a machine" (translation in Cordeschi 2002, p. 71). Driesch argued, therefore, that morphogenesis should not be understood in mechanical terms. On the contrary, there was a vital principle responsible for the development of the organism as a whole, even if this was cut up. Following Aristoteles, he named this vital force *Entelechia*, or the molding principle of form.

During the twentieth century, a third approach to the study of organic form was formulated. Their practicians considered this methodology to be in between vitalism and mechanism. They named it organicism; this third way found great recognition in the first half of the twentieth century biology and recently made a resurgence the fore of today's evolutionary thought. As philosopher Jan Baedke showed, the basics strands of organicism were, "i) neither vitalism nor reductionist mechanicism is the right theoretical or methodological framework for biology, ii) "Organism" is (one of) the most central theoretical concept(s) in biology, iii) Biology should study the organism as a whole" (Baedke 2019). Organismic biologists, such as Ludwig von Bertalanffy (1901–1972), Conrad Hal Waddington (1905–1975), and Paul Alfred Weiss (1898–1989), defended an anti-reductionistic definition of organic form and strongly condemned any use of vital forces (see Peterson 2016; Haraway 1976). Echoing Goethe and other romantic biologists, they put an emphasis on the notion of form as more than the mere sum of the parts that compose it. Furthermore, they stressed that form's material properties are key factors in morphogenetics processes. They defended the idea that the engineers could take advantage of form's intrinsic dynamics to design nature-inspired technologies and products (Tamborini 2020b, under review). A decade ago, computer scientist Rolf Pfeifer explained in an influential *Science* paper exactly that the translation from nature to technological artifacts is based on form's intrinsic proprieties. As they put it, "exploiting the dynamics provided by materials and morphological properties as well as the interaction between physical and information processes promises to extend the capabilities of established control-based robot design methodologies" (Pfeifer et al. 2007, p. 1093).

Besides these three movements, which fought against each other in the mainstream biological debate thorough the first half of the twentieth century, another, albeit apparently quite peripheric, approach to the analysis of organic form problem made its mark. It never became a unitary movement. Rather, it traversed the other three movements during the last century. Biologists who supported this study of form, which I would like to call the architectural approach to morphology, often ended up being either mechanists, or vitalists, or organicists. Furthermore, its supporters came from a myriad of biological subdisciplines. It was defended by biologists interested in evolutionary questions, behavioral and biomechanical issues, and paleontology, and other areas of investigation.

The practitioners of this morphological attitude identified form as what emerged from organizational principles. The chemical properties of organisms or machines, i.e., its materiality, were only one aspect for understanding the essence of form. Central was rather the notion of arrangement. As American zoologist Herbert Spencer Jennings (1868–1947) wrote, "we find in lower organisms, as in higher animals, that the nature of the reactions is mainly to characteristics *arrangements* of material, not to the proprieties of simple unarranged substance. These lower organisms therefore furnish problems which do not differ in kind from what we find in higher animals" (Jennings 1910, p. 368). The focus on form's functional[3] arrangement enabled the biologist to link organisms to machines, from a different and new perspective. Jennings announced that this methodology was able "to show that lower organisms, like higher ones, are typical *arrangements* of material; are structures; are in this respect machine-like; not masses of a uniform substance" (Jennings 1910, p. 360; italics in original). By shifting the stress from materials to structures, the morphologists would be able to begin an investigation on how possible structural elements may be combined to obtain organized forms. "From a certain mass of material," noted Jennings, "we could make either a clock or a doorbell or a steel trap or a musical instrument,—and we could easily so arrange these that each would respond in its characteristic way when acted upon by an electric current […] The

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[3] As philosopher Roberto Cordeschi noted Jennings' principle it "seems correct to call functional, since it concerns the organization of an action system and not its material composition" (Cordeschi 2002, p. 24).

specific action of each depends on the specific arrangement of its material. This is exactly what we find in organisms, including the lowest as well as the high" (Jennings 1910, p. 361).

Though he came from a different background, German anatomist and physician Hans Petersen (1885–1946) stressed the same point. He came up with a new definition of form that cogently summarized this idea. He defined form "as a ready-to-use solution to a constructional task [*fertige Lösung einer konstruktiven Aufgabe*]" (Petersen 1922, p. 339). Forms were equated with constructions, i.e., they were meant as the coherent result of assembling different elements to obtain a stable and ordered object. Therefore, an organism's development was primarily meant as a technical problem.

