

Towards Parametric Design for Additive Manufacturing of Coral Structures Using a Digital Twin Approach

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Abstract

The coral restoration community has recently recognized the value of using a Digital Twin (DT) approach to the urgent problem of coral reef restoration and regeneration, and Additive Manufacturing (AM) is also emerging as a technology of interest in building physical reef structures. This work proposes a framework comprising three components: maps, models and data, that leverages AM within a DT framework to design and fabricate artificial coral structures and makes the case for their integration using Artificial Intelligence technologies. In addition to this, a first-of-its-kind structural classification for corals is proposed, separating form from texture, to enable implementation in design tools. A parametric design algorithm using the Grasshopper plugin in Rhinoceros 3D version 7 is also shown to generate forms resembling branching corals, which may be coupled with biological and environmental models to obtain a more accurate DT for the design and manufacturing of restorative coral structures.

Keywords

Additive manufacturing, coral regeneration, digital twin, bio-inspired design

Introduction

Coral reefs are currently experiencing several challenges to their survival, the resolution of which is vital given the significant impact they have on the ecological and human communities they serve. The engineering response to addressing this challenge has primarily involved the design, manufacturing and deployment of artificial reefs that combine architectural design with ecosystem regeneration. There have been concerns however about the limitations of these structures and the potential they have for long-term damage to marine ecosystems [1]. A key gap that has been identified is the underlying substrate materials in use that have included Portland cement, 3D printed polymers and binders, and metal, which do not typically provide the right chemical environment or meet targeted pH values [2]. Current approaches to this challenge include the use of nanotechnology for synthesizing new materials, for sensing, biobanking and supplements [3]. However, in addition to the development of sustainable materials for manufacturing artificial reefs, there is also a need to address the morphology and scalability of artificial coral structures [1], and an opportunity to make them more resilient to a changing climate.

Digital Twins (DT), while initially proposed primarily in the domain of product lifecycle management, have come to take on a more generalized interpretation. However, it is important to address the question of whether it is an appropriate term and approach for representing a biological system such as coral reefs. While the rest of this work attempts to make this justification, the definition of DT that it relies on comes from an often-cited work where a DT is defined as “*an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates etc., to mirror the life of its corresponding twin*” [4]. By a simple replacement of the word “product” with “ecosystem” or “organism,” or in the case of this work, “coral morphology,” the same term and methodology developed within it may be applied to natural structure – and that is the central premise of this work.

While there exists prior work on aspects of a DT for corals, such as algorithmic design of coral structure, underwater digitization and monitoring of corals, and simulation of the physical environment in coral ecology, these have not been integrated within a true DT framework. Recently however, one DT framework for corals has been proposed [1], with an emphasis on modeling and simulation. This work argues that it as a subset of a larger, more comprehensive DT and does not address the potential for Artificial Intelligence (AI) tools to accelerate its development. In this article, a more comprehensive framework for a DT of coral morphology is proposed, along with examples of elements of the framework as they are currently being developed. In the context of enabling the utilization of Additive Manufacturing (AM) technologies for coral regeneration, this is likely to be a critical step.

Framework

This work seeks to set the foundations for the development of a DT for coral structure. This DT can then generate scientifically informed coral morphologies. Prior work has sought to develop equivalent models for reefs by placing a large emphasis on 3D imaging of coral reefs to reconstruct their structural features as a central aspect of the approach [1]. While an important element of coral reef digitization, it is merely one aspect of a true physics, biology, and chemistry-informed DT. Figure 1, adapted from [5], demonstrates how coral reef morphology is strongly influenced by the environmental conditions it finds itself in. Variables such as light, hydrodynamic stress, sediment quality, and subaerial exposure results in varying geometric features. The analogy with manufacturing is apparent: a range of input conditions result in variations in design, even for an underlying process that is shared across all designed objects. The goal of this work is therefore to identify the models that relate all inputs of relevance to the emergence of coral form and leverage those models to generate accurate and valid three-dimensional representations. While digitization of existing coral can be used to inform these models, they are not sufficient to simulate changes in form under varying conditions, nor are they amenable to studies to enhance coral survivability by modification of design. The DT proposed in this work has a three-part framework, as shown in Figure 2, each of which is discussed below, followed by a discussion of how they may be integrated.

