Additive Manufacturing for Nautical Design

An Automated Approach to Marine Manufacturing

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An Automated Approach to Marine Manufacturing

by

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Introduction

1 INTRODUCTION

RESEARCH QUESTION

How can Additive Manufacturing technology be applied to automate the production of marine vessels?

Additive Manufacturing (AM) has the potential to transform the marine manufacturing industry, particularly for vessels below 40 meters. Most boats in this size range are currently made using a labor-intensive method known as moulded fiber reinforced plastic (FRP) (Dokos, 2013; Marsh, 2003). Moulds are, by far, the most expensive part of the manufacturing process and they tend to inhibit formal variation and low-cost customization. AM allows the manufacturing of complex surfaces without the need for moulds thereby removing one of the most costly and restrictive aspects of the moulded FRP manufacturing process. By using AM in marine vessel manufacturing the hull, deck, and superstructure forms of smaller marine vessels will no longer be geometrically restrained by the limited formal capabilities of moulded construction offering potential new performance criteria and formal aesthetic opportunities for naval architects and designers.

Using AM and the underlying logic of digital design procedures, the fundamental logic of assembly governing how a vessel is put together can be radically reconceived such that hull, deck, and superstructure may no longer be considered as necessarily separate components. Manufacturers will have the freedom to design and bring new models to market without expensive start-up costs, and the iterative development and improvement of existing model lines will be able to progress at a far more rapid pace as new versions of existing model lines are subtly modified based on post-production analysis and customer feedback. An era of mass-customization in yacht design may become feasible. While the technology required to achieve these goals already exists in isolated domains, the applied research in manufacturing processes to synthesize these technical procedures for the benefit of the nautical design and marine manufacturing sector remains incomplete.

Adopting AM for marine vessel manufacturing is by no means a simple application of technology from one manufacturing sector to another. Marine vessels are both technically and structurally complex assemblies that require a carefully considered approach for the application of new manufacturing technologies (Guillermin, 2010). At the same time, AM is a broad term that encompasses many different types of technologies using many different processes and disparate materials. Until quite recently, AM has been constrained to much smaller scales rendering it fundamentally unsuitable for marine vessel manufacturing. Recent advances in scaling up AM have now made it a potentially viable approach for the production of marine vessels and products that are typically fabricated using moulded FRP (Post et al., 2018).

To determine the most fruitful approach to this question it will be necessary to first 1) review how boats are typically built, 2) examine the existing state of AM technology, and 3) review robotic kinematic systems. In the next chapter this information will serve as a foundation for evaluating a series of case study projects that have demonstrated successful applications of AM to the marine industry. Analysis of the successes and shortcomings of these projects points to several approaches that appear promising not only for the marine sector but for large-scale automated manufacturing in general. At the same time, this study also reveals serious challenges that must be addressed in order to determine how to deploy AM for marine vessel manufacturing. To further investigate these approaches and challenges will require the development of both novel robotic manufacturing tools and software modeling and tool path generation techniques that are optimized for these manufacturing methods.

The Role of Design in Advancing Manufacturing Technology: Why is this a task for a designer rather than an industrial engineer? Naval architects and designers have a rich history of adopting and developing new manufacturing methods that impact society in profound ways. In the 12th Century a high-speed shipbuilding method employed at the Venetian arsenal relied on the practice of moving ships that were under construction along a canal lined with a series of specialized workshops and staging areas. This serial method allowed the Venetian Arsenal to produce up to one ship a day during its most productive period, leading, in part, to its military and economic ascendency in the Mediterranean in the following centuries (Wilson & Favotto, 2016). Scholars of the industrial revolution have identified naval architect Samuel Bentham's 1793 patent for woodworking equipment to produce uniform parts for wooden pulleys and blocks as an important and provocative moment in the emergence of the Industrial Revolution (Morriss, 2020). A little over a century later Ransom Olds patented the first assembly line for manufacturing the Curved-Dash model Oldsmobile in 1901. Henry Ford adapted and improved this manufacturing innovation with a moving conveyor system – arguably one of the first applications of automation to the emergence of mass-production in the 20th Century (Thomopoulos, 2014). An examination of 21st century robotic automotive manufacturing lines reveals a remarkable similarity of this production model to that employed nearly 800 years earlier in the Venetian Arsenal. However, due to a variety of concerns including lower overall market demand and the continuing demand for semi-custom and fully customized vessels, most contemporary boat manufacturers have been unable or unwilling to employ these same methods for the mass production of marine vessels (Ponticelli et al., 2013).

At the dawn of the 4th Industrial Revolution, designers in the marine sector are experimenting with new materials and technologies to manufacture vessels and marine products with improved accuracy and tighter tolerances, lower labor costs, improved worker safety standards, higher standards for sustainable manufacturing, and with a greater capacity for low-cost customization. Automation with AM offers one potential solution to address these concerns (Huang et al, 2013). AM offers designers the opportunity to rethink how we apply formal geometric solutions to complex design problems. Developing new ways of deploying this technology at scale is an important area of study and experimentation not only for manufacturers and industrial engineers, but also for designers.

Naval architects and industrial designers in the nautical sector play a critical role in determining how marine vessels are conceived and produced. The hulls, decks, and superstructures of marine vessels are complex structural topological manifolds that are designed according to a series of interdependent constraints that draw on several different domains of knowledge (Sahoo, 2021). These constraints, in descending order of consequence, are 1) hydrodynamic and structural considerations, 2) material properties, 3) manufacturing methods, 4) programmatic concerns, and 5) aesthetics.

Marine vessels must pass through the water with some degree of efficiency, so this fundamental constraint relies on the naval architect and engineer to perform the correct calculations to ensure an efficient hydrodynamic form and an effective propulsion system appropriate to the intended use of the vessel. While this primary constraint is relatively inflexible it relies heavily on both the construction methods and the materials used in the process as well as programmatic and aesthetic concerns related to usage. The selection of an appropriate material and manufacturing system builds upon this initial design work with input from the shipyard and the builder, but ultimately coordinated by the designer. These constraints are a negotiation between economic considerations balanced against performance and aesthetic concerns, but they also rely on material properties and technical procedures in the manufacturing process. Programming is the result of an interaction between the designer, the manufacturer, and the client: sometimes active in the case of custom or semi-custom yachts, but often passive in the case of fully pre-designed production series vessels. Finally, aesthetic considerations are the domain of the designer and marketing teams who must coordinate the efforts of all parties involved in design and manufacturing while also both appealing to and influencing the desires of the client or end users. In this way, we can understand that the designer plays a central role in coordinating not only how marine vessels look, but also how they are built.

Before examining how AM technology can be applied to automate the production of marine vessels, a brief review of how boats have been built in the past, including an examination of both the construction methods and materials that have come to dominate the industry, will be necessary. A description of the way that boats are currently built will provide a clear understanding of the strengths and shortcomings of current manufacturing practices and help to support the argument in favor of automation and the application of AM technology to marine vessel manufacturing.

A Brief History of Nautical Design and Manufacturing: The first boat used to navigate upon water was likely the trunk of a tree. This primitive vehicle was a product made by transforming a tree from its original state into a floating vessel, essentially creating a new transportation tool made from a singular piece of wood. With time and experience two procedures for improving on the original design emerged: by carving out the inside of the trunk to create a volume one could occupy - commonly known as the dugout canoe, and by connecting several trunks together to form a wider and more capacious surface - commonly known as a raft. Naval architecture was born from the union of these initial operations (Thubron, 1987), joining a hollow volume known as a hull to a broad surface in the form of a deck.

Wood: Wood and other natural fibers have been used for millennia to construct boats (Thubron, 1987). Typically, wooden parts are joined together to create a singular hull form that contains a volume of space to pass through the water. A surface above this volume of space protects it from water, sun, and weather allowing passengers or cargo to travel with limited exposure to the exterior elements. The weakness of this method of construction is in the material properties of wood and the tendency for different parts of a wooden hull to move separately from one another. Wood is subject to shrinkage and expansion, and hulls are subject to dynamic loads that deform their aggregate surface form, leading to wear between mated surfaces and gaps or voids in the components that make up the hull. Exposure to sun and the water also take their toll on the wooden components of a boat as well as any metal or other material components that may be used to fasten them together. As tools for transporting people and materials, wooden boats are easily worn on their interior surfaces due to the cargo and crew they transport and on their exterior surfaces due to fastening lines, and the docks, quays, and piers the hull may be fastened against in a dynamic marine environment. Finally, the marine ecosystem itself subjects the wooden parts of a boat to numerous organisms that can degrade the integrity of the individual components. Frequent and regularly implemented maintenance is a necessary practice that has enabled wooden boats to remain solid and functional over time.

Iron: The 19th Century witnessed a complete transformation in the materials used to construct larger ships. While specialized metal components had been used in wooden vessels as fasteners for thousands of years, and examples of military vessels that had been clad in metal sheets to protect their hulls from projectiles are quite common especially in the 18th and early 19th Century, the Industrial Revolution gave rise to steam powered ships built entirely from metal. Metal hulls presented a huge advantage in strength and durability, but the design of these vessels still traced their conceptual roots to wooden boats, and therefore suffered similar problems of wear, corrosion, and necessary periodic maintenance. While 19th century metal ships used different materials, they relied on similar construction methods to their wooden predecessors. Metal frames replaced wooden ones while copper, bronze, or steel plates fastened with rivets took the place of wooden planks fastened with pegs or bronze nails - conceptually the construction methods used to produce early metal ships was not far removed from how boats had been built for thousands of years (Allen, 1987).

Steel: The 19th and 20th Century witnessed unprecedented advances in metallurgic science and fastening technologies for ship construction. The application of steel arc welding to naval construction led to the first modern ship hulls since the invention of the dugout canoe that could be considered as singular manifold surfaces without any breaks in the continuity of their surfaces. The durability of metals and the new technologies for fastening ships together represent nearly ideal solutions for solving the problem of hulls made from multiple components and therefore reducing periodic maintenance costs (Strohmeier, 1963). However, these advances were only feasible for larger vessels; wood was still the primary material used for the manufacture of smaller vessels in the early 20th Century.

Aluminum: Aluminum was first used in marine vessel construction beginning in the 1890's, but it wasn't until the middle of the 20th century with the advent of newly developed fusion welding techniques that aluminum became a truly viable material for boat hulls (Holtyn, 1966). With its characteristic low weight to strength ratio and the relative ease of joining separate parts, aluminum was seen as an ideal material for smaller vessels. However, there remain serious technical challenges to welding marine grade alloys that have inhibited its more widespread adoption for the production of marine vessels. Aluminum is a chemically active metal that exhibits good corrosion resistance through oxide film formation on its surface. However, the addition of magnesium to increase strength leads to greater susceptibility to corrosion and increased technical challenges to welding dissimilar alloys (Wahid et al., 2019).

Fiber Reinforced Plastic: The 1950's saw widespread advancements in the development of industrial plastics including the development of composite materials (Dokos, 2013). Experiments with embedding various fibers in thermoset plastics, known as FRP, led to the application of this material technology to the marine sector. This low-cost construction method fed growing market demand for smaller, inexpensive, low-maintenance boats from a growing market force – a post-war middle-class population eager to get into recreational boating. FRP vessels can be quite easily produced with re-useable moulds, delivering a somewhat economical mass production solution for low maintenance watertight hulls. The material properties of FRP allow for uniform, unbroken surfaces that can efficiently bypass the typical problems of hulls made from multiple parts. In the yacht market, FRP is now the most common material used for vessels below 40 meters due to its material efficiency and the relatively low costs associated with its capacity for serial reproduction (Neşer, 2017).

FRP Manufacturing: The yacht design industry currently relies on moulded FRP as the primary technology for producing small and medium sized marine craft ((Neşer, 2017; Rubino et al, 2020). This method uses expensive moulds that often constrain formal variation and may demand formal simplification to achieve the necessary draft angles for removing objects from their moulds. FRP boats are manufactured at an increasing rate as production series rather than as one-off custom projects due to the labor involved in producing FRP moulds. Fiberglass and carbon fiber hulls using this construction technology are most common in boats 40 meters or less due to issues of market demand, cost of production, material strength, and material efficiency (Stewart, 2013).

Plug Mould: The first step in producing an FRP vessel is to build a plug mould. Most often, this is a wooden form built using strip planking or plywood sheathing over plywood ribs sometimes reinforced with a steel frame. This plug conforms to the exact form, shape, and desired surface smoothness of the finished hull, deck, or superstructure component (Steward, 2011). The plug mould is typically covered with a hand layup of glass fabric and thermoset plastic resin and then faired and polished to a smooth finish. Recently, wide bead thermoplastic extruders have been used for part of this process, most notably by the US-based Thermwood Corporation for the 17' Tahoe open skiff (Musio-Sale et al., 2019).

3D-printed plug mould milling process, image courtesy of Thermwood Corporation (Thermwood, 2018).

Cavity Mould: In the next step of the process, a release agent is applied to the plug mould, and a cavity mould is built on top of it using sprayed gel coat and successive layers of hand-laid glass fabric and thermoset resin. Sometimes a reinforcing core is added to the cavity mould to increase its strength while decreasing its weight and its build time. Once a sufficient mould wall thickness and stiffness has been achieved, based on the size and form of the mould, an external network of reinforcing wood and steel frames is added to ensure the mould stays rigid. If the draft angles of the finished form are such that the plug cannot be removed vertically, the mould may be split down the centerline to be removed horizontally. Once the plug is removed from the cavity mould, it is discarded, or it may be stored for re-use in the production of additional cavity moulds. The cavity mould is polished to a mirror finish and additional structural reinforcements may be added to assist with moving, rolling, and clamping the mould

(Stewart, 2011). In the example image above one can clearly see the single-piece cavity mould built with a steel reinforced frame and a smooth FRP interior surface in the process of being removed from the 3D printed, milled, and surfaced plug mould. Later, this cavity mould will be used for hand layup of an open skiff.

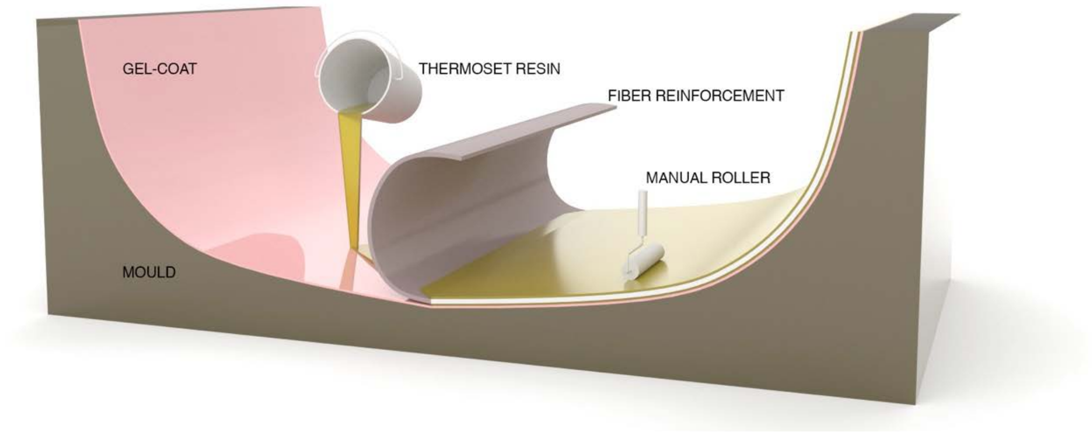
Cavity mould removal from plug mould, image courtesy of Thermwood Corporation (Thermwood, 2018).

While it is somewhat uncommon to produce a cavity mould without first producing a plug mould, there are examples of projects of this type including a successful demonstration project at Oak Ridge National Laboratories in which additive manufacturing and high precision CNC milling was used to produce a cavity mould for a catamaran (Post et al., 2019).

The production of a hull, deck, or superstructure assembly can now begin. The cavity mould is waxed, coated in a release agent, and gel coat is applied to the surface. Layers of loose fiber, chopped strand mat, or woven fabric made from glass strands, carbon fiber, Kevlar, or other proprietary materials are laid up in a series of layers to construct the hull deck or superstructure assembly. Thermoset plastic resin binds the layers together and can be added using one of several distinct manufacturing methods.

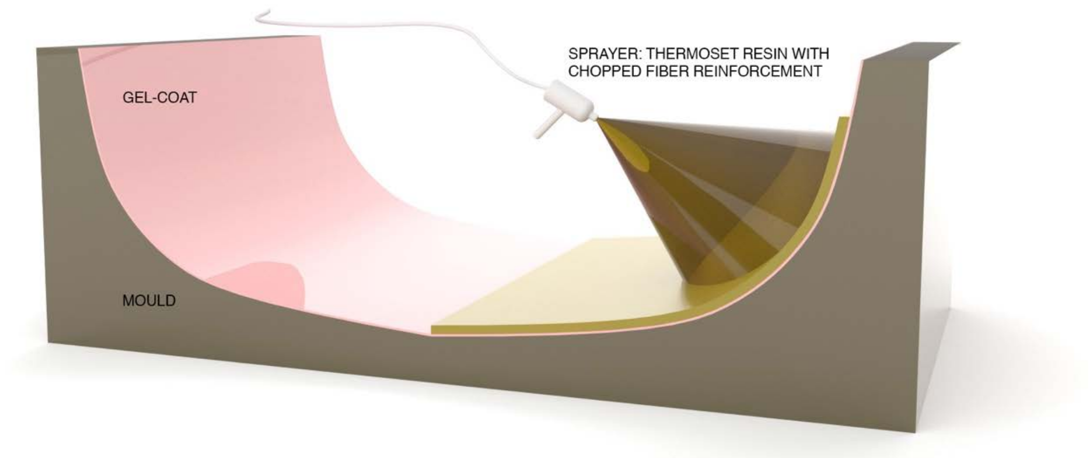
<u>*Hand Lay-up:*</u> The first method uses a simple process of applying catalyzed liquid resin to the mould with a special roller similar to those used by painters. Reinforcing fiber mats (either chopped strand or woven fiber) are applied to the wet surface by hand and the material is consolidated using the roller. Skillful craftspeople can apply multiple layers of reinforcing materials using this method resulting in a relatively uniform thickness that features a low ratio of resin to reinforcing fiber which can be both strong and lightweight. However, during the process workers may be exposed to hazardous materials and chemicals as well as challenging

working conditions that may necessitate the use of protective gear and clothing including respirators.



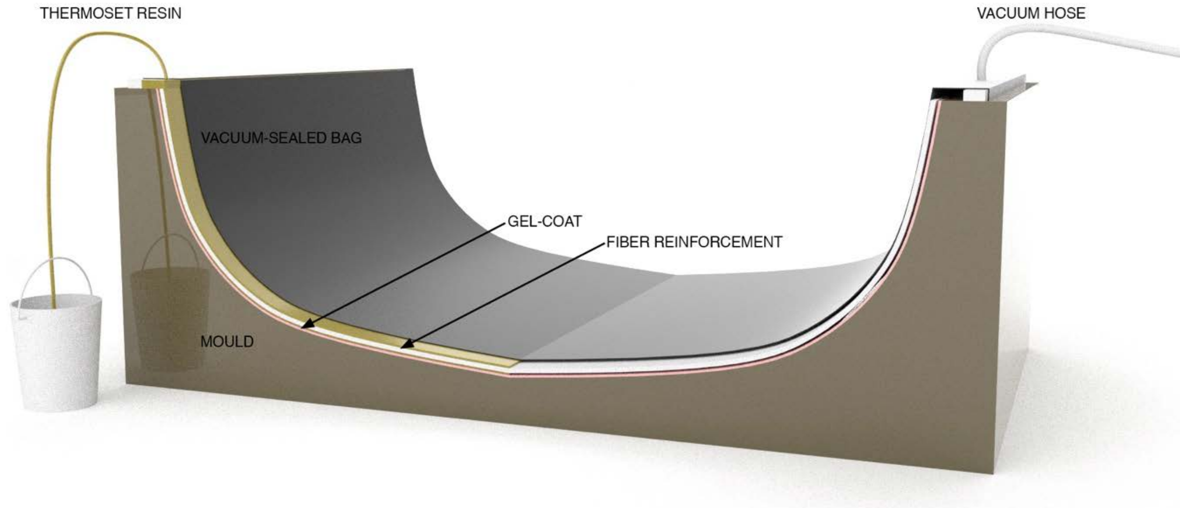
Hand layup process using woven fiber reinforcement and hand-rolled resin over gel-coat.

Spray Lay-up: A second method for creating a fiber reinforced hull relies on a sprayer that applies both chopped fibers as well as liquid resin catalyzed in the sprayer. This method also relies on a skilled craftsperson to apply the materials in a uniform fashion in order to achieve uniform thickness as well as a low resin to reinforcement ratio. Skilled spray lay-up technicians can produce strong and lightweight assemblies quickly and efficiently, however, they may also be exposed to similar hazardous working conditions requiring the use of protective gear and clothing including respirators and face shields.



Spray lay-up process using chopped fiber reinforcement and sprayed resin over gel-coat.

Vacuum Assisted Resin Transfer Molding (VARTM): The VARTM process has become a common manufacturing method for controlling the introduction of liquid thermoset resin to successive layers of hand-placed fiber reinforcement materials (Stewart, 2011). Dry chopped materials, chopped strand mat, or woven fabric materials are positioned by hand with a modest amount of liquid thermoset resin applied to affix them to the mould. A large vacuum bag is placed over the moulded assembly with specialized attachments to remove air from the system, and channel liquid resin to and from the layup. Vacuum pressure is applied to drive resin into the multilayered laminate assembly and to remove excess resin from the layup. Vacuum pressure compresses the layup assembly allowing for a more precise control over the ratio between fiber reinforcement and resin. The VARTM process can improve the fiber-to-resin ratio resulting in stronger and lighter products (Scott, 1996). However, in spite of the ability to reduce off-gassing in the infusion process workers may also be exposed to hazardous working conditions requiring the use of protective gear and clothing including respirators during certain parts of the layup procedure.



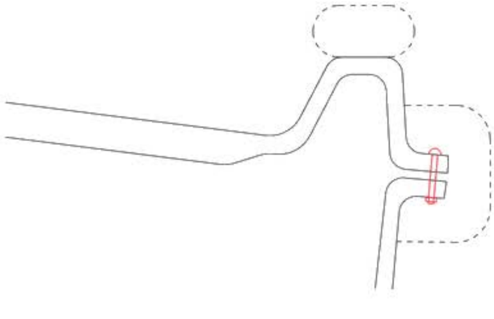
VARTM process using resin drawn through a preformed fiber reinforcement stack over gelcoat with a vacuum.

<u>*Sandwich Construction:*</u> Hull, deck, and superstructure components often use a core material to reduce weight and increase strength of the surface manifold assembly (Marsh, 2003). Sandwich construction results in a stronger surface due to the way that two modestly dissimilar surface forms, bound together in a layered assembly, reinforce one another. Core materials may be made from lightweight fast-growing wood such as end grain balsa, vinyl or polyisocyanurate foam, or pattern grid or honeycomb materials such as Airex or Corex (Bitzer, 1994).

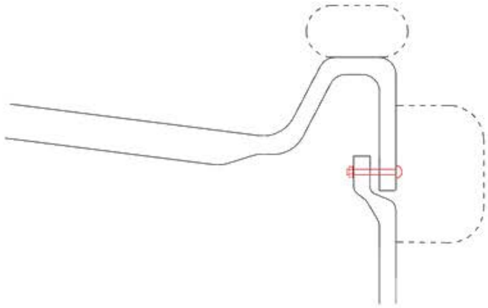
<u>*Interior Reinforcement:*</u> Once the thermoset resin has cured, the next step is the introduction of internal structural reinforcement. In the case of a hull, elements cut from foam, wood, plywood, or metal are added as a structural system to provide longitudinal and lateral stiffening. These structures also serve as mounting surfaces for equipment such as tankage and a propulsion system, and as surfaces for programmatic activities such as cabins and furniture. These may be modest in the case of small open craft, or more complex for larger vessels with enclosed interior volumes. In certain cases, FRP assemblies are constructed and used for both structural reinforcement as well as for technical or programmatic purposes. For example, FRP water tanks can be built in place to reinforce a hull, provide both ballast and storage for fresh water, and serve as the base upon which to build a berth or settee (Junhou & Shenoi, 1996). Using a hand layup process with several layers of fiber reinforcement and thermoset resin, internal structures are bonded or “tabbed” to the interior of the hull (Dodkins et al, 1994). Stringers, floors, beams, and bulkheads as well as the cabin sole, and built-in furniture work together as a system to maintain the form and shape of the hull, deck, and superstructure in a dynamic environment.

<u>*Hull to Deck Joint:*</u> Once the interior structure and fit out is nominally complete, the deck and superstructure(s) are added to complete the integration of the structural system. The attachment method is either a mechanical fastening system using bolts, a chemical bonding system using a specialized adhesive or thermoset resin, or a combination of the two involving periodic bolts and glue, and in certain cases an additional hand layup of resin impregnated woven fiber

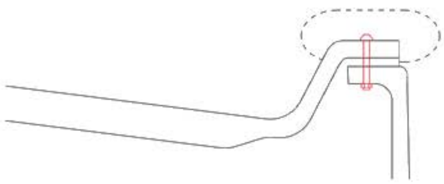
reinforcing materials (Hentinen, 2021). The hull may be either removed from the mould prior to adding the deck, or in certain cases the deck may be added while the hull remains in the mould. Additional superstructure assembly is usually completed while the vessel rests in a purpose-built cradle.



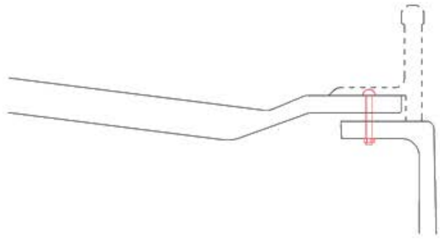
OUTWARD HULL FLANGE with Cap Rail and Rub Rail



SHOEBOX JOINT with Cap Rail and Rub Rail



INWARD HULL FLANGE with Cap Rail and Rub Rail



INWARD HULL FLANGE with Aluminum Toe Rail

Shortcomings of Moulded FRP Manufacturing: Despite its widespread use in manufacturing smaller marine vessels, moulded FRP has significant limitations. Building moulds is, by far, the most expensive and labor-intensive part of the boat manufacturing process. Complex topological forms are often difficult to produce with moulded FRP: surfaces with undercuts or overhanging folds are difficult or impracticable to produce. Naval architects and nautical designers must often simplify the forms of hulls, decks, and superstructures to meet the required draft angles for mould removal, or else complex surfaces must be broken into multiple parts for subsequent reassembly using handicraft processes (Nazzaro, 2019). Such forms are both labor intensive and expensive to manufacture. Furthermore, customized FRP components made by joining separately moulded parts may suffer from significant topological deviations as well as variation in size, thickness, density, strength, and weight due to reliance on hand-crafted manufacturing techniques for specialized components. Even with experienced craftspeople, dimensional variation is often a serious challenge.

The contemporary yacht market is currently geared toward semi-custom production: clients select a vessel based on broad requirements (size, cost, and other factors) and then customize the final product with various interior spatial configurations, interior design finishes, and equipment packages. Modifications to the hull itself, while theoretically feasible, are often too expensive for the typical client. Common hull or topside customizations that are simple for small boats constructed using wood remain elusive or prohibitively expensive for boats fabricated using moulded FRP. Typical customizations such as changing the interior ceiling height, the number or location of ports and hatches, or adding equipment such as a bowsprit or a stern swim platform can prove quite challenging for the contemporary yacht market to economically provide, given current manufacturing processes.

PROBLEM STATEMENT

For the past 50 years the production of smaller marine vessels has been dominated by one material and one technology: moulded FRP. Early experiments with FRP in the marine industry in the 1950's eventually led to its widespread adoption, and by the early 1970s it was the material of choice for most small production series vessels. Small marine vessels and yachts below 40 Meters (by far the vast majority of vessels in production) are typically built using this method as it has proven to be an economically efficient method for producing durable marine vessels (Scott, 1996).

There are several shortcomings to this manufacturing method that affect both the formal outcome and the manufacturing process of boats built in FRP. 1) Because FRP construction relies on moulds, formal geometric freedom of the hull or deck surface is necessarily limited. In order for the finished form to be successfully extracted from the mould its draft angles must be carefully considered. 2) Overhanging surface folds, while not impossible, are difficult to achieve and are necessarily limited in both their extent and axes of orientation. 3) Special assemblies such as inverse tapered apertures or protrusions with positive angular orientations must be moulded separately and then joined to the hull or deck assembly in a separate hand-crafted process that is both labor intensive and difficult to reproduce within strict tolerances. 4) Due to both the curing times for certain thermoset plastics and the time needed to custom fit and build interior structures that ultimately keep the hull from collapsing under its own weight, a mould may be "occupied" for a substantial period of time – days, weeks, or even months for larger vessels (Scott, 1996). 5) Moulds are expensive to produce and difficult to duplicate within strict tolerances. As such, boats are necessarily produced serially rather than in an assembly line, and customization to the hull or deck form is limited by the prohibitive cost of moulds.

According to an interview with a custom marine product manufacturer in La Spezia Italy in 2018, tolerances for some high-end yachts are often measured in centimeters rather than millimeters effectively rendering dimensional drawings and computer models relatively useless for mass production of many aftermarket products (Nazzaro et al, 2018). Dimensional variation may be at least partially the result of a hand-crafted approach to yacht manufacturing in which multiple layers of reinforcing fabric are cut and laid by hand resulting in surfaces that have significant thickness variability. Internal reinforcing structures such as stringers, floors, and bulkheads are typically added in a custom fabrication process: cutting individual scribe-to-fit members to be bonded to the interior of the hull using a hand layup and tabbing process.

There are additional shortcomings to FRP manufacturing that affect worker safety and health, as well as environmental safety (Kong et al.,1996). Many of the materials used in FRP construction are topical and respiratory irritants or known carcinogens (Frassine, et al, 2014). Glass and carbon fiber roving shed fine particles that can abrade and irritate the skin as well as the mucus membranes of the eyes, nose, and mouth, and the lining of the lungs (Omran, 2018). Many thermoset plastics and their catalysts contain chemical substances known to be hazardous to the health and well-being of those who work with them (Chia et al., 1994). Excessive exposure to these chemicals can be dangerous requiring special protective clothing and respirators to be worn when working with them (Tarvainen et al., 1993). In some shipyards and manufacturing facilities chemical exposure is partially mitigated by simple procedures such as working outside or opening large windows and doors to improve ventilation in the workspace (Carlo et al., 2007). However, many of these same chemicals are known to have deleterious effects on the environment (Stockton & Kuo, 1990; Nunez et al, 1999; Tajuelo et al., 2019) The widespread adoption of vacuum infusion moulding in which liquid resin is introduced to the reinforcement fiber layup in a large, sealed plastic membrane with negative atmospheric pressure has led to both more precise resin to fiber ratios as well as significant reductions in the release of chemicals into the environment. However, vacuum infusion is not feasible during many stages of manufacturing such as the hand layup of structural elements, or in the process of joining the hull and deck, resulting in the release of hazardous chemicals and exposure to workers during these procedures.

Automation as a Solution: The shortcomings of the FRP manufacturing method may be partially resolved by automating the manufacturing process using AM technology. There are several ways to approach manufacturing large objects for the marine industry using 3D printers: 1) use small equipment and a componentry method featuring specialized joints to assemble larger marine components such as a hull, deck, or sub-component from smaller 3D printed parts, 2) scale up the 3D printer with a large gantry system and a wide bead extruder to print large monolithic objects including moulds, hull and deck components, or entire boats, 3) mount a specialized 3D printer extruder on an articulated robotic arm to print large subcomponents or entire boats. The first example requires extensive labor to assemble the parts, and additional layers of FRP material may be required to waterproof the assembly and bind the parts together. The second approach has proven effective for making both moulds and small vessels, but the result is an excessively thick and heavy product that has not been proven effective for long-term exposure to the marine environment. The third approach has had limited success with several examples of boat hulls printed in smaller parts, but the labor costs can be prohibitive to join the parts, waterproof, and reinforce the assembly with both inner and outer layers of FRP material.

Robotic Tool: This research project aims to design a variation of the third approach described above using a 6-axis Kuka robotic arm with a prototype thermoplastic extruder that I have designed and built to print large surfaces using specialized multi-bias tool paths that construct a surface not in horizontal layers, but in configurations that are optimized for the specific formal requirements of each component or assembly. This tool is intended as a prototype for testing toolpath generation and deployment, and as a first step in developing a manufacturing process that deploys a continuous fiber thermoset resin FRP extruder yet to be fully developed. The design for this tool will be described in chapter four, and it will be discussed in the final section of the study on recommendations for future research.