Another important feature of this architectonical approach to morphology was the use of a technical vocabulary to describe form adaptation. For example, German paleontologist Adolf Seilacher (1925–2014) described the morphological features of fossilized life traces in a very technical way:

> the shape characteristics of many life traces (="animal artifacts"!) [(="tierische Artefakte!")] are primarily *purpose-related* [*zweckbedingt*]. They can therefore be directly understood not only by their causal relationship with the construction of their author [*mit der Konstruktion ihres Urhebers*], but also by their ecological and "technical" meaning (i.e., teleological) [*ihre ökologische und "technische" Bedeutung (d.h. teleologisch)*]. (Seilacher 1951, p. 279)

Moreover, British invertebrate paleontologist Martin Rudwick (1932–) spoke of a quasi-engineering approach to form analyses to indicate his emphasis on form arrangement. He used it for grounding the inference from a form, i.e., a structure, to its possible function. For instance, he wrote

> From our knowledge of natural and artificial aerofoils, and of the structural requirements of their successful operation, we conclude that the pterodactyl forelimb would have been physically capable of functioning as an aerofoil. From our knowledge of the energy requirements for powered flight and of the energy output of vertebrate muscle, we conclude that it would not have been capable of functioning as a flapping wing for powered flight. (Rudwick 1964, p. 33)

Following this lead, in their influential book *Mechanical Design in Organism*, Stephen A. Wainwright and colleagues declared: "We believe that the study of mechanical design in organisms using the approach of the mechanical engineer and the materials scientist can promote an understanding of organisms at all levels of organization from molecules to ecosystems"

(Wainwright et al. 1976, p. v). Therefore, the use of a technical vocabulary encouraged the examination of the similar design principles shared by both machines and organisms.

From a methodological perspective, these practitioners quite chorally hold the view that the functional organization of organic form, i.e., the principle responsible for its internal construction, could be grasped only by bringing together all the diverse elements and relations that hold it together. Consequently, the majority of them defended what they termed a synthetic methodology. For instance, Seilacher (see Figure 1) proposed a working concept for morphology aimed at encompassing all the possible elements responsible for morphogenesis. He saw form as the result of three mutually constraining factors: fabrication, functional, and phylogenic limitations. In order to provide possible morphological explanations, the biologists should focus on all of them and examine which of these elements played a greater role. This was, in a nutshell, the main aim of his famous triangle (Tamborini 2020a).

The architectonical approach to form would be adopted at-length in biomechanical studies, and, as I will show in the following pages, it would offer the theoretical and historical framework for the current implementation of robotics in morphological investigations.

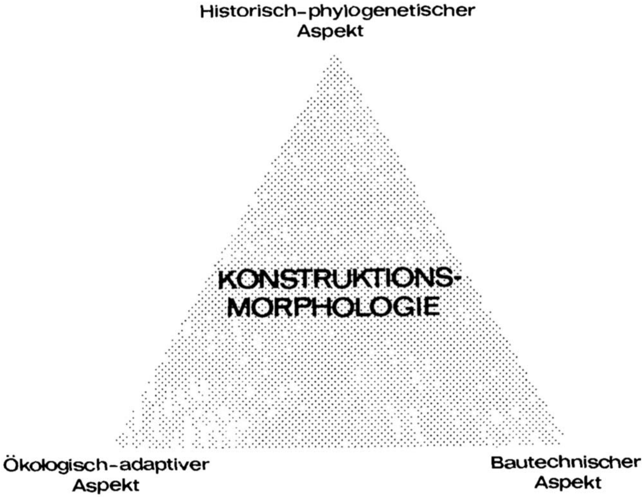

**Figure 1.** Seilacher's triangle as published in 1970. Reprinted with permission from Wiley.

## 2. From Bio-Robotics to Robotics-inspired Morphology

### 2.1. Case 1: OroBOT

To illustrate the role of robotics in recent morphological investigations, I will now turn to two emblematic case studies. The first one is about a classic topic in mechanical morphology: the reconstruction and explanation of organisms' locomotion. Although the topic is rather conventional—for instance, it was one of the main research topics of Petersen—the methods of investigation are pretty innovative. The organism under investigation is the *Orobates pabsti*. It is a 4-legged vertebrate that went extinct about 300 million years ago. The study of the morphology of this well-preserved specimen is quite important since it could offer some precious insights into the evolution of terrestrial vertebrates. Since the *Orobates* are an early outgrowth of the lineage that led to amniotes, which really completed the vertebrates' transition to land by becoming independent from open water during early development, the comprehension of how these specimens were able to move from water onto land is essential for a better understanding of one of the major transitions in vertebrate evolution.