Maps

The first of the three parts of the DT framework for corals addresses the development of ontological maps that relate the different structures to each other, identifies their function and

locates them phylogenetically (i.e. an evolutionary tree of organism relationships). This is a crucial aspect of the framework since it establishes the basis for the models, and enables a comparative study of form, which has been shown to be crucial in establishing a stronger basis for structure-function relationships and abstracting principles for bio-inspired design [6].

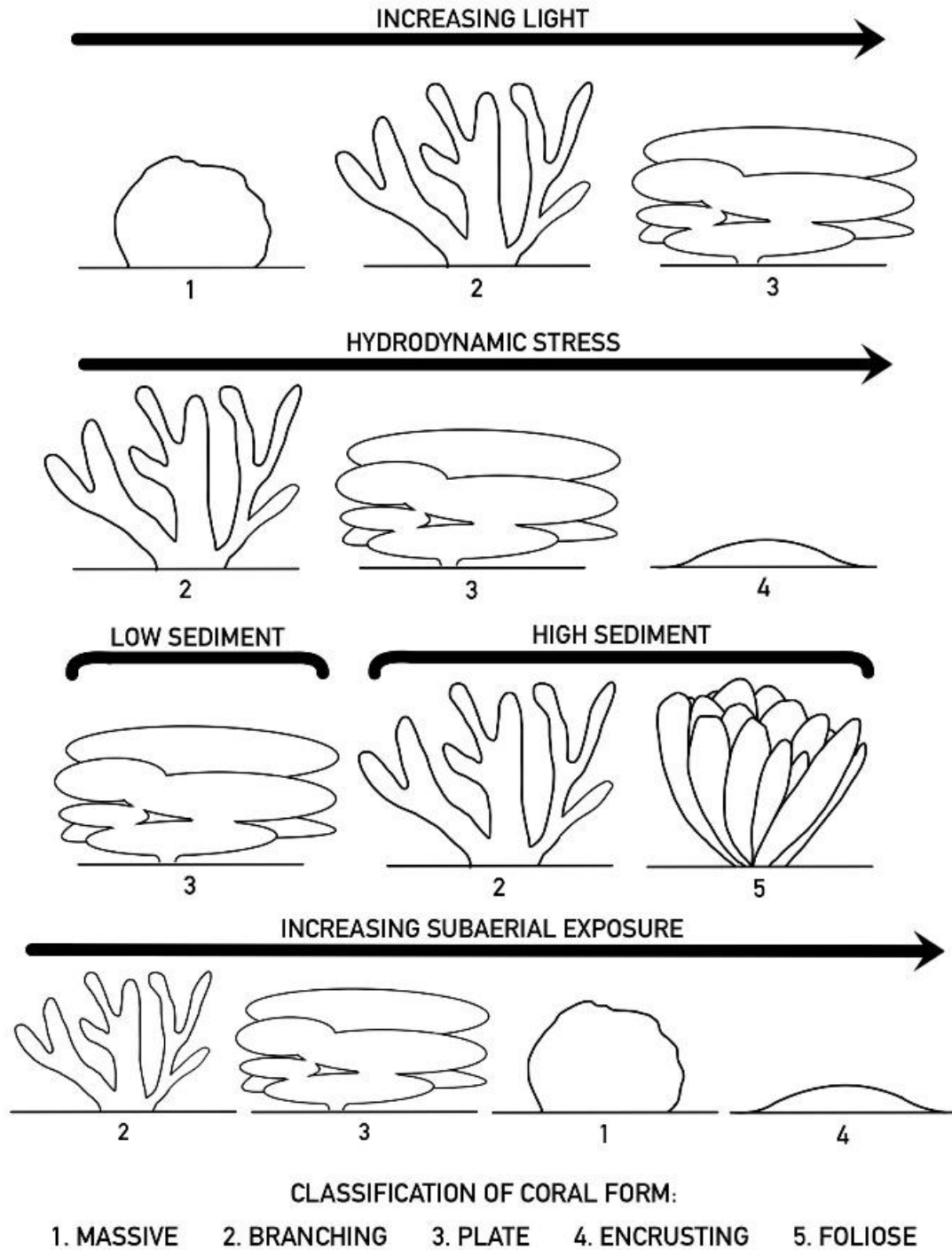


Figure 1. Coral structure is highly responsive to environmental conditions, adapted from [5]

