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Rapid Prototyping and Fabrication of Unmanned Surface Vessels: A 3D Printing Case Study

ABSTRACT

The transition from a computer-aided design (CAD) model to physical fabrication is a critical stage in the development of Unmanned Surface Vessels (USVs). Despite the efficiency of computational approaches for accelerating the design and optimization of complex geometry forms, the physical validation of these digital models remains a key step to ensure their viability. The proposed paper offers a holistic case study on the fabrication of parametrically designed USVs using 3D printing technologies. The primary objective is to evaluate the practical constructability of the algorithmically generated geometries in order to transform them into tangible products. The physical prototypes are evaluated based on the following parameters: printability, structural continuity of segmented hull parts, surface smoothness, and assembly capabilities. Based on the findings, the integration of additive manufacturing into a parametric design workflow can be established within a reliable framework considering manufacturing methods and assembly strategies that the product requires depending on its operational conditions.

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KEY WORDS
Unmanned surface vessels, 3D printing, rapid prototyping, computational design, modular assembly, fabrication

1. Introduction

The design and manufacturing of Unmanned Surface Vessels (USVs) require a methodical approach to ensure that complex hull forms can withstand real-world operational demands. Traditionally, the development cycle of marine vessels has relied on extensive physical modeling and iterative testing.

Recently, this process has been significantly streamlined by computational design tools that automate the generation of hull geometries to achieve rapid prototyping. However, a successful design is not defined solely by its digital representation; it must also account for production limitations and physical constructability. Transforming a digital USV design into a physical prototype introduces several manufacturing challenges, particularly when utilizing additive manufacturing. A holistic product design approach must consider how the vessel will be fabricated, evaluating parameters such as the structural integrity of the printed parts, the continuity of segmented sections, and the overall surface smoothness and curve fairness, which impacts hydrodynamics. The purpose of this paper is to evaluate the transition of algorithmically generated USV geometries into tangible, functional prototypes. Rather than focusing on the computational mechanics of the generative algorithm, this study serves as a practical evaluation of its physical output.

By producing scaled models utilizing 3D printing technologies, the research assesses important fabrication factors: the compatibility of the generated models with 3D printing hardware, the structural continuity of segmented hull parts upon assembly, the resulting surface smoothness, and the overall ease of assembling the modular components. Ultimately, this physical validation aims to confirm that the generated geometries are not merely theoretical concepts, but practical, constructible solutions for rapid marine prototyping.

2. Literature survey

Nowadays, algorithmic and computational design represent a transformative methodology in modern product development, shifting the focus from manual geometric manipulation to parameter-driven processes (Kyratsis et al., 2025b). By establishing a direct relationship between design intent and mathematical parameters (Pektas, 2023), this approach allows for the automated generation of complex forms. The dynamic nature of parametric modeling means that any adjustment to foundational variables automatically updates the entire model (Janssen & Stouffs, 2015), enabling rapid exploration of diverse design iterations without needing to rebuild geometries from scratch. This continuous evolution of shapes based on predefined rules ensures both flexibility and precision.

In recent years, the integration of computational design directly with digital manufacturing technologies has emerged as a cornerstone of Industry 4.0 (Kyratsis et al., 2025a). This alignment optimizes not only the generation of the product's form but also its physical fabrication. Automating the product design phase creates a seamless pipeline that drastically reduces development time and enhances manufacturing efficiency across various industries (Aidinli et al., 2025).

2.1. Prototyping in Marine Design

Historically, marine architecture relied heavily on the systematic testing of scaled physical models to analyze factors like resistance and hydrodynamics (Fonseca et al., 2022). As computational technologies advanced, software-based simulations largely replaced physical models during the preliminary design stages, allowing for automated generation and testing of various hull forms (Park et al., 2022).

However, despite these digital advancements, physical prototyping remains a critical step in the modern design cycle. Computational design systems excel at creating diverse, complex geometries tailored to specific operational requirements. Yet, translating these digital variations into functional marine vessels requires rigorous physical validation to assess practical constructability (Minaoglou et al., 2025). Implementing physical prototyping methodologies alongside computational design ensures that customized algorithms yield products that perform reliably in real-world scenarios.