A multidisciplinary team of biologists, engineers, and designers was set up to cope with this problem. They were faced with the difficulty of reconstructing the morphology of an extinct animal, coming up with a possible hypothesis on its locomotion, and ultimately using morphological data to investigate broader biological transitions and evolutionary mechanisms. Their method of investigation was technologically guided. German biologist John Nyakatura and colleagues carefully reported in *Nature* their methodology. First, they used CT and 3D reconstructions to obtain a digital model of the fossilized *Orobates*. Second, they digitalized the fossil trackways, which were supposed to belong to the *Orobates*. Third, they obtained data on the mechanical principles of sprawling locomotion of extant tetrapod species. Fourth, a digital marionette of the *Orobates* was designed, and dynamic and kinematic simulations of *Orobates*' locomotion were run. Fifth, having obtained this great mass of data, the scientists used it to narrow down the possibilities and thus were able to eliminate unlikely gaits. This led to the creation of what they termed the sprawling gait space of the *Orobates* (Nyakatura et al. 2019).

Last, they designed the robot OroBOT (see Figure 2) to account for dynamics of locomotion of the *Orobates*. The OroBot was built in collaboration with bioengineers at the École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne. The OroBot's spine was segmented into eight operated joints: two for the neck, four for the trunk, and two for the tail. The feet consisted of three passive, compliant joints. The designed parts of OroBOT were made of polyamide plastic material and created with laser selective sintering.

**Figure 2.** OroBOT (Nyakatura et al. 2019). Credit: Alessandro Crespi (EPFL Lausanne).

Nyakatura and colleagues described their intent; the

> OroBOT was designed to closely mimic the anatomy of the Orobates fossil, the mass distribution of body segments and the position of the centre of mass - The design and control of the robotic system (the physical OroBOT model) was based on a previous biomimetic platform that successfully replicated the kinematics and dynamics of a walking salamander, which was here altered to match *Orobates* morphology. (Nyakatura et al. 2019, p. 354)

The robot was employed as a technical platform for understanding the animal's gait function. Scientists analyzed its form-function complex and tested 15 possible gaits against OroBOT's functional arrangement. Based on the digitalized data and on the use of the robot, the biologists were then able to understand how Orobates moved its four legs on the land. In fact, with the OroBOT the scientists were able to perform experiments under real world physical conditions (gravity, friction, etc.) and to estimate power expenditure in different simulated gaits and postures. The results suggested that the Orobates had a more upright, advanced, and mechanically energy-saving locomotion than the first tetrapods. This discovery, therefore, suggested that "these advanced terrestrial locomotor properties may be assumed to have been present in the last common ancestor of diadectids and amniotes—that is, within the amniote stem lineage and preceding the subsequent rapid radiation of crown amniotes" (Nyakatura et al. 2019, p. 354). As paleontologist Stuart Sumida reported to *Scientific American*, "Nyakatura and his colleagues have gotten us as close as we can get without a time machine" (Wong 2019).

Nyakatura and colleagues' robotics-inspired morphological research was so innovative that the journal *Nature* dedicated the cover of Volume 565, Issue 7739 to it. Indeed, the OroBOT was not only used as a platform to ask new questions and gain more data on what happened in earth history millions of years ago but due to its salamander-like structure, it was also used as inspiration to further combine bioinspired robots with neuroscience and genetic data to investigate broader biological questions. The salamander is a prime model organism due to its ability to regenerate locomotion after a total spinal resection; in a recent publication, neuroscientist Dimitri Ryczko and colleagues proposed to bring together "functional genomics, systems neuroscience, numerical modeling, and robotics approaches [to] understand the interplay between central and peripheral mechanisms" (Ryczko, Simon, and Ijspeert 2020, p. 1). Specifically, they used salamander neuromechanical models and robots to "decipher how movements emerge from the interactions between central and peripheral signals" (Ryczko, Simon, and Ijspeert 2020, p. 1). Hence, the robotics-inspired morphology was used to both gain access to the form study of extinct animals and ask broader questions about major biological transitions.