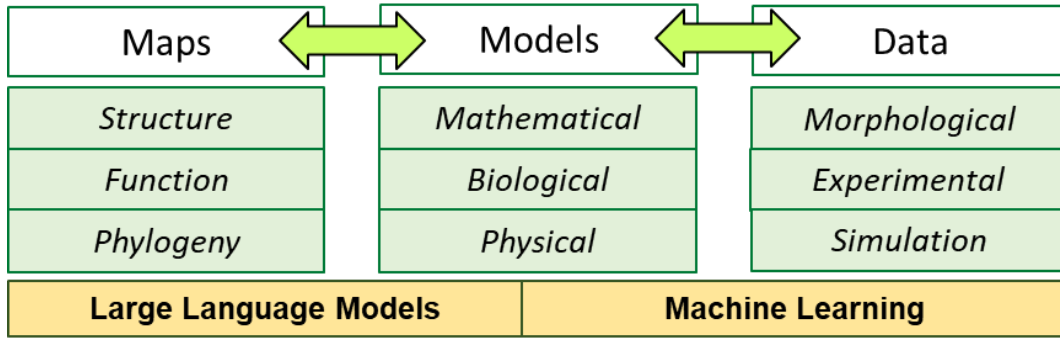


Figure 2. High level framework of the digital twin for coral morphology, consisting of three main elements: maps, models and data, and the underlying AI foundations

Models

The second, and most central piece of the DT is the identification and development of models. In the context of this work, a model is any formulation that represents, generates, constrains, and/or optimizes coral structure and/or its functional performance. This is a vital bridge between the ontological aspects of the framework (i.e. the maps) and its implementation in a design generating computational platform. Models can be mathematical, biological or physical. To cite one example of branching structures within internal fluid flow, several mathematical branching algorithms have been developed, many of which have been used for studying specific phenomena and structures in nature [7], [8]. In addition, several bio-inspired “laws” have been proposed, relating branch parameters [9], [10], [11]. Finally, there is a vast body of literature in fluid mechanics, with mathematical relationships between channel geometry and flow performance [12].

Data

The third part of the DT framework addresses data, which can come from several sources. For corals, this would include in it the empirical work to digitize coral structures alluded to previously, but also data obtained from experimental and computational studies, on the influence of hydrodynamics on the growth and form of corals, for example [13]. Since these datasets are often quite limited and species specific, this represents an opportunity for training Machine Learning (ML) models with available data, to enable exploration within and beyond it, to establish stronger ties between designed structure and the associated biological and environmental basis for it.

Integration

The three elements proposed above need to be integrated, ideally into a single platform. Further, they need to enable the flow of information in such a way as to enable the DT to be responsive to changes in both the digital and physical realms. As shown later, a modular design tool has the potential for integrating all three aspects of this work. As shown in Figure 2, we also propose the use of Large Language Models (LLMs) to peruse the vast and growing literature to identify and update maps and models, and also the use of ML for integrating the models with data

generated from multiple sources as discussed above. The maps and models can all be related to each other using robust knowledge graphs. Lastly, corals are not static entities, they grow and shrink in response to environmental stimuli and biological needs. Much of this has not been explicitly modeled in the literature, but several efforts are ongoing in this direction. An AI-enabled framework will be responsive to these models as they improve and be able to incorporate them within the DT.

Classification of Coral Structure

Corals represent an opportunity to study variation of design, as morphological differences occur throughout reef-building stony corals [14]. The task of classifying coral structure from the perspective of engineering design requires an emphasis of the morphological structure than on the individual species and taxonomy, which has been the standard means of classification of coral polyps and coral structures [15], [16]. This led to the design classification parameters of form and texture [17], shown in Figure 3. A coral's form refers to the overall shape of the calcium carbonate structure created by the coral polyps, while its texture refers to the surface characteristics of said structure. To the best of the authors' knowledge, this is the first such design-oriented classification of corals.

