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PERSPECTIVE

Biodiversifying bioinspiration

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Abstract

Bioinspiration—using insights into the function of biological systems for the development of new engineering concepts—is already a successful and rapidly growing field. However, only a small portion of the world's biodiversity has thus far been considered as a potential source for engineering inspiration. This means that vast numbers of biological systems of potentially high value to engineering have likely gone unnoticed. Even more important, insights into form and function that reside in the evolutionary relationships across the tree of life have not yet received attention by engineers. These insights could soon become accessible through recent developments in disparate areas of research; in particular, advancements in digitization of museum specimens, methods to describe and analyze complex biological shapes, quantitative prediction of biological function from form, and analysis of large digital data sets. Taken together, these emerging capabilities should make it possible to mine the world's known biodiversity as a natural resource for knowledge relevant to engineering. This transformation of bioinspiration would be very timely in the development of engineering, because it could yield exactly the kind of insights that are needed to make technology more autonomous, adaptive, and capable of operation in complex environments.

1. Biodiversity as a natural resource for engineering

Bioinspiration draws ideas for engineering solutions from living systems. The world's biodiversity can be seen as a natural resource for technology development, much like forests, water, minerals, fossil fuels, or geothermal energy serve as resources to meet different needs [1, 2]. Despite its proven utility, the current pace of bioinspiration as a field has left this natural resource largely unexplored and underused. Bioinspiration is currently progressing at an irregular pace where periods of slow progress are punctuated by bursts of rapid innovation that occur whenever one of the relatively few organismal models is introduced. For example, the development of a wide array of liquid-repellent materials was largely inspired by only two model organisms, the lotus leaf [3] and the pitcher plant [4]. How would greater access to biodiversity increase bioinspired innovation?

In this perspective, we argue that incorporating biodiversity in bioinspiration through collaboration between disparate fields of research could increase scientific and economic impacts by facilitating questions based on broad evolutionary patterns. Ongoing developments in digitization of natural history collections, computational analysis, engineering, and machine learning may allow robust access to the natural resources of evolution's design bank.

2. Bioinspiration's potential for scientific and economic impact

Advances in characterizing the function of biological organisms, concurrent with the development of advanced fabrication techniques, have resulted in a

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five-fold increase in bioinspired grants, research, and patents since 2000 [5]. Indeed, one economic study predicts that bioinspiration could generate $1.6 trillion of total output (research, products, investments, start-up companies, etc.), while saving another $500 billion via resource and pollution mitigation by 2030 [5]. Despite bioinspiration's successes and potential for growth as a field, the pace of innovation has been restricted by the ad hoc methodology by which engineers identify organisms of interest.

Current limitations to accessing and navigating information amassed by biodiversity researchers as well as a lack of awareness regarding the potential of biodiversity have led most engineers working in the area of bioinspiration to focus narrowly on a small number of established organisms. Particularly successful cases of bioinspired engineering tend to trigger innumerable follow-up studies that most of the time only provide incremental advances at best. For example, a 1997 report [3] on the self-cleaning functionality of superhydrophobic lotus leaves, coupled with a 1999 report of fabricating controlled superhydrophobic structures [6], have directly inspired over 1700 follow-up studies on the wettability of lotus leaves and engineered lotus mimics. While the follow-up reports did serve to mature our understanding of superhydrophobicity [7], they never moved beyond the same basic concept of trapping air pockets underneath water. The next major disruption in bioinspired wettability did not come until 2011, where pitcher-plant inspired porous surfaces were impregnated with lubricant to durably repel a wide variety of test liquids [8, 9]. These two works have already been cited over 1000 times and elicited well over 100 follow-up studies and patents that similarly involve lubricant-impregnated materials [10–12].

In other words, the current pace of bioinspiration is characterized by bursts of innovation that are often triggered by new sources of biological inspiration. Interspersed between these bursts are long periods of incremental advances and conceptual stagnation. Even the limited number of organisms that have served as sources for bioinspired research so far have unleashed substantial scientific and economic potential. How high could the ceiling be raised by integrating more organisms and their associated functionalities into bioinspired research?