Toolpath Generation: AM is not yet fully optimized for reliably printing large-scale structurally performative components. The first step in this research is the development of a toolpath generation method for extruding materials in novel patterns derived from an analysis of the structural loading conditions of the surface or component under consideration. This involves the NURBS surface modeling tool Rhinoceros and the plugins Grasshopper and KukaPRC. This facilitates modeling procedurally generated linear paths and surfaces while also supporting simulation of robotic movements and generation of robotic movement instructions in g-code, a computer language for controlling the movement of robotic tools. This method, its benefits and shortcomings will be discussed in detail in Chapter 4 and 5.

Design and Testing: Robots and end of arm tools are separate electronic systems that require a specialized procedure known as *integration* to control them using a single input system or programming method. Integration is typically a late-stage process in the development of an end of arm tool and falls outside the scope of this research project. In order to understand the end of arm tool control systems while testing toolpath generation methods, I developed a thermoplastic filament extruder and a secondary electronic switching and control system to communicate various extruder functions such as power on, heat setting, feed rate, and direction, as well as secondary controls such as a temperature display and a cooling fan. The design and fabrication of this tool and control system informed the design of the extruder while also facilitating the opportunity for preliminary proof of concept toolpath testing. As such, integration of the end of arm tool was not deemed critical to the research project but can be pursued as an additional avenue of research. This end of arm extruder is intended to be used for testing toolpaths for printing specific nautical design assemblies that can demonstrate the efficacy of both the AM toolpath generation method and the application of the tool to real-world manufacturing problems.

PURPOSE AND SIGNIFICANCE

The purpose of this research project is to evaluate existing AM technology and assess its potential for application to small marine vessel manufacturing. The project aims to investigate new methods for generating novel AM tool paths and demonstrate through proof of concept that it may be possible to produce complex topological surfaces and assemblies that are common in marine vessels without the need for moulds.

Additive Manufacturing for the Marine Industry: One of the greatest innovations for industrial design in the 21st Century is the development of AM (Goodship et al., 2015). It has taken off in the past decade with dramatic reductions in the cost of 3D printing materials and equipment. In response, industrial design is experiencing a significant change in the roles design development and prototyping play in the design process. To a limited degree, it is now possible to use AM for product manufacturing especially when customization is a common product feature. For the design of marine products and vessels AM technology promises far greater formal variation and topological complexity than traditional FRP moulding techniques permit. It allows the designer to directly control the form, strength, and weight of complex formal components using a computer model rather than handicraft techniques. Objects made using AM demonstrate low deviation between their specified and actual dimensions eliminating the need for expensive field measurement and complex templates that are typically required in the fitting out process of vessels made with moulded FRP.

Computer modelling and the 3D printer control software driving AM allow for the design of not only the exterior surfaces of an object but also their internal structures (Musio-Sale et al., 2019). Complex simulation tools in design software allow hull forms and structural systems to be optimized for stability, hydrodynamic efficiency, strength, and material efficiency. An integrated design and manufacturing approach that has been made possible for smaller scale industrial design by 3D modelling, performance simulation, and AM may soon allow yacht designers to exercise precise control over many areas of naval construction.

This study aims to explore new methods for manufacturing marine vessels that will have significance for the nautical industry as well as industrial manufacturing at large. The application of automation and AM to marine vessel manufacturing can have many positive effects on the marine industry including 1) increased performance, 2) ease of customization, 3) reduced production cost, and 4) improved worker and environmental safety.

Increased Performance: AM, and automation more broadly, can lead to greater adherence to strict dimensional tolerances in the production of marine vessels. This precision will result in assemblies that are more highly optimized for specific loading conditions. At the same time, localized variations in surface thickness can be precisely controlled to reduce weight and increase performance.

Customization: Because this manufacturing method has the potential to partially or completely eliminate the need for moulds, AM will allow an increased capacity for customization to meet variable localized performance criteria within hull and deck surfaces. Within a single surface assembly, performance characteristics can be precisely calibrated to feature variable density, variable thickness, and variable load resistance based on local structural needs and weight constraints. The hull thickness can be tapered evenly or abruptly as needed in response to local loading conditions, and mounting surfaces for hardware can be designed for optimal load resistance without the need for backing plates. More dramatically, the entire form of the hull, deck, or superstructure can be modified to suit the desires of a potential client: raising the deck height, extending the length or depth of the hull, or increasing the size or configuration of the cockpit may all be easily achieved with AM, while remaining exceedingly costly for standard moulded FRP. Interior structural conditions can also be reconceived leading to new programmatic and spatial conditions for interior designers.

Reduced Cost: Meanwhile manufacturers can dramatically reduce labor costs while still offering substantial customization. By modifying digital models rather than relying on the limitations of moulded construction and hand layup methods which are more labor-intensive, manufacturers can dramatically reduce the cost of their custom or semi-custom products.

Workplace Safety and Environmental Safety: Robots will be able to perform work in hazardous conditions in segregated spaces with robust air purification systems that spare workers exposure to toxic materials and fumes while simultaneously limiting emission of harmful chemicals into the environment.

This manufacturing method has the capacity to benefit other industries as well. Ultimately, this may lead to more efficient manufacturing and distribution networks with a more prevalent on-demand and just-in-time production as well as decentralized production capabilities that can reduce the need for long distance shipping and distribution. AM has the potential to lead to widespread mass customization of a broad range of durable goods and products including sporting goods, furniture, automotive components, and architectural components and assemblies (Khajavi, 2014). At the same time, these applications may have similar positive impacts on performance, customization, cost, and environmental and workplace safety.

CONCEPTUAL FRAMEWORK

Additive Manufacturing is a broad term that describes a variety of different ways to manufacture objects. As such, AM can be applied to marine manufacturing in a variety of different ways, in different phases of the manufacturing process, and to different extents. Building boats is a complex process that presents specific problems that must be addressed in any automation solution. As such, various kinematic approaches must be investigated, evaluated, and analyzed relative to the specific context of marine vessel manufacturing. The mass production of hulls, decks, superstructures, and other marine components using AM will require additional applied research in the design and use of robotic tools, kinematic systems, and the software tools used to control their movement and operations. This section will provide an introduction to the most common AM methods and materials followed by an introduction to robotic kinematics.

Additive Manufacturing Technology: The terms Additive Manufacturing (AM) and 3D printing describe several very different methods for producing 3-dimensional forms. First developed in the 1980s for small scale rapid prototyping applications, AM remained a high-end prototyping tool and an area of research and development for nearly 20 years. This method for constructing 3-dimensional forms typically uses layers of deposited or hardened materials to build up an object in laminar procession (Huang, et al 2012). There are several distinct AM processes that fall into five main categories that will be discussed below: 1) Photopolymer rapid prototyping using liquid resin bath process, 2) Photo-activated or liquid chemical binder-activated granular material processes, 3) Cut shape lamination process, 4) Material jetting process, and 5) Thermoplastic deposition process.

For the purpose of this exercise, only the most common methods of 3D printing that feature commercially available devices and products are discussed. While there are a broad array of emergent technologies awaiting commercialization or recently come to market, these fall outside the scope of this investigation. 3D printing research dealing with food, chemical compounds, pharmaceuticals, internal organs and body parts, and other biomedical applications have little relevance to the marine industry. Likewise, specialized projects such as Enrico Dini's mega-scale plaster printing exercises (Dini et al., 2015), regolith printing habitats on the moon or mars (Roman et al., 2016), gas metal arc welding printing technology (Van Thao, 2020), and the various large-scale clay and concrete printing projects also fall outside the scope of this survey as they are not directly applicable to marine vessel manufacturing. While aluminum gas metal arc welding may have potential applications for ship building and small vessel manufacturing (Taşdemir & Nohut, 2021), it is outside the scope of this investigation.

AM Materials: Small marine vessels under 40 meters are typically made from fiber reinforced thermoset plastics. Thermoset plastics are liquid resin materials that require a catalyst to harden, either with the addition of a chemical activator or through exposure to light of a particular wavelength, frequency, and amplitude (Arrabiyeh et al, 2021). These catalysts typically generate heat which aids in the hardening process, however, once a reaction occurs the plastic is *set* and cannot be returned to its pre-reactive state. Fiber reinforced thermoset plastic construction is relatively inexpensive, the material can be easily formed into a variety of 3 dimensional shapes, and it exhibits excellent strength to weight ratio while maintaining robust resistance to osmotic effects in the marine environment. For these reasons it has become the dominant material in use for boats under 40 meters. Thermoset plastics for marine manufacturing are remarkably stable over time and exhibit low but not inconsequential osmotic tendencies which are typically mitigated with surface treatments such as gelcoat and periodic maintenance procedures such as painting (Garcia-Espinel et al., 2015, Sateesh et al., 2015). The combination of UV light and water has a tendency to degrade the long-term strength and performance of certain plastics over time (Dodiuk, 2021). For this reason, research into thermoset plastics and composites is an important area of continued research.

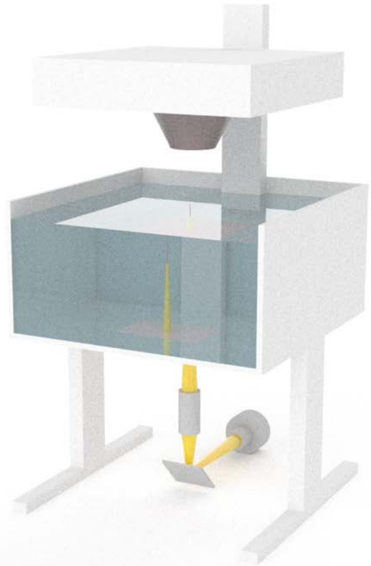
Thermoplastics, on the other hand, are typically activated with the application of heat either in the form of a simple heating element or with a laser. Though there are examples of smaller, light-duty vessels such as kayaks and dinghies made from unreinforced thermoplastics using a rotary moulding or injection moulding process, thermoplastics are relatively uncommon for the production of small and medium sized marine vessels. While many thermoplastics can be reshaped with the reapplication of heat, it is well documented that thermal stress, deconsolidation, and the "springback" effect are problematic issues of concern, particularly with fiber reinforced thermoplastic composites (Wan & Takahashi, 2014). In a marine environment, these qualities can lead to delamination and premature failure of the hull. More exotic carbon fiber reinforced high-temperature polymers such as polyetherethylketone (PEEK) and polyethylketoneketone (PEKK) may one day prove to be effective for the production of marine vessels, but they remain prohibitively expensive in the near term. Additional research regarding the material behavior of high temperature thermoplastic composites over time, particularly their long-term resistance to salt water is incomplete (Neşer, 2017). For these reasons, fiber reinforced thermoplastics have not been widely used in the nautical design and marine manufacturing industry (Bel Haj Frej et al., 2021).

There are a limited number of examples of case studies demonstrating successful application of AM technology to marine manufacturing. There are several examples of a similar automated manufacturing applications that have proven effective for aerospace research and development. This chapter will feature descriptions and evaluations of six distinct AM and automated manufacturing applications suitable for marine manufacturing: 1) thermoplastic and composite thermoplastic parts and components fabricated using consumer grade desktop 3D printers with proprietary joinery and finishing techniques 2) composite thermoplastic moulds produced with large-scale industrial extruders and CNC mills, 3) composite thermoplastic hulls and hull parts produced with large-scale industrial pellet extruders, 4) composite thermoplastic hull components produced using narrow bead extruders that are joined and wrapped in FRP skins on both interior and exterior surfaces using hand layup techniques, 5) continuous fiber FRP hull components that are printed with narrow bead extruders and joined and wrapped with FRP skins using hand layup techniques, 6) Automated Fiber Placement (AFP) of high-temperature semi-crystalline thermoplastic prepreg continuous fiber tape featuring In Situ Consolidation (ISC) using laser sintering and high-pressure rollers on a heavy duty mould or mandrel.

Additive Manufacturing Processes: AM was first developed in the 1980's and was soon after, deployed as a high-end prototyping tool (Pham & Gault, 1998). When Adrian Bowyer published his open-source RepRap Project in 2005 (Bowyer, 2014) 3D printing entered the mainstream with a "self-replicating" machine using the FFF process to reproduce 3D objects. The introduction of the first MakerBot in 2009 made off-the-shelf 3D printers affordable and easy to use for the general public (Goldberg, 2018). The commercial development of Large-Scale Additive Manufacturing (LSAM) in 2016 by Thermwood Corporation introduced the possibility to build very large objects using a wide bead (3cm) extruder mounted on an industrial gantry coupled with a CNC surfacing tool mounted on a second gantry (Scott, 2016). In 2019, the University of Maine printed a 7.6 meters (25 feet) patrol boat, the largest object ever made at the time with a 3D printer using a gantry-mounted, wide-bead, thermoplastic composite pellet extruder using the FFF process (UMaine News, 2019). There are a variety of 3D printing methods and material processes available to produce 3-dimensional forms from a digital model. The most common equipment and processes are described below.

1) Photopolymer rapid prototyping using liquid resin bath process:
a. The Digital Light Processing (DLP) method uses a high intensity light source to harden sequential layers of a form in a liquid resin bath (Hull, C. 1988).
b. Stereolithography (STL) uses a similar process with ultraviolet lasers and a horizontal skimming tool for uniform application of each layer of resin. These techniques are typically used for high resolution prototyping. The example below shows a laser used for curing liquid

resin material at the boundary between the liquid medium and the finished object. In this example the platen is designed to moves upwards as the emerging form is hardened at the upper boundary of the liquid resin reservoir.



Photopolymer rapid prototyping using liquid resin bath process, also known as Stereolithography.

2) Photo-activated or liquid chemical binder-activated granular material processes:
a. Selective Laser Sintering (SLS) uses dry granular plastic materials that are superheated with a laser to adhere to one another in successive layers (Beaman et al 1996).
b. Selective Laser Melting (SLM) and c. Electron Beam Melting (EBM) both deploy a similar process but use metallic powders melted with either a high-power laser or an electron beam in a vacuum chamber. These techniques are typically used for high performance prototyping and one-off manufacturing for automotive and aerospace industries.
d. Binder Jet (BJ) printers typically use a liquid chemical binder sprayed onto successive layers of powdered material to build a 3-dimensional form; however, they can also be used with common materials such as water and powdered clay or porcelain. This method is often used for prototyping low-resolution and low-performance objects in design and form-finding applications. The example below shows a roller transferring a new layer of granular material to the build area where a laser fuses materials onto the emerging form.

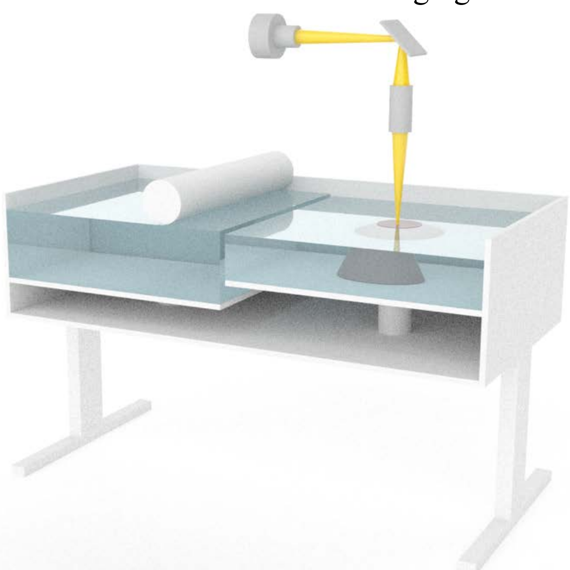
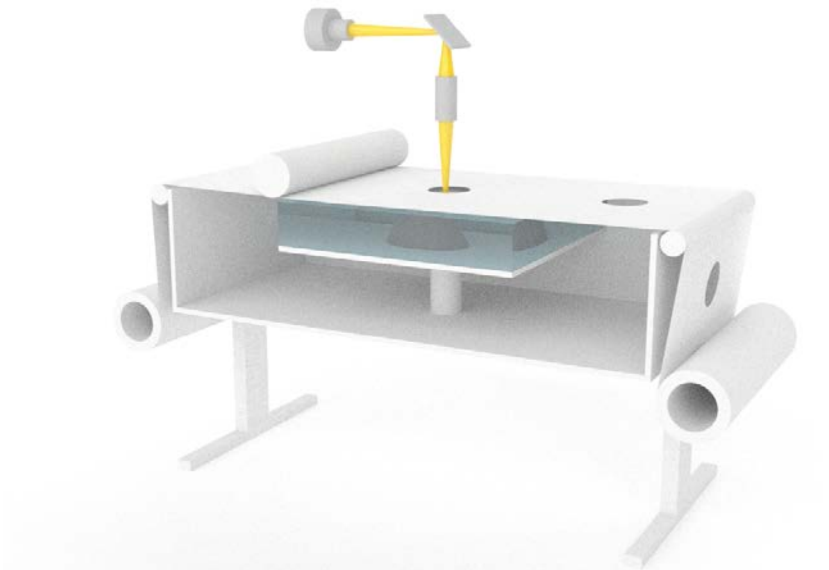


Photo-activated or liquid chemical binder-activated granular material processes, also known as SLS.

3) Cut shape lamination process:

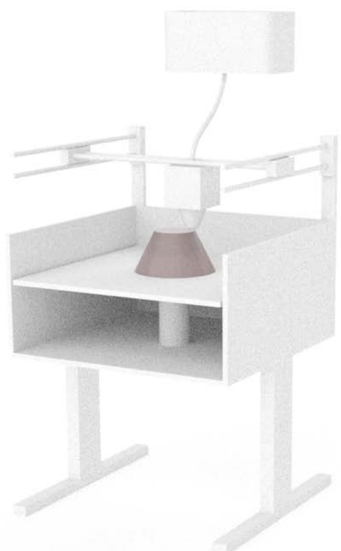
a. Laminated Object Manufacturing (LOM) uses a series of shapes cut from a common material such as paper or plastic sheets that are glued or fused together using a heated roller to build up an object in a series of layers. This is an inexpensive and fast prototyping or modeling tool most often used for design and form-finding. The example below shows a continuous roll of heat-activated adhesive material passing over the build area where a laser cuts out the shapes of serial cross sections and a heated roller laminates them to the emerging form.



Cut shape lamination process, also known as LOM, is primarily used in a limited capacity by architects.

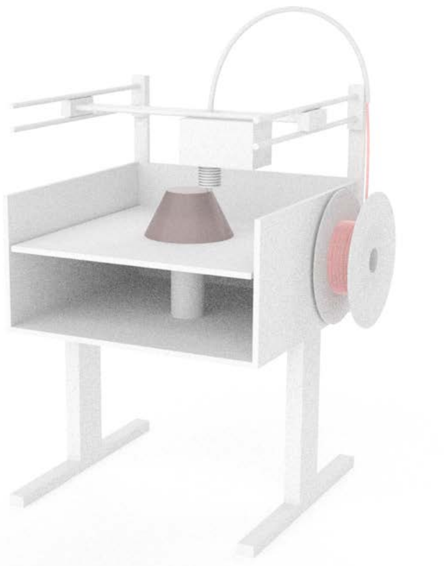
4) Material Jetting (MJ) process:

a. This technique also known as Wax Casting uses molten wax extruded in successive layers onto a surface platen to build 3D forms in layers, sometimes deploying a second print head to build scaffolding from a dissimilar material. This process is typically deployed for jewelry industry in lost wax casting smaller objects. The example below shows a liquid extruder drawing molten wax from a receptacle and depositing it directly onto a form emerging on the build plate.



Material Jetting process, also known as wax-casting is primary used in the jewelry industry.

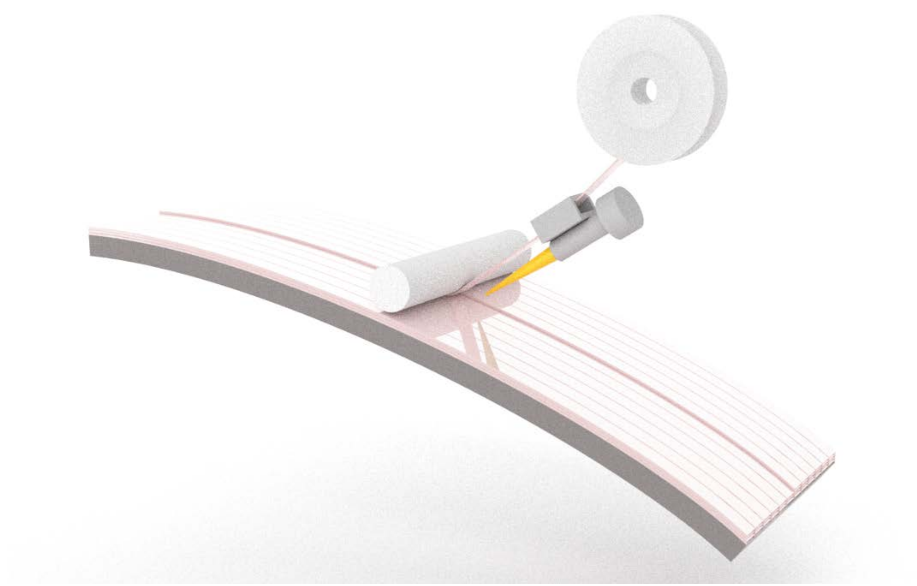
5) Thermoplastic deposition process:
a. Fused Filament Deposition, also known as Fused Deposition Modeling, and Fused Filament Fabrication (FFF), feeds a filament of thermoplastic polymer through a heating element and extruder nozzle depositing a rapidly cooling molten material onto a build surface in successive layers (Crump, s. 1991. This method has been successfully scaled up with wide-bead thermoplastic pellet extruders deployed on robotic arms and mounted on gantries. Additives such as chopped fibers, cellulose pulp, or continuous stranded fibers can be added to thermoplastic mixtures. FFF is an extremely common prototyping method that has gained in popularity with many unique applications including applications to the nautical design and marine manufacturing industry.



Thermoplastic deposition process or FFF is the most common method used for 3D printing.

Variations of the FFF process feature high-temperature polymer thermoplastics such as PEEK and PEKK as well as other high temperature polymer composites that may include strands of glass, carbon, nylon, and Kevlar fibers in discontinuous or continuous strands. Desktop-ready examples of this technology include Markforged Onyx and Mark 2 printers (Markforged, Inc., 2021) as well as 9T Labs (9T Labs, 2021) Carbon Fiber printer.

6) Automated Fiber Placement with In Situ Consolidation:
Automated Fiber Placement (AFP) with In Situ Consolidation (ISC) uses a tape winding end-effector on an articulated multi-axis manipulator to draw high-temperature thermoplastic pre-impregnated (prepreg) carbon fiber tape across or around a heated aluminum mandrel or mould. A laser melts the thermoplastic, and an integrated roller subsequently compresses the molten plastic to ensure a consolidated matrix with minimal voids. While not technically an AM process, it suggests a manufacturing methodology that may be a fruitful model for this study. Initially developed for aerospace fabrication research (Gardiner, 2018), AFP is currently used for manufacturing high pressure pipe fittings for the petrochemical industry.

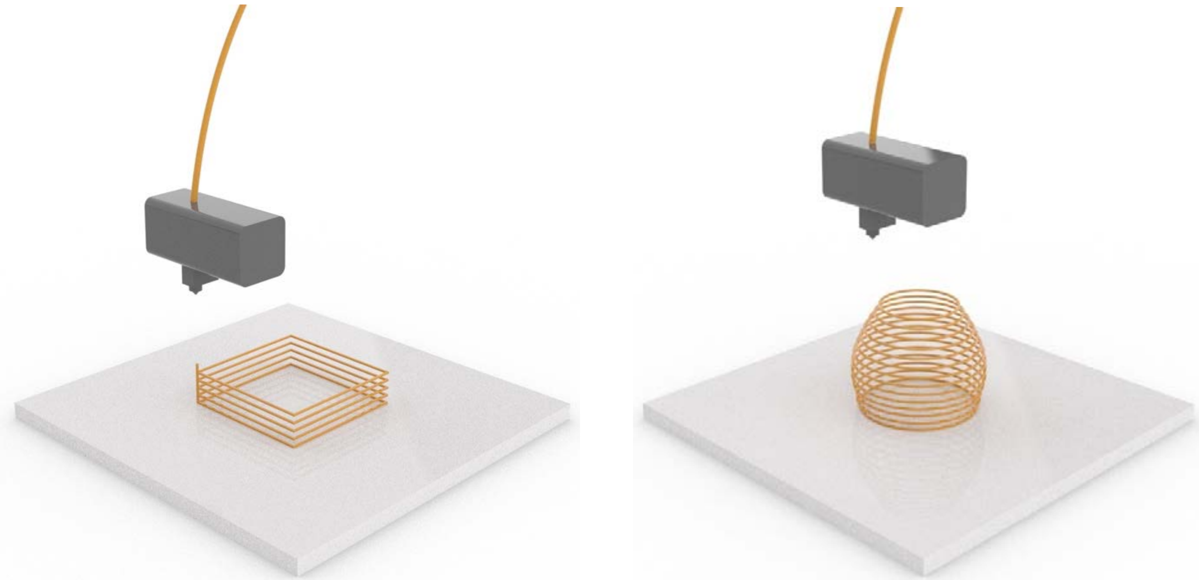


Automated Fiber Placement process or AFP is automated manufacturing using prepreg carbon fiber tape.

The Limitation of AM Logic: An important aspect of the AM process is the software that is used to drive 3D printers and other robotic tools. Many common 3D printers resolve a form in a series of horizontal layers built up in a sequence. The orientation of the object relative to the extruder head and the platen or build surface can have a dramatic effect on the final object including the amount of material used to produce the object, its material strength, and its structural performance. The proprietary slicer or CAM software tools that drive many 3D printers have pre-set values that make generic assumptions about how to produce 3D forms using a particular material or process. (Šljivic, 2019; Zhou et al., 2018) While they are convenient and easy to use, they mask important and sometimes complex aspects concerning structural performance that should be considered when producing an object. These aspects include orientation of the object, speed of material deposition, density of core material, and configuration and location of support material.

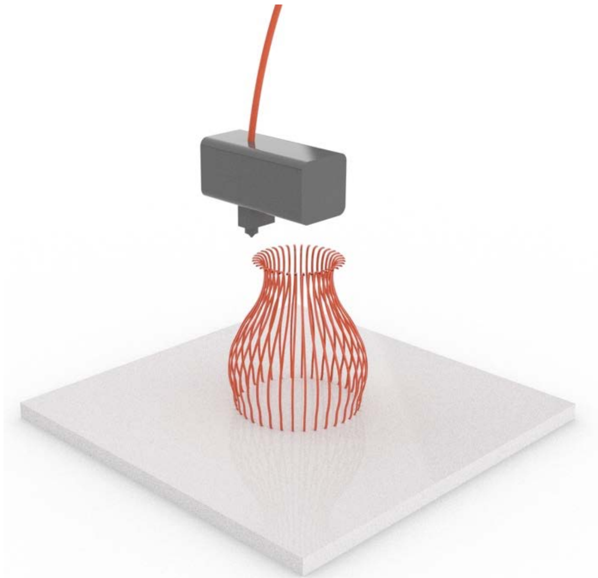
Typically, slicer software used in FFF printers produces a form by tracing successive laminar profiles - driving the print head to a series of x and y coordinates to describe a horizontal *slice* and then activating the Z-axis servo motors once the layer is completed to begin the next horizontal slice. The most significant shortcomings of the laminar FFF printing method are 1) the relative weakness of the bonds between the layers of deposited material and 2) the uneven or stepped surface characteristics of laminar extrusion of thermoplastic materials (Levy et al, 2003, Kantaros, & Piromalis, 2021). Poor adhesion between layers can lead to sub-standard performance for objects built using this method, and uneven surface characteristics may require labor intensive post-processing (Šljivic, 2019). Post-processing procedures to improve strength and surface qualities include heating printed objects to anneal the layers and improve intralaminar bonding, CNC milling to smooth finished surfaces, and cold-moulding or wrapping printed parts in FRP. Recent developments in non-planar FFF 3D printing point to one possible solution for this problem simultaneously addressing the stepped appearance of tapered surfaces and the intralaminar weakness of objects manufactured using this method. The non-planar building method develops a form by dynamically activating the Z axis servo motor along with the X and Y axes (Alsharhan et al., 2017; Królczyk et al., 2014). The result is both a smoother appearance to inflected surfaces and potentially superior material performance for the built object. This is an area of active research for nautical design applications for AM.

This research project is aimed at Multi-Bias Additive Manufacturing (MBAM). MBAM uses a 6-axis robotic arm to print objects using an alternative system of kinematic logic described in the diagrams below.



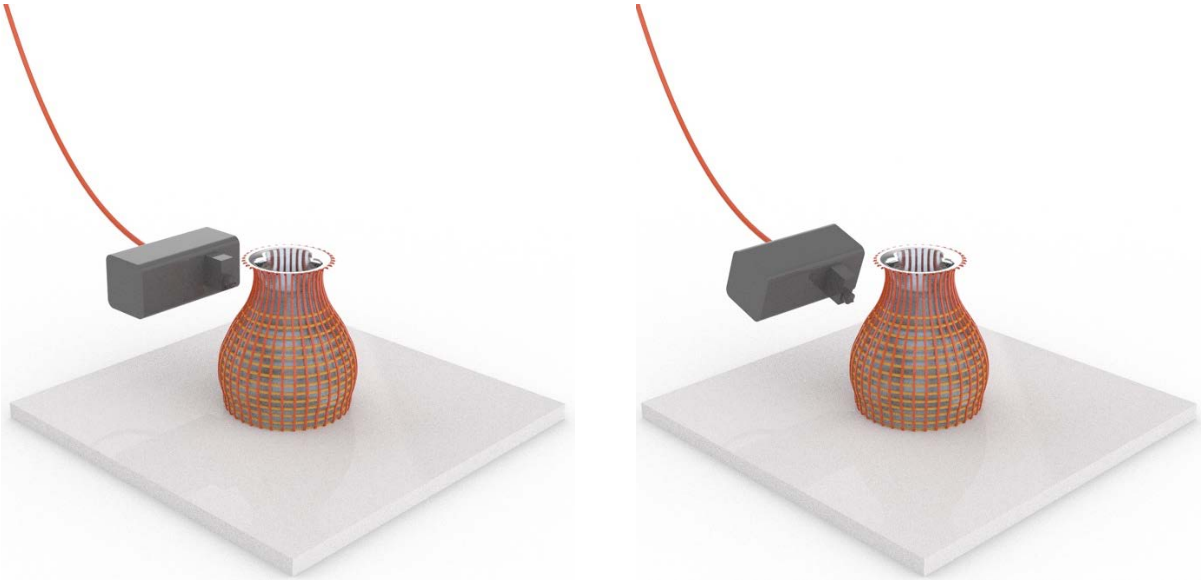
Commercial 3D printers are optimized for building objects using a series of laminar toolpaths.

These diagrams demonstrate how the typical AM kinematic logic relies on a gantry system optimized for laminar printing. Material is deposited in patterns tracing the orange curves relying on a series of XY coordinates. Once the 2-dimensional shape or pattern is completed the Z axis is actuated and the next “slice” is traced directly atop the previous layer. Modest overhangs are possible without the need for additional support material.



Commercial 3D printers are not optimized for building objects using toolpaths not parallel to the build-platen.

This diagram demonstrates that the typical AM kinematic logic that relies on a gantry system is wholly unsuited to printing alternative tool paths such as the vertical curves shown in red. Because the tool approaches from the top, after the first tool path is traced (assuming that the material will stand up) the extruder will collide with the material deposited by subsequent tool paths.



AM kinematics need to be modified in order to print these vertical curves.

These diagrams demonstrate that AM kinematic logic must be adapted in order to follow alternative tool paths such as the vertical curves shown in red. First, a scaffolding surface is required, demonstrated by the orange curves. This can be easily produced using standard laminar AM logic. Next, the tool needs to be reoriented so that it can approach each vertical curve in a radial orientation (perpendicular to its curvature profile) so that it will not collide with the emerging geometry. Finally, where possible, the tool needs to be oriented perpendicular to the tangent of the curvature normals (at any point along the curve the tool should approach as close as possible to a perpendicular orientation). The approach orientation of the tool will always be dependent on both the geometry of the object being manufactured and the physical size of the tool performing the manufacturing operation. Clearly, at the bottom of each red curve, the tool will collide with the platen if it is not properly oriented at an angle less than perpendicular to the curve normal until it has traveled vertically to point at which it may be reoriented perpendicular to the curve normal without danger of collision with the platten.