Form

In terms of form, this classification proposes five types, informed by the literature [18], [19], [20]:

1. Branching: These corals have a branching, tree-like structure.
2. Massive: These corals have a solid, compact appearance and form large, rounded or boulder-like structures.
3. Plate: These corals grow horizontally, forming structures that resemble flat or slightly curved plates or saucers.
4. Encrusting: These corals grow as a thin layer against a substrate, such as rocks or other corals, spreading outwards across the surface.
5. Foliose: These corals have broad plate-like portions rising in whorl-like patterns that produce a leaf-like appearance.

Texture

In terms of texture, the classification proposes six types:

1. Smooth: These corals have a flat and even surface without any major protrusions. (e.g. *Solenastrea bournoni* i.e. Smooth Star Coral)
2. Knobbed: These corals have rounded bumps on their surface. (e.g. *Dipsastraea rotumana* i.e. Knob Coral)
3. Protrusive: These corals have individual projections that extend out from their surface. (e.g. *Porites porites* i.e. Clubtip Finger Coral)
4. Grooved: These corals have indented lines or channels on their surface forming a network-like pattern. (e.g. *Diploria labyrinthiformis* i.e. Grooved Brain Coral)
5. Ridged: These corals have raised ridges or bands running along their surface. (e.g. *Mycetophyllia lamarckiana* i.e. Ridged Cactus Coral)
6. Lobed: These corals have rounded or semi-rounded projections that resemble lobes. (e.g. *Orbicella annularis* i.e. Lobed Star Coral)