3. The untapped engineering potential of biodiversity

The success of bioinspiration depends on whether a good match between an engineering problem and a biological solution can be found. The small number of biological systems currently being used in bioinspiration represents only a negligible fraction of the world's biodiversity (estimated at about 8.7 million eukaryotic species [13]). This narrow focus limits the matches that can be made between the biological and engineering domains and hence the innovation potential of bioinspiration as a whole. Harnessing a substantial fraction of the world's biodiversity for bioinspiration would reduce this bottleneck and would enable a dramatic increase in scientific output and technological innovation.

The scientific and innovation benefits of putting a substantial fraction of the world's biodiversity to use for bioinspiration could go far beyond increasing the number of one-to-one matches between engineering problems and biological solutions. It would give engineers the opportunity to learn from evolutionary patterns that exist across species. Such patterns contain information on how a general solution approach (e.g. quadrupedal walking [14]) can be adapted to suit an entire family of problems (e.g. locomotion at different speeds and on different terrains [15], maneuverability in confined spaces). Moreover, access to increased biodiversity for engineers could facilitate research for broad questions that span convergent adaptations across disparate taxa (e.g. flight, conserving water, how to make the color blue).

Increasing the awareness of biodiversity in bioinspired engineering provides engineers in the field with an evolutionary context that can facilitate development of technological frameworks based upon functional relationships in nature. Biological evolution includes processes such as adaptive radiation [16] that have led to the modification of a single biological principle according to the constraints of multiple ecological niches. Understanding the 'design rules' behind these evolutionary diversification events will give engineers a way to create a large number of customized engineering solutions in a highly effective manner. This would make customized engineering solutions more accessible (e.g. to small and medium-sized companies) and could hence result in increased and more efficient economic activity.

4. Biodiverse bioinpiration: a 21st-century opportunity

At present, the convergence of three scientific developments (figure 2) is finally placing biodiversity within the reach of bioinspired engineering:

(i) Obtaining detailed quantitative phenomic biological data (i.e. on all the physical traits of an organism) across a large number of species has been prohibitively difficult, but progress on the digitization of natural history specimens is about to change that. Natural history collections [17] are currently being digitized with an ever-increasing degree of automation and efficiency. At the same time, the employed digitization methods are also progressing with respect to the information that they can capture,