Summary of AM processes: AM methods other than FFF are generally not particularly well-suited to scaling up for large product manufacturing for a variety of reasons: inherent strength of certain materials (BJ and MJ), time-dependent chemical processes that may be optimized for thinner layers resulting in excessive build times (DLP, STL, SLS), surface tension of liquid materials that can make large scale applications unfeasible (STL and MJ), and the size and mechanical requirements for a build chamber that may be sub-optimal for large-scale applications (for example, an unreasonably large vacuum chamber for EBM). FFF is the only method currently well-suited for transitioning from large-scale prototyping to large-scale manufacturing applications. However, there are potential issues for marine manufacturing using this method due to the relative weakness of the bonds between the layers of deposited material and the uneven or stepped surface characteristics of laminar extrusion of thermoplastic materials (Levy et al, 2003, Kantaros, & Piromalis, 2021). Poor adhesion between layers can lead to sub-standard performance for objects built using this method, and uneven surface characteristics may require labor intensive post-processing (Šljivic, 2019). Post-processing procedures to improve strength and surface qualities include heating printed objects to anneal the layers and improve intralaminar bonding, CNC milling to smooth finished surfaces, and cold-moulding or wrapping printed parts in FRP. Recent developments in non-planar FFF 3D printing point to one possible solution for this problem simultaneously addressing the stepped quality of tapered surfaces and the intralaminar weakness of objects manufactured using a laminar printing method. The non-planar building method develops a form by dynamically activating the Z axis servo motor along with the X and Y axes (Alsharhan et al., 2017; Królczyk et al., 2014). The result is both a smoother appearance to inflected surfaces and potentially superior material performance for the built object.

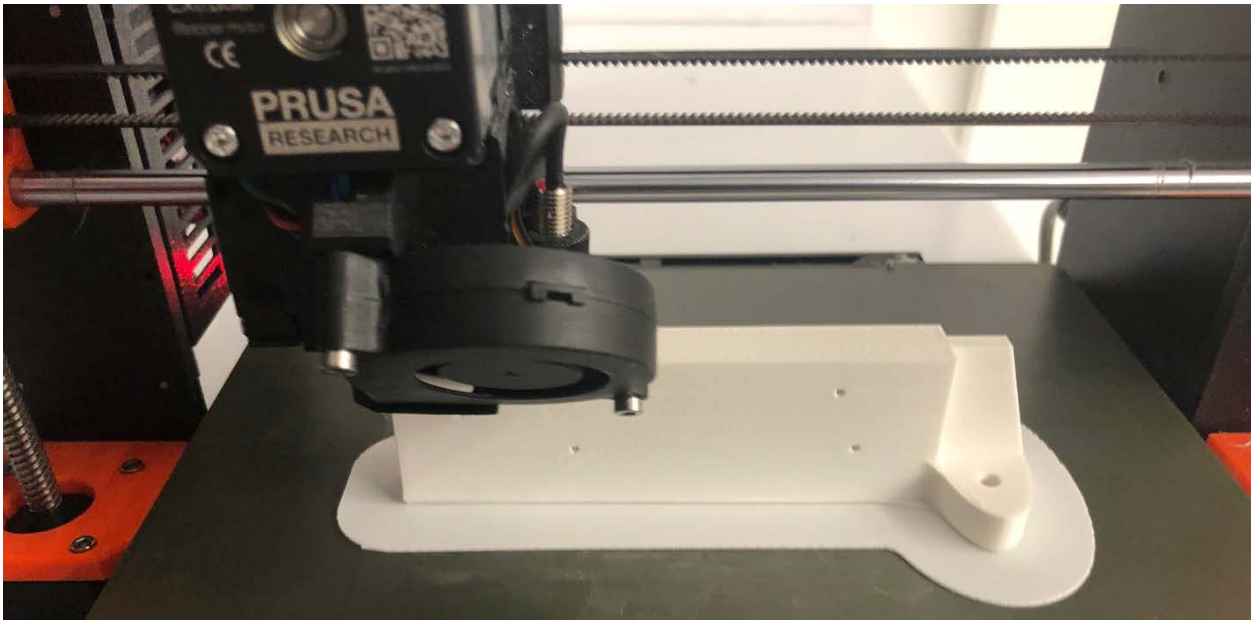


Image shows the smooth surfaces of a primarily rectilinear solid infill object being printed using PLA filament.

Scaling up Additive Manufacturing: There are a variety of methods to increase the scale of AM devices to print large objects and there are a host of problems that attend this increase in scale. There are two primary components to AM devices: the print head or extruder and the kinematic systems that position it in cartesian space. The methods for scaling up AM devices treat these two systems in one of two different ways: 1) use the logic of existing 3D printers to make very large machines with large extruders, 2) increase size and reach of the kinematic system, but not the size of the extruder itself.

There are two primary approaches to scaling-up FFF printers that may be suitable for marine manufacturing: 1) Gantry-mounted pellet extrusion features wide-bead extruders often using discontinuous or chopped glass, carbon, Kevlar, or nylon fibers in composite thermoplastics, 2) Robotic arm-mounted Continuous Fiber Manufacturing (CFM) extrusion features narrow-bead drawn-extruders using continuous strands of glass, carbon, Kevlar, or nylon materials in either thermoset plastic or composite thermoplastics. In the former case, the extruder simply features a larger nozzle fed with pelletized thermoplastic composite materials mounted on a scaled-up servo motor actuated 3-axis CNC delivery system. Instead of a vertically actuated print platen, the extruder moves up and down, and can even be configured with additional axes to modify the build angle or orientation of the extruder nozzle. In the latter case, pre-impregnated strands of material are either pushed and/or drawn out of the nozzle by the prepreg filament feed mechanism and the coordinated movement of a robotic arm which can approach the build surface from a variety of angles dependent on the geometry of the object being printed. This allows a rethinking of the fundamental laminar approach to additive manufacturing and may be appropriately referred to as MBAM because it potentially allows 3-dimensional manifold surfaces to be constructed following toolpaths along multiple biases.

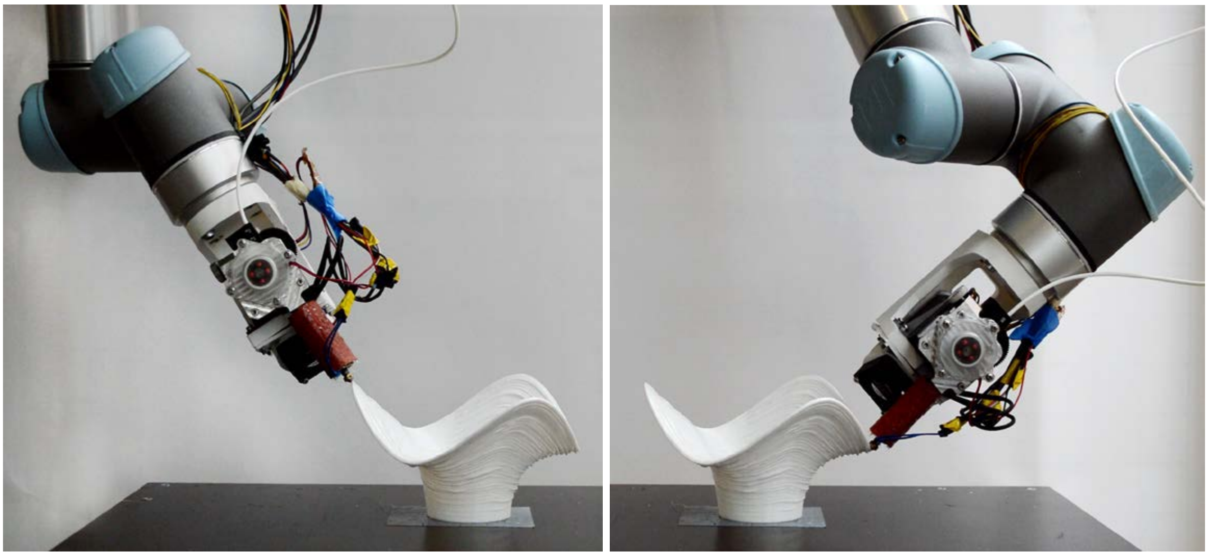
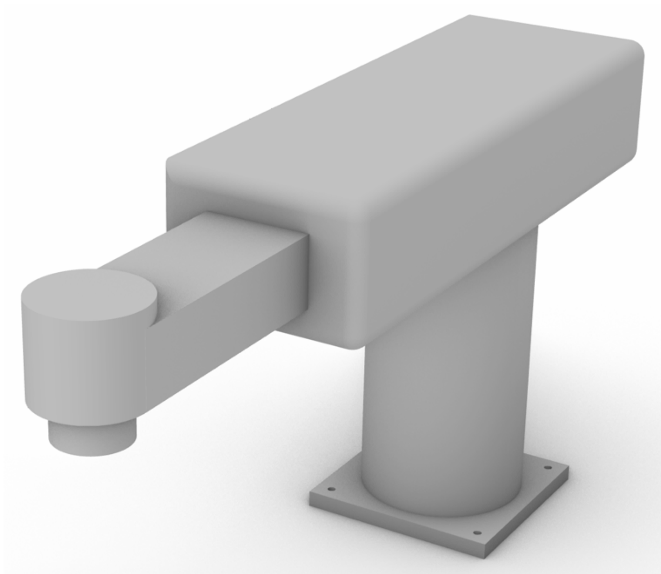


Image courtesy of Ioanna Mitropoulou, (ETH Zurich, 2020) showing non-planar toolpaths for AM.

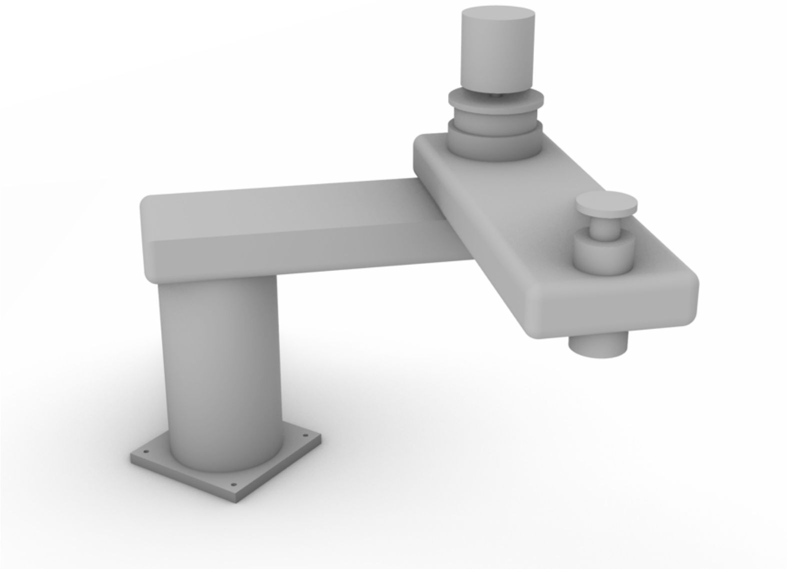
<u>*Kinematic Systems:*</u> There are a range of different industrial robots with kinematic solutions for automating manufacturing processes. Industrial robots are limited by their range of motion (degrees of freedom) and their reach (work envelope). Six common industrial robotic kinematic configurations will be discussed below.

1) Cylindrical Robots:
Cylindrical robots are often robust and capable of heavy duty or repetitive operations with multiple duty cycles. They use a radial coordinate system and feature both a limited work envelope and a limited range of motion with only one or two servo motors. Their ability to orient tools is limited to one axis. They are typically used in material handling operations or in simple repetitive operations requiring limited tool orientation.



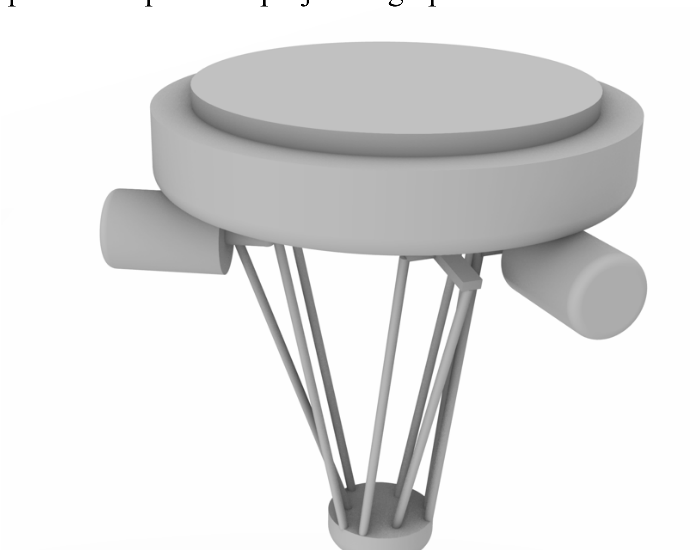
Cylindrical Robots are typically used for material handling and repetitive operations requiring low dexterity.

2) SCARA Robots:
SCARA robots are also often robust and capable of repetitive operations with multiple duty cycles. With one additional radial joint, they use a radial coordinate system and feature both a moderately less limited work envelope and range of motion than a Cylindrical Robot. With only two servo motors and two joints, their ability to orient tools is limited to one axis. They are typically used in material handling operations or in simple repetitive operations requiring limited tool orientation and moderate reach.



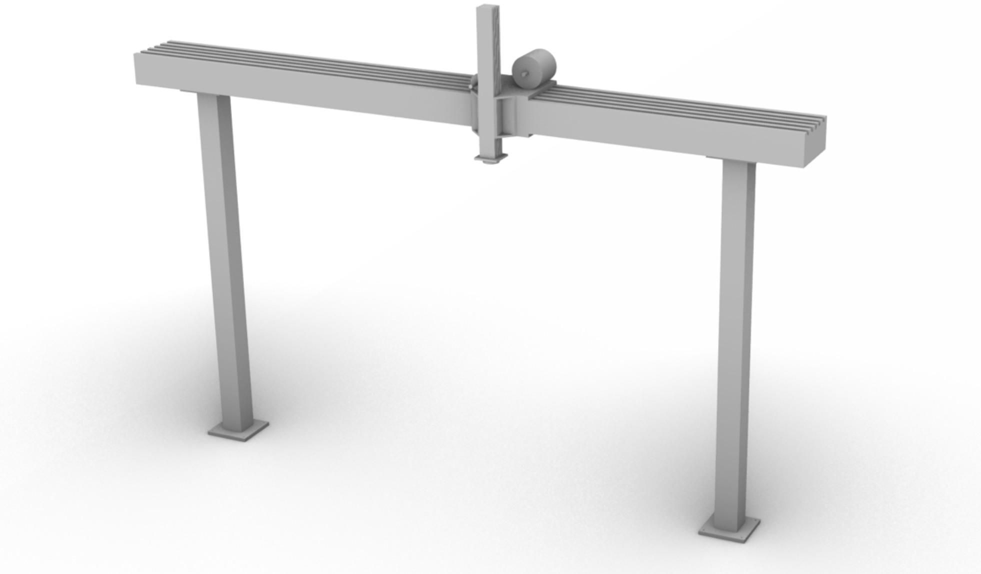
SCARA Robots are typically used for material handling and repetitive operations requiring low dexterity.

3) Parallel Robots:
Parallel Robots, also called Delta Robots, are named for their non-sequential joints which allow a freedom of operation and maneuverability that is optimal for high-precision manufacturing. Using three servo motors they can position a tool with a great precision in multiple axial orientations, but they have a highly limited work envelope. While they are typically used in electronics manufacturing, they are also well-suited to applications that may require a deck surface to be quickly reoriented such as flight simulators or other immersive technologies that reorient a physical space in response to projected graphical information.



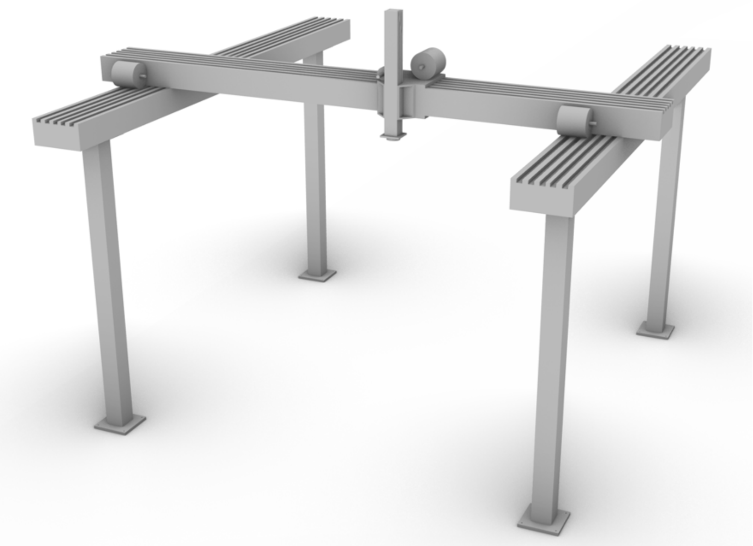
Parallel Robots are typically used for high-precision limited reach operations in electronics manufacturing.

4) Linear Robots:
Linear Robots are typically robust, heavy-duty kinematic systems that do not require a broad range of maneuverability. They use a Cartesian system to position a tool along a single axis featuring a rather restrictive work envelope. Modular in their design, they can be expanded as required or curved for specific manufacturing requirements. With only one or two servo motors, they are commonly used in heavy and repetitive material handling and limited range of motion operations.



Linear Robots are typically used for heavy-duty applications requiring a limited range of motion.

5) Gantry Robots:
Gantry Robots are typically robust, heavy-duty kinematic systems that feature a broad range of maneuverability. They use a Cartesian system and three or four servo motors to position a tool in cartesian space. While tool positioning is highly maneuverable, tool orientation is limited unless additional axes are added. Modular in design, they can be expanded as required, and can be found in a variety of different scales from simple desktop printers to automated carwashes. They are commonly used in heavy material handling, 3D printing, milling, and moderate precision manufacturing.



Gantry Robots are typically used for heavy-duty applications requiring a broad range of motion.

6) Revolute Articulated Robots:
6-Axis Robots are robust, moderate-duty kinematic systems that feature exceptional maneuverability and an expansive work envelope. They use polar or Cartesian systems and six servo motors to position and orient tools relative to the work surface. Both tool positioning and tool orientation are highly maneuverable and additional axes can increase their range of motion and their work envelope. They are commonly used in moderate and high precision manufacturing.

6-Axis Robots are typically used for moderate precision manufacturing.

Commercially available 3D printers bear a close resemblance to common robotic gantry systems such as what one might find in a typical automated car wash. Automated gantry systems use a simple CNC style configuration featuring three or more servo motors that allow a tool to be positioned in space using cartesian coordinates. Additional axes can be easily added to control the orientation of a tool relative to the work. However, this method of automated tool movement and positioning is limited by the system itself which typically approaches the work from a singular preferential orientation – usually from above. A more flexible system is an articulated robotic arm which typically exhibits six degrees of freedom and has the capacity for as many as six additional external axes to reorient the work relative to the tool.

SUMMARY OF METHODOLOGY

To investigate the potential application of robotic AM to marine vessel manufacturing, a mixed research method is used that relies on both Qualitative Analysis of a series of case studies and Design-based Research (DBR) applied to the design and testing of a novel tool path generation procedure and an experimental robotic extruder prototype.

Qualitative Analysis: Qualitative analysis is an approach to literature review that seeks to support the fundamental research question with reference to existing and emerging research and scholarship in a particular topic area (Onwuegbuzie et al., 2012). According to Machi and McEvoy (2021), "A literature review is a written document that presents a logically argued case founded on a comprehensive understanding of the current state of knowledge about a topic of study. This case establishes a convincing thesis to answer the study's question." This framework will guide the selection and evaluation of several case studies in Chapter 2.

The case studies in Chapter 2 describe a variety of recent manufacturing experiments and practical methods used to produce marine replacement parts, components, moulds, and entire hulls. A qualitative analysis of these methods in Chapter 3 explains the criteria used to evaluate their potential for further development. The outcome of this exercise establishes several technical challenges that must be addressed and provides guidance for the development of a novel method for manufacturing marine vessels.

Design Based Research: Manufacturing and fabrication challenges are often best understood through direct experience; therefore, the project aims to produce representative excerpts of typical marine vessel components using a specific reference vessel described below. A design-based research method guides the development of this manufacturing method which requires the design of new tools and toolpath generation procedures for applying AM to the problems specific to both marine vessel manufacturing and robotic application of AM.

DBR is "a systematic but flexible methodology aimed to improve… [research outcomes] through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually sensitive design principles and theories." (Wang & Hannafin, 2005). While DBR has historically been associated with educational research in curriculum development and the design of pedagogical and evaluation tools, it is a methodological approach ideally suited for design and prototyping of real-world objects and physical processes with emerging technologies.

DBR relies on serial iteration and pragmatic testing that is subsequently integrated into the development of the research. DBR includes ongoing analysis of the performance of an artifact or process under development to understand, explain, and improve its attributes and effectiveness (Wang & Hannafin, 2005). DBR reduces development time by building on progressive refinements through continuous testing, analysis, and improvement of the design from the earliest stages of development until the final iteration rather than testing the intervention only after it has been completed. The design and testing of the tools and methods used to address these manufacturing challenges are described in Chapter 4 and discussed in Chapter 5.

Qualitative analysis of marine vessel and marine product design case studies reveals the strengths and shortcomings of existing applications of AM to marine vessel manufacturing, thus informing the application of DBR to the design and development of a series of prototypes that can address the question of how AM technology can be applied to automate the production of marine vessels. An examination of common varieties of AM technology reveals certain materials and methods that may be suitable for the constraints of manufacturing marine vessels without the use of moulds. Building on this premise, the research project describes the design and testing of a purpose-built tool for AM production of marine vessel components, and the application of software modeling tools to the problem of novel toolpath generation for this manufacturing process.

Reference Vessel: The 1927 Francis Sweisguth design for the 22' catboat *Secret* serves as a reference vessel to test the fabrication method. I have selected this particular boat because it represents a well-documented classic design for an enduring regional American sailboat that has already successfully transitioned through two distinct fabrication methods and typological uses. At the same time, the 100-year-old tradition of racing and sailing catboats for pleasure is in danger of dying out due to steadily increasing production costs for these small vessels and a decreasing supply of alternatives. Currently there are only three manufacturers producing FRP catboats in the United States (Plate, 2021).

Several portions of the hull and deck assemblies have been selected from the reference vessel that represent specific applied fabrication challenges. The research project proposes testing of the following component assemblies, 1) A method for printing thin, solid, compound-curved surfaces with extrusion materials oriented in multiple biases such as at the turn of the bilge amidships where it meets the hull side, 2) A method for printing thin, solid, folded surfaces with continuous toolpaths oriented in multiple biases such as at the crease of the transom and hull side, 3) A method for printing curved sandwich constructions similar to pattern-grid air-cored sandwich assemblies commonly featured in decks and cabin tops, 4) A method for printing a common deck mounting such as a winch base that requires both an embossed region over a solid core deck and a surrounding pattern-grid air-cored sandwich. Testing this method to fabricate these partial components without the use of moulds can demonstrate the efficacy and the shortcomings of this method for printing portions of small marine vessels.

LIMITATIONS

This study will focus on developing recommendations for the most fruitful avenues of continued research that can lead to the successful application of AM to small marine vessel manufacturing. The study is limited in four distinct ways: 1) As an emerging technology, AM is constantly changing, 2) Robotic toolpath generation has not been standardized for additive manufacturing, 3) Marine vessel manufacturing is a complex process, 4) The researcher has a lived experience that frames and limits how they evaluate technology.

AM as an Emerging Technology: Because AM is a rapidly evolving emerging industry with a diverse range of companies and entrepreneurs pursuing a variety of different technologies and processes (Arrabiyeh et al., 2021; Bae et al., 2018; Wong & Hernandez, 2012), it will not be possible to identify and examine every variation of AM currently in use or under development. An example of this is gas metal arc additive manufacturing, which is not part of this study, but has nevertheless produced recent high-profile projects in architecture, mechanical manufacturing, shipbuilding, and aerospace (Van Thao, 2020; Nickels & Fowler, 2017; Taşdemir & Nohut, 2021). By focusing on materials and methods that are common to the manufacture of yachts and small marine vessels, it is hoped that the most fruitful avenues of applied research will have revealed themselves for this industry sector.

Emerging AM research may change the landscape of additive manufacturing in rapid and unexpected ways. The marine manufacturing industry is comprised of thousands of shipyards, factories, small businesses, and entrepreneurs. While every effort has been made to survey the most recent and most high-profile examples of AM applications in small marine vessel manufacturing, there are likely to be recent or emerging developments as well as oversights of projects that may have the potential to alter the outcomes of qualitative analysis in a literature and case study review.

Toolpaths for Additive Manufacturing: The software that is used to resolve 3-dimensional objects into printable parts is not optimized for the material and structural requirements of marine vessels. Most common FFF 3D printers resolve a form in a series of horizontal layers built up in a sequence. The proprietary slicer or CAM software tools that drive many 3D printers have pre-set values that make generic assumptions about how to produce 3D forms using a particular material or process. (Šljivic, 2019; Zhou et al., 2018) While they are convenient and easy to use, they mask important and complex aspects concerning structural performance that should be considered when producing an object. These aspects include orientation of the object, speed of material deposition, density of core material, and configuration and location of support material. The orientation of the object relative to the extruder head and the platen or build surface can also have a dramatic effect on the final object including the amount of material used to produce the object, its material strength, and its structural performance.

Typically, slicer software used in FFF printers produces a form by tracing successive and uniform laminar profiles - driving the print head to a series of XY coordinates to describe a horizontal *slice* and then activating the Z-axis servo motors once the layer is completed to begin the next horizontal slice. This is a simple method to avoid collisions between the robotic tool and the emerging 3-dimensional object. However, FRP marine manufacturing relies on reinforcing materials oriented in multiple axes throughout a complex topological surface using either chopped or woven reinforcing fibers embedded in a thermoset plastic matrix. In order to achieve a similar strength to weight ratio using AM, new software for generating complex 3-dimensional toolpaths will need to be developed that are optimized for marine manufacturing. Further, robotic tool movement programs can fail when they include too many lines of code suggesting that more robust computer hardware may be required for operating industrial robots with long-string movement programs.

Advances in AM technology over the past three decades have been revolutionary for the field of industrial design, and some of these advances are beginning to work their way into the marine vessel design and manufacturing sector. But until software for generating complex and very long 3-dimensional toolpaths is developed to support MBAM, marine vessel manufacturing will be limited in how it applies AM to the problem of building boats.

The Complexity of Marine Vessel Manufacturing: While recent developments in additive manufacturing technology may initially appear as an emerging opportunity for multiple manufacturing sectors, there are several serious challenges to the proposed application of AM to the marine vessel design and manufacturing industry. Several boat hulls have been produced using AM, but these remain experimental prototypes that will require additional testing before the technology proves commercially viable as a manufacturing method. The use of AM for making plug moulds is a promising initial application for 3D printing in commercial yacht manufacturing. Other applications of AM technology to marine parts and components have proven viable, especially for small-scale replacement parts and retrofit components. These initial steps into AM are promising advances for the marine vessel manufacturing sector, but serious technical challenges remain before FRP hulls can be produced using additive manufacturing technology.

In order to understand the technical challenges for adopting additive manufacturing for producing small marine vessels it is useful to understand both the particularities of boat hulls and how 3D printing technology is used to make large 3-dimensional forms. As described earlier in the chapter, marine vessels in the sub-40 Meter range are typically produced using moulded FRP. The hull shape is formed with multiple layers of biaxial fiberglass or carbon fiber roving applied with thermosetting resin to either a plug or a cavity mould. The outer layer of the hull is a highly polished water impervious plastic surface that is optimized both in form and texture to move through the water with minimal resistance. On the interior, yacht hulls are composite structural systems designed to respond to the dynamic loading conditions of the marine environment. They are typically composed of two primary parts: a lower FRP hull chemically and/or mechanically bonded to an internal structural system of metal, wooden, or lightweight foam stringers, ribs, floors, and bulkheads; and an upper FRP deck and superstructure that is mechanically and/or chemically bonded to the hull and its attendant structural components. Each of the subcomponents is optimized for minimal weight and size to resist loads while maximizing useable interior volume within the hull. All of the subcomponents work together to define, support, and maintain the shape of the hull as it supports its own weight and resists the forces that act upon it in the water.

AM systems applied to large-scale projects typically rely on slicing a 3-dimensional computer model of an object into a series of horizontal layers. The 3D printer builds the physical object by tracing the 2-dimensional profiles or slices of the 3-dimensional object with extruded material. Each successive layer of molten plastic bonds thermally to the layer below. As the 3-dimensional form begins to emerge, sacrificial support material called scaffolding may be printed to strategically buttress overhanging surfaces and keep the 3-dimensional form from collapsing or deforming under its own weight.

From a structural perspective, the technical challenges that remain for large-scale AM to produce entire boats fall into three main categories. 1) Surface integrity: FFF methods rely on strong bolds between sequential laminar depositions of molten plastic materials (Johansson, 2013; Królczyk et al., 2019). It is quite possible that using this method will prove exceedingly difficult to ensure a water-tight seal between layers, requiring all vessels to be coated with a secondary water-tight skin such as FRP, carbon fiber, or another material yet to be commercialized (Renap & Kruth, 1995; Jamie, 2017). This presents refitting challenges to extend the life of 3D printed yachts and challenges for recycling at the end of lifecycle. 2) Laminar structural integrity: FFF methods typically use unidirectional laminar slicing for building up a manifold surface (Bhandaria et al., 2019). Until such time that layers of material can be oriented in multiple directions to counteract forces in 3 dimensions (MBAM), boat hulls will, of necessity, be required to be somewhat thicker and heavier in order to resolve common loading conditions, particularly at points of inflection on their surfaces (UMaine News, 2019). Recent experiments with small-scale non-planar AM could prove to be very useful if applied to this particular large-scale 3D printing problem (Bae et al., 2019). 3) Macro-level structural integrity: boat hulls are complex structural manifolds that must resist dynamic loads due to the force of the water pushing inward on the hull and the changing nature of loading conditions in the marine environment. Typical FRP hulls integrate structural elements made from metal or wood by chemically and/or mechanically bonding them to the hull manifold itself. These structural systems are optimized to reinforce the hull while also shaping spatial volumes to house equipment, cargo, and people. It is unclear if 3D printed materials will have the strength to replace these members or whether new structural integration methods will need to be developed.

Once these technical challenges are successfully addressed, we may see a new era of marine vessels produced entirely or in part by additive manufacturing. In the meantime, the most urgent areas of applied research fall into three primary areas: hardware, software, and materials. 3D printers will need to be successfully scaled up to address the specific challenges of marine vessel construction. Meanwhile, the typical slicer software that is used to rationalize 3-dimensional forms for 3D printers is wholly inadequate for the manufacture of yachts. Yacht designers and manufacturers will need to control the robotic placement of materials using easy to define 3-dimensional toolpaths. Further, the programming of patterns of material placement in response to static and dynamic load analysis should be standardized and automated. The yacht design and manufacturing industry may need to re-evaluate its commitment to cheap thermoset plastics such as polyester and epoxy. While initial projections may indicate that new polymer thermoplastics will be more costly to adopt, the labor savings and economies of scale that accompany widescale industrial implementation of a novel material might quickly bring down the overall production costs for the marine vessel manufacturing sector.

Potential Bias in the Study: There is enormous potential for AM technology in the nautical design and manufacturing sector in the production of marine components and smaller vessels. In the past several years there are already several examples of small boats that have been produced using AM technology. These first tentative steps in deploying a new technology for yacht manufacturing must be followed by additional advances in material applications, manufacturing process and tooling design, and software tools for streamlining the design and fabrication method. AM presents the opportunity for greater flexibility in the customization of yacht hulls at far lower cost, provided equipment can be scaled up and 3D printed material properties and manufacturing methods can rise to meet the exacting demands for the marine industry. Despite current limitations in AM materials and equipment, several recent projects show great promise for future deployment of this technology at industrial speed and scale.

However, choices in what materials and technologies to investigate for this study have been guided by personal experience and familiarity with common boat-building materials and methods. As such, inferences made in the study have the potential to emerge from insufficient, biased, or constantly changing data. To mitigate biases in the literature review the research relies on a personal network of scholars and professionals engaged in additive manufacturing research and entrepreneurship for the marine industry. The research draws upon written resources from both traditional scholarly sources and less formal academic sources including press releases, magazines, and newspapers. It is hoped that this broad approach to a literature review has provided a sufficient base of projects from which to draw, and that contact with industry insiders has provoked investigations into the most relevant emerging projects.