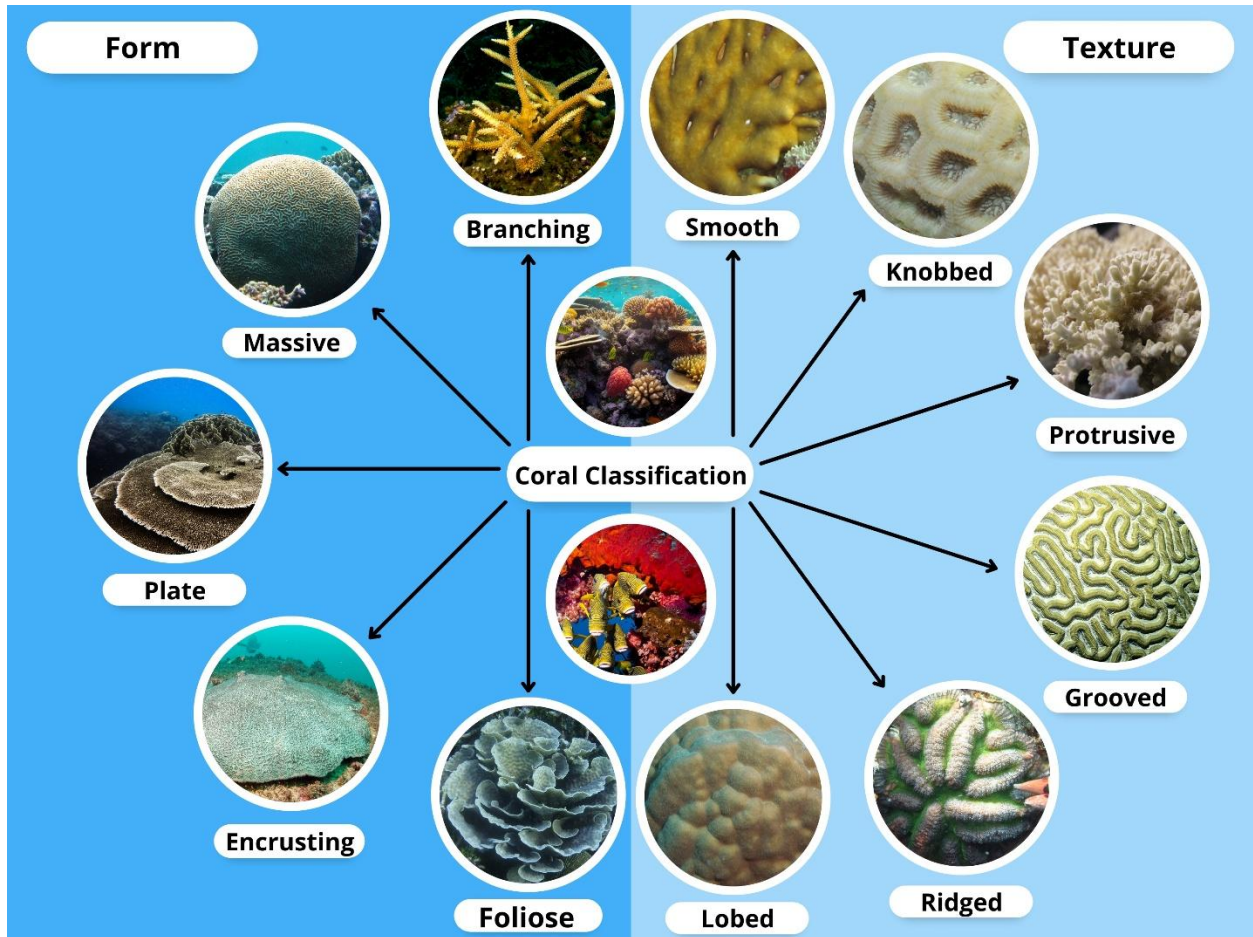


Figure 3. Classification of coral structure at two levels: form and texture (created using images in public domain, no attribution needed)

To see how this classification would be implemented, one may consider an example of the *Diploria labyrinthiformis* species of coral, shown in Figure 4, classified below using both a taxonomy-based system and the form and texture-based system. While the taxonomy-based system is useful biologically, the proposed classification developed here simplifies this for implementation in computational design and modeling.

Taxonomy-based classification [20]:

Domain: Eukaryota; Kingdom: Animalia; Phylum: Cnidaria; Class: Hexacorallia; Order: Scleractinia; Family: Mussidae; Genus: *Diploria*; Species: *Diploria labyrinthiformis*

Design classification (proposed here):

Form: Massive; Texture: Grooved



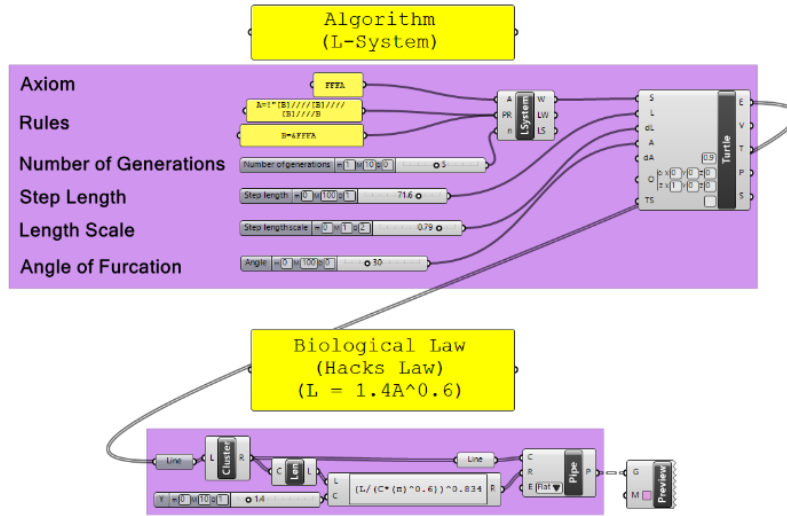
(a)

(b)