### 2.2. Case 2: Tunabot

The second case study about tuna robotics presents the implementation of robotics in the study of the morphology of recent organisms. Yellowfin tuna are high-performance swimmers who often operate at high frequencies, particularly when escaping predators or capturing their prey. Their swimming is extremely efficient, and they can change their tempo between moving quickly and moving relatively slowly. Although several fish-like robots and autonomous underwater vehicles have been produced in the past, these robots cannot achieve the performance level of tuna. This shortcoming was based on a lack of morphological understanding of tuna and other scombrid fishes' form-function complex. As biologists Dylan K. Wainwright and Lauder put it, "in many cases, we lack a mechanistic understanding of the functional morphology of swimming animals" (Wainwright and Lauder 2020, p. 1). To understand how the form-function arrangement of Tuna does work, Lauder's team, together with mechanical and aerospace engineer Hilary Bart-Smith's team, decided to use robotics-inspired procedures. Consequently, these scientists developed a Tunabot, a robot that replicated a "simplified version of scombrid fish morphology" (Zhu et al. 2019, p. 2). Like the OroBOT, the Tunabot was also designed through a biomimetic process: its design "was inspired by computed tomography (CT) scans of yellowfin tuna (*Thunnus albacares*), and the size of the platform is similar to adult-sized Atlantic mackerel (*Scomber scombrus*) or young yellowfin tuna" (Zhu et al. 2019, p. 2). Here again, the biomimetic principle was instrumental in the creation of a robot that would enable the scientists to ask new biological questions. As they put it,

> whereas biology can inspire a high-performance robotic platform, development of such a platform will also provide an opportunity to experimentally study both high-speed swimming and the function of features unique to high-performance fishes. Designing fish-inspired platforms that are capable of high-performance swimming is therefore crucial for expanding the capabilities of nontraditional propulsors in both a utilitarian and a scientifically relevant way. (Zhu et al. 2019, p. 1)

Tunabot's external shape took inspiration from a "yellowfin tuna body with all fins removed" (Zhu et al. 2019, p. 8), whereas the motor in the Tunabot's head was connected to the caudal fin via an actuating mechanism. Once designed and 3D-printed (see Figure 3), the Tunabot's velocity was measured.

The implementation of robots seems straightforward in disciplines where experimentation in vivo is excluded on principle, such as when the organisms are extinct, and therefore the rationale for using robots in neontology is quite different. The justification for designing the Tunabot was the conviction the form-function complex needed to be understood in

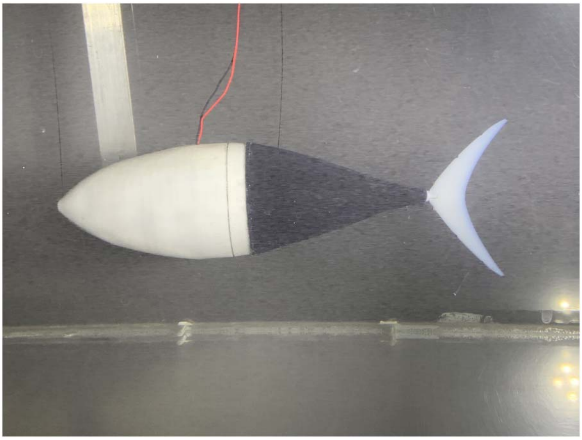

**Figure 3.** Tunabot (Zhu et al. 2019). Credit: George Lauder.

conjunction with the environment in which it operates. The control of how form-function is possible only if its medium is considered in the morphological investigations. Lauder, in another programmatic paper, noted, “the feedback loop between animal movement and the flow and force response from the surrounding environment can lead to non-intuitive and novel movement biomechanics that can be studied with robots” (Gravish and Lauder 2018, p. 4). This interaction generates new questions and hypotheses on animal locomotion. In the case of the Tunabot, for instance, the goal was to come up with new questions and data for understanding the biomechanical efficiency of open-ocean fish.