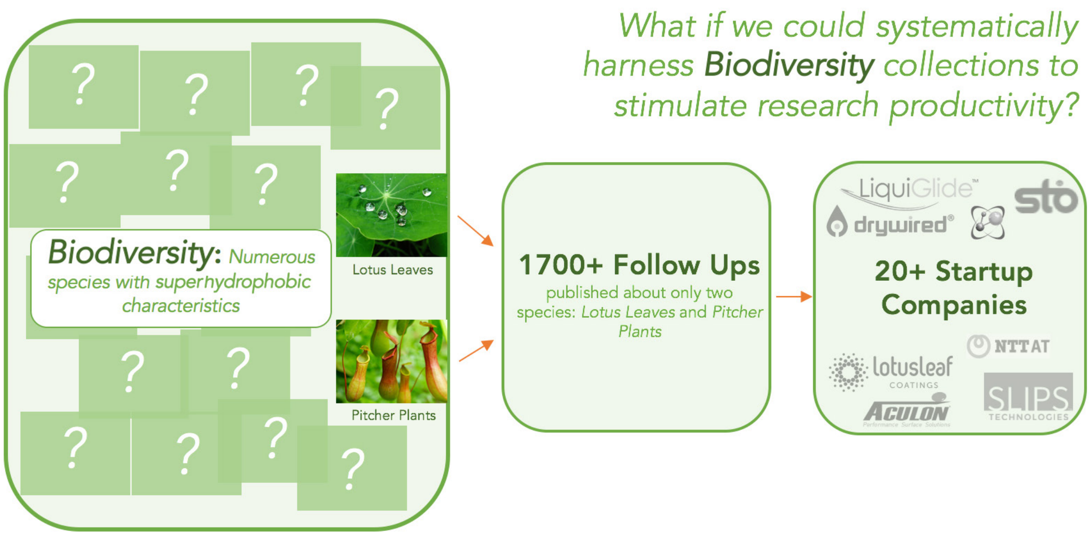

Figure 1. Impact of two related model systems for bioinspired engineering (lotus and pitcher plant) on scientific output and technology development.

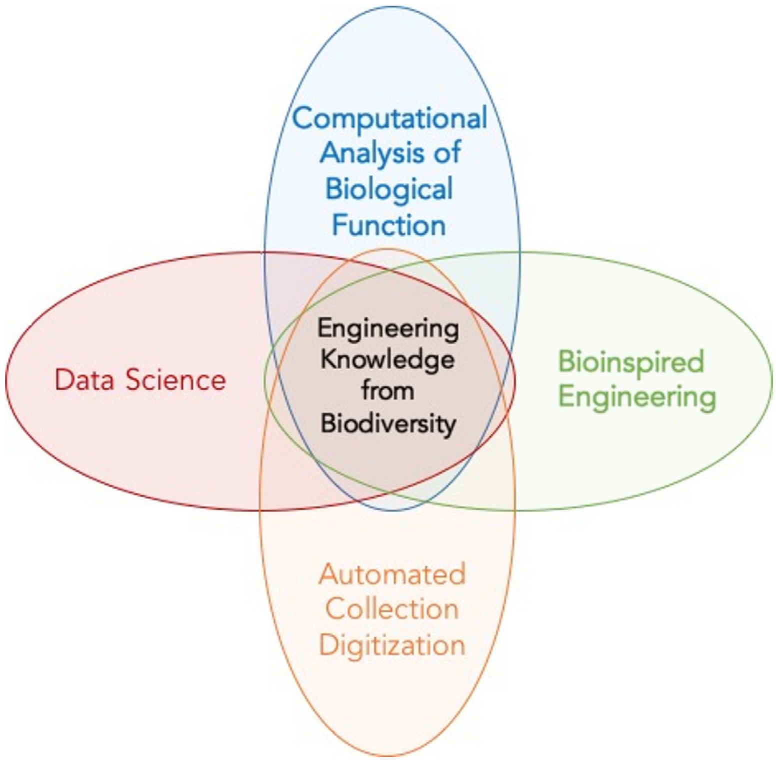

Figure 2. Convergence of scientific developments that enables harnessing biodiversity for engineering knowledge.

from digital photos to 3D tomographic models of specimens. Other modalities, (e.g. spectroscopic analysis of materials), could be added to the mix to extend the types of available information. Through the digitization of specimens in large natural history collections, quantitative data representing substantial portions of the world's cataloged biodiversity could become available in the near future.

(ii) Currently, phenomic data collected from dead museum specimens is often difficult to connect to *in vivo* function. However, this is increasingly mitigated by advances in computational methods for the simulation of biological function that allow detailed predictions of function from form. For example, the aero- or hydrodynamic effects of biological shapes can be predicted by virtue of computational fluid dynamics. With access to such computational predictions for a large number of species, searches for biological systems of interest to engineering could be based on form as well as on functional effects, e.g. one could ask which biological body shape produces the lowest drag force.