2.2. Geometry and Constructability

The geometric definition of a vessel's hull is the key attributing factor to its stability, operational efficiency, and structural integrity. Parametric algorithms effectively manage this complexity by utilizing fundamental defining curves, such as the centerline and deckline, to generate the broader hull surfaces (Harries, 1998).

Advanced mathematical representations, particularly Non-Uniform Rational B-Splines (NURBS) (Zhou et al., 2022) and Bézier curves (Khan et al., 2017), provide the necessary flexibility to create smooth, continuous shapes required for marine applications.

What bridges the gap between these mathematical definitions and physical reality is the vessel's constructability. The algorithmic generation of shapes and structures must follow the vessel's physical constraints to ensure the final product is structurally viable and sea-worthy. During the computational phase, design parameters should be managed in a way so that the resulting geometry is not only hydrodynamically sound but also match the limitations of the chosen manufacturing technique.

2.3. 3D Printing Computational Forms

Additive manufacturing has become tightly integrated into parametric design workflows since it allows complex, algorithmically generated geometries to be fabricated directly, without the constraints imposed by traditional tooling (Kourmouki et al., 2025). This creates a direct pathway from the digital concept to the physical object. To prepare a computational hull for 3D printing, the algorithm must carry out a series of geometric modifications. These include scaling techniques to shell the geometry, defining precise wall thicknesses, and executing Boolean operations to ensure the model is solid, watertight and 3D-printable.

How well the digital model translates into a physical object depends largely on the quality of the fabrication process itself. For thin-walled components printed in materials such as PLA or PETG, production parameters such as layer height, print speed and extrusion settings, directly influence whether the final part conforms to the design's geometric and structural requirements. When carefully controlled, these parameters ensure that the algorithmically generated surfaces are translated reliably into the physical prototype, with adequate surface finish and mechanical integrity.

2.4. Assembly and Modularity

Most commercially available 3D printers have a limited build volume, resulting in large computational forms such as Unmanned Surface Vessels being divided into manageable segments for fabrication. Algorithmic systems address this by using automated planar slicing cuts that divide the hull into individual parts that fall within the printer's build parameters. A key concern in segmented 3D printing is ensuring that the individual parts reassemble with structural continuity and hold their original form. To address this, algorithms generate internal connectors and interlocking joints tailored to each sliced surface, providing both alignment and structural coherence.

The physical assembly of the segments serves as a practical test of the algorithm's viability, evaluating the ease of construction, the tightness of the joints, and the overall integrity of the final assembled prototype. By embedding manufacturing and assembly constraints directly into the generative process, the workflow can become an efficient pipeline from digital modeling to the physical object.

3. Design methodology

The transition from a digitally generated geometry to a physical object requires a systematic and structured approach to ensure the result is both functional and constructible. The computational tool used is designed to manage the full design-to-fabrication pipeline, from generating the hull geometry to automating the segmentation, and finally producing the connectors and joints required for assembly. An important aspect of the case-study is the calibration of the fabrication parameters controlling these processes, as finding the appropriate values is essential in producing a result that is geometrically accurate and straightforward to manufacture. To evaluate the practical output of the computational design process, a fabrication methodology was developed around the additive manufacturing of scaled physical prototypes, turning theoretical hull designs into tangible test models.

3.1. Fabrication targets and data

The primary objective of producing 3D-printed models is to empirically verify the practical viability and constructability of the computational designs. Converting these digital USV hulls into physical constructs allows for the examination of several design aspects. The first one being geometric compatibility, ensuring that the generated models can be 3D-printed without extensive manual intervention.

Closely related to this is the question of segmentation continuity. Once the individual sections are assembled, they must maintain both structural and visual coherence, which is essential to the integrity of the scaled prototype.