This investigation generated a productive loop between robotics and biology. Lauder and Gravish announced that this approach, which involves reciprocal illumination and experimentation between biology and mechanical systems, highlights how close-knit robotic and biological experiments can lead to a research feedback loop whereby robots can be used to generate biological hypotheses. The end result of this intellectual feedback loop is that roboticists expanded their control capabilities using wave modulation, and biologists, in turn, were able to develop and test new control strategy hypotheses for maneuvering [organisms] (Gravish and Lauder 2018, p. 5). The construction of the Tunabot thus enabled scientists, step by step, to control all the factors and elements that might have affected the form-function complex.[4]

## 3. The Integrative Approach of Twenty-First Century Robotics-inspired Morphology

The employment of robotics in these two case studies is quite representative of the methodology of recent morphological research. First, in both cases, robots were used to enable morphological investigations. They allowed the scientists to come up with possible theories of locomotion for both an extinct organism, the *Orobates*, and a high-performance fish, the Yellowfin tuna. Therefore, they were not simply used to test possible background hypotheses but rather as proper targets for their investigations. Due to the scarcity of data and the impossibility of obtaining direct access to the phenomena under investigation, the robots, constrained through a series of parameters obtained from other physical models (in the case of Tunabot) or via a morphological study of related organisms (like was done with the OroBot), became the morphological explanandum. As bio-engineers Barbara Mazzolai and Cecilia Laschi observed, “bioinspired

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[4] From the concepts used in the quotations presented in this paragraph, such as the notion of feedback loop, the debt twenty-first century robotics-inspired morphology owes to cybernetics is quite evident.

robots turn particularly useful whenever it is practically impossible to investigate a biological question (in a non-simulated way) by means of any living organism" (Mazzolai and Laschi 2020, p. 1088). Robots are therefore understood as concrete objects that need to be built for understanding something that is not otherwise accessible nor manipulable.

Hence, by studying morphology through the use of robots, biologists are able to study the form-function complex in vivo, though through the use of robots that biomimetically represents natural processes. By doing so, besides playing the classical epistemic functions of testing hypotheses and validating background theories,[5] robots assume a further function. Philosopher Edoardo Datteri named it a prediction-oriented task. Within this task, the robots' "goal is to predict the behaviour of the living system whose theoretical model is implemented in the robot" (Datteri 2020, p. 10). Furthermore, "the behavior of the robotic system in particular circumstances is regarded as informative about the behavior that the target system would display in similar circumstances" (Datteri 2020, p. 10). I agree with Datteri; these devices are prediction oriented. To push this interpretation further, I would also argue that in robotics-inspired biology, the devices concretize a morphological scenario, the form-function complex, not reachable otherwise. This robotically given scenario is what biologists aim to explore and control. The hybrid environment-robot-complex becomes the target of the morphological investigations since it presents how form and function work together in vivo. This is one of the main peculiarities of twenty-first century robotics-inspired morphology: the possibility of experimenting with a not otherwise given explanandum. Therefore, I would like to expand on Datteri's definition of non-interactive robots, such as the OroBOT and the Tunabot, to better define their function in morphological investigations: "by observing how the robot behaves in controlled experimental settings, one acquires new knowledge about the target system" (Datteri 2020, p. 9), which is only accessible through robots' design.[6]

This point has one main consequence. It stresses the pivotal role of biomimicry in this set of morphological investigations. Biomimicry plays an important role in the so-called interactive robots which interact with living systems (see Datteri 2020) and robots that only marginally interact with the environment like the OroBOT. The design of nature-inspired

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[5] As Datteri noted, this is the task of the so-called standard model in robotics: its purpose "is to test a how-possibly theoretical model of the mechanism enabling a living system to behave in a certain way. The model is implemented in the robot, and the behavior of the robot is compared with the behavior of the target system in suitable experimental settings" (Datteri 2020, p. 9).

[6] This brings the discussion on the differences between robots and, broadly, models in knowledge production. See, for instance, Datteri 2020.

machinery is an essential step to make visible all the parameters that influence form's structure. Biomimicry offers the starting point for a deeper study of morphogenetic dynamics.