(iii) Finally, advances in data analytics and machine learning, such as the abilities to carry out unstructured searches and match semantic queries across very large datasets (e.g. search for small mammals that are flying predators), are making it possible to search through the large amounts of data that are necessary to represent biological form and function across a substantial share of the world's biodiversity (e.g. [18, 19]). Having demonstrated efficient mining of text-based data sets for biological function information, these methods show promise for expansion to other types of data. When applied to the morphological data obtained from the digitization of natural history specimens and computational estimates of their *in vivo* functions, these data analysis methods should be able to discover new insights into the evolution of biological function. Several frameworks already exist for organizing information about form and function of biological systems to make it useful for biologists, engineers, and designers [20]. For example, the design by analogy to nature engine (DANE) [21] supports unstructured searches over structure-behavior-function (SBF) models of both biological and engineering designs. An SBF model of a design [22] explicitly specifies the functions of the system, the heterogeneous components and connections in the structure of the system, and the causal behaviors by which the system's structure achieves its functions. The text understanding technique [19] is intended to automatically build the SBF models in the DANE library to enable semantic searches. Such an approach would enable the development of objective/systematic methods for driving engineering innovation through bioinspiration on an unprecedented scale.

4.1. Digitization of natural history collections

Natural history museums are archives for the known portion of the world's biodiversity with collections that have often been accumulated over more than 100 years and can contain in excess of 100 million specimens [23]. It has been estimated that the total amount of curatorial units (registered data records) in natural history collections around the world fall between 1.2–2.1 billion (10^9) of which, about 3% are currently accessible over the Internet [24].

Specimens cataloged in natural history collections typically also contain valuable contextual data such as collection date, location, and field notes which place biological models within their relevant ecological context. Most major natural history museums [17], as well as many smaller institutions, now have ambitious programs to digitize their collections. Over the years, these programs have developed from the digitization of specimen metadata (e.g. textual collection information), to digital photographs, and to various state-of-the-art tools for 3d digitization, such as laser scanners, photogrammetry, CT scanners, or confocal microscopes [25, 26]. Some of these methods allow the non-destructive imaging of internal and external structures. Such non-destructive imaging techniques allow data to be extracted from a large number of specimens that include rare or extinct organisms, thus increasing access to biodiversity.

Efforts have been underway to increase the efficiency of the digitization process through automation [27]. So far, the most striking successes in the automation of digitization have been achieved with specimens that allow for uniform handling such as herbarium sheets [28, 29], but digitization efficiency has been increasing broadly. All these developments are creating a rapidly growing body of digital data that represents an expanding portion of the world's biodiversity with more and more detail. Programs like integrated digitized biocollections (iDigBio [30]), and various projects funded by the National Science Foundation's Advancing Digitization of Biodiversity Collections Program [26] are currently underway to digitize biological collections from a collective of institutions across the US. Individual institutions are also establishing in-house infrastructure to digitize their specimen collections such as Smithsonian Digitization Program Office (DPO) [31], and American Museum of Natural History's Microscopy and Imaging Facility. These programs offer free, publicly accessible databases that democratize access to this knowledge and provide research opportunities for scientists, students, and educators around the world.

4.2. Computer simulation and functional understanding

Deriving functional properties from the morphologies of biological systems using physical experimentation is far too costly to allow for analyses across a large number of species. Fortunately, rapid growth in computing resources combined with more sophisticated numerical methods, has made it possible to utilize computational simulation to accurately predict functional characteristics for a substantial number of domains and increasingly complex morphologies. Examples include biomechanical simulation of kinematics and motor control (e.g. walking gaits [32], manipulation, biting [33]), fluid dynamics (e.g. flight [34, 35], swimming [36], blood flow [37]), acoustics