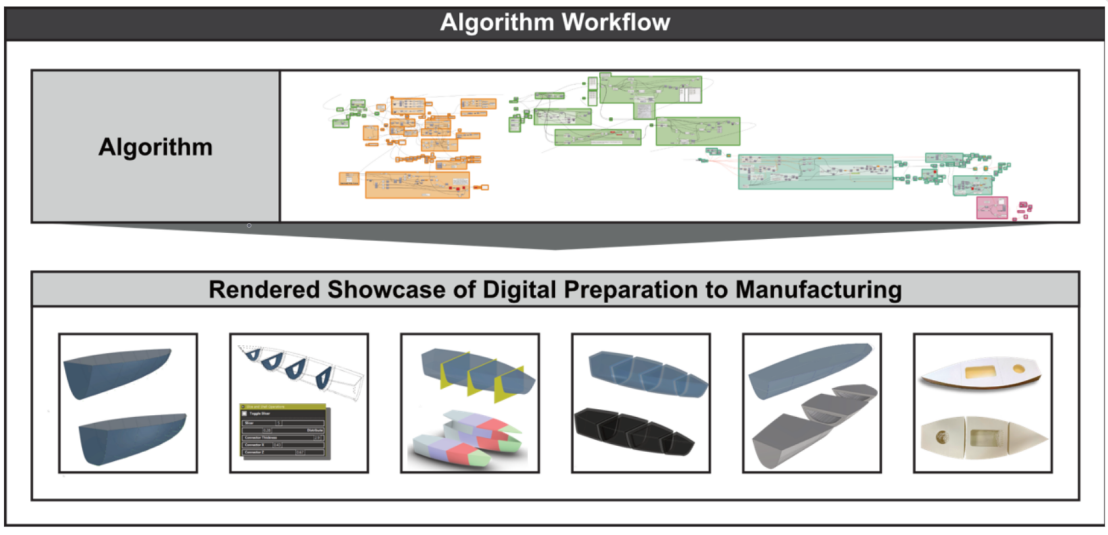
The surface quality of the printed hulls is equally important, as smoothness and curve fairness directly affect the hydrodynamic performance and can be a decisive factor in any transition to full-scale production. Finally, the ease of physical assembly is assessed, since the practicality of assembling the printed segments is a strong indicator of how well the design approach would scale.

3.2. Digital Preparation for Manufacturing

Before physical fabrication can begin, the algorithm automatically processes the generated surface geometry through a series of preparation steps to make it 3D printed-ready (Figure 1). The process begins with shell generation, where a non-uniform scaling technique is applied to the outer hull surfaces to produce a solid geometry with a defined wall thickness. The deck is then extruded to match these thickness parameters, ensuring it integrates flush with the hull and fully encloses the vessel.

Once the base geometry is established, the hull is divided into segments to accommodate the build volume constraints of standard desktop 3D printers. The algorithm generates cutting planes at equal intervals, systematically splitting the hull, deck, and any internal structures into manageable parts. At each cut seam, internal connectors are automatically generated to facilitate structural alignment during assembly.

This is achieved by extracting the cross-sectional profile at each split plane and extruding it inwards, forming precise interlocking joints between adjacent segments.



» **Figure 1:** *Digital Preparation Steps*

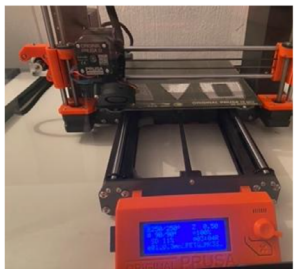
When the segmented hull is complete, rectangular and circular openings are incorporated into the deck geometry to serve a dual purpose: providing physical access to the internal compartments and acting as the interface through which the two hulls are joined.

The hull is then mirrored across a centerline that is calculated based on user-defined parameters and the housing dimensions required to enclose the electronics and propulsion components, producing the full catamaran configuration with a precisely controlled separation between the two hulls.

3.3. Fabrication of Test Model 01 (Scale 1:10)

In order to conduct a quick and affordable analysis of the computational design process, a prototype on a 1:10 scale was produced first.

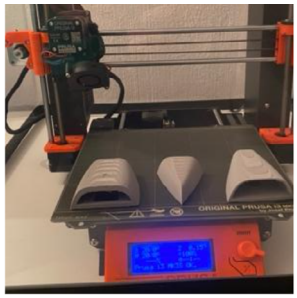
This scale provides sufficient physical volume to inspect design features and print quality while minimizing material usage and print time. Figure 2 depicts the different stages of the 3D printing process completion.



(a)



(b)



(c)

» **Figure 2:** *Printing Stages of Test Model 1*

The model was fabricated using an Original Prusa™ i3 MK3S+ 3D printer, with the print files prepared in PrusaSlicer™ version 2.7.4. Prusament™ PETG was selected as the material for its durability and layer adhesion properties.

The print was performed at a temperature of 250°C, utilizing a 0.30 mm layer height and a 20% infill density, successfully completing without the need for additional support structures (Table 1).