Summary: In this chapter the research question was introduced with a clear justification for applying AM to marine vessel manufacturing. The problem statement addressed the challenges for small marine vessel manufacturing as it is currently practiced using traditional FRP methods. It included a brief history of boat building and a discussion of the primary issues that must be considered when building a vessel using FRP. A discussion of the significance of the study to contribute to new manufacturing knowledge for transforming the marine manufacturing industry with AM and automation focused on issues of standardization, precision, formal aesthetics, mass customization and digital workflows, as well as worker safety and environmental protections. The discussion of the conceptual framework of the study addressed the issues of AM processes, materials, and kinematic logic, and suggested that due to the topological complexity of marine vessels and physical sizes of equipment required for marine vessel manufacturing the scaling up of AM will need to rely on kinematic systems such as large gantry systems and 6-axis robotic manipulators. Finally, the section on limitations acknowledges four ways in which the study may be limited including a discussion of the rapid changes and complexity inherent in an emerging technology, the complexity of the problem, and potential bias in the study. The next chapter will investigate a series of case studies demonstrating five distinct approaches to the problem of applying AM to marine vessel manufacturing.

Literature Review and Case Studies

2 LITERATURE REVIEW AND CASE STUDIES

INTRODUCTION

To establish an approach to the question of how Additive Manufacturing (AM) technology can be applied to automate the production of marine vessels a survey of recent projects that have successfully deployed this emerging technology in the marine sector is necessary. The previous chapter included summaries and discussions of both AM technology and robotic kinematic systems that could be used for scaling up AM for marine manufacturing. The most significant shortcomings of the laminar AM printing method were discussed and suggestions for new toolpath generation procedures optimized for marine applications was discussed. This chapter will investigate the most current applications of AM to marine vessel manufacturing.

Adopting AM for marine vessel manufacturing is not a simple application of technology from one manufacturing sector to another. Marine vessels are technically and structurally complex assemblies that require a carefully considered approach for the application of new manufacturing technologies (Guillermin, 2010). In the marine environment boats are expected to withstand dynamic loading conditions, UV exposure, continuous contact with water, and repeated cycles of ambient heating and cooling (Sahoo, 2021). AM encompasses many different types of technologies using many different processes and, until quite recently, it has been constrained to much smaller scales. However, many of the materials commonly used for AM have not been extensively tested in the marine environment (Rubino et al., 2021)). New extruders are being actively developed to deploy AM with proven marine materials, but AM processes are not always well suited for the material consolidation requirements of marine vessels and components. Recent advances in scaling up AM with robotic arms and gantry systems has now made it a potentially feasible approach for producing marine vessels and products. Yet there remain serious challenges to successfully deploy this technology to the manufacturing of small marine vessels.

There are several potential approaches to manufacturing large objects for the marine industry using AM technology: 1) Use small equipment and a componentry method featuring specialized joints to assemble larger marine assemblies from smaller 3D printed component parts. This method typically requires hand layup of additional layers of FRP material to waterproof the assembly resulting in extensive labor to assemble and waterproof the parts. 2) Scale up the 3D printer with a large gantry system and a large extruder to print large moulds. This usually results in thick-walled objects with excessive weight to strength suitable for moulds but not for hulls. 3) Scale up the 3D printer with a large gantry system and a large extruder to print hull and deck components, or entire boats. This approach has proven somewhat effective for direct printing of small vessels, but the result is an excessively thick and heavy wall surface that is perhaps too heavy for boats. Demonstration projects using this method have not yet been proven effective for marine use and long-term exposure to the marine environment. 4) Mount a specialized 3D printer extruder on an articulated robotic arm to print large subcomponents or entire boats. This approach has had limited success with two examples of boat hulls printed in smaller parts, but the labor costs in these examples to join the parts, waterproof, and reinforce the assembly with both inner and outer layers of FRP material are excessive. 5) Wrap fiber tape pre-impregnated with heat sensitive thermoplastic around a heated mould using an articulated robotic arm. In this chapter, these five approaches will be investigated using a series of case studies applied to marine product and marine vessel manufacturing.

CASE STUDIES

1 Marine Products Manufactured with Small 3D Printers

1.1 Parts

Image courtesy of Paulo Nazzaro (Superfici S.c.r.l., 2018)

3D printing in the last decade has been transitioning from a prototyping method to a means of direct manufacturing. Additive manufacturing allows formal variation and topological complexities that have proven unattainable or prohibitively expensive using traditional manufacturing techniques. The computer modelling and printer controller software that underlies 3D printing allows for the design not only of the exterior surfaces of an object, but the internal structure of it as well. This allows the design of an object to satisfy aesthetic and performative goals while also accommodating the integration of standardized parts such as bolts, clevis pins, shackles, blocks, and other hardware. Through a combination of 3D modelling and adjusting 3D printing controller software a product designer can create hollow void spaces, structural ribs, and lattices of varying density within an object to regulate weight, density, strength, and stiffness of an object while also accommodating non-printed parts.

Using an integrated design approach made possible by 3D modelling and 3D printing components it is possible for a designer to exercise direct control over the production of some areas of marine product manufacturing. These areas of control are limited only by the scale of current 3D printing equipment and the physical properties of 3D printable materials but can now include interior and exterior furnishings as well as customizable component parts.

Traditional FRP components are typically topological forms that have either been simplified for easy removal from their moulds, or they are more complex assemblies that require hand-crafted procedures to join them causing potentially significant dimensional deviations from one another. FRP components do not lend themselves well to customization at low cost and it is difficult or impossible to control for lightness and density without compromising strength and performance. Additive manufacturing on the other hand allows direct control over considerations of strength and weight, material optimization, material efficiency and waste, and the use of more easily recycled materials. Since the production of 3D printed objects can be directly controlled by the designer, there is less chance for deviation between a component's specified and actual dimensions. This introduces a level of efficiency into the boat building and fitting out process that typically relies on costly field measurement and complex templates.

1.2: Small Components

Product: ABS Woofer and Subwoofer Housings for Tankoa – Genoa, Italy
Production Series: 30 pcs

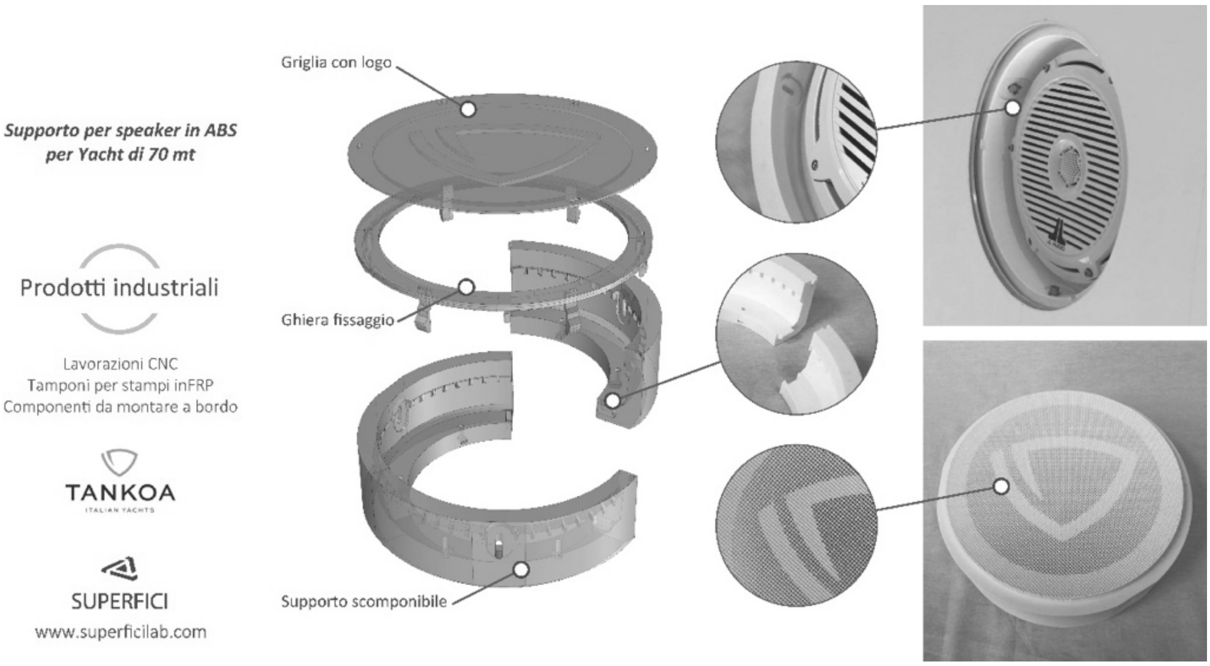


Image courtesy of Paulo Nazzaro (Superfici S.c.r.l., 2018)

Since 2016 the design laboratory Superfici S.c.r.l. based in La Spezia, Italy has been bypassing the typical prototyping process for nautical design by introducing 3D printed components directly to the nautical industry. In spite of the fact that shipbuilders are naturally conservative and somewhat bound by tradition, Superfici has succeeded in meeting the demanding requirements of the nautical industry by using innovative additive manufacturing technology. Their first small-scale case study was a series of customized speaker housings, retainers, and decorative grills designed and produced for an Italian shipyard. The innovation demonstrated by Superfici lies primarily in the sophisticated use of componentry to create larger direct to market marine products that can be printed on standard off the shelf 3D printers. While it is unlikely that these design and fabrication methods will be deployed for mass production, it is an agile and adaptive approach for a marine market more likely to demand customized design solutions. The componentry approach demonstrated by this project lends itself to mass customization, and may be one of the best suited applications, in the short term, to deploying AM in the marine industry.

1.3: Large Components

Product: ABS Flybridge console for Amer Yachts – Sanremo, Italy
Production Series: 1

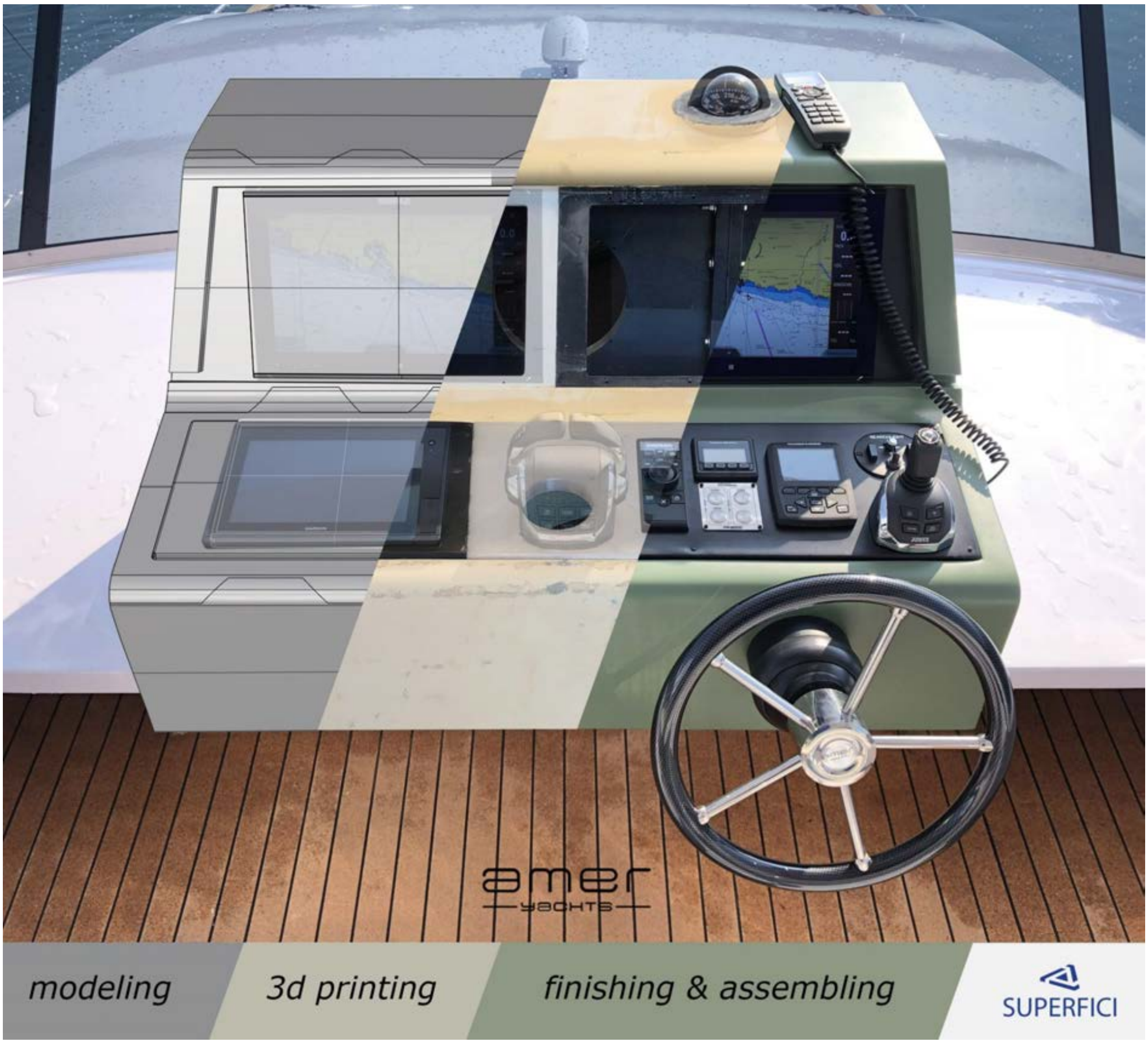


Image courtesy of Paulo Nazzaro (Superfici S.c.r.l., 2019)

The Amer Yachts Flybridge Console dashboard is the first large-scale 3D printed product Superfici has designed and installed onboard a yacht. The design and manufacturing were entirely in-house: it was modelled, printed using a FFF method, and finished in their laboratory in La Spezia. The designers were able to optimize its geometry for greater control of the printing process and the structural performance of the dashboard. The main body is a multi-part ABS structure with a PET instrument cluster housing. The design offers the freedom to periodically update the instrumentation requiring the reprinting of only the instrument cluster insert. Using additive manufacturing as a production process made it possible to plan for the positioning of installation tools upstream without having to intervene during the installation process, as is typical in traditional FRP plank console installation. This eliminates the need for an installer to drill and cut the console during installation, also greatly reducing waste and excessive handling of the component during installation.

1.4: Direct to Market Marine Components by Superfici S.c.r.l.

Product: HDPE Strider 700 Series Console for Sacs Marine – Roncello, Italy
Production Series: 1

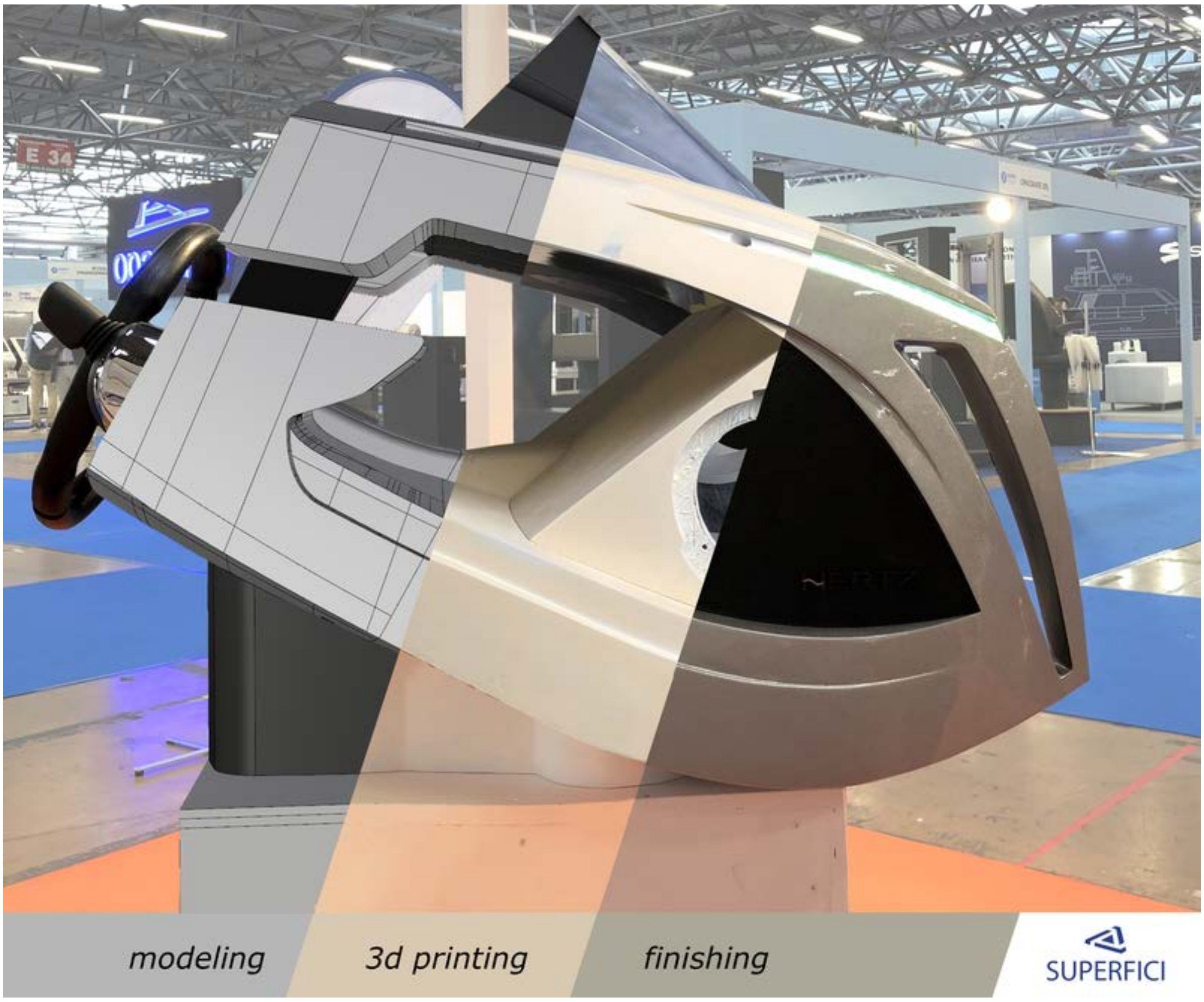


Image courtesy of Paulo Nazzaro (Superfici S.c.r.l., 2019)

Since 2016 the design laboratory Superfici S.c.r.l. based in La Spezia, Italy has accelerated the typical product development process for nautical design by designing and fabricating 3D printed one-off marine components (Nazzaro, 2019). The Sacs Marine 700 Series console is an award-winning demonstration project that uses computer modelling and AM to design and produce a direct to market product for the marine industry. The HSM plastic console was designed and fabricated in less than four weeks with a small design and fabrication team including interns from the Design Navale e Nautico program at University of Genoa. The form of the console demonstrates through its complex surface topology that it cannot be fabricated using traditional FRP moulded methods. It was designed using Superfici's proprietary componentry method and printed as multiple subcomponents using the FFF process on standard size commercially available 3D printing devices. The assembled form was coated with a thin layer of marine grade fairing material and finished with automotive paint. Strategic panels, wiring chases, and filler plates allow the console to be periodically updated with new electronic components without damage to the whole.

The innovation demonstrated by Superfici S.c.r.l. lies primarily in the sophisticated use of componentry to create larger direct to market marine products that can be printed on standard off the shelf 3D printers. While it is unlikely that these design and fabrication methods will be deployed for mass production, it is an agile and adaptive approach for a marine market more likely to demand customized design solutions. The componentry approach demonstrated by this project lends itself to mass customization, and may be one of the best suited applications, in the short term, to deploying AM in the marine industry.

1.5: Re-Designed MCY 76 Motor Yacht

Image courtesy of Massimo Musio-Sale (UniGe, Design Navale e Nautico, 2019)

Additive manufacturing at larger scales using a component-oriented approach has the potential to completely transform the yacht construction industry. While the size of current 3D printing materials and devices limits the scale of objects that can be produced, innovations in joining sub-components may offer solutions for future yacht design projects. Ideally, these solutions can offer an alternative to our current reliance on FRP, avoiding the formal limitations and excessive production costs associated with customized products. Theoretically, hulls and superstructures can be produced almost entirely from single 3D printed components. As demonstrated, 3D printed components allow for high fidelity topological complexity with relatively easy pre-production customization. The ability to completely control the design of joints between parts allows for removable, replaceable, and renewable components that can be more easily recycled than traditionally moulded FRP components.

Before 3D printing larger boat hulls with single compound materials can proceed there will need to be significant advancements in the material properties of FFF materials including improvements in the bonding between layers. Furthermore, the logic underlying multi-bias filament deposition may also need to improve in order to meet the exacting demands of dynamically loaded nautical components. Once these problems are overcome, large yachts up to 40 meters or more may be possible without the need for FRP materials.

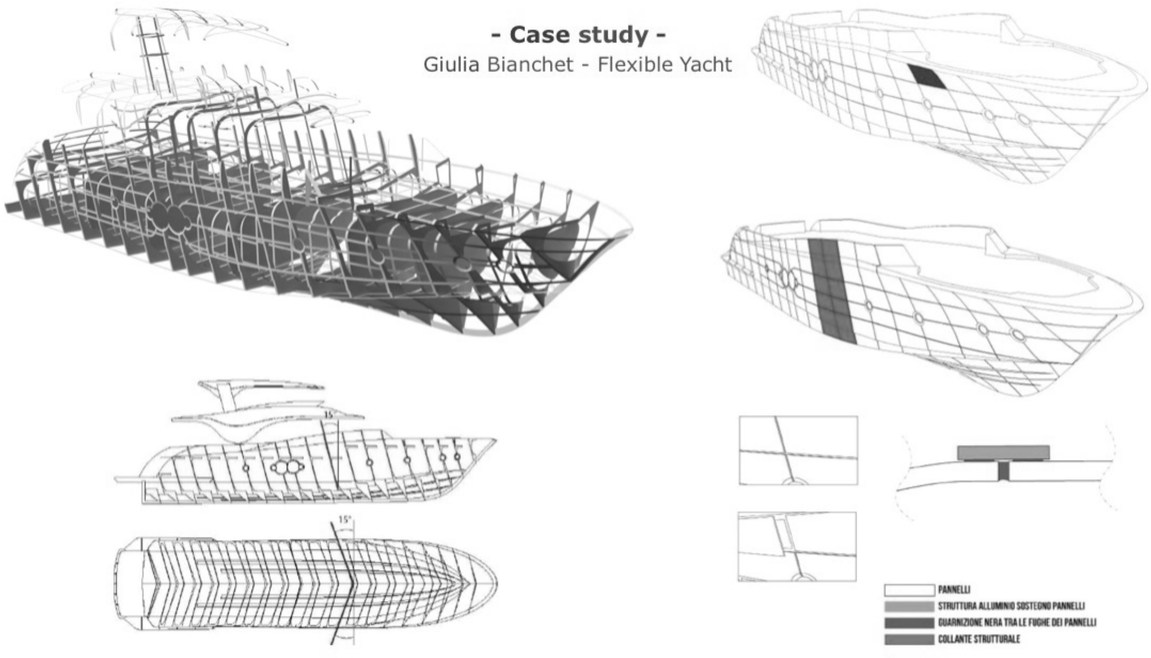


Image courtesy of Massimo Musio-Sale (UniGe, Design Navale e Nautico, 2019)

The aesthetic challenge facing contemporary yacht designers lies in understanding the formal potential offered by alternative shipbuilding methods and finding innovative formal and aesthetic solutions that can negotiate 3D printed component-based manufacturing processes. The aesthetics of so-called traditional forms are a powerful force in the yacht design industry. For example, in the past several decades, some yacht designs have continued to use the formal language of clinker plating more commonly associated with wooden boats even after the materials used to produce hulls and superstructures had largely transitioned to FRP. The material properties and fabrication process associated with FRP construction have naturally resolved into an aesthetic of mirror smooth, gently curved and folded liquid monolithic surfaces. This is a result of both the materials used for hulls and superstructures and the properties and requirements of the moulds used in their construction. It is reasonable to expect that new aesthetic approaches to an emerging construction method may continue to feature smooth curving surfaces while also highlighting the joints between component parts.

Design research developed by Giulia Bianchet, a graduate student in Naval and Nautical Design at University of Genoa explores the potential aesthetic transformation of a well-known motor yacht (MCY 76) imagined as a hull produced using component-based additive manufacturing. Bianchet's proposal includes a new interior frame system designed to accept hull plating tiles produced using component-based additive manufacturing. The design proposal is inspired by contemporary architect Zaha Hadid's funicular station at Innsbruck, in which individual curved glass tiles topologically developed and split using computer modelling operations are combined to present a large unitary manifold surface while a contrasting material between the constituent parts highlights the joints. The re-imagined hull features a similar contrasting material between the component parts. This design proposal offers the possibility to modify the hull after it has been manufactured, adding or removing ports as desired, and changing the hull surface topology to fit variable performance criteria.

The scale and technology of current additive manufacturing equipment suggests that a component-based approach to 3D printing is an important area of continued development for medium to large-scale applications in the yacht design and manufacturing sector. While material performance properties will need to improve, the benefits of solid 3D printed thermoplastic materials over traditional FRP manufacturing is clear in many respects, including the computer modeled design process for making a hull from multiple components, the relatively simple customization operations, the modular production stage, and the end of useful life recycling opportunities.

2 Moulds Made with Large-Format Printers

2.1 Thermwood Corporation's Tahoe Open Skiff (LSAM)

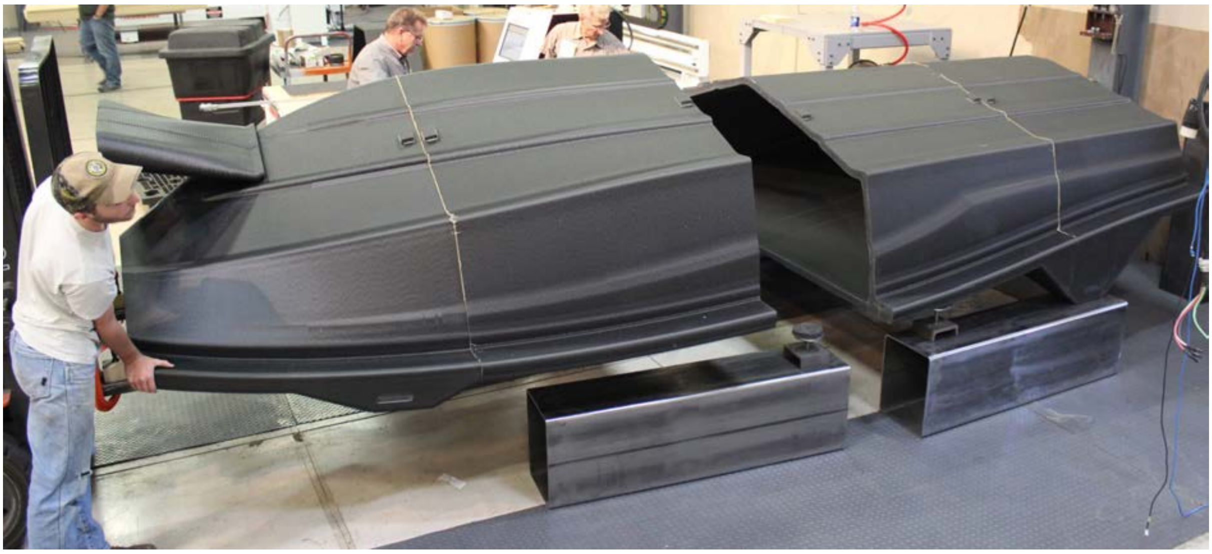


Image courtesy of Thermwood Corporation (Thermwood, 2018)

In 2017 the US based firm Thermwood used its proprietary LSAM (Large Scale Additive Manufacturing) technology to print a positive plug mould for a production series open skiff demonstrating the feasibility of using FFF 3D printing in small marine craft production (Thermwood, 2017). FFF 3D printing uses a variety of plastics that are heated and forced through an extruder head onto a surface and then built up in successive layers. In this particular case, the mould was printed from an ABS composite material as 6 separate parts that were then joined together and milled as a single unit using a large format CNC machine. The final form was coated with fiberglass and polished for use as a positive plug mould. The entire production duration of the project was under two weeks – a significant reduction in time for producing a similar mould for production boat manufacturing. While this particular hull-moulding project was printed on a 3 x 6 meter (10 x 20 feet) dual gantry printer, the LSAM system has been tested on much larger machines with the potential for producing very large 3D printed components.

Thermwood LSAM is currently investigating the potential for using the technology to directly print small boat hulls, bypassing moulds altogether. There are, however, several drawbacks to this particular technology for boat manufacturing. The positive plug mould was printed using a 3 cm (1-1/4 inch) extruded bead of ABS, which produced a thick, heavy hull with an excessive wall thickness for a boat of similar size. While ideal for a plug mould, which must be durable, the finished mould weighed nearly 1500 kg. A comparable sized hull weighs 4-5 times less. While reducing the bead thickness will result in a lighter hull form, it remains unclear how durable the horizontally fused layers may be under dynamic loading conditions in the marine environment.

2.2 Oak Ridge National Laboratories Big Area Additive Manufacturing (BAAM)

In 2018 a team of researchers at the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility in Tennessee was sponsored by the US Department of Energy Advanced Manufacturing Office to assess the feasibility of producing molds for the manufacture of FRP boat hulls using resource-efficient, fast, and cost-effective methods. Over five days the manufacturing research team used Big Area Additive Manufacturing (BAAM) to fabricate a 10.36-meter (34 feet) catamaran boat hull mold using a 2.44 x 6.01 x 1.83 meter (8 x 20 x 6 feet) gantry mounted large format 3D printer. Typically, boat hull molds are built in a multistage process that is both labor intensive, reliant on traditional handicraft methods, and prone to formal deviations from the original intention of the naval architect or designer.

Typically, boat hull moulds are built in a multistage process that is both labor intensive, reliant on traditional handicraft methods, and prone to formal deviations from the original intention of the naval architect or designer. BAAM has the potential to allow boat hulls to be produced directly from a computer-aid design (CAD) model. However, the surface characteristics of forms made from wide-bead thermoplastic extruders often require extensive post processing using thick and expensive coatings to both accommodate the uneven surface characteristics of extruded materials and to achieve the necessary smoothness required for boat hull moulds. These moulds also require additional support material and structures to prevent the mould from deflection due to loading and thermal stress in the manufacturing process. These inefficiencies and associated expenses may inhibit the widespread adoption of BAAM for the production of moulds unless new design and manufacturing methods prove effective for mitigating these issues.

Image courtesy of the Oak Ridge National Laboratory (Post et al., 2019)

The Research team at ORNL designed the catamaran hull mould to be produced in a four-step process of extrusion, precision milling, assembly, and surface finishing. The mould CAD model was designed with an integrated extruded structure, over-thickened walls to accommodate milling the finished surfaces, and assembly tabs for fastening the separate parts together. The mould was printed over 48 hours in twelve parts using 20% chopped carbon fiber in an ABS thermoplastic. Each part was subsequently milled on a 5 axis CNC machine using a precision laser guided orientation system to align the physical coordinate system of the individual parts to the reference frame of the CNC machine. Finally, the milled parts were fastened together using threaded rods and glue before being sanded and finished with a thin coat of vinyl ester mould coating.

This demonstration project proved that an effective cavity mould can be produced with the requisite strength and surface qualities using a two-stage AM and surface milling method. Further, the team at ORNL showed that with proper structural design and precision manufacturing tolerances secondary structural elements and thick coatings need not significantly add to the cost of producing moulds for boat hulls in the 10 Meter size range. Finally, the mould was produced in only five days demonstrating that the labor costs for producing a mould of this size can be significantly reduced using AM methods.

3 Boat Hulls Made with Larger Format Printers

3.1 University of Washington Fabbers Club Milk Carton Derby

In 2012 several members of a student 3D printing club at the University of Washington used FFF Additive Manufacturing (AM) to construct a small vessel for competition in a local regatta. The race, known as the Milk Carton Derby, is a community demonstration and fund-raising event to bring awareness to the public about pollution and recycling. The event is aimed toward informal floating vessel designs using repurposed containers – boatbuilding that might likely be taken on by local youth groups and volunteers more interested in recycling than naval architecture. Typical entrants to the race are not yacht designers and may have little to no knowledge about hydrodynamics and the development of stable hull shapes. The rules for qualifying in the event simply stipulated that all vessels must be made from recycled milk jugs.