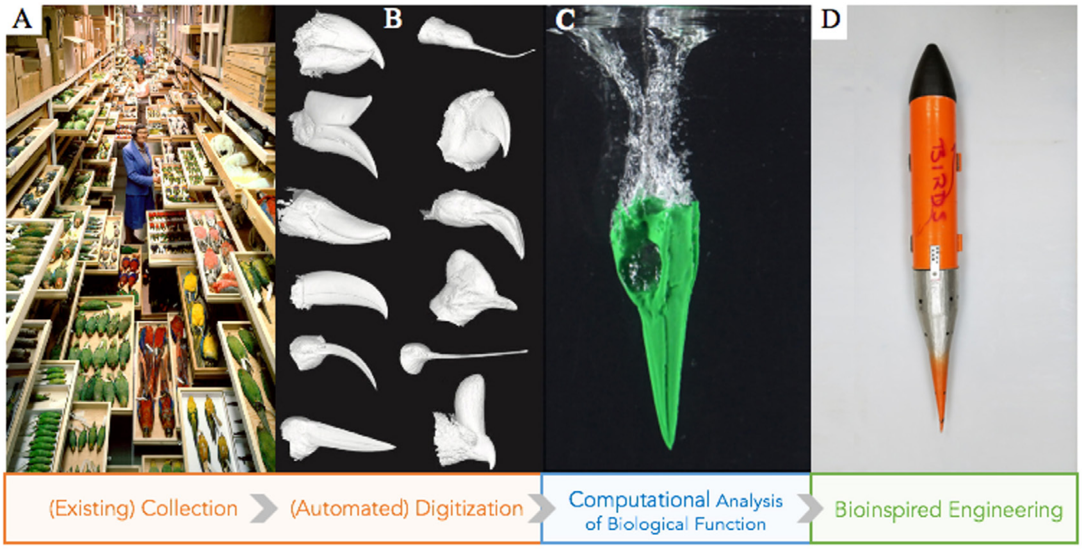

Figure 3. Example of research spanning natural history collections, digitized specimens, physical analysis of biological function, and bioinspired engineering: (a) view of the bird collection of the National Museum of Natural History (photo: Chip Clark, NMNH); (b) 3d models of bird beaks from digitized specimens (Photo: Gavin Thomas/University of Sheffield, scans from the Natural History Museum, London); (c) 3d printed prototype of Gannet specimen diving into water [42]; (d) prototype for a water-plungeable vehicle inspired by bird-beak morphology [42] (photos: Brian Chang and Sunny Jung, Virginia Tech).

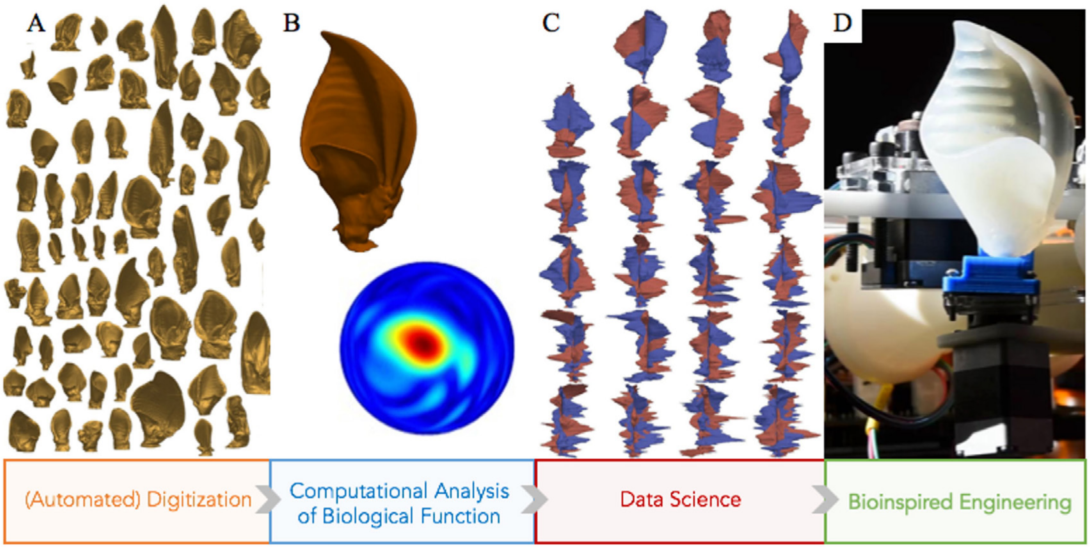

Figure 4. Example of research spanning natural history collections, digitized specimens, computational analysis of biological function, machine-learning analysis of biodiversity, and bioinspired engineering: (a) digital models of bat pinna shapes obtained by micro-computer tomography; (b) acoustic pinna characteristics (beampattern) predicted from pinna shape using numerical methods; (c) analysis of diversity in pinna shapes using principal component analysis ('eigenears'); (d) sonar head with a receiving baffle mimicking a horseshoe bat pinna.