Table 1

Print data of test model 01

Print Data of Test Model 01	
Printing Material	Prusament™ PETG
Printing Temperature	250° C
Layer Height	0.30 mm
Infill Density	20%
Supports	No
Printing Time	3 hours and 30 minutes
Dimensions	209 x 71.5 x 26 mm

3.4. Fabrication of Test Model 02 (Scale 1:3)

Upon the validation of prototype 01, a much larger prototype at a 1:3 scale was printed. The maximum wall thickness of this model equals to 21 mm to save time and reduce material consumption (Figure 3).

This larger prototype was printed on a CreatBotTM D600 Pro industrial printer using PLA EVOTM material.

Manufacturing parameters included a printing temperature of 220 degrees Celsius, a layer height of 0.30 mm, and 0% of infill with necessary supports added. The total time for printing prototype 02 amounted to more than 30 hours (Table 2).

Table 2

Print data of test model 02

Print Data of Test Model 02	
Printing Material	PLA EVO™
Printing Temperature	220° C
Layer Height	0.30 mm
Infill Density	0%
Supports	Yes
Printing Time	30 hours and 30 minutes
Dimensions	696 x 238 x 86 mm



(a)

(b)

(c)

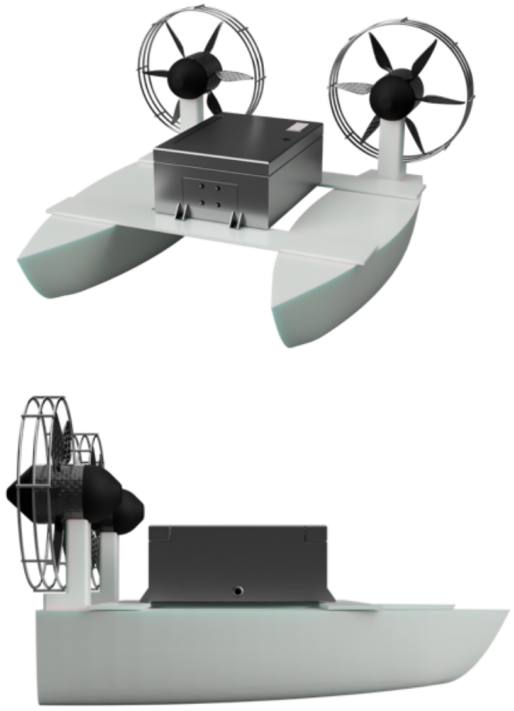
» **Figure 3:** *Printing Parts of Test Model 2*

3.5. Assembly and Physical Evaluation

The physical realization of the USV models allowed for a comprehensive evaluation of the digital-to-physical workflow. The assembly phase served as a direct test of the algorithmically generated internal connectors.

For both Test Model 01 and Test Model 02, the generated joints provided adequate tolerance and structural alignment, confirming the capability to accurately join segmented hull parts. Furthermore, the physical prototypes verified that the surface geometries remained smooth and continuous across the segmented boundaries.

The larger scale of Test Model 02 provided detailed insights into how the printed geometries behave under greater volumetric demands, successfully demonstrating the system's capacity for creating large-scale, modular marine prototypes (Figure 4).



» **Figure 4:** *Final Assembly with Integrated Propulsion Mechanisms*

4. Conclusions

This paper presented a holistic case study on the transition of algorithmically generated Unmanned Surface Vessel (USV) hull geometries from digital models into physical objects through additive manufacturing. By fabricating two scaled prototypes, a 1:10 model in PrusamentTM PETG and a larger 1:3 model in PLA EVOTM, the study evaluated the practical constructability of computationally designed hulls across the key dimensions of printability, structural continuity, surface smoothness, and assembly feasibility.

The results confirmed that the automatically generated internal connectors provided adequate tolerance and structural alignment, allowing the segmented parts to be joined accurately, while preserving smooth, continuous surfaces across the seam boundaries.

The larger-scale model further demonstrated the workflow's capacity to produce modular marine prototypes under greater volumetric and material demands.

Overall, the case study shows that embedding manufacturing and assembly constraints directly into the parametric design process yields a reliable digital-to-physical pipeline, provided that the fabrication and assembly methodologies are calibrated to the material, scale, and operational environment of the vessel. Future work will focus on extending the modular fabrication approach to larger, multi-hull configurations.

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