The biomimicry principle behind robots' design implied that the process of morphogenesis should be applied to the development and design of robots as well. That means that "in diverse ecological niches, such bioinspired robots would develop purposive morphologies and abilities for negotiating their environments" (Mazzolai and Laschi 2020). This is, in fact, what bioengineer Mazzolai has recently called for. For instance, together with her team, she developed a robotic device that grows from the tip, as plant roots do. Through this addition of material, the robot is able to move through different environments (see, for instance, Mazzolai et al. 2014; Mazzolai 2017; Sadeghi et al. 2017). Despite the strong biomimicry aim of Mazzolai's research, the robot could then be used to explore broader biological phenomena such as, for instance, the notion of plasticity and the relation between growth, development, and movement.

Robotics-inspired morphology has deep historical roots. These case studies reveal something important about the origins of current robotics based morphology and biology. The notion of organic form advocated by the supporters of a robotics based morphology was deeply technical. They meant organic form as the emergent arrangement of different factors, which could be best understood as a construction. This remark is important both historically and theoretically. It suggests another genealogy from the Kantian-Romantic paradigm of morphology.[7] This paradigm, which put a premium on, among others, the notion of Gestalt and form's intrinsic proprieties, was taken up by the organicism movement during the twentieth century. Recently, it has been used to frame the bio-inspired disciplines, such as biomimicry and bionics. Concisely put, the motto of the supports of bionics and biomimicry is "form follows nature" (Tamborini under review). As nature-inspired scientists, they also shared the idea that nature proceeds technically in producing their forms. Unlike the former group, the latter scientists are not interested in form's intrinsic dynamics. They aim at developing constructional analyses to discover how organisms' parts can be harmonized into an ordered and versatile construction (as the fourth approach to morphology described above emphasized). This is the rationale that enables "map[ping] biological mechanism descriptions into robotic mechanism descriptions" (Datteri and Tamburrini 2007), thus biomimetically constructing robots. Therefore, robotics-inspired morphologists only marginally, if at all, underwrite the form-follows-nature

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[7] For the romantic conception of machine, see Tresch 2012.

organicist motto. Rather, they support the fourth group of morphologists discussed in the first section of this paper.

This different theoretical and historical root is clearly mirrored in Nyakatura and colleagues' methodology. They criticized the methods that had previously been used to investigate *Orobates*' morphology and locomotion. These have analyzed the organism only from a restricted perspective. For instance, the scientists reported that morphological studies have manly focused on either the anatomical aspects or on the biomechanical features of the *Orobates*. Furthermore, classical morphological analyses have looked only at the trackways of extant organisms or have too easily connected form and function without taking broader environmental factors into account. Conversely, Nyakatura and colleagues pursued "an integrative approach that combines the advantages of these different strategies to reconstruct the locomotion of tetrapod fossils" (Nyakatura et al. 2019, p. 352). This is a classical methodological choice proper of the supporters of the architectural approach to form. Since the organic form is meant to be a construction, an assembly of elements that are heaped together, the combination of historical with structural, functional, and environmental elements is mandatory for understanding the organizational properties of form. This was the essence of Seilacher's triangle.

Therefore, the second pillar of twenty-first century robotics-inspired morphology is its integrative approach. In order to understand what organic form is and how it changes through time, different datasets and approaches should be brought together. Morphology became a collective effort not reducible to one single discipline. This development, in turn, has a long history and has shaped what I have called the twentieth-century desire for morphology (Tamborini under contract).

## Conclusion: The Material Turn in Morphology

This paper has called attention to the knowledge production mechanisms of twenty-first century robotics-inspired morphology. This methodology, even if in close relationship with other engineering-based approaches to morphogenesis, differs from the nature-inspired program advocated by biomimetics and other disciplines, for it designs robots to biologically examine and directly experiment with morphogenetic processes. In other words, nature inspired robotics is specular to robotics-inspired morphology. Both share the idea of being able to technically control the phenomenon of natural morphogenesis. With its origin in the same engineering or technoscientific vision of nature, robotics-inspired morphogenesis takes a step forward. It sought not only technoscientific control of the development of possible forms, but it deeply aspires to explain them.