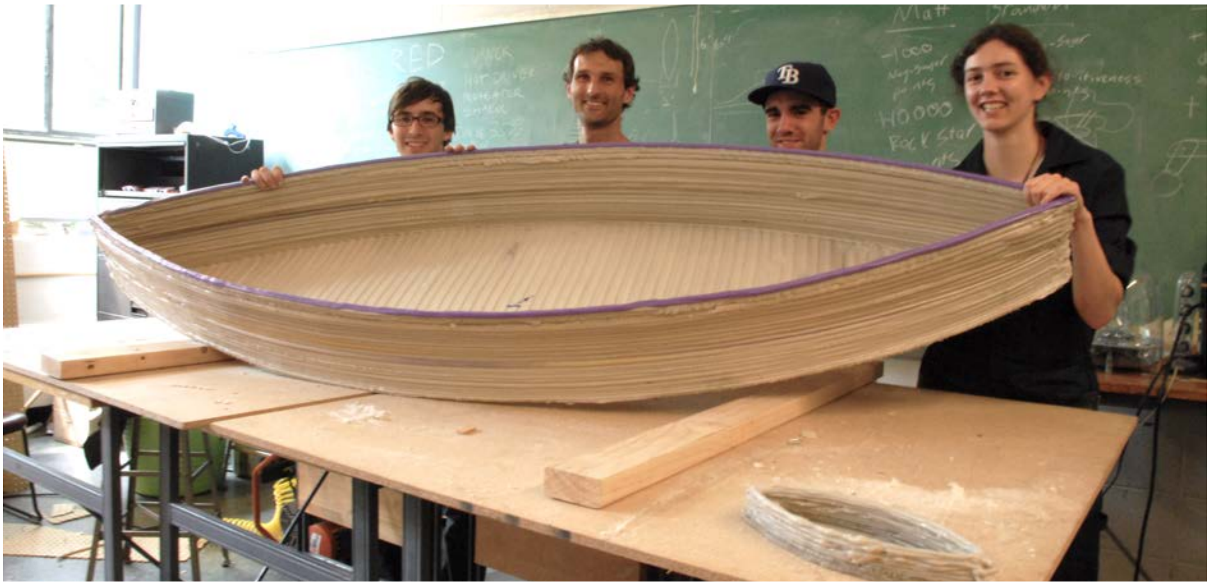


Image courtesy of UWNews (Hickey, 2012)

The students from the UW Fabbers team researched ways to process HDPE material from reclaimed milk jugs and developed a specialized extruder head that they mounted on a repurposed industrial CNC plasma cutter. The material processing, testing, and development of this project demonstrates an innovative approach to working within challenging guidelines (HDPE is a notoriously difficult material to work with). The ad hoc bootstrapping approach to tooling development is also admirable considering that the team developed the entire printing device without any precedent models. The UW Fabbers team designed and printed a simple 2.2 meter (7 feet) vessel made entirely from recycled milk jugs that the students had collected. While the project is a primitive (even retrograde) example of naval design, it demonstrates the ingenuity of an academic team working to solve the technical challenges of up-scaling AM technology. This was the first full-scale boat ever produced using a large format 3D printer.

3.2 University of Maine Advanced Structures and Composites Center 3Dirigo Project

In 2019 the University of Maine demonstrated the feasibility of using wide bead AM to produce a 7.6 meters (25') deep vee-shaped boat hull in a single discrete object printing operation (UMaine News, 2018). This project produced not only the world's largest 3D printed object, but the first fully 3D printed boat hull. The boat was printed on a custom-built prototype Ingersoll Machine Tools plastic polymer printer capable of producing plastic polymer objects up to 30.5 meters (100 feet) long, 6.7 meters (22 feet) wide, and 3.05 meters (10 feet) high. It used a proprietary wide bead extruder head with a bio-based plastic polymer. The hull, weighing a reported 2268 kilograms (5000 pounds), was printed in under 72 hours.

Image courtesy of UMaine News (UMaine News, 2019)

This exciting achievement lends credence to the argument that it may soon be possible to use AM for producing small production boats and yachts. It should be noted however, that in spite of the very positive results of this fabrication experiment there remain significant challenges for 3D printing entire boats. The hull that was produced by researchers at the Advanced Structures and Composites Center at the University of Maine weighs approximately 20% more (500 kilograms) than comparable vessels of the same general hull shape and size. It is currently undergoing extensive evaluation in an indoor testing facility featuring high-performance wind simulation in a multi-directional wave basin. Of particular interest is an evaluation of ultimate water resistance of the hull – will it form a truly watertight barrier that remains resistant to osmotic penetration over time? While we wait eagerly for the results of these tests to be published, it is apparent that boats produced using this method are not yet ready for the open market.

4 Hulls Made with Narrow Bead Extruder on Robotic Arm
4.1 Livrea Yachts Mini 6.50

In 2019 the young Italian yacht design firm Livrea Yacht launched the Mini 6.50 class ocean racing prototype to compete in a transatlantic race from France to South America. Livrea partnered with Italian start-up firm OCORE to develop and manufacture the carbon fiber reinforced composite thermoplastic hull for this 6.5-meter (21 feet) racing sailboat. Essentially, the core material was printed in several parts and was then assembled and used as an integrated internal mould – similar to the cold-moulding process sometimes used in contemporary wooden boat production (Nasso et al., 2018).

Image courtesy of 3DNatives (Jamie, 2017)

It was produced as a series of a single piece monolithic hull sections using a multi-axis robotic arm fitted with a proprietary thermoplastic filament extruder head and materials developed by Lehvoss. The sophisticated computer modeling for the hull together with the robotic controller software allow the robot to precisely control the placement of extruded filament, building a sandwich surface with a variable density core optimized for the loading and performance conditions of a high-performance racing sailboat. The hull thickness was carefully controlled for weight and stiffness while not being subject to the typical problems associated with conventionally moulded hull shapes. This method of variable density sectional manufacturing of the hull solved the problems of the hull to deck joint – a common area of weakness in traditional moulded FRP boats.

Image courtesy of 3DNatives (Jamie, 2017)

The excessive weight and hull thickness that potentially constrain hulls formed with wide-bead laminar printing and the associated issue of laminar weakness was solved by wrapping the entire hull in a secondary carbon FRP shell in a traditional cold-moulding process.

Image courtesy of 3DNatives (Jamie, 2017)

While this technology is still in its early stages, we can imagine that larger custom and semi-custom hulls will be easily produced without the need for physical models and expensive moulds. Further, each vessel can be modified to accommodate integrated accessories and performance criteria specified by the end user. Customization and modifications can be incorporated into the hull form itself without the need for complicated post-production or mid-production alterations in the manufacturing process.

4.2 Politecnico di Milano MOI Composites MAMBO Project

In 2020 the young Italian start-up firm MOI Composites launched MAMBO (Motor Additive Manufacturing BOat) the first Fiber Reinforced Plastic (FRP) motorboat fabricated using Continuous Fiber additive Manufacturing (CFM) technology (Loibner, 2021). This project is part of a Politecnico di Milano spin-off program supported by a team of sponsors and partners including Autodesk, Mercury Marine, and Owens Corning. This 21' fiberglass motorboat project which debuted at the 2020 Genoa Boat Show relied on a hybrid manufacturing process that included both AM using robotic arms and traditional handicraft FRP boat building techniques.

Image courtesy of Gabriele Natale (MOI Composites, 2020)

The hull was produced as fifty separate parts extruded with a proprietary continuous resin impregnated glass fiber extruder mounted on a 6-axis robotic arm (Mason, 2021). The benefit of this method is the opportunity to orient fibers in multiple axes to substantially stiffen the surface manifold. However, this project did not employ a MBAM toolpath method opting rather to print the individual parts using a laminar toolpath method. Multi-bias strength was achieved using a hand-crafted cold moulding process.

Typically, FRP hulls rely on a uniform wall thickness of resin impregnated glass fibers oriented in layers of uniform biaxial fabric optimized for areas of maximum stress. This results in heavier hull forms that do not efficiently manage weight using variable thickness and optimized fiber orientation. At a lean 800 Kg (1765 lbs.) MAMBO weighs 30% less than a production FRP hull of similar length (Mason, 2021) suggesting that either a) the longitudinal folds in the hull surface lend a remarkable robustness to the structural manifold or b) the vessel structure may be sub-optimal for long-term durability. The separate hull components were bonded to a PVC core and laminated with several layers of cold-moulded glass fiber fabric before being integrated into the overall hull form. This is a manufacturing method that results in remarkable stiffness without corresponding increase in weight. Finally, the exterior surface of the hull was sanded and faired before painting.

Image courtesy of Gabriele Natale (MOI Composites, 2020)

While this project relies as much on traditional FRP handicraft techniques as advanced AM technology, it represents a first step toward directly producing FRP hulls from CAD files. Future applications of this manufacturing method will allow hulls to be produced using many fewer individual parts, representing a major reduction in labor costs. Most significantly, hulls produced using this method can be highly customized and optimized for various performance criteria with only modest variations in production costs.

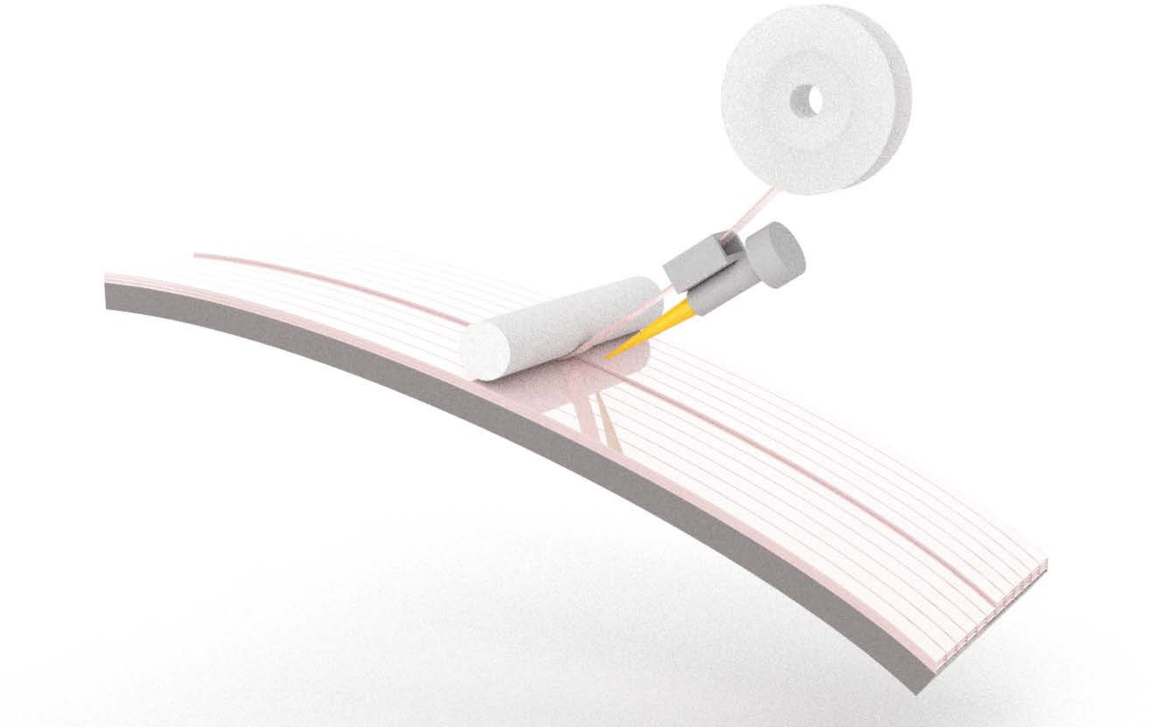
5 Aerospace Applications

5.1 Automated Fiber Placement of High-Temperature Prepreg with In Situ Consolidation

Automated Fiber Placement of high-temperature thermoplastic composite pre-impregnated carbon fiber tape using laser sintering and high-pressure rollers on a mandrel or heavy-duty cavity mould.

Not strictly an AM process, this method of automated fabrication was originally developed for aerospace manufacturing to replace reliance on aluminum and other metals for both structural elements and surface applications. It has since found many applications, especially for high temperature pipe fittings in the petrochemical industry.

Beginning in the 1980's applied manufacturing research by the Dutch firm Fokker Aerostructures demonstrated the potential of using high temperature thermoplastics in aerospace applications. The primary issue to be solved (beyond developing cost-effective composites with the appropriate material properties) was the consolidation of thermoplastic material without the need for an excessively large autoclave. With the invention of polyetheretherketone (PEEK) impregnated carbon fiber tape and the use of heated compaction rollers the US aerospace company, Automated Dynamics, perfected a method for producing composite cylindrical parts and became a major supplier of specialized components for the petrochemical industry. They later developed a successful manufacturing method for producing the fuselage for a helicopter in 2012 using an adaptation of that process for more complex formal geometries and structural assemblies.



Automated Fiber Placement with high-temperature thermoplastic pre-impregnated carbon fiber tape.

At the 2017 Paris Air show the French company Stelia Aerospace exhibited a thermoplastic composite airplane fuselage featuring heat welded stringers and frames as well as lightning strike protection integrated into the skin during the automated fiber placement process (Gardiner, 2018). These exciting proof-of-concept manufacturing projects, while not strictly additive manufacturing, demonstrate the potential to use automation to build strong and lightweight complex assemblies with integrated structural components.

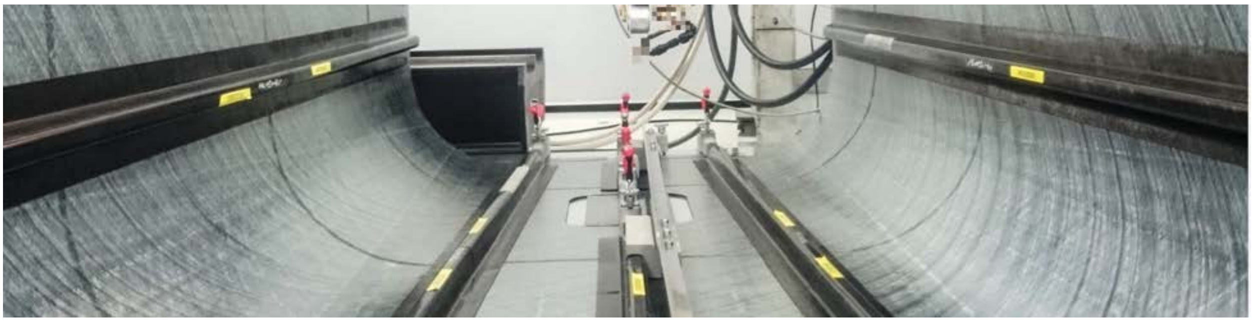


Image courtesy of Ginger Gardiner (Composites World, 2018)

While these are exciting developments for aerospace, it remains to be seen whether these manufacturing methods can be adapted for the marine industry. The major issue is material cost: will exotic high temperature thermoplastics ever be produced at a scale feasible for the margins typical of small and medium size marine vessels? Additional concerns include (but are not limited to) the long-term viability of exotic thermoplastic composites in the marine environment, environmental concerns related to their use in sensitive marine ecosystems, and the feasibility of end of useful life recycling. Due to their high melting point these materials have embodied energy levels which may limit their feasible use in highly regulated markets.

Images courtesy of Ginger Gardiner (Composites World, 2018)

Perhaps, the more fruitful outcome of investigating these developments in a related industry is to reflect on certain aspects of the manufacturing solutions developed by aerospace and to look for potential crossover applications for the marine sector. For example, how might a narrow thermoset resin roller or wiper assist in consolidating or smoothing the surface qualities of objects printed using a continuous strand thermoset FRP extruder? This is an intriguing area of manufacturing research that remains unexplored.

INFERENCES FOR FORTHCOMING STUDY

These case studies reveal two promising extrusion processes, three material systems, and two primary candidates for kinematic systems for manufacturing marine vessels without the need for moulds. These will be introduced briefly in this section and discussed in greater detail in Chapter 4.

Extrusion Processes: There are two methods for extrusion that appear promising for further manufacturing research and development.

<u>*Narrow Bead Thermoset FRP Extrusion (Pultrusion):*</u> Essentially this is an extruder that relies on the precisely controlled movement of a robotic arm to pull a continuous strand of thermoset resin pre-impregnated glass fiber twine through a nozzle. An onboard UV light source initiates the curing process. It is optimized for medium/large format applications. This manufacturing method was described in Case Study 4.2: Mambo by MOI Composites with support from AutoDesk. It is currently limited only by the reach of the robotic manipulator – a shortcoming that can be easily addressed by mounting the arm on a linear track or gantry.

<u>*Continuous Strand Fiber Reinforced High-Temperature Thermoplastic Composite Extrusion:*</u> Essentially this is an extruder that pushes continuous strands of fiber and thermoplastic through a high temperature hot end and nipple. This extrusion process was described in the discussion

of FFF Printers with reference to Markforged (Markforged, Inc., 2021) and 9T Labs (9T Labs, 2021). This extrusion method features high-temperature polymer thermoplastic pre-impregnated continuous strands of glass, carbon, nylon, or Kevlar fibers. Case Study 5.1 described a version of this process known as ISC that includes a heated roller and mandrel to consolidate the material and reduce the formation of voids. Large format versions of this technology have been developed for aerospace applications but have not yet been approved for commercial use by regulatory agencies. It is commonly used in the petrochemical industry for high pressure pipe fittings. It is limited by the high cost of the material and the requirement for an autoclave for small-scale parts or a high-pressure heated roller and mandrel to consolidate the thermoplastic matrix and eliminate voids for larger scale applications.

Material Systems: There are several material approaches that appear promising for further manufacturing research and development.

Continuous Strand Thermoset FRP: This material approach uses continuous glass fiber twine soaked in UV activated thermoset resin. This manufacturing method was described in Case Study 4.2: Mambo by MOI Composites with support from AutoDesk. It is limited by the inability to precisely control the density of the composite matrix and the proportion of resin to glass fiber. Poor consolidation has deleterious effects on strength to weight ratios.

Continuous Strand Fiber Reinforced High-Temperature Thermoplastic: This material system relies on continuous strands of fibers in a matrix of high temperature thermoplastic. This process was described in the discussion of FFF Printers with reference to Markforged (Markforged, Inc., 2021) and 9T Labs (9T Labs, 2021). It is limited by the high cost of the material and the requirement for either a high-pressure roller or an autoclave to consolidate the thermoplastic matrix and eliminate voids. Additional long-term testing in marine environments is likely necessary before this material can be approved for marine vessel manufacturing.

Thermoplastic Composite Core with a Thermoset FRP Cold-Moulding Process: This material approach relies on two distinct materials and processes to create a watertight hull form. It was described in Case study 4.1: Livrea 6.50. Essentially, a robotic arm builds the hull in sections with a narrow bead thermoplastic extruder. The hull sections act as a semi-rigid core that is wrapped in FRP in a cold-moulding process. The limitations of this method and material are the reach of the robotic arm and the need for extensive hand processes in the cold-moulding procedure.

Kinematic Systems: There are two kinematic systems that appear promising for further manufacturing research and development.

Open Build Area Gantry Systems: Essentially this is a scaled-up version of a 3D printer. It was described in Case Study 2.1: Thermwood Corporation LSAM system and Case Study 3.2: The University of Maine Composites Center 3Dirigo project. The strengths of the system include its ability to be scaled to very large sizes, the addition of secondary tool attachments such as a spindle, and the extruder orientation can theoretically be controlled with additional axes for pitch, roll, and yaw. Its primary shortcoming is the excessively thick extrusion bead that is not optimized for the material and weight requirements of small marine vessels.

Articulated Robotic Manipulators: Essentially this is a robotic arm with an extruder attachment. It was described in Case Study 4.1: Livrea 6.50 and Case Study 4.2: Mambo by MOI Composites. Its primary benefit is its versatility and maneuverability. Its primary drawback is the limited reach of a fixed robotic arm that necessitates construction in segments or parts. However, this limitation can be easily addressed by mounting the robotic manipulator on a linear track or gantry which can extend its reach.

Chapter 3 will lay out the criteria for evaluating these manufacturing processes and the remaining chapters will provide conclusions and discussion of the most promising areas for continued manufacturing research.

THEORETICAL/CONCEPTUAL FRAMEWORK FOR FORTHCOMING STUDY

This research project aims to address the question of how additive manufacturing technology can be applied to automate the production of marine vessels. In order to answer this question, this chapter has examined a variety of AM processes, materials, and equipment with case studies demonstrating various applications of AM technology to marine parts, components, and vessel manufacturing.

Adopting AM for marine vessel manufacturing is not a simple application of technology from one manufacturing sector to another. Marine vessels are technically and structurally complex assemblies that require a carefully considered approach for the application of new manufacturing technologies (Guillermin, 2010). In the marine environment boats are expected to withstand dynamic loading conditions, UV exposure, continuous contact with water, and repeated cycles of ambient heating and cooling (Sahoo, 2021). AM encompasses many different types of technologies using many different materials and processes and, until quite recently, it has been constrained to much smaller scales. However, many of the materials commonly used for AM have not been extensively tested in the marine environment (Rubino et al., 2021)). New extruders are being actively developed to deploy AM with proven marine materials, but AM processes are not always well suited for the material consolidation requirements of marine vessels and components. Recent advances in scaling up AM with robotic arms and gantry systems has now made it a potentially feasible approach for producing marine vessels and products. Yet there remain serious challenges to successfully deploy this technology to the manufacturing of small marine vessels.

To answer the primary research question, this study uses qualitative analysis of case studies and a design-based research approach to develop a practicable method for small marine vessel manufacturing. A prototype tool that can be applied to excerpts from a reference vessel serve to demonstrate the practical application of this method to a real-world manufacturing problem.

Summary: This chapter has described the existing state of the industry in AM with particular attention to processes and materials used in marine manufacturing. It has also presented a series of conceptual and practical applications of AM to marine product and vessel manufacturing. The forthcoming study will evaluate existing technologies, examine manufacturing challenges, assess what has already been accomplished, and use a proof-of-concept manufacturing strategy to demonstrate the potential feasibility of building complex partial yacht hull assemblies using a common AM process and material. This Design Based Research approach will lead to a design for an AM manufacturing method that will be described in Chapter 4 and discussed in Chapter 5.

Methods

3 METHODS

METHODOLOGY

Research Question: How can Additive Manufacturing (AM) technology be applied to automate the production of marine vessels?

Problem Statement: Traditional FRP construction using moulds is an expensive, laborious, and inefficient method for building marine vessels that restricts formal variation and limits easy customization. For large assemblies, the hand layup process often leads to products with inconsistent dimensional variability. This process also releases fumes into the atmosphere and exposes workers to hazardous materials. While the VARTM process, discussed earlier, reduces the escape of VOCs into the atmosphere and exposure of workers to carcinogenic chemicals there remains a significant risk to both environmental and worker health in many steps of the process that cannot rely on VARTM methods. These include the tabbing process, as well as the integration of structural elements into the hull: procedures that rely on a hand layup process. VARTM is a laborious process that generates large volumes of plastic waste including vacuum bags and the tubing used to distribute resin (Sanchez et al, 2014). Automation with AM may have the capacity to alleviate the shortcomings of this construction method, but the technology to investigate this has not yet been fully developed.

Methodology: To investigate the application of robotic AM to marine vessel manufacturing, a mixed research method relying on Qualitative Analysis of case studies and a Design-Based Research (DBR) approach has been applied to design and testing of an experimental robotic extruder prototype and a novel tool path generation procedure. The implicit assumption within the study is that only through applied experimentation with robotic AM for marine components and assemblies can one understand the complex inter-relation between issues of AM processes, materials, scale, kinematic systems, and software approaches.

Qualitative Analysis: Qualitative Analysis is an approach to literature review that seeks to support the fundamental research question with reference to existing and emerging research and scholarship in a particular topic area (Onwuegbuzie et al., 2012). According to Machi and McEvoy (2021), “A literature review is a written document that presents a logically argued case founded on a comprehensive understanding of the current state of knowledge about a topic of study. This case establishes a convincing thesis to answer the study’s question.”

The case studies in Chapter 2 describe a variety of recent manufacturing experiments and practical methods used to produce marine replacement parts, components, moulds, and entire marine vessel hulls. A thorough review of case studies examining various applications of AM to the marine industry, reveals the successes and shortcomings of these projects. Investigations outside the nautical sector in aerospace manufacturing research suggest that applications of advanced AM and automation using processes and materials atypical to the nautical sector might point to potential future applications of AM to marine vessel manufacturing.

While there are some promising examples of AM applied to the problem of manufacturing large and complex surface assemblies both within the marine sector and outside of it, there is a broad area of applied research in this area that remains underdeveloped. In particular, there is a notable lack of any standard tool or device for large scale AM that is appropriate for marine vessel manufacturing. The case studies point to two kinematic configurations of robotic tools for the automated manufacture of large surfaces with compound curvature typical to boat hulls.

The various strengths and shortcomings of different kinematic configurations as they relate to the specific problem of manufacturing marine vessels and components have been discussed in the previous chapters which included a synopsis of typical AM methods with a particular focus on the requirements of the marine industry and the challenges of adapting this technology to a larger scale. The introduction also included a broad overview of the history of boatbuilding with a focus on FRP materials, as well as moulding and assembly procedures, discussing the strengths and shortcomings of both the material and the methodology.

Design Based Research: DBR is "a systematic but flexible methodology aimed to improve [research outcomes] through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually sensitive design principles and theories." (Wang & Hannafin, 2005). While DBR has historically been associated with educational research in curriculum development and the design of pedagogical and evaluation tools, it is a methodological approach ideally suited for design and prototyping of real-world objects and physical processes with emerging technologies.

Manufacturing and fabrication challenges are often best understood through direct experience; therefore, the project aims to produce representative excerpts of typical marine vessel components using a specific reference vessel described below. A design-based research method guides the development of this manufacturing method which requires the design of new tools and toolpath generation procedures for applying AM to the problems specific to both marine vessel manufacturing and the deployment of AM using large scale kinematics.

DBR relies on serial iteration and pragmatic testing that is subsequently integrated into the development of the research. DBR includes ongoing analysis of the performance of an artifact or process under development to understand, explain, and improve its attributes and effectiveness (Wang & Hannafin, 2005). DBR reduces development time by building on progressive refinements through continuous testing, analysis, and improvement of the design from the earliest stages of development until the final iteration rather than testing the intervention only after it has been completed. The design and testing of the tools and methods used to address these manufacturing challenges are described later in this chapter and discussed in greater detail in Chapters 4 and 5.

Qualitative Analysis of marine vessel and marine product design case studies reveals the strengths and shortcomings of existing applications of AM to marine vessel manufacturing, thus informing the application of DBR to the design and development of prototypes that can address the question of how AM technology can be applied to automate the production of marine vessels. An examination of common varieties of AM technology reveals one material and method that is potentially the most suitable for the particular constraints for manufacturing marine vessels without the use of moulds: a continuous strand FRP extruder using the Fused Filament Fabrication (FFF) method mounted on a robotic arm.

In order to test the viability of automated AM technology for marine vessel manufacturing it became clear that a specialized tool as well as a software workflow optimized to generate AM toolpaths were necessary to describe the complex topology of a boat hull while attempting to fulfill the structural requirements of a traditionally built FRP vessels. This tool was developed in response to a series of contingent questions that examined scaling up AM technology, 1) selecting an appropriate AM method, 2) selecting a material suited to marine manufacturing, 3) selecting a robotic system that was both feasible, 4) developing a software workflow that supports the topological description of complex surface forms that can also be optimized to respond to structural loading conditions typical to marine vessels. Finally, 5) an appropriately sized reference vessel was selected to test the viability of the manufacturing method, extracting a series of strategic excerpts from various parts of the assembly that could be used to test the AM tool and method.

Prototype Robotic Extruder: Building on this premise, the research project describes the design and testing of a purpose-built tool for AM production of marine vessel components, and the application of software modeling tools to the problem of novel toolpath generation for Multi-Bias Additive Manufacturing (MBAM).

For the purposes of this research project, I designed a proprietary end of arm tool for a Kuka robotic arm using a Continuous Strand (CS) FFF method with FRP featuring glass fiber roving pre-impregnated with an Ultraviolet (UV) light-activated thermoset resin. However, due to the complexity of its construction and the laborious testing that its development would require I developed a series of preliminary tools using common thermoplastic filament to test toolpath and G-code generation workflows for manufacturing a series of representative assemblies on a small reference vessel. This method and approach allow a broad range of experimentation in how to fabricate typical component assemblies common to small FRP boats. The material application, while distinctly different than FRP, facilitates a comparison between traditional moulded FRP manufacturing and the potential for Continuous Strand Fiber Reinforced Plastic Additive Manufacturing (CSFRPAM) once a CSFRPAM extruder can be built and tested.

In order to understand the end of arm tool control systems while refining toolpath generation methods, I developed a testing tool: a thermoplastic filament extruder and a secondary electronic control system to communicate various extruder functions such as power on, heat setting, feed rate, and direction, as well as secondary controls including a temperature display and a cooling fan. The design and fabrication of this tool and control system informed the design of the continuous fiber extruder while also allowing preliminary proof of concept toolpath testing.

Robots and end of arm tools are separate electronic systems that require a specialized procedure known as *integration* to control them with programming code. Integration is typically an end-stage process in the development of an end of arm tool and falls outside the scope of this research project. Further testing with a robotic arm-mounted commercial pellet extruder supported this early proof of concept testing with full-scale thermoplastic prototypes.

Reference Vessel: The 1927 Francis Sweisguth design for the 22’ catboat *Secret* serves as a reference vessel to test the fabrication method. This particular boat was selected because it represents a well-documented classic design for an enduring regional American sailboat that has already successfully transitioned through two distinct fabrication methods and typological uses. At the same time, the 100-year-old tradition of racing and sailing catboats for pleasure is in danger of dying out due to steadily increasing production costs for these small vessels and a decreasing supply of alternatives. Currently there are only three manufacturers producing FRP catboats in the United States (Plate, 2021). This vessel and how it was used in the study will be discussed later in the chapter.

EXPLORATORY QUESTIONS

There are a series of contingent questions that must be answered before arriving at an automated AM solution for producing marine vessels: 1) What process? 2) What material? 3) What kinematic system? 4) How to generate toolpaths? 5) What application for testing? These questions are described below.

1) AM Process: the previous chapters presented five distinct processes for AM, describing the various technologies and procedures for creating 3-dimensional forms from computer models. Based on those descriptions it is eminently clear that the Fused Filament Deposition (FFF) method, above all others, is best suited for adaptation to large-scale manufacturing. Further, it is clear that a variation of this method using a continuous strand fiber (CF) composite material is most suitable for adapting for the manufacture of marine vessels. These results will be discussed further in Chapters 4 and 5.

To determine what type of AM tool to develop it was first necessary to select an appropriate 3d printing method. This was a fairly straightforward choice. Chapter 1 introduced five distinct additive manufacturing methods describing the printing process including physical procedures, materials and mechanical equipment required. Typical applications were discussed for each technology describing the limitations and potential opportunities for scaling up this technology for marine manufacturing in Chapter 2. The five processes are: 1) Photopolymer rapid prototyping using liquid resin bath process, including: Digital Light Processing (DLP), and Stereolithography (STL); 2) Photo-activated or liquid chemical binder activated granular material processes including : Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Binder Jet (BJ); 3) Wax-casting process commonly known as Material Jetting (MJ); 4) Cut shape lamination method known as Laminated Object Manufacturing (LOM); and 5) Thermoplastic deposition process known by its various names Fused Filament Deposition (FFD), Fused Deposition Modeling (FDM), or Fused Filament Fabrication (FFF). Methods 1-4 can be rejected outright as unsuited for scaling up to the size and material requirements for manufacturing a typical boat hull. A sixth method known as AFP was introduced, but the extremely high cost of exotic polymer high temperature thermoplastic materials and the fact that they have not been tested for marine applications suggests that it is not a suitable method to investigate at this time. Only the thermoplastic deposition process is suited to producing large, waterproof, structurally performative objects due to the diversity of materials and composite materials that it can support, and the modest ancillary equipment requirements (for example, there is no need for a very large vacuum chamber, or an oversized autoclave, or an enormous resin bath). The sole modification to the additive manufacturing method is modestly scaling up the size of the extruder nozzle and using a continuous fiber pre-impregnated with UV-activated thermoset plastic resin rather than a thermoplastic or a thermoplastic composite.

2) Material: the introductory chapter explained boat building in general terms and laid out a convincing argument for conceiving the hull as a singular and unbroken surface manifold or two-part assembly (hull and deck). The discussion on FRP construction described the ideal qualities of a hull surface as waterproof, smooth, lightweight, and resistant to puncturing. It is clear that FRP is a low-cost material that is well-suited to meet these criteria, taking into consideration that there remain many FRP boats from the 1960’s and 1970’s that are still in service, and that thermoset resin remains relatively inexpensive on one hand, though somewhat less than ideal in terms of environmental health and safety on the other hand. Automated AM,

however, may be able to mitigate some of its shortcomings by providing greater capacity for recapturing fumes in the manufacturing process while limiting worker contact with hazardous materials. The previous chapter introduced alternative materials in aerospace case studies. While high temperature composite thermoplastics such as PEEK or PEKK may ultimately be determined to be well-suited for marine applications, their exorbitant cost and the fact that this method requires an aluminum mould or mandrel makes it unlikely these exotic materials can economically be adopted for the mass production of marine vessels in the near term.