(e.g. echolocation [38], communication [39]), and bulk molecular dynamics (e.g. friction, wetting [40]). A critical factor for advancing biodiversity-based bioinspiration will be the development of methods that can exploit information from a small number of live specimens to predict functional traits across a large number of related species for which only morphological data is available.

4.3. Bioinspiration and data analytics

Extracting scientific knowledge and engineering inspiration from computer simulations of biological function obtained across large numbers of taxa and specimens poses a major challenge. Algorithms for statistical analysis on large-scale data sets can be used to address this challenge [41]. It should be possible to adapt statistical machine learning methods developed for processing massive 'big data' sets to mine dense digital representations of biological form (e.g. from CT scans) and function (simulation results) and combine them with other information resources, (e.g. databases of descriptive annotations/specimen metadata and the biological literature). Machine learning should be able to identify functional evolutionary trends within the underlying complexity of these massive biological data sets and facilitate the creation of descriptive models that are useful for engineers.

The convergence of current scientific developments in digitization of natural history collections, computational analysis of biological function, machine learning, and bioinspired engineering enable the harnessing of biodiversity and will direct the future of bioinspired engineering.

4.4. Progress towards integration

At present, mature research approaches that fully integrate all three aspects (i-iii) described above (figure 2) with bioinspired engineering have yet to be developed. However, there are already some incomplete examples illustrating that such an integration is possible—despite the remaining wide gaps between some of the pieces. For example, a large number of digitized bird beaks have been used to discover evolutionary trends [43] and 3D-printed replicas of beaks from diving bird specimens have been used to study the fluid dynamics of these animals crossing the air–water boundary [42]. Insights from these analyses can be used in the design of shapes for vehicles that can cross the air–water boundary efficiently (see figure 3).

For echolocating bats, the outer ears have diverse shapes across different species, where at least some shape features could play a critical role for the encoding of sensory information [44]. A large data set of digitized ear shapes has been used to predict the functional acoustic properties (beampatterns) of the ears [38], explain the biodiversity in terms of 'eigenears' [45] for the structures and 'eigenbeams' for their acoustical properties [46], and use insights from this analysis to design biomimetic microphone baffles [47] (see figure 4).

4.5. Transformative impact on open science and engineering challenges

Future smart engineering systems should be highly integrated, multifunctional, cognizant, and capable of fast adaptation in response to external stimuli or changes in the environment. Designing such systems poses a challenge, because it will typically require finding good solutions to highly dimensional optimization problems. Biological systems have evolved to satisfy such high-dimensional functional requirements in constrained and resource-limited environments similar to the ones that future smart engineering systems will be expected to operate in. The solutions offered by biological model systems are very much in tune with the present and future needs of technology development. Mobilizing the natural knowledge resource provided by biodiversity will likely have a transformative impact on technology.

The convergence described above will not only affect bioinspired engineering, but will also contribute to a better understanding of biodiversity. Natural history collections provide temporally and spatially distributed data which can be used to extract valuable insight into the evolutionary processes that have enabled these biological features. Deep learning methods that handle big data which are space and time varying are essential for this purpose. Enhanced understanding of specific and generic evolutionary processes will better inform engineering design both in algorithm development and in conceiving novel devices that can meet specific requirements. Insight into the morphology, relationships between form and function, and the mechanisms through which these 'biological designs' realize desired engineering functions will enable novel engineering designs. Furthermore, the wealth of natural collections allows inspection of classes of organisms which achieve desired functions, leading to more robust and resilient engineering designs, not necessarily limited to bioinspiration.

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