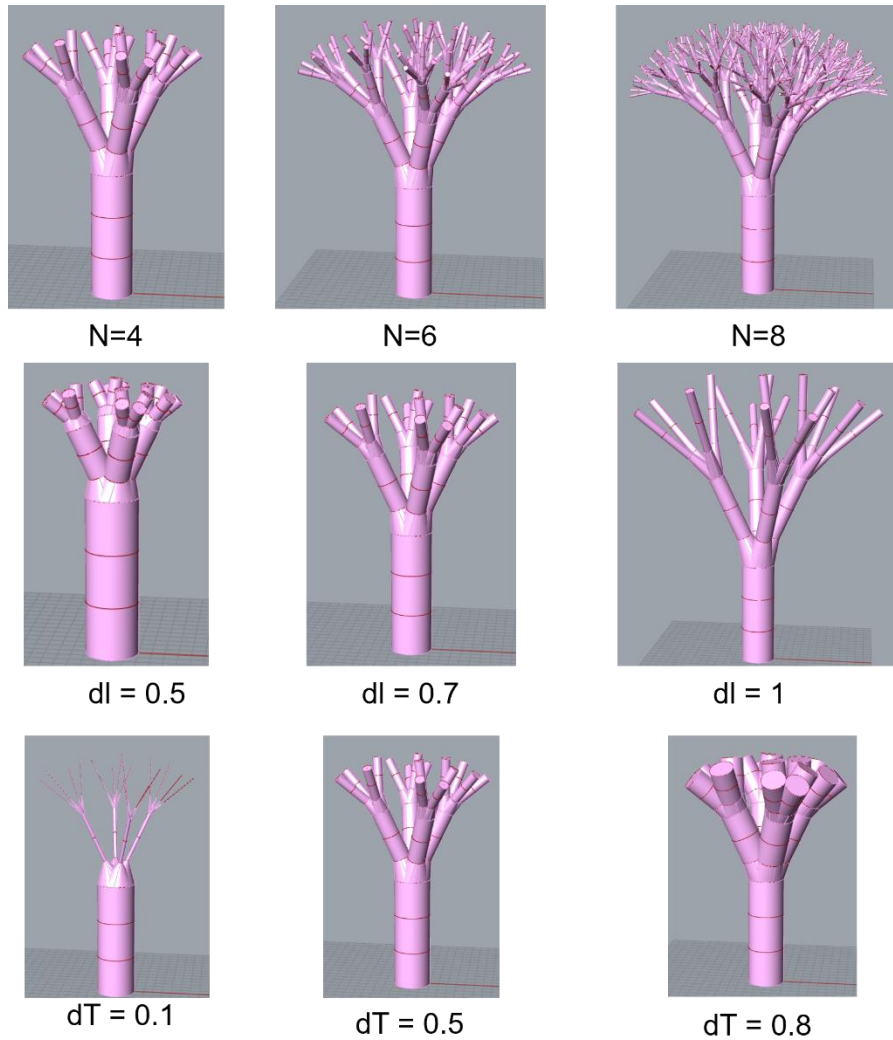
Figure 4. *Diploria labyrinthiformis* coral as classified from this work (a) Form: massive, (b) Texture - grooved (images in public domain, no attribution needed)