The marine manufacturing industry has an over 60-year history with moulded FRP. While roto-moulded polyethylene has been used for some smaller marine craft with some success (Alemán et al, 2018), thermoplastics have not yet been widely accepted as a suitable alternative material for the hulls of larger boats (Boating, 2002). This may be due to concerns about structural performance issue or simply a mistrust of new methods and materials for manufacturing. AM experiments using thermoplastic have been selected because it remains the most common and lowest cost AM material and process but it is anticipated that further research will be required with CSFRPAM once an extruder is developed.

3) *Robotic Kinematics:* the introductory chapter described a variety of kinematic systems for deploying a novel AM technology. The case studies further described these systems and showed examples of marine vessel manufacturing projects that used these methods. Two systems emerged as particularly well-suited to automated AM: a large gantry system such as that used for the University of Maine 3-Dirigo project, and an articulated robotic arm system similar to that used by both OCORE on the Livrea 6.50 and by Moi Composites on the MAMBO project. It is clear, however, that the projects using these kinematic systems exhibit significant shortcomings. The gantry systems featured wide bead thermoplastic extruders that resulted in thick-walled and heavy hulls not optimized for the marine environment: this system appears to be more well-suited to producing moulds than directly printing marine vessels. The articulated robotic arm projects were limited in their physical reach, so the projects were manufactured in parts and wrapped with an inner and an outer skin using a traditional hand layup procedure, thereby failing to address many of the shortcomings of traditional FRP construction (beyond the elimination of the mould). It is likely that a fully developed solution will feature articulated multi-axis robotic arms on linear tracks, mounted on gantries, or in cylindrical configurations.

The choice of which style of robot to use was determined by the particular geometry and topology of marine vessels that often feature long overhanging surfaces and the kinematic flexibility of serial six-axis robots also known as revolute configuration or articulated robots that have the capacity for a broad range of orientation relative to overhanging topological surfaces. Extending its range of motion with a linear rail system that moved either the work surface or the manipulator could extend the reach of the robot. Adding additional manipulators could greatly reduce fabrication time. Due to the requirements for a rather long reach and a flexible orientation relative to large surfaces with compound curvatures typical in naval architecture this fabrication method is not particularly well-suited to parallel robots, nor is it well-suited to horizontally articulated configurations such as Cylindrical and SCARA robots that tend to be more restricted in vertical reach (Ross et al, 2018). It would be quite simple to adapt a version of this manufacturing methodology to a Cartesian configuration such as an overhead gantry system with some particular orientation limitations. For example, it would not be feasible for the extruder to approach the underside of an overhanging surface due to the limitations of overhead cartesian gantry configurations. The kinematic configuration at the University of Maine Advanced Composites Center is an example of a gantry system that allows some flexibility in the orientation of the extruder nozzle relative to the object under construction (Godec et al, 2022; Caramatescu et al, 2019), however, it is not ideal for performing operations underneath an overhanging surface: a morphology that is very common in boat hulls. This type of kinematic set-up is only possible if the manufacturing method approaches the build surface from above, either with a hull being built upside down, or being built up from the outside, inward.

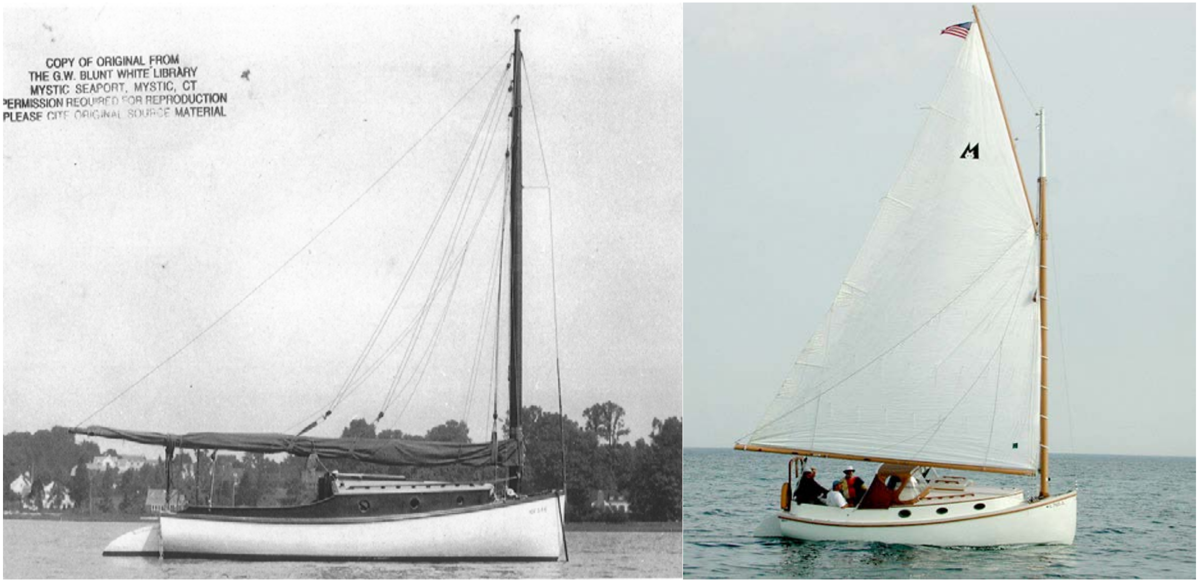
4) *Toolpath Generation:* the introductory chapter described in general terms the shortcomings of traditional AM slicers – software that resolves a 3-dimensional model into a series of sequential 2-dimensional laminar toolpaths. The primary issue is the problem of intralaminar bonding: objects fabricated using this method may be strong in certain planes and weaker in other planes (Gardner et al, 2018). The solution to this issue appears to be a multi-bias approach to depositing a material that resists stretching and breaking such as continuous glass or carbon fiber strand in thermoset resin (or high temperature thermoplastic). The next chapter will describe in detail a novel method for generating toolpaths and discuss ways that software may be used to optimize the placement and orientation of fibers to respond to both local and global loading conditions within a complex surface manifold.

While there are a variety of ways to generate topological forms and translate them into toolpaths using g-code, a common computer language used to control the movement of industrial robots. Two workflow methods for generating g-code were tested to identify strengths and shortcomings of each method and determine the most accurate, efficient, and easy to use software tools and procedures that lead to predictable outcomes in most toolpath situations.

The industry standard software tool in the marine industry is the NURBS surface modeling software tool Rhinoceros. Using the Rhino 7 plugin Grasshopper, and its specialized plugin KukaPRC supports modeling complex geometry, toolpath simulation, and G-code generation without leaving the Rhino / Grasshopper interface. This allows easy topology and machine settings modifications within a single interface that is already widely accepted in the nautical design sector. Once G-code is output as a .src file it is loaded into the Kuka Teach Pendant, and it is executed as a typical robotic movement program.

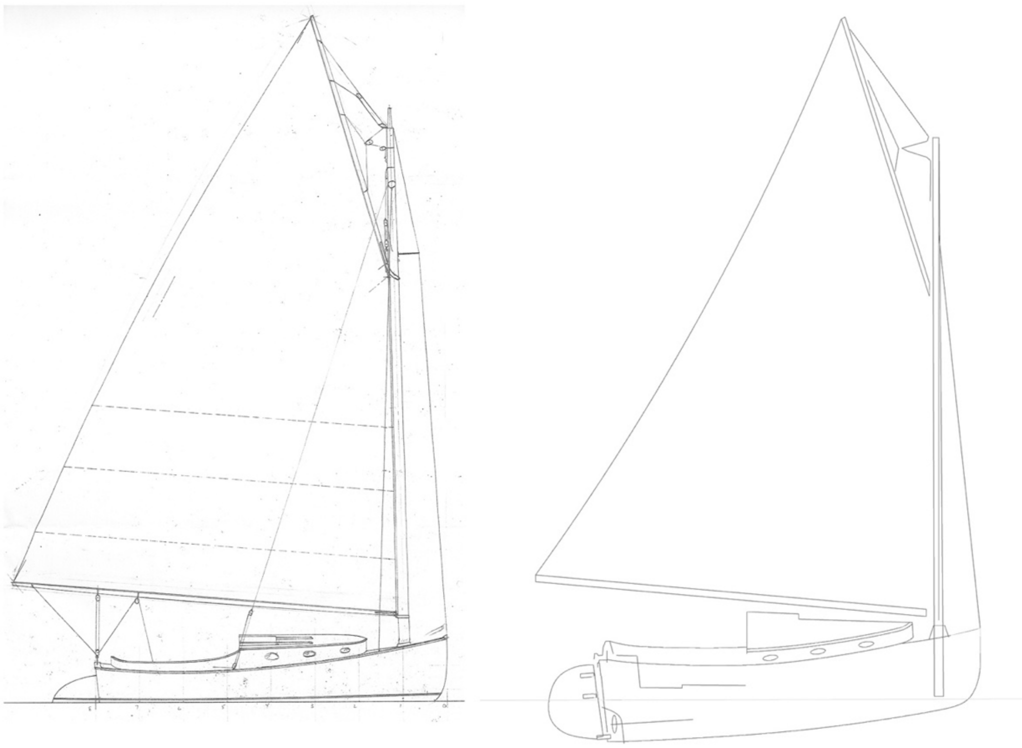
A second workflow used Fusion360 as a modeling tool and RoboDK for toolpath generation and simulation. This offers a somewhat more rigorous modeling approach with both integrated topology optimization and generative design options in Fusion360. Once the topology is completed it is opened in RoboDK for toolpath generation, simulation, and G-code output. Again, the resulting .src file can be loaded into the Teach Pendant or it can be executed directly out of RoboDk with a PC communicating with the Kuka Controller using a Local Area Network (LAN) connection. The downside of this second software workflow is that any modification to the topology requires leaving one software interface, resaving the file, loading into a second software interface and reconfiguring the settings for simulation and g-code output. While both software workflows have positive and negative attributes this method was ultimately abandoned due to its unwieldiness for prototype testing.

5) *Reference Vessel:* The 1927 Francis Sweisguth design for the 22’ catboat *Secret* serves as a reference vessel to test a novel AM fabrication method. This particular boat represents a well-documented classic design for an enduring regional American sailboat that has already successfully transitioned through two distinct typological uses and fabrication methods.



Images courtesy of Mystic Seaport Archives and Jerry Thompson of Thompson Boatworks, 2022.

Catboats were originally fishing boats, though *Secret* was designed as a day-sailor and club racer. While originally designed and built as a wooden vessel, it has since been reproduced in fiberglass by a number of different manufacturers including Americat, Menger, and Thomcat.



Digital drawings and computer model from original Francis Sweithguth drawings from Mystic Seaport Archive.

Catboats evolved from single-masted gaff-rigged 19th century coastal fishing boats commonly found along the northern Atlantic coast of the United States from the Chesapeake Bay to southern Maine (Leavens & Lund, 2015). These shallow centerboard vessels are small, lightweight, fast, and feature both low freeboard and an extraordinary two to one length to beam ratio. In the 1920's and 1930's they became popular for racing, often featuring enormous gaff rigs on their forward mounted masts with large headsails on long bowsprits.

Throughout its evolution, the catboat has evolved from a simple working vessel made in wood, to an early 20th century high-tech racer and pleasure craft to a popular production series FRP family pocket cruiser. The tradition of racing and sailing catboats for pleasure is in danger of dying out due to steadily increasing production costs for these small vessels and a decreasing supply of affordable alternatives. Currently there are only three manufacturers producing FRP catboats in the United States and the majority of catboats in service today were produced in the last century (Leavens & Lund, 2005).

Secret was initially built as a custom handcrafted carvel planked wooden day-sailor by shipwright William E. Haff in Long Island Sound in New York. It was reproduced several times in wood by other local shipwrights until the design was eventually adapted in 1970 by Brown's River Marine on the south coast of Long Island for a production series FRP vessel known as the AmeriCat 22 (Hubbard, 1970).

Over the next 30 years production shifted among several neighboring boatyards before the moulds were eventually acquired by Menger Boatworks in 2003 and, later, by Thompson Boatworks where it was produced until 2010 as the ThomCat 23. In recent years it has become increasingly challenging for small semi-custom boatyards to profitably produce small niche market sailboats due to rising labor costs which drive prices upward (Thompson, 2021). AM automation offers a potential solution to keep this valuable sailing tradition alive in the face of mounting financial pressure on small yacht builders with low margins and limited production demand due to high labor costs.

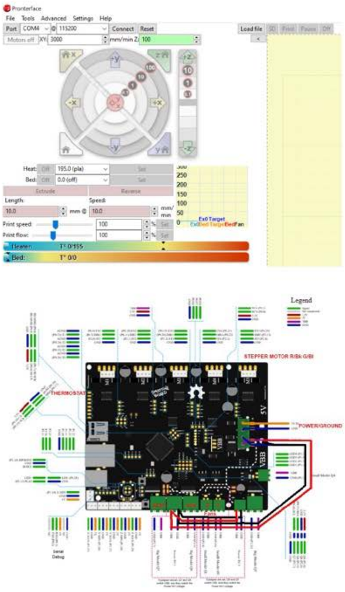
Extruder Prototypes: The DBR method was applied to the development of a series of small-scale thermoplastic extruding testing tools, because there are currently no off-the-shelf solutions for robotic AM. It was necessary to develop a testing tool for 3D printing experimental partial assemblies of the reference vessel to address the research question: *how can Additive Manufacturing technology be applied to automate the production of marine vessels?* In order to conduct practical testing of the manufacturing methods described in this research project, small-scale thermoplastic extruders were assembled from available parts and control systems were developed to operate them. Five iterations of the testing tool developed using DBR method will be described in this section including a brief analysis of their relative strengths and shortcomings for producing parts. Successful partial assembly 3D prints from these tools will be described in the following chapter.

Robotic extruders are made up of multiple interconnected systems and electronic parts including, but not limited to, 1) power supply and voltage regulator, 2) central processing unit, 3) controller software, 4) communications system, 5) power management and distribution, 6) extruder motor, 7) hot end and nipple, 8) cooling fan(s), 9) temperature sensor. The development of any robotic extruding tool must therefore accommodate the various power and data requirements for each of these systems.

Prototype Extruder 1

METHODOLOGY: Testing Tool 1 Titan Extruder + Smoothie Board

Titan Extruder
Modular extruder. Universal for multiple filament diameters.
3:1 gear reduction precision milled hobbed gearing.
E3D extruder for a variety of filament material types and sizes.



Smoothie Board
Numerical fabrication controller. Open-source.
32-bit Cortex-M3 LPC1769 with 512kB flash and 64kB RAM.
Open-source CNC controller for 3d printers.

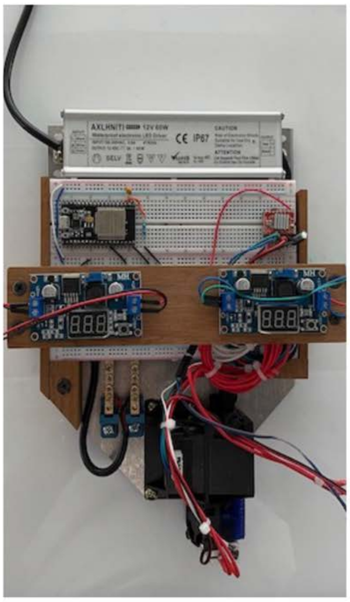
RDF Lab Robotic 3d Printer
Thermoplastic Extruding End Effector. 2020.
Kuka KR10-1100 Robotic arm-mounted Titan extruder.
Extruder for small-scale robotic control and toolpath testing.

Titan extruder with Smoothie Board running Pronterface software with hardwired USB control functionality.

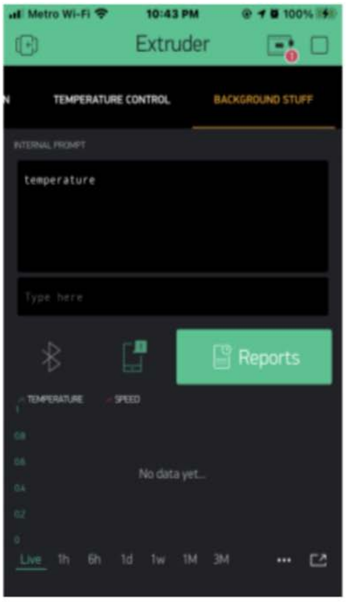
This .4 mm extruder, made from off-the-shelf parts and open-source software was effective for basic extruding but suffered from poor interface design and unreliable connectors on the circuit board. However, Pronterface requires G-Code command line user input. Ultimately, this prototype was challenging to use due to both poor software design and unreliable wiring.

Prototype Extruder 2

METHODOLOGY: Testing Tool 2 Extruder + Arduino + Blynk IoT



Custom End-Effector
Arduino micro-controller. Open-source.
Bluetooth enabled control of heat, speed, direction.
Open-source IoT management via ESP 32.



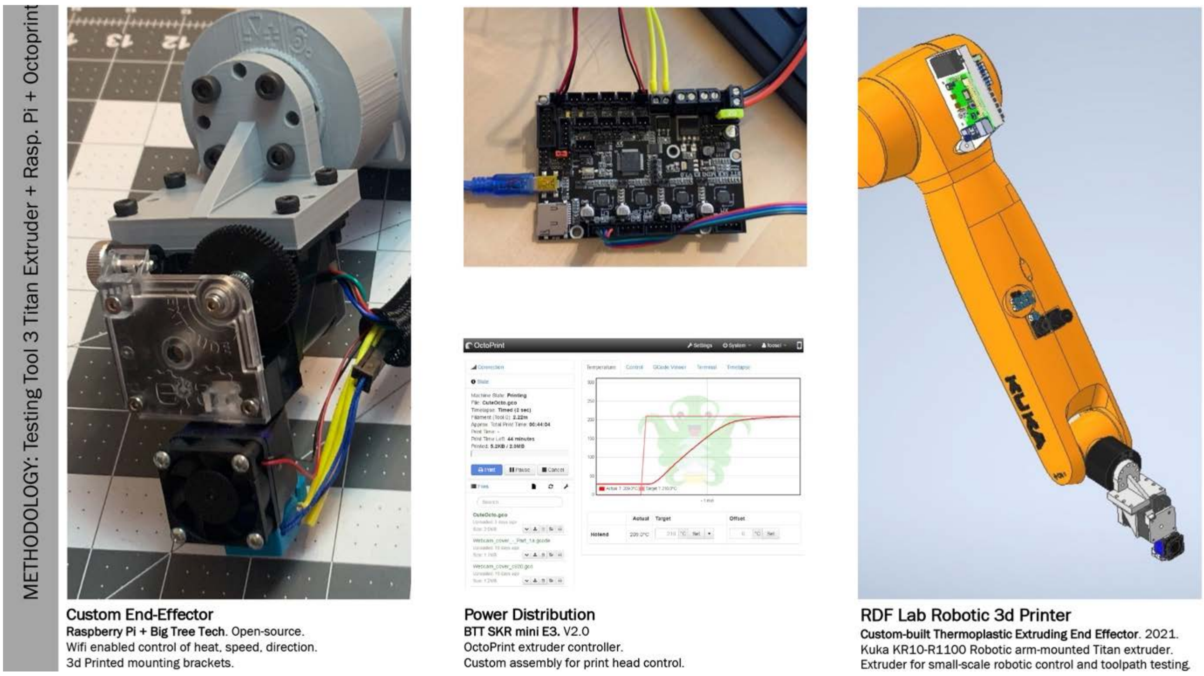
Smartphone Controller Interface
Blynk IoT API. Open-source.
Mobile application custom controller.
Fully customizable display monitors and input tools.

RDF Lab Robotic 3d Printer
Custom-built Thermoplastic Extruding End Effector. 2021.
Kuka KR10-1100 Robotic arm-mounted Titan extruder.
Extruder for small-scale robotic control and toolpath testing.

Titan extruder with Arduino ESP32 running Blynk IOT with Bluetooth wireless control functionality.

This .4 mm extruder made from readily available parts relied on Arduino and the Blynk IOT API. The all-in-one compact design reduced stress on electrical connectors but resulted in greater movement programming challenges to accommodate collision avoidance with objects on the platen. While it was a moderate improvement on the previous design it had one major shortcoming. The Arduino ESP32 proved unable to handle the power distribution and processing demands of both maintaining a Bluetooth connection and simultaneously providing the constant oscillating power fluctuations of the hot end. A second version of this prototype used parallel ESP32s on a custom printed circuit board (rather than the breadboard version shown here) but required two separate controllers to isolate the power fluctuations of the hot end. Ultimately, this prototype was challenging to use due to the unreliable wireless connection. When Blynk IOT discontinued support for Bluetooth it was abandoned.

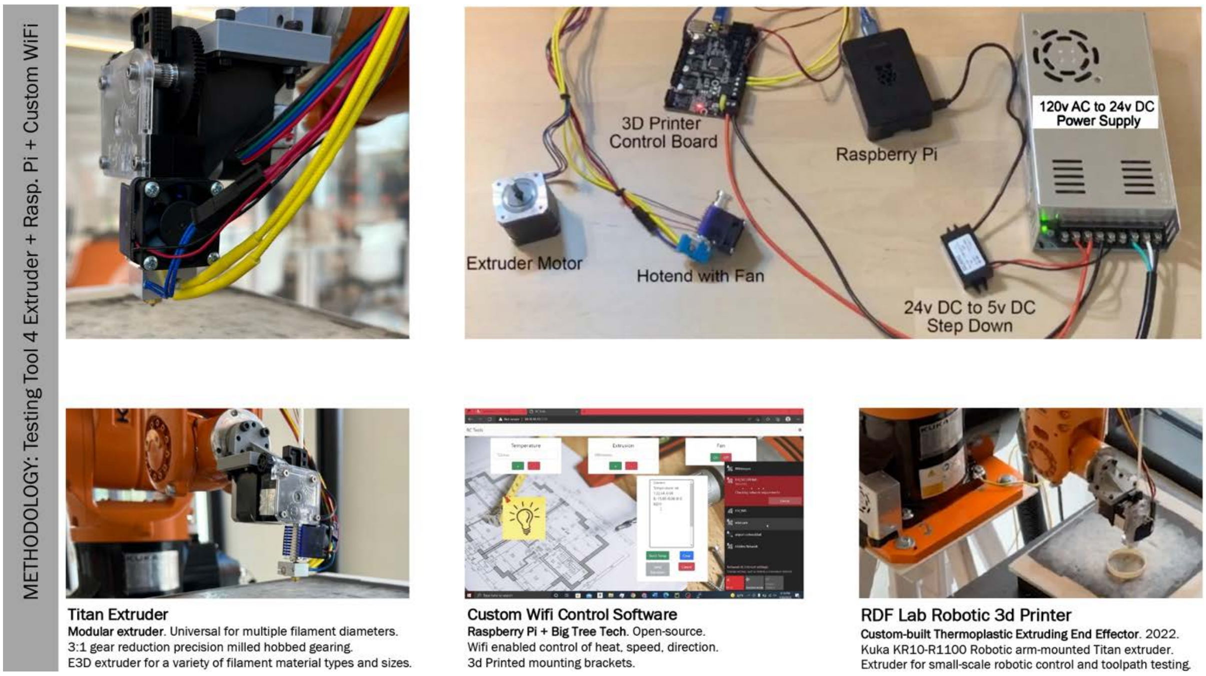
Prototype Extruder 3



Titan extruder with Raspberry Pi and BTT SKR Mini E3 running OctoPrint with WiFi control functionality.

This .4 mm extruder made from readily available parts and 3d printed hardware mounting connectors relied on a Raspberry Pi CPU running the open-source G-Code controller, OctoPrint. Using a remote design with a Big Tree Tech SKR mini E3 power distribution board on a custom 3D-printed mounting plate at the elbow and a Titan extruder and hot end on a custom 3D-printed wrist connector, this extruder was one of the most successful printers developed. The more robust Raspberry Pi and BTT configuration was better able to handle the power and data requirements. Meanwhile, a direct WiFi connection with the Raspberry Pi proved to be a more reliable wireless connection. Its primary shortcoming was the open-source controller software which was unwieldy for real time adjustments to printing parameters. Ultimately, this prototype was both robust and easy to use but presented modest shortcomings in the design of the controller interface. Its success revealed a fundamental shortcoming in the extruder prototype series. The .4 mm size of the Titan extruder nozzle and the resulting extrusion itself was too small relative to the typical tolerances of the KR10-R1100 Sixx. Modest oscillations in the movement of the robot resulted in poor adhesion between layers and unreliable surface qualities of the printed material making it unsuitable for testing.

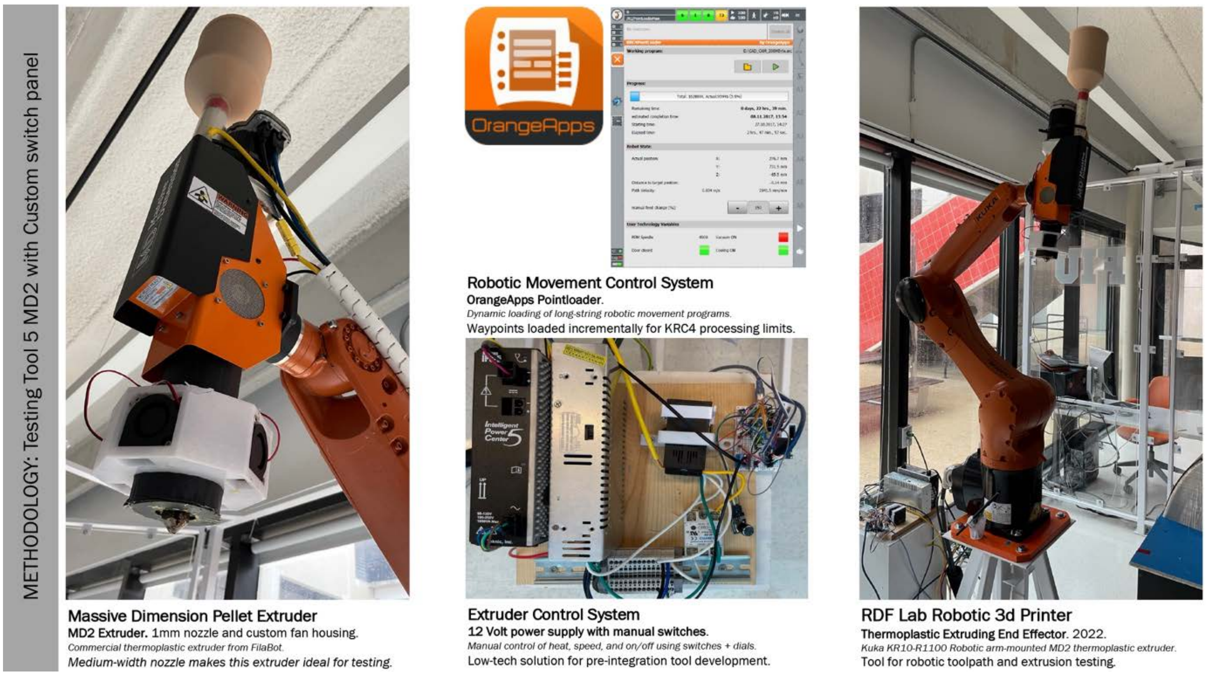
Prototype Extruder 4



Titan extruder with Raspberry Pi and BTT SKR Mini E3 running custom WiFi-enabled controller software.

Prototype 4 was an incremental advance with identical hardware. Raspberry Pi ran a custom software for on-the-fly adjustment of temperature and extrusion rate. Ultimately, this extruder was reliable only for laminar prints due to issues of the size of the extrusion and movement tolerances of the KR10 which produced uneven stepped surfaces on even moderate slopes.

Prototype Extruder 5



Massive Dimension MDP2 extruder with manual switchbox and point loader plugin software.

This 1 mm MDP2 pellet extruder from FilaBot relies on a hardwired switchbox using rheostats and digital displays for non-integrated control (due to time constraints, the extruder has not yet been set up with a wireless control system). The thicker bead of the MDP2 is ideal for testing as it does not suffer from the same tolerance issues that afflicted thinner extruders. Surface qualities of sloped surfaces remain consistent within the tolerance of the KR10. The bead size is only moderately smaller than the anticipated CSFRPAM extruder allowing a more direct comparison between the two different material types and the anticipated behavior of the tool relative to the surface volumes it produces.

Robotic AM experiments with previous prototypes revealed a second fundamental issue with the design of the extruders. The Kuka control system, designed to handle short and repetitive movement commands typical of industrial robotics, was unable to process long string movement commands due to shortcomings in its CPU and memory architecture. Integrating a point loader system from Orange Apps into the movement programming allows long strings of code to be fed incrementally to the Kuka KRC4 Compact controller. This facilitates processing more complex and longer-duration movement instructions that are typically not supported by industrial robots. While continued integration is anticipated, at the time of writing, this extruder prototype is now the primary tool used at the FIU RDF Lab for continued MBAM experimentation for marine vessel manufacturing.

Toolpath Generation: The typical workflow for generating toolpaths for this project is as follows: 1) a model is built using the NURBS modeling software Rhino, 2) Grasshopper is used to reconfigure the surfaces as a series of oriented points that can be sorted in a variety of ways such as horizontally, vertically, etc., 3) KukaPRC is used to establish toolpaths between the oriented points using them as a series of waypoints in a robotic movement program, 4) the movement instructions are fed to the robot which executes the toolpath program.

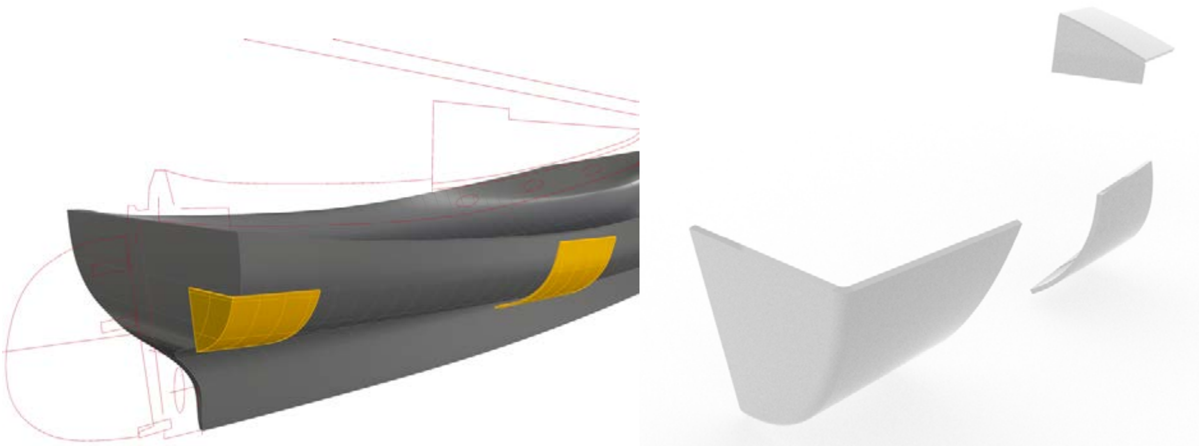
Toolpath Generation Workflow

Rhino -------------------> Grasshopper -------------------> KukaPRC -------------> Kuka Robotics

Build model with NURBS surfaces.	Reconfigure model as series of oriented points.	Create movement paths between oriented points	Run movement program with extruder attachment.

Typical workflow for generating toolpaths for robotic AM using Kuka robots.

Experimental Partial Assemblies: Several portions of the hull and deck assemblies of the reference vessel *Secret* have been selected that represent particular applied fabrication challenges. These excerpts were selected due to their common topological features that can be found on a variety of different marine vessels of different sizes and types.



Computer models derived from the original drawings yield excerpt for testing with prototype extruders.

The information gathered in these activities has led to a novel applied research approach to the problem statement. To demonstrate conclusions about the most suitable AM method, material system, and kinematic configuration, for applying AM to the automation of marine vessel manufacturing I designed and assembled a robotic additive manufacturing end-of-arm tool that can be used for testing how to print several typical assemblies common to small FRP boats. This led to the design for a manufacturing system using Continuous Strand Fiber Reinforced Plastic Additive Manufacturing (CSFRPAM). This system uses one or more 6-axis robotic arms mounted on external axes to extend the range of motion of a robotic manipulator with a CSFRPAM extruder. The system is designed to print large and complex FRP surfaces using specialized toolpaths that build up a surface not only in horizontal layers, but in specially designed configurations that are optimized for the structural needs and loading conditions typical of small FRP marine vessels.

Without the use of moulds, testing with a thermoplastic extruder revealed 1) A method for printing thin, solid, compound-curved surfaces with continuous extrusions oriented in multiple biases such as the at turn of the bilge amidships where it meets the hull side, 2) A method for printing thin, solid, folded surfaces with continuous toolpaths oriented in multiple biases such as at the crease of the transom and hull side, 3) A method for printing curved sandwich constructions similar to pattern-grid air-cored sandwich assemblies commonly featured in decks and cabin tops. Testing this method to fabricate these partial components without the use of moulds demonstrates the efficacy and the shortcomings of this method for printing portions of small boats. While additional testing is required with a CSFRPAM printer and larger components, this first step establishes a method and approach that can lead to generalized principles supporting recommendations for manufacturing marine vessels.

LIMITATIONS

This methodological approach to the question of how AM technology can be applied to automate the production of marine vessels is limited in four distinct ways. 1) As an emerging technology, the AM landscape is constantly changing, resulting in a host of new developments; 2) Robotic toolpath generation has not been standardized for additive manufacturing beyond simple\ laminar slicing protocols that are not suited to the specific requirements of marine vessel manufacturing; 3) Marine vessel manufacturing is a complex process that features many different ways to accomplish analogous final results, particularly in the domain of FRP construction; 4) As a researcher I have a particular orientation and world view that frames how I evaluate what technology to examine and how to conceive of its deployment for the manufacturing of marine vessels.

1) *AM as an Emerging Technology:* During the research project there were major advances in AM technology applications to the marine industry. When the project started there were only a few examples of boats and marine products that had been produced using AM. Several years later, new products and large-scale application projects are published monthly. Staying up to date with these advances has been a major challenge and it is doubtless that some important information may have been overlooked. To keep pace with these advances I have maintained regular contact with colleagues (primarily in Italy) to discuss the latest advances and imminent projects that can only be learned about through informal networks. Working on research at the edge of an emerging field of manufacturing application has required a more agile approach to data collection and qualitative analysis.

2) *Robotic Toolpath Generation:* There is no standardized software, system, or method for generating robotic toolpaths optimized for AM projects of this complexity. As such, the project relies on a toolpath generation procedure that has not yet been optimized for AM. While Grasshopper and KukaPRC allow the procedural generation of serially oriented points that can be translated into a robotic toolpath with specified tool orientation criteria, the data volume can quickly become unmanageable for complex and multi-layered forms. This causes serious challenges for creating surfaces with complex topological characteristics or assemblies that feature variable interior reinforcing structures such as grid pattern cores. Research at ETH Zurich (Mitropoulou et al., 2020) points to one possible approach for multi-bias toolpath generation, but additional research is needed to streamline this process (Kaill et al., 2021) for practical application to marine vessel manufacturing.

3) *Variation and Complexity in FRP Marine Manufacturing:* The technology used to produce marine vessels in the sub-40 meter range varies dramatically from one manufacturer to the next. According to researcher Gökdeniz Neşer regarding FRP construction methods, “It can seem that there are almost as many product and process variations as there are individual structures, a fact that makes it difficult to formulate industry standards and qualification routes,” (2017). It is difficult to identify typical manufacturing challenges in an industry where manufacturing processes and material assemblies feature such variability. Likewise, it is difficult to identify manufacturing performance criteria for assemblies that feature such a broad range of materials and processes. Case studies and informal discussions with boat building industry professionals verified with a survey of academic research in material science has helped to ground this investigation with an understanding of best practices.

4) *The Role of the Researcher:* In conducting this research I have drawn upon my existing knowledge base, and I have been guided by specific personal orientations that are a result of my own lived experience. This necessarily shapes and focuses my vision and attention in distinct ways that direct and limit the potential outcomes of this study. In the 1980’s I served an apprenticeship as a jointer and a carpenter, I later built and renovated a variety of wood and steel frame buildings, worked in two modular housing factories building wood and steel frame prefabricated dwellings, became a CNC operator and programmer, earned factory certifications in BMW and Ducati motorcycle commissioning and refurbishment, earned a professional Master of Architecture degree, worked as an architectural intern and computer modeler, and I have lived aboard a 1979 classic FRP sailing yacht that I have refurbished and renovated over the past 10 years. I am currently a Teaching Professor at Florida International University where

I teach design studios, serve as Associate Director of the Robotics and Digital Fabrication Laboratory, conduct academic research in technology-enhanced learning, and lead semester-long travel/study trips to Genoa, Italy.

These experiences have shaped the way I look at design problems and how I understand the application of technology to specific challenges. Likewise, they both scaffold and delimit my frame of reference in specific ways. I have used case studies and a broad survey of academic literature in AM, materials science, naval architecture and engineering, robotics, manufacturing technology, and the history of technology to reorient my perspective and conduct research that presents what I hope is a balanced view of the state of existing AM technology and an approach to automated marine vessel manufacturing that is grounded in relevant research and best practices.

Summary: This chapter has described a specific methodological approach that relies on qualitative analysis and design-based research to investigate an automated approach to marine vessel manufacturing. A discussion of the technical challenges of AM processes, materials, kinematics, and toolpath generation established an experimental method for applying a design solution to a specific reference vessel using an as yet undeveloped tool. The selection of a reference vessel has been justified as both culturally and economically relevant while also representative of several significant manufacturing challenges for applied AM research. A description of DBR applied to a series of prototypes developed for testing a MBAM method for manufacturing marine vessels has revealed the key issues for generating these types of formal topology. A discussion of workflow described the software and methods used to generate complex MBAM toolpaths. The chapter has also discussed the limitations of the methodological approach with specific reference to the challenges associated with conducting this research within the context of a rapidly changing technology. The next chapter will present the results of the research suggesting a novel approach to marine vessel manufacturing using AM.

Results

4 RESULTS

This chapter aims to address the question of how Additive Manufacturing (AM) technology can be applied to automate the production of marine vessels with a series of substantiating questions. These questions involve the use of 1) qualitative analysis of material presented in previous chapters and, 2) design-based research applied to fabrication testing using a prototype extruder. The chapter will include a detailed description of a manufacturing system for producing marine vessels and components using AM with a series of practical experiments that demonstrate the feasibility of this fabrication method.

Introduction: Chapter 1 introduced the research question and problem statement, and it included a discussion of AM processes and materials with a brief discussion about the typical logic used for creating complex topological forms using this technology. Briefly, a slicer transforms a 3-dimensional digital object into a series of horizontal profiles or shapes that can be traced with a tool such as an extruder, laser, or spray nozzle that can harden material on the build platen or in the build-material reservoir. This method for creating forms is effective for avoiding collisions between the robot and the object but has serious limitations for its application to marine vessel manufacturing and must, therefore, be adapted to trace toolpaths in multiple biases (MBAM). The chapter also discussed the materials used for these varied processes and conjectured about their suitability for large scale AM and marine vessel manufacturing. A section on robotic kinematics presented six typical kinematic configurations that can be evaluated for their suitability for large scale marine manufacturing using MBAM. Finally, a section on the limitations of the study indicated the challenges related to the topic with specific reference to the changing terrain of AM technology, the lack of standardized toolpath generation procedures for non-planar slicing, and the complexity of marine vessels relative to long-string robotic toolpaths.

Chapter 2 used case studies as a mechanism for exploring AM processes, materials, and kinematic systems that have been successfully deployed for marine product and vessel manufacturing. Five distinct methods were described with several variations including one developed for aerospace applications. The chapter concluded by identifying potential AM methods in three categories:

1) Extrusion Processes:
    a. Modified FFF Narrow-Bead Continuous Strand FRP (pultrusion)
    b. Modified FFF Continuous Strand High-Temp Thermoplastic Prepreg (AFP)
2) Material Systems:
    a. Continuous Strand Thermoset Resin
    b. Continuous Strand Fiber Reinforced High-Temperature Thermoplastic
    c. Thermoplastic Composite Core with FRP Cold-Moulding
3) Kinematic Systems:
    a. Gantry
    b. Revolute Articulated Manipulators
    c. Hybrid Systems: Gantry-mounted Robotic Arms

Chapter 3 discussed the methodological approach to the research question using 1) Qualitative Analysis of the case studies: essentially a descriptive evaluation and critique of previous projects that address the research question in whole or in part. This helped to build a comprehensive understanding of the current state of knowledge in this domain. And, 2) practical testing of a manufacturing method using Design-Based Research applied to a representative reference vessel. This approach is meant to maximize progress on identifying an approach and developing effective tools for pragmatic testing on a relevant project. The chapter described five iterative prototypes developed for testing novel AM printing and discussed the method for developing MBAM toolpaths that might be typical for marine vessel manufacturing.

QUESTIONS

In order to determine how AM technology can be applied to automate the production of marine vessels it is necessary to design a manufacturing approach combining an AM process, material system, and robotic configuration. The purpose of this part of the study is to determine:

1. Which AM processes can be scaled up for manufacturing small marine vessels?
2. What materials are best suited for this type of project?
3. Which kinematic configurations are suitable for AM manufacturing of marine vessels?

The charts in the next section will address these questions. The qualitative analysis is presented as a series of charts that will be followed by a description and a discussion of the proposed manufacturing method including its relative strengths and shortcomings. Finally, a series of AM experiments with prototype extruders will demonstrate the feasibility of the toolpath generation method indicating its applicability to typical topological assemblies common in marine manufacturing.

CRITERIA FOR QUALITATIVE ANALYSIS

Which AM processes can be scaled up for manufacturing small marine vessels?

RESULTS: Question 1 Criteria for Qualitative Analysis of Methods

AM METHOD	MATERIAL	CATALYST	BENEFITS	SHORTCOMINGS
FFF	Thermoplastic FRP Thermoset	Heat Chemical or UV light	Versatile Material diversity Inexpensive	Standard toolpaths are unsuited to structural loading conditions typical of boats.
AFP	Prepreg with fibers	Laser + Heated roller	High strength Fiber reinforced Consolidated	Expensive, long-term testing of materials for marine applications remains incomplete, requires a heated mandrel or mould.
DLP, STL	Liquid Resin	Laser	Precision	Requires large build chamber, no fiber reinforcement.
SLS, SLM EBM	Granulated plastic	Laser Electron beam	Precision High strength Heat resistance	Requires large build chamber and an autoclave, no fiber reinforcement.
BJ	Plaster, clay, etc.	Chemical binder	Precision Inexpensive	Requires large build chamber, material unsuited to marine environment.
LOM	Adhesive paper	Heated roller	Inexpensive	Material unsuited to marine environment.
MJ	Wax	Heat	Precision	Material unsuited to marine environment.

Table 4.1-1 shows qualitative analysis of various AM processes for applicability to marine vessel manufacturing.

A modified FFF method offers the most benefits for marine manufacturing. It is versatile and inexpensive, requiring no specialized equipment such as lasers, electron beams, or large autoclaves for catalyzing and consolidating materials. It supports a wide range of materials including a continuous strand reinforced resin pultruder that has been successfully deployed for manufacturing a 25’ boat. New MBAM toolpath generation procedures will be required to adequately address the structural requirements of marine vessels.

RESULTS: Question 1 Criteria for Qualitative Analysis of AM Methods

AM METHOD	MATERIAL	CATALYST	BENEFITS	SHORTCOMINGS
FFF	Thermoplastic FRP Thermoset	Heat Chemical or UV light	Versatile Material diversity Inexpensive	Standard toolpaths are unsuited to structural loading conditions typical of boats.
AFP	Prepreg with fibers	Laser + Heated roller	High strength Fiber reinforced Consolidated	Expensive, long-term testing of materials for marine applications remains incomplete, requires a heated mandrel or mould.
DLP, STL	Liquid Resin	Laser	Precision	Requires large build chamber, no fiber reinforcement.
SLS, SLM EBM	Granulated plastic	Laser Electron beam	Precision High strength Heat resistance	Requires large build chamber and an autoclave, no fiber reinforcement.
BJ	Plaster, clay, etc.	Chemical binder	Precision Inexpensive	Requires large build chamber, material unsuited to marine environment.
LOM	Adhesive paper	Heated roller	Inexpensive	Material unsuited to marine environment.
MJ	Wax	Heat	Precision	Material unsuited to marine environment.

Table 4.1-2 shows that FFF is the most suitable process for scaling up AM for marine vessel manufacturing.

<u>What materials are best suited for this type of project?</u>

RESULTS: Question 2 Criteria for Qualitative Analysis of Materials

AM PROCESS	MATERIAL	CATALYST	BENEFITS	SHORTCOMINGS
FFF	Thermoplastic FRP Thermoset	Heat Chemical or UV light	Versatile Material diversity Inexpensive	Standard toolpaths are unsuited to structural loading conditions typical of boats.
AFP	Prepreg with fiber	Laser + Heated roller	High strength Fiber reinforced Consolidated	Expensive, long-term testing of materials for marine applications remains incomplete, requires a heated mandrel or mould.
DLP, STL	Liquid Resin	Laser	Precision	Requires large build chamber, no fiber reinforcement.
SLS, SLM EBM	Granulated plastic	Laser Electron beam	Precision High strength Heat resistance	Requires large build chamber and an autoclave, no fiber reinforcement.
BJ	Plaster, clay, etc.	Chemical binder	Precision Inexpensive	Requires large build chamber, material unsuited to marine environment.
LOM	Adhesive paper	Heated roller	Inexpensive	Material unsuited to marine environment.
MJ	Wax	Heat	Precision	Material unsuited to marine environment.

Table 4.2-1 shows qualitative analysis of various AM materials for applicability to marine vessel manufacturing.

FRP Thermoset offers the most benefits for marine manufacturing. As the current industry standard material, it is inexpensive and can be cured using a chemical catalyst or an onboard UV light source. While high-temperature thermoplastic preimpregnated carbon fiber offers many potential benefits, it is currently very expensive and has not been tested for marine applications. Until costs for these materials come down and extensive testing in marine environments proves its suitability it is unlikely that it will be adopted.

RESULTS: Question 2 Criteria for Qualitative Analysis of Materials

AM PROCESS	MATERIAL	CATALYST	BENEFITS	SHORTCOMINGS
FFF	Thermoplastic FRP Thermoset	Heat Chemical or UV light	Versatile Material diversity Inexpensive	Standard toolpaths are unsuited to structural loading conditions typical of boats.
AFP	Prepreg with fiber?	Laser + Heated roller	High strength Fiber reinforced Consolidated	Expensive, long-term testing of materials for marine applications remains incomplete, requires a heated mandrel or mould.
DLP, STL	Liquid Resin	Laser	Precision	Requires large build chamber, no fiber reinforcement.
SLS, SLM EBM	Granulated plastic	Laser Electron beam	Precision High strength Heat resistance	Requires large build chamber and an autoclave, no fiber reinforcement.
BJ	Plaster, clay, etc.	Chemical binder	Precision Inexpensive	Requires large build chamber, material unsuited to marine environment.
LOM	Adhesive paper	Heated roller	Inexpensive	Material unsuited to marine environment.
MJ	Wax	Heat	Precision	Material unsuited to marine environment.

Table 4.2-2 shows that FRP Thermoset or Prepreg exhibit the greatest potential for marine vessel manufacturing.

Which kinematic configurations are suitable for AM manufacturing of marine vessels?

RESULTS: Question 3 Criteria for Qualitative Analysis of Kinematics

KINEMATIC SYSTEMS	APPLICATIONS	BENEFITS	SHORTCOMINGS
6-AXIS MANIPULATOR 	Moderate precision manufacturing Welding, cutting, boring, milling Precision material handling	6 degrees of freedom High dexterity Large envelope External programmable axes	Somewhat limited reach Serial linkage creates singularity issues
HYBRID Gantry-mounted multi-axis manipulator Rail-mounted multi-axis manipulator	Large-format manufacturing Moderate precision manufacturing	7 or 8 degrees of freedom Heavy-duty Modular	Complex collision avoidance
GANTRY 	Large-format manufacturing Long and wide applications Heavy material handling	Heavy-duty External programmable axes Modular	Limited degrees of freedom Low dexterity More suitable to laminar printing
LINEAR 	Large-format manufacturing Long applications Heavy material handling	Heavy-duty Modular	Limited degrees of freedom Low dexterity More suitable to laminar printing
PARALLEL 	High precision manufacturing Circuit boards, electronics Flight simulators	6 degrees of freedom Very high dexterity Precision Parallel linkage	Limited reach Limited envelope
SCARA 	Material Handling	Simple to program Robust design	Limited reach Limited degrees of freedom Limited orientation
CYLINDRICAL 	Material Handling	Simple to program Robust design	Limited reach Limited degrees of freedom Limited orientation

Table 4.3-1 shows qualitative analysis of kinematic systems applicability to marine vessel manufacturing.

6-Axis Manipulators offer the most benefits for marine manufacturing. They exhibit the optimal compromise between reach and orientation with the capacity to precisely orient the extruder from multiple approach vectors. While there are several examples of large-scale AM successfully using gantry systems, which exhibit demonstrably simpler collision avoidance, they are far more limited in their ability to orient the tool to the work surface. An excellent compromise between these two methods is a hybrid kinematic system which can feature a rail or gantry mounted robotic arm and/or a dynamically oriented work surface of platen.

RESULTS: Question 3 Criteria for Qualitative Analysis of Kinematics

KINEMATIC SYSTEMS		APPLICATIONS	BENEFITS	SHORTCOMINGS
6-AXIS MANIPULATOR		Moderate precision manufacturing Welding, cutting, boring, milling Precision material handling	6 degrees of freedom High dexterity Large envelope External programmable axes	Somewhat limited reach Serial linkage creates singularity issues
HYBRID Gantry-mounted multi-axis manipulator Rail-mounted multi-axis manipulator		Large-format manufacturing Moderate precision manufacturing	7 or 8 degrees of freedom Heavy-duty Modular	Complex collision avoidance
GANTRY		Large-format manufacturing Long and wide applications Heavy material handling	Heavy-duty External programmable axes Modular	Limited degrees of freedom Low dexterity More suitable to laminar printing
LINEAR		Large-format manufacturing Long applications Heavy material handling	Heavy-duty Modular	Limited degrees of freedom Low dexterity More suitable to laminar printing
PARALLEL		High precision manufacturing Circuit boards, electronics Flight simulators	6 degrees of freedom Very high dexterity Precision Parallel linkage	Limited reach Limited envelope
SCARA		Material Handling	Simple to program Robust design	Limited reach Limited degrees of freedom Limited orientation
CYLINDRICAL		Material Handling	Simple to program Robust design	Limited reach Limited degrees of freedom Limited orientation

Table 4.3-2 shows that 6-axis manipulators and 6-axis hybrid gantry systems are most suitable for applications of robotic AM to marine vessel manufacturing.

<u>Summary:</u> Qualitative analysis of case studies and a thorough review of existing and emerging AM technology reveals a narrow range of options for a manufacturing system that can deploy AM for the production of marine vessels. While there are myriad solutions for deploying AM technology for this application in limited ways, a comprehensive design for a manufacturing system that uses AM to produce marine vessels may look like this: continuous strand fiber preimpregnated with UV activated thermoset resin is drawn through an extruder (pultruder) attached to a robotic arm that is mounted in a robotic gantry.

Benefits: There are multiple benefits to this method; 1) The inexpensive material is commonly used in marine manufacturing; 2) an extruder using this design has proven effective for making complex forms; 3) the robotic arm is the most maneuverable for approaching complex topology from multiple orientations; 4) the gantry has the capacity to expand the potential work envelope of the robotic manipulator.

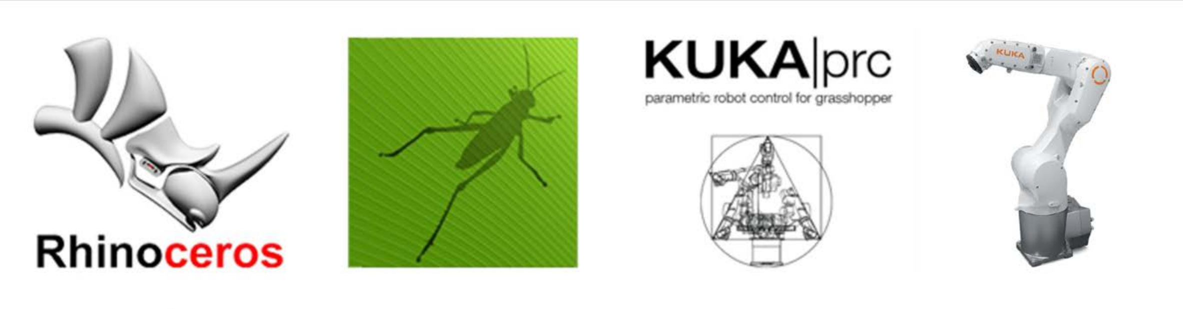
Limitations: There are several limitations to this proposal; 1) the proposed material has shortcomings due primarily to off gassing during production and the difficulty of recycling composites; 2) the method may not significantly decrease exposure to hazardous materials during certain phases of the construction process and may increase off-gassing compared to VARTM unless manufacturing takes place in a large controlled environment; 3) AM and robotic movement programming are not optimized for creating the types of tool paths this manufacturing method will require - a single small vessel built using this method would require many complex and unique robotic toolpaths utilizing hundreds of thousands, or even millions of oriented points that will need to be programmed in small batches and assembled by a programmer/designer. Until these operations can be automated this method may be unfeasible.

RESULTS OF DESIGN-BASED RESEARCH

DBR was used to conduct testing of the research question: how can AM technology can be applied to automate the production of marine vessels? This testing and experimentation included the development of tools, software workflows, and targeted manufacturing tests. DBR allows a flexible approach to solving contingent problems by supporting a continuous feedback between designed solutions, testing outcomes, and iterative re-design of tools, assessments, and methods. Chapter 3 described five extruding tools that were designed to help address the research question and introduced both the toolpath generation procedure and the method for extracting geometry from the reference vessel. This section will focus on two areas of DBR, 1) the software workflow for generating toolpaths, and 2) the outcomes of AM testing using the prototype extruders. Finally, the chapter will introduce the design for a CSFRPAM extruder and describe how it can be deployed for robotic AM of small marine vessels.

Toolpath Generation: Several portions of the hull and deck of the reference vessel *Secret* were selected that represent particular applied AM fabrication challenges. These excerpts were selected due to their common topological features that can be found on a variety of different marine vessels of different sizes and types. The typical workflow for generating toolpaths for these excerpts follow this software workflow: 1) a model is built as a singular surface manifold with no thickness from the original drawings using the NURBS modeling software Rhinoceros, 2) Grasshopper is used to reconfigure the surfaces as a series of oriented points that can be sorted in a variety of ways such as horizontally, vertically, etc., 3) KukaPRC is used to establish toolpaths between the oriented points using them as a series of waypoints in a robotic movement program, 4) the movement instructions are fed to the robot which executes the toolpath program, 5) subsequent layers used to create thickness and add strength are developed in Grasshopper / Kuka PRC, and exported to the robot as subsequent movement programs.

Toolpath Generation Workflow

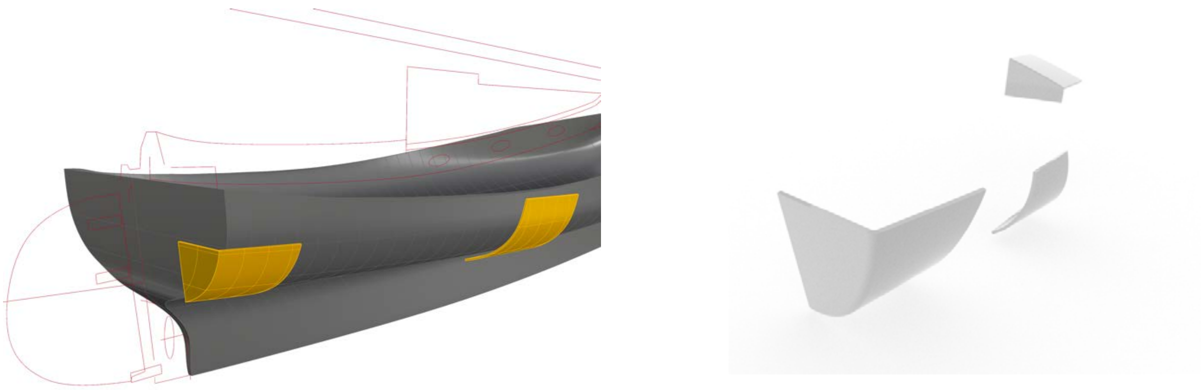


Rhino -------------------> Grasshopper -------------------> KukaPRC -------------> Kuka Robotics

Rhino	Grasshopper	KukaPRC	Kuka Robotics
Build model with NURBS surfaces.	Reconfigure model as series of oriented points.	Create movement paths between oriented points	Run movement program with extruder attachment.

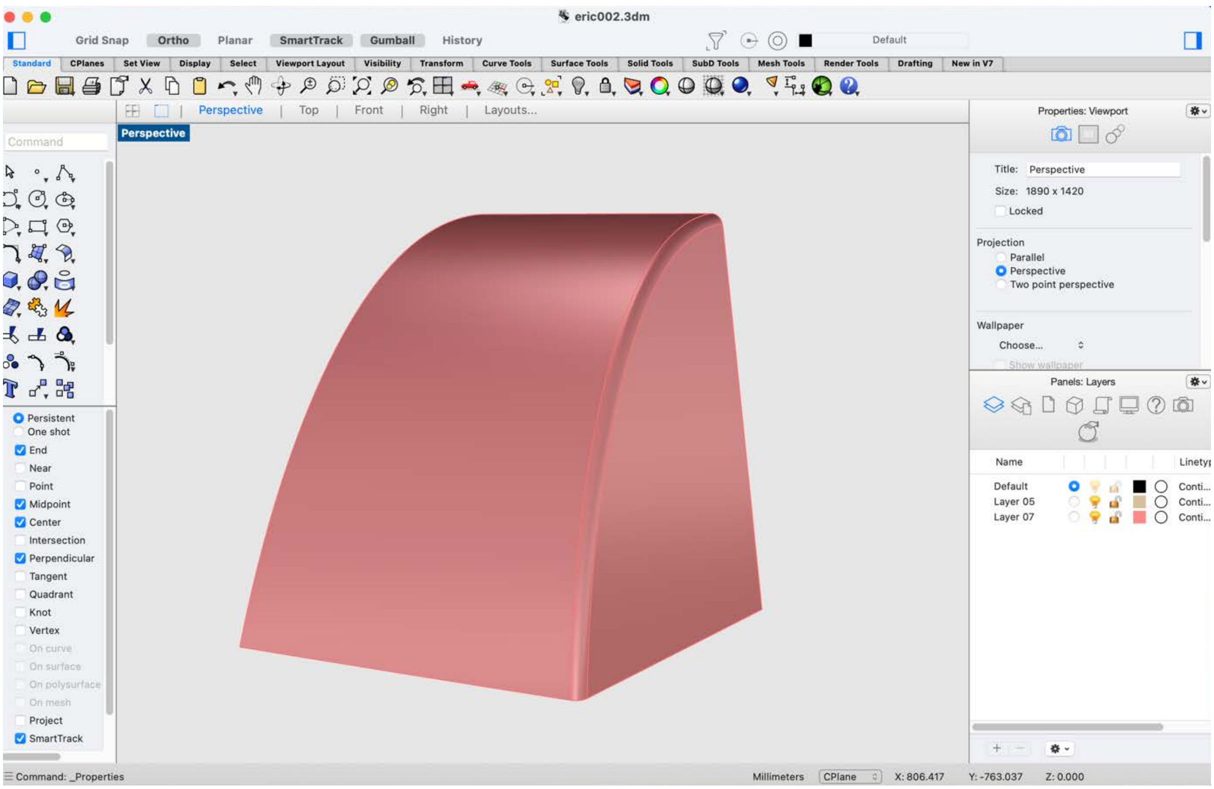
Typical workflow for generating toolpaths for robotic AM using Kuka robots.

Step 1: Develop a model of the hull using Rhinoceros and extract portions for testing. Three excerpts from the hull were selected for testing: 1) A method for printing thin, solid, compound-curved surfaces with continuous extrusions oriented in multiple biases such as the at turn of the bilge amidships where it meets the hull side, 2) A method for printing thin, solid, folded surfaces with continuous toolpaths oriented in multiple biases such as at the crease of the transom and hull side, 3) A method for printing curved sandwich constructions similar to pattern-grid air-cored sandwich assemblies commonly featured in decks and cabin tops.



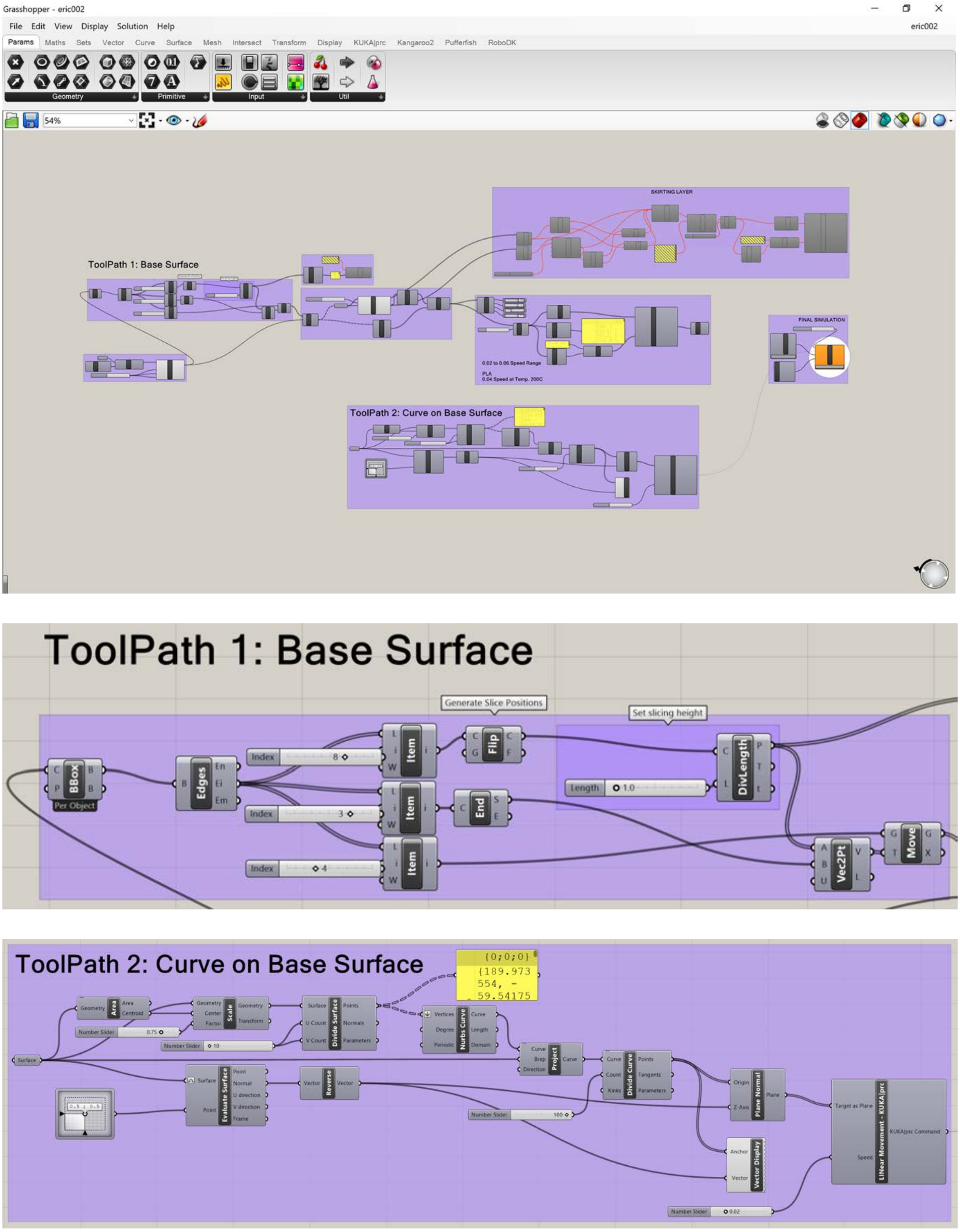
Preliminary model of Secret's hull and deck was built from original drawings by Francis Sweithguth with feedback from Jerry Thompson, the last known builder of this vessel known as the Thomcat 23.

The separate parts should be reoriented to optimize for printing. The part shown below is a transom and hull side excerpt rotated 180° for printing upside down.



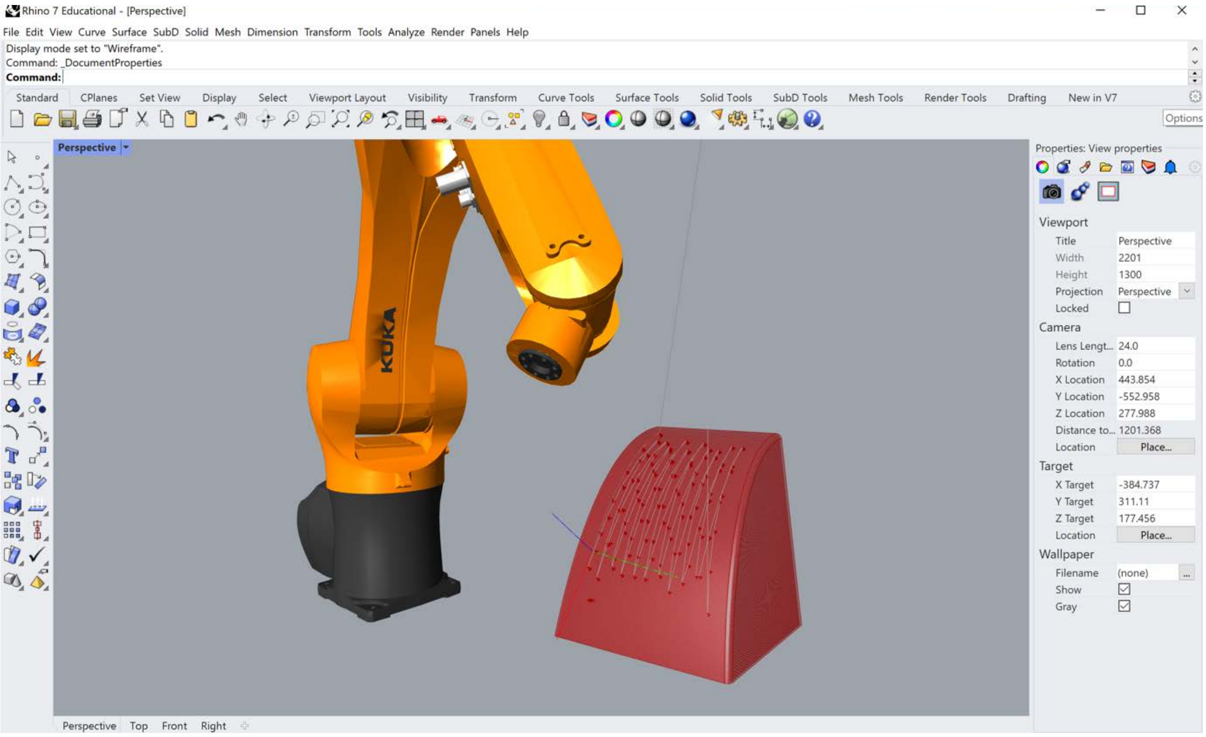
Parts are modeled with no thickness, toolpaths and offset thicknesses are applied in Grasshopper.

Step 2: Break down geometry into a series of oriented points and create a skirt to anchor it to the platen. In the example, Toolpath 1 is a series of horizontal movements that trace the original geometry from Rhino with a 1 mm vertical offset. Toolpath 2 is a series of zigzagging vertical curves that move vertically along Base Surface offset 1 mm from its face.



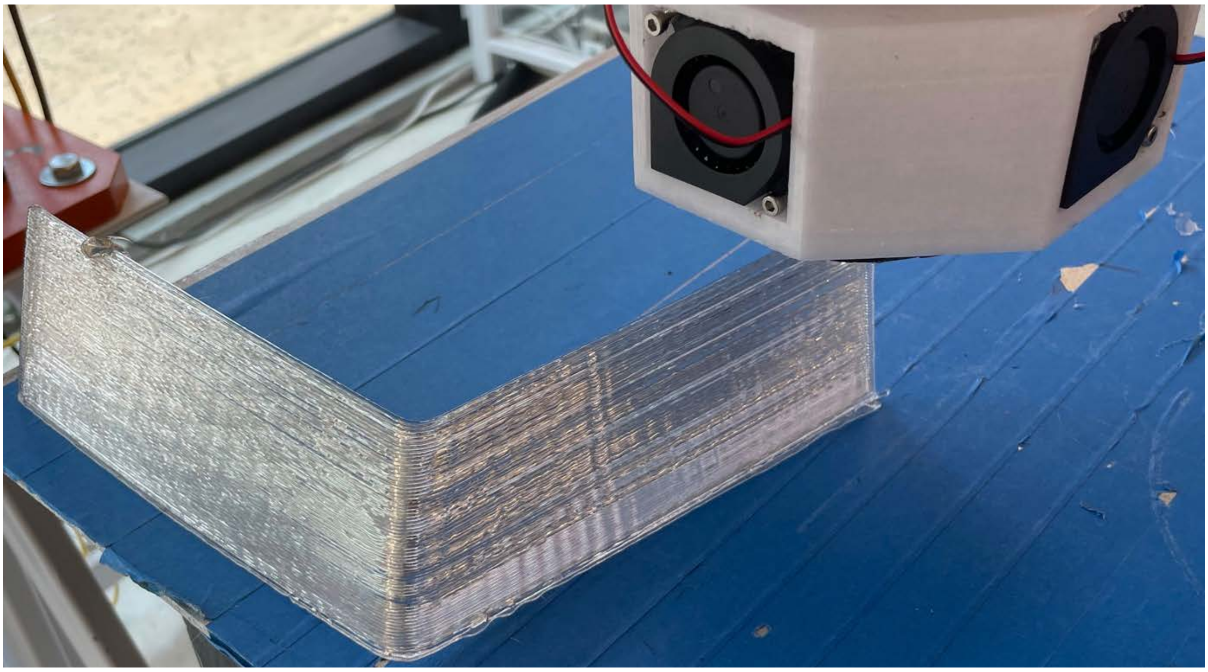
Grasshopper references a Rhino file and breaks down the topology into constituent operations.

Step 3: Use geometry from Grasshopper (a list of oriented points) to create movement paths with KukaPRC that can be traced by a specific robot. In the simulation below, a KR10-R1100-Sixx is tracing the movements described by the Grasshopper file on the previous page.



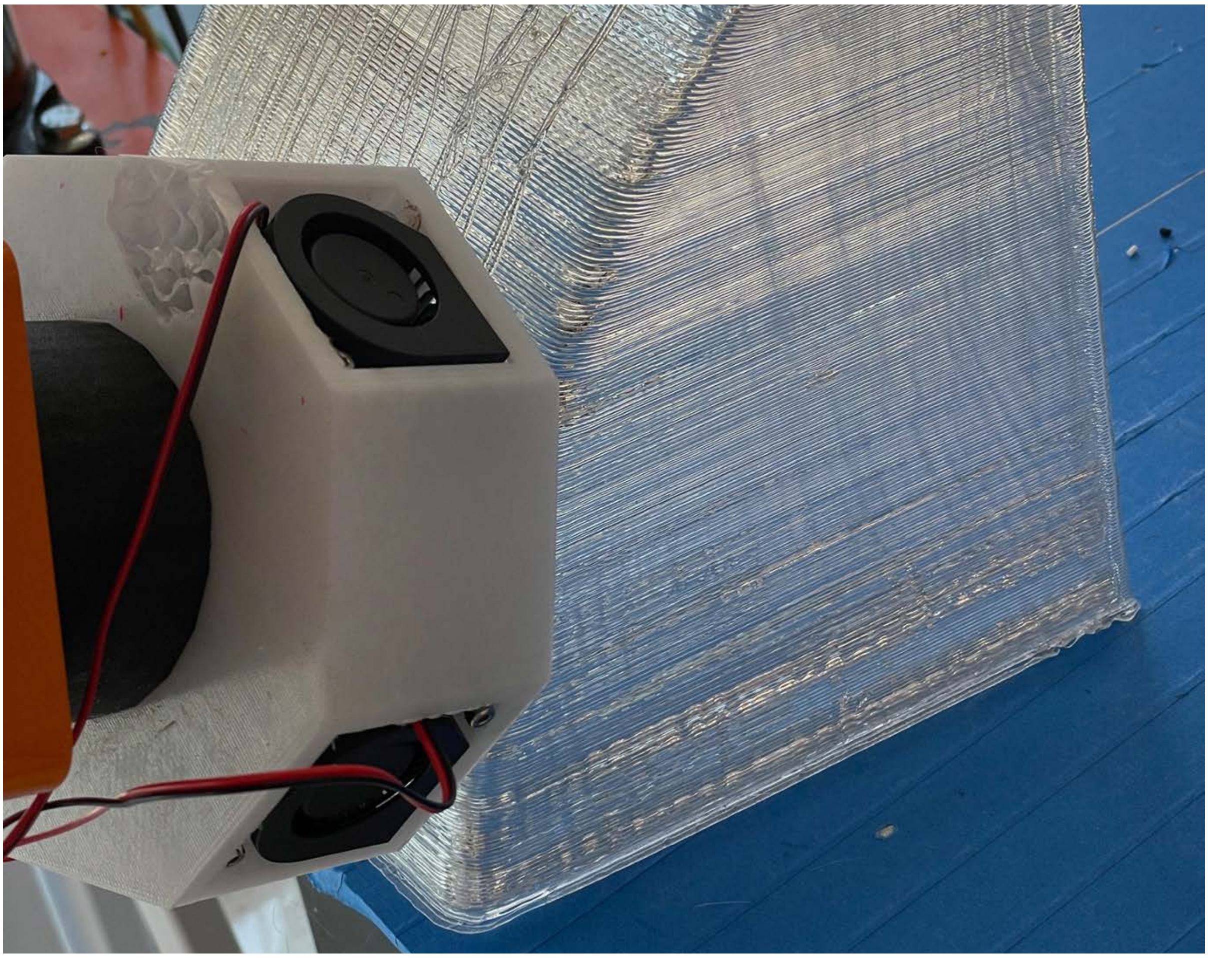
Grasshopper references a Rhino file and breaks down the topology into constituent operations.

Step 4: Export the KukaPRC file as a robotic movement program and run it on the robot. After verifying that there are no potential collisions the project can be printed using the extruder.



The part is printed as a laminar toolpath using the MDPE-6 with Pointloader and custom cooling fan assembly.

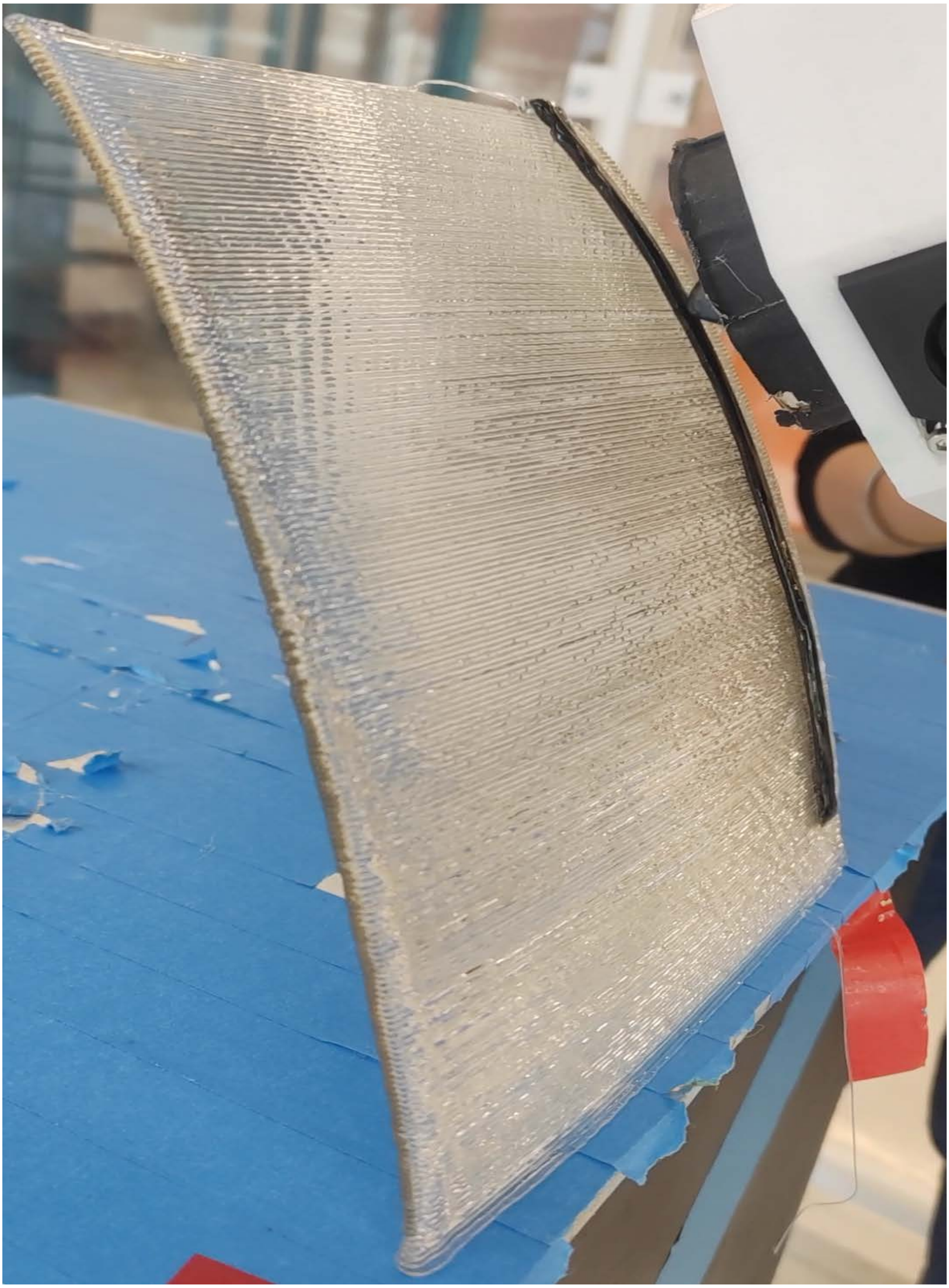
Step 5: Subsequent layers used to create thickness and potentially add strength are developed in Grasshopper / KukaPRC and exported to the robot as additional movement programs. The example below shows Toolpath 2 – a series of zigzagging vertical curves – applied to the base surface which was built as a simple laminar print using Toolpath 1.



Subsequent layers are printed on the laminar printed surface to increase thickness and add strength to the part.

The MBAM method described in these fabrication tests has many potential benefits over standard laminar printing. Parts can be thicker with tool paths tracing along multiple axes through the part. Toolpaths can orient fibers to counteract the forces that pass through the surface. Fabrication can be automated to reduce the exposure of workers to hazardous materials. While additional testing is necessary, this research offers an effective proof of concept demonstration that the MBAM method has a good potential for successful application to the project of applying AM technology to automate the production of marine vessels.

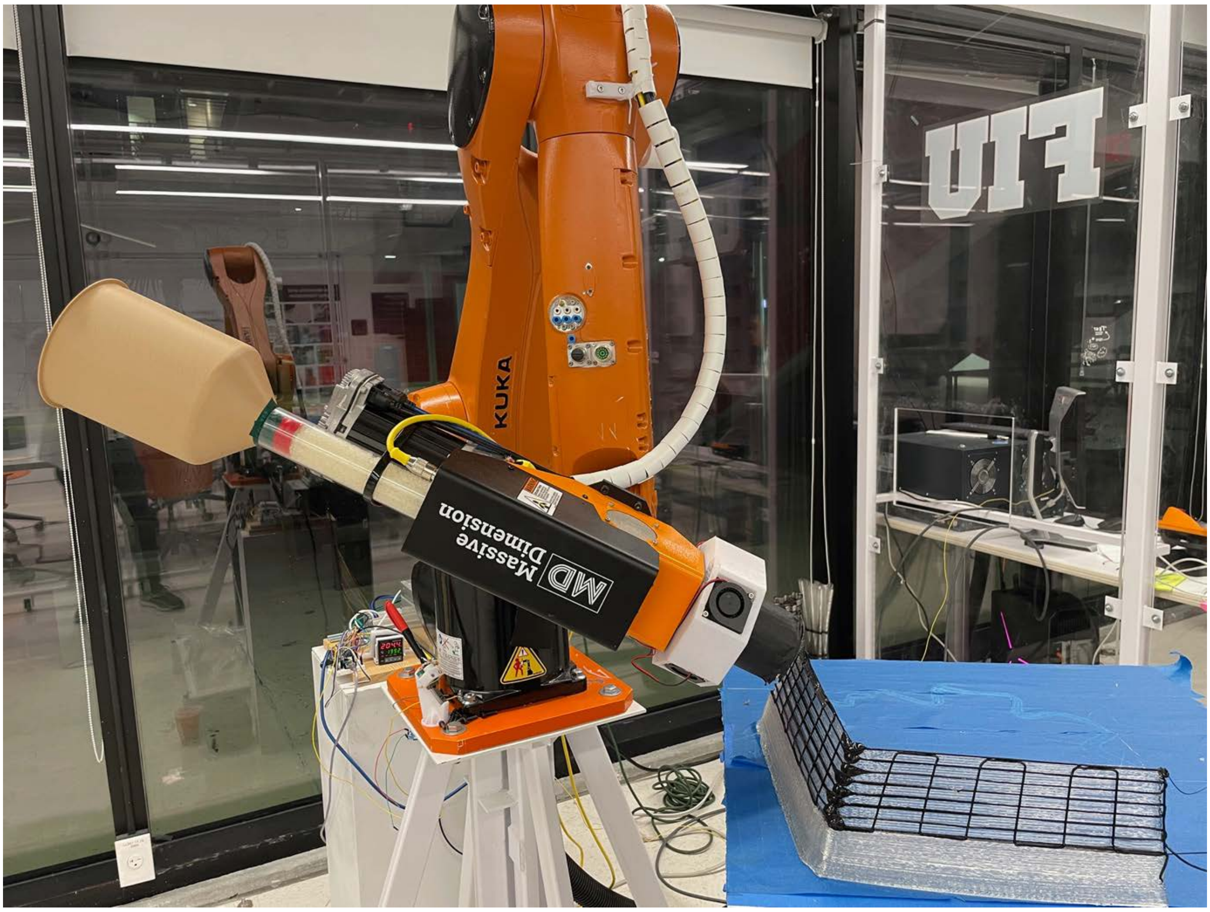
<u>*3D Printed Parts:*</u> The parts shown in this section demonstrate three excerpts of a typical small sailing vessel. Testing with a thermoplastic extruder revealed 1) A method for printing thin, solid, compound-curved surfaces with continuous extrusions oriented in multiple biases such as the at turn of the bilge amidships where it meets the hull side, 2) A method for printing thin, solid, folded surfaces with continuous toolpaths oriented in multiple biases such as at the crease of the transom and hull side, 3) A method for printing curved sandwich constructions similar to pattern-grid air-cored sandwich assemblies commonly featured in decks and cabin tops.



Hull side: Vertical toolpaths are printed on a laminar printed compound curved surface.

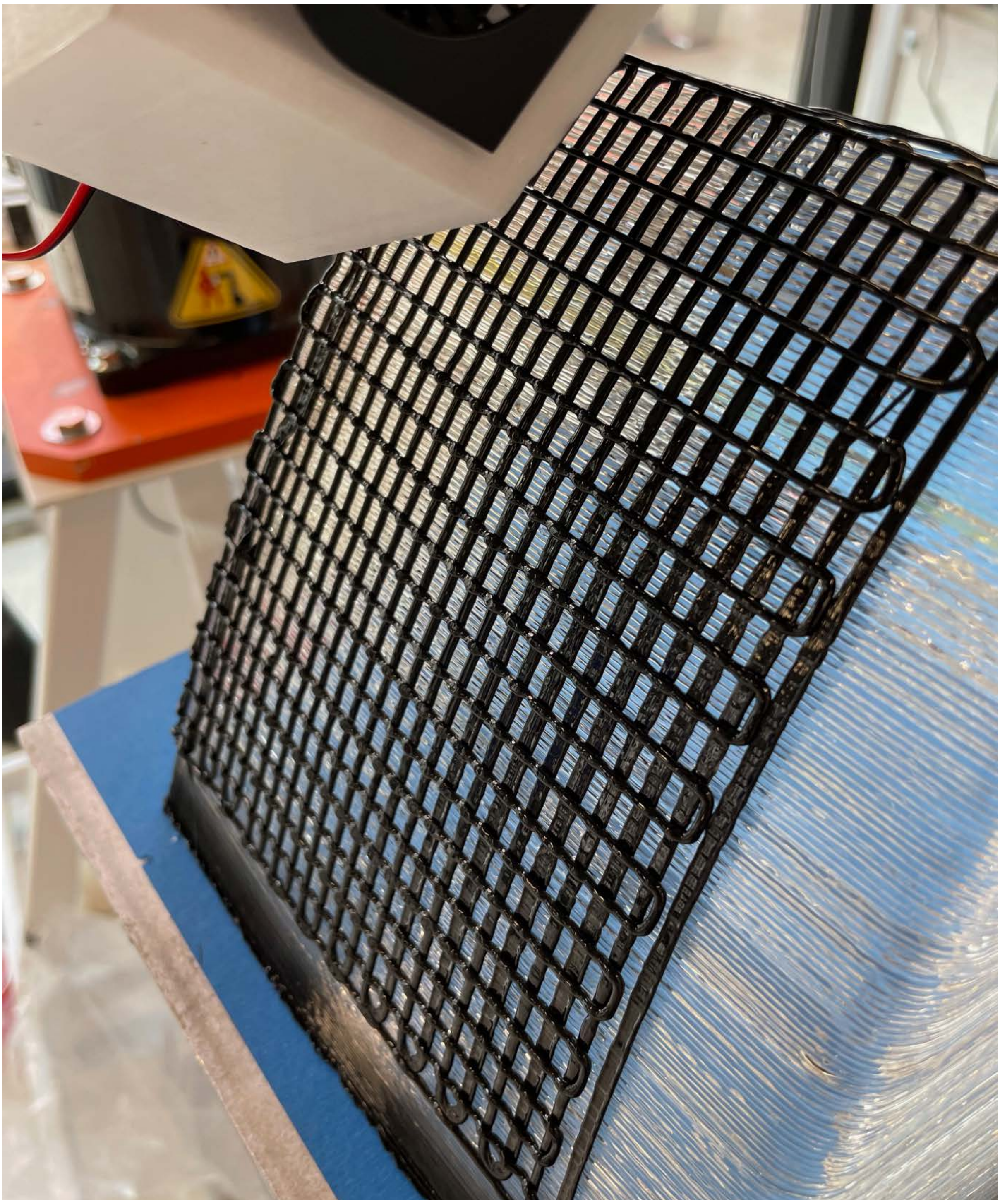
1) A method for printing thin, solid, compound-curved surfaces with continuous extrusions oriented in multiple biases such as the at turn of the bilge amidships where it meets the hull side. This test demonstrates how tool paths in two biases on a compound curved surface can

be produced using MBAM. In order to successfully print this part, it was buttressed with a raft at the base and reoriented to be slightly more vertical than its excerpt location. Using a thicker, lofted approach with more toolpaths in the shell may allow much larger portions of a hull to be extruded using this method. Additional testing with FRP extrusion may allow more deeply sloped surfaces to be fabricated using this toolpath and extrusion method.



Transom to hull joint: Multi-layered MBAM toolpaths are used to construct a reinforced crease in the hull.

2) A method for printing thin, solid, folded surfaces with continuous toolpaths oriented in multiple biases such as at the crease of the transom and hull side. This test demonstrates the capacity to use MBAM toolpaths on the exterior side of folded surfaces or creases. Interior creases are more challenging due to the potential for collision between the tool and the geometry. A serial lofting approach may be a potential solution to this issue, as demonstrated in the image above where the transom is in the process of receiving a laminar outer shell after reinforcement in two axes has been previously extruded. The excess material that can be clearly seen at the crease can be easily eliminated with extruder on/off commands encoded in the robotic program – a process that is not possible using this manually controlled (non-integrated) extrusion device. Using a stepped or *lofting* approach, it may be possible to create much larger self-supporting structures using this toolpath and fabrication method.

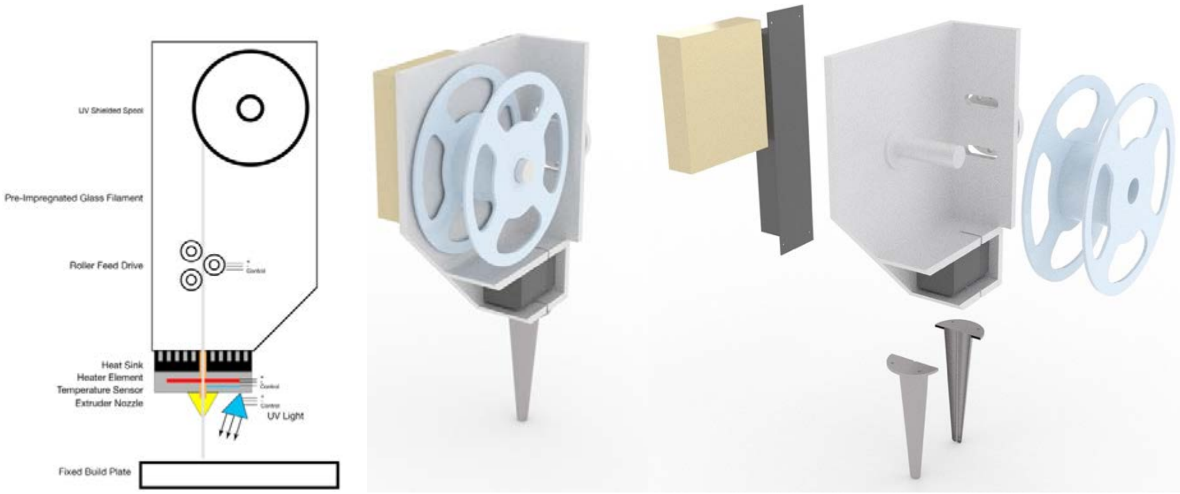


Cabin top: Grid-pattern toolpaths printed on a laminar surface in preparation for a sandwich assembly.

3) A method for printing curved sandwich constructions similar to pattern-grid air-cored sandwich assemblies commonly featured in decks and cabin tops. This multi-step toolpath procedure allows the potential for thickened sandwich constructions. The next steps in this toolpath testing will involve printing a double layer exterior skin as a vertical laminar toolpath with 1 mm stepover and a horizontal laminar toolpath with a 1 mm layer height.

Testing this method to fabricate these partial components without the use of moulds demonstrates the efficacy and the shortcomings of this method for printing portions of small boats. While additional testing is required with a CSFRPAM printer and larger components, this first step establishes a fabrication approach that can lead to generalized principles supporting recommendations for manufacturing marine vessels using this method.

<u>*Design for a CSFRPAM Extruder / Pultruder:*</u>



Prototype 6 will allow the extrusion of continuous fiber reinforced thermoset plastic CSFRPAM.

The Continuous Strand Fiber Reinforced Plastic Additive Manufacturing (CSFRPAM) extruder / pultruder will rely on tension from the movement of the robotic arm to draw glass fiber strands pre-impregnated with UV curing thermoset resin from the extruder nozzle. A roller feed drive inside the light-shielded extruder housing will assist with drawing the prepreg strands off of the spool. Meanwhile, a UV light source on the bottom of the extruder housing will focus light onto the work surface to cure the resin as it is extruded. An extra-long nozzle will allow more precise positioning of the tool while reducing the probability of collisions with both the platen and the part. It is possible to imagine this automated extrusion process taking place isolated from workers, within a controlled environment that filters fumes and provides precisely focused UV light to aid in the curing process. Variable atmospheric pressure within the build chamber might also offer additional benefits for a more controlled curing process.

<u>*Summary:*</u> DBR led to the design and development of five iterations of extruders and electronic control systems for testing an extrusion method that can be applied to the question of how AM technology can be applied to the automation of marine vessel manufacturing. A reference vessel was used to provide excerpts of typical parts that could be encountered in real-world applications of this manufacturing method. A toolpath generation procedure was developed that successfully demonstrates a procedure for creating toolpaths appropriate to this application. Several parts were printed as a proof-of-concept demonstration of both its effectiveness and its limitations. Finally, a CSFRPAM extruder was designed that can lead to additional manufacturing testing using the appropriate materials.

Benefits: The MBAM method described in these fabrication tests has many potential benefits over standard laminar printing. Parts can be thicker with tool paths tracing along multiple axes through the part. Toolpaths can orient fibers to theoretically counteract the forces that pass through the surface. Fabrication can be automated to reduce the exposure of workers to hazardous materials. While additional testing is necessary, this research offers an effective proof-of-concept demonstration that the MBAM method has a good potential for successful application to the project of applying AM technology to automate the production of marine vessels.

Limitations: The toolpath and manufacturing tests are preliminary and need to be refined with continued iterations. Parts were oriented to optimize successful printing – long overhanging surfaces may exhibit specific manufacturing challenges due to the weight of the uncured material including a lack of adhesion between layers, drooping, or deformation of the manifold surface. Larger parts have not been tested and may present additional unforeseen challenges. While thermoplastic provided a relatively easy material system for preliminary toolpath testing it is inadequate for material testing, FRP must be used in future to verify how the materials behave in the extrusion / pultrusion process. The issue of material consolidation has not been addressed by these tests.

SUMMARY

Description of the manufacturing process: A pair (or several pairs) of 6-axis robotic arms mounted on a modular gantry system with overlapping work envelopes allow precisely oriented and positioned delivery of extruded materials to all parts of a marine vessel hull surface. A linear track may coordinate the movements of the robotic arm(s) with movement of the emerging object on the build platen to extend the effective work envelope of these manipulators. At first, continuous fiber extruder/pultruders use glass or carbon fibers preimpregnated with a UV activated thermoset resin to trace standard laminar tool paths in order to create a thin-wall armature. More complex multi-bias tool paths will then be printed against the thin wall of the laminar printed hull tracing vertical, horizontal, and diagonal curving lines through the hull surface. A wiper or roller attachment may be deployed to aid in consolidation and remove voids. Support materials may be printed as required to help buttress the emerging hull form and/or a lofting approach may be used whereby only a short segment of the hull is printed using laminar tool paths before a series of overlapping MBAM tool paths are added. Coring materials may be added manually or printed with alternative tool paths to help reduce weight where necessary. Keel, floors, stringers, frames, beams, and bulkheads can be integrated manually or printed, as required. Continuous strands of reinforcement fibers will integrate them into the hull which can now be understood as a singular complex manifold surface with variable thickness and density and integrated structural elements with precisely oriented reinforcing fibers positioned to counteract anticipated loading conditions.

Qualitative Analysis of case studies and a review of the current state of technology have led to this proposal for a fabrication method that uses a modified FFF process with a continuous strand fiber reinforced thermoset resin extruder /pultruder. The system relies on one or more 6-axis robotic arms mounted in a modular gantry system to extend the reach and work envelope while maintaining optimal maneuverability of the extruder. Additional linear or rotational axes on the build platen could offer additional opportunities to enhance the maneuverability of the extruder relative to the printed part.

Design-Based Research demonstrated the effectiveness of a toolpath generation method using Rhinoceros, Grasshopper, and KukaPRC to convert manifold surfaces typical of marine vessels into MBAM toolpaths that can be effective for applying AM methods to the manufacturing of small marine vessels. A prototype extruder using thermoplastic (a different material but a similar-sized extrusion bead) has demonstrated a variety of effective toolpaths that could be used for producing yacht hulls and other marine parts or components. A design for a

Continuous Strand Fiber Reinforced thermoset Plastic pultruder (CSFRPAM) has established the next stage of research and development required for continuing the investigation.

This chapter has established the criteria for evaluating applications of AM technology to marine vessel manufacturing. The main considerations for analysis are the scalability of AM processes, the materials used for AM extrusion and their suitability for marine applications, and the kinematic systems used for deploying AM processes to marine vessel manufacturing. The outcome of this analysis informed the design of both a manufacturing method and a toolpath generation process. The most fruitful approach is an extrusion method called CSFRPAM a process that uses glass fiber twine pre-impregnated with a UV activated resin. With this extruder attached to one or more 6-axis manipulators on an overhead gantry system, it may be feasible to manufacture an entire hull and deck structure for small marine vessels with minimal reliance on moulds and hand layup processes. The next chapter will include a discussion of the benefits and limitations of the study including recommendations for continued research.

Discussion

5 DISCUSSION

SUMMARY OF THE STUDY

<u>Research Question:</u> How can Additive Manufacturing technology be applied to automate the production of marine vessels?

<u>Summary:</u> To address the research question, the project first introduced how AM could transform the marine manufacturing industry. A discussion of the role that naval architects and designers have historically played in exploring and developing new manufacturing methods provided justification for the research. A brief review of the history of marine vessel manufacturing described the typical materials and processes for building small marine vessels with a detailed discussion of moulded FRP materials and procedures used for this manufacturing method.

The problem statement addressed the shortcomings of moulded FRP construction directing the study toward several areas of consideration: the potential for greater dimensional fidelity with