Second, by investigating how robotics-inspired morphology is conducted, I am now able to call attention to what I would like to call a material turn in the study of form.[8] In the study of organic form a first digital turn took place in two phases; first, during the 1960s and, second, at the beginning of the twenty-first century. During the 1960s, paleontologist Dave Raup used computers to create and visualize a virtual space in which, given certain physical parameters, all the possible theoretical shell forms could be generated. This was a turning point in morphological research since it entailed the possibility of visualizing and controlling the dynamic morphogenesis (see, for example, Raup 1961, 1962, 1969; Sepkoski 2012; Tamborini under contract, under review b).

Second, between the end of the twentieth and early twenty-first centuries, the introduction of CT scanners, 3D images, and 3D prints fully digitalized the morphological workflow. Forms could now be virtually manipulated and simulated. Furthermore, morphospaces and computer simulations were used to narrow down the morphological elements that may contribute to shape changes. This brought morphology closer to other engineering and technoscientific disciplines.

Today, we are witnessing a material turn. The simulated and digitalized morphological data are used only as starting points for further technical elaborations. The process of morphogenesis needs to be studied in its own environment to possibly master all the factors and variables responsible for morphogenesis. In a simulated and virtual scenario, every variable that co-participates in the form-function complex can be represented. For instance, while many of the obvious features "of a live stimulus can be adequately mimicked in computer animated images, other features, like depth, motion, and texture, cannot be equivalently represented" (Spinello et al. 2019, p. 2). Biologist Krause and colleagues commented extensively on the limitations involved in experiments with 2D simulated animals.[9]

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[8] I am not arguing here for a material turn in biology, only in morphology. For what may be called a digital-material turn in biology, i.e., its computerization and the use of big data in biology, see, for instance, Agar 2006, Garcia-Sancho 2012, Leonelli 2016, Sepkoski 2017, Sepkoski and Tamborini 2018, Strasser 2019, Tamborini 2020c.

[9] Philosophers Edoardo Datteri and Guglielmo Tamburrini described the difference between computer simulation and biorobots as follows: "biorobotic experimental practice does not give rise to the methodological problem of controlling whether behavioral (dis-)similarities between target biological systems and computer-simulated agents take their origin in ad hoc or inaccurate simulations of the environment. One should be careful to note, however, that there is a methodological trade-off between computer simulation and robotic implementation of mechanism schemata. Computer simulations are unaffected by methodological problems arising in biorobotics on account of the fact that biorobots are immersed in natural environments" (Datteri and Tamburrini 2007, p. 413; see also Datteri and Schiaffonati 2019).

Fish species can usually sense the presence of conspecifics through the lateral line (via mechanical stimuli), and most species of social insects require olfactory stimuli for social recognition. Computer visual simulations simply do not exist in the third dimension. Animal interactions "require the physical presence of a con- or heterospecific to fight, mate or cooperate with and these types of interaction, by their very nature, cannot be established with a virtual partner and require a robot" (Krause et al. 2011, p. 370). This material turn in morphology is marked by the coexistence of the robotic, the virtual, and the real to understand the structures and dynamics of shape. The physicality of the robot, its capacity to be immersed in real mediums, is the essential epistemic feature of robotics-inspired morphology. This materiality makes robots worth actually making.[10]

Hence, and to conclude, what will be the identifying feature of twenty-first century robotics-inspired morphology? By using robots as targets for their investigations, these analyses made clear the passage from biorobotics, or nature inspired robotics, to robotics-inspired biology. This transition implies a bridging of the gap between technology and nature. Shape changes should now be studied through in vivo investigations (such as the classical anatomical dissection of Tuna), in silico (as, for example, through CT scanners or computer simulations), and eventually again in a hybrid and highly integrated *in vivo-silico-robotic* environment. The full integration of these methodological layers would help illustrate the elements' structural interplay that characterizes shape change.

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[10] This recent shift is reminiscent of the use of automata during the eighteenth century. As historian Jessica Risikin argued, both the late eighteenth and twentieth centuries were time periods in which machines were used to analogically explain organisms, as well as to simulate them. This, Riskin argued, implied that machines were used as "an experimental model from which one can discover properties of the natural subject" as their counterparts in the twenty-first century (Riskin 2003, p. 98; see also Riskin 2016). The difference between the simulation of organisms pointed out by Riskin and the material turn in morphology I have revealed is that the latter, unlike the former, implies a continuum between the digital, the robotic, and the real. Through feedback loops, both co-participate in the making of the morphological explanandum.

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