Implementation

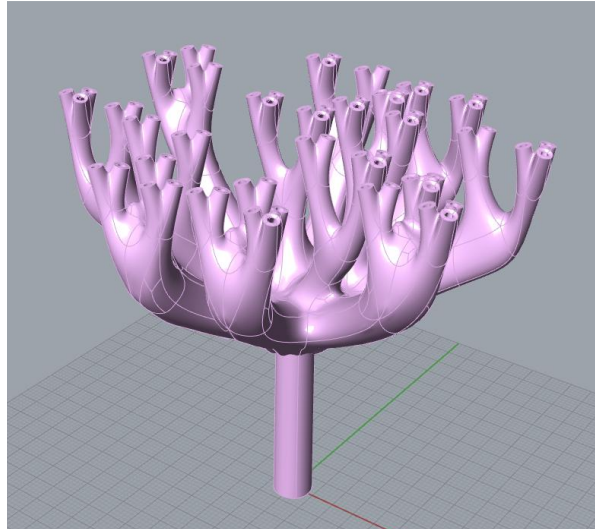
To demonstrate how the framework can be implemented computationally, a generic branched coral design was implemented in Rhinoceros 3D version 7 using Grasshopper plugin [21]. The tree skeleton was modeled using the L-system [22]. A plugin was used to implement the L-system in Grasshopper. Grasshopper is a powerful tool in which mathematical algorithms can be combined with biological models and bio-inspired design principles [23]. Figure 5a demonstrates this: the skeleton of the tree was created by the L-system and was combined with Hack's law, a biological branching principle that relates the length of the branch to the cross-section of the branch [24] – to add thickness (t) to the skeleton. Figure 5b shows how different designs can be generated with different inputs for the L-system. Here, N corresponds to the branching order of the tree and is essentially 2 multiplied by the number of furcations (branching points) in the structure. In addition to specifying the branching order, length and thickness are the variables that constrain the final geometry. These ratios are typically defined as the relationship between daughter (or child) branch and the mother (or parent) branch from which it emerges. dl is the length ratio of the daughter to the mother branch, and dT is the thickness ratio of the daughter to the mother branch. The values selected here are for demonstration purposes only, however it may be imagined how a sweep of these values across a range could establish the basis for further studies and to generate datasets for ML algorithms to train on. This could be from Computational Fluid Dynamics (CFD) or experimental studies, for example, with the results from each informing the ML-driven design. Figure 5c shows a coral-like structure using this platform, generated after smoothing functions have been applied.



(a)



(b)



(c)

Figure 5: (a) Design implementation of form-generating mathematical algorithm constrained by a biological law, (b) parametric designs, (c) coral-like emergent form

Challenges and Future Directions

Even if one allows for the framework proposed here as being one that is sufficiently comprehensive, there remain several challenges to truly realizing it, and with each is the potential for a future research direction, some of which are being pursued by the authors presently:

- A key challenge with corals is their significant diversity of form. The classification proposed here, while complete in one sense, is very likely to require updating as new information is obtained. It will also likely need to have more levels of classification than the highest level proposed here and allow for hybridization of categories where complex coral structures do not neatly fit within the identified ones. We believe a dynamic knowledge graph developed with a formal ontology has the potential to help make this challenge more manageable.
- Another challenge is one of scalability of the computational approach, in particular given the above-mentioned diversity, coupled with the complex and variable environmental conditions that, as shown, have a significant influence on morphology. While knowledge graphs will help, multi-modal data fusion will likely be needed to enable the identification of corals from digital data, as well as extract key design and environmental variables, and represent their relationships in usable models.
- A key opportunity, in particular for the AM community, is to embody AM constraints and design guidelines into the DT itself – these can be implemented as mathematical models that quantify process specific constraints such as minimum feature size or maximum build envelope.
- Finally, there are several knowledge gaps preventing the framework proposed here from being fulfilled, even if the underlying computational apparatus was complete. However, the interdisciplinary field of coral reef restoration is growing rapidly, with new findings reported in the literature almost daily. AI tools like LLMs have the potential to harness this growing body of work, and ML has the potential to fill gaps that remain in our knowledge.

Conclusion

This work made two contributions to the coral and AM communities: (i) it proposed a framework for a DT of coral structure, with maps, models and data as the three central elements, resting atop an AI-enabled foundation, and (ii) a first-of-its-kind classification for coral morphology was also developed, separating it into form and texture. Preliminary results from implementing form-generating mathematical algorithms and biological principles were demonstrated, but more needs to be done. This framework, if successfully developed and implemented, has the potential to aid in the design and manufacturing of coral reef structures that are regenerative and less impacted by a changing climate. Furthermore, it can serve as the foundation for AM technologies to leverage towards having a significant impact on coral reef restoration efforts globally.

This DT approach to biological form may be extended to other organisms where the primary intent is to understand and leverage the basis for the structures found in nature. Doing so will not only deepen our understanding of why natural form has the shape it does but also enable the discovery of novel materials and structures for a range of engineering applications, thereby enabling a paradigm shift in bio-inspired design.

Supplementary Materials

The Grasshopper script used to generate the structures shown in Figure 5b is available for download here: <https://data.mendeley.com/p67pxrdtmv/1>. It requires Rhino 7 or above to view this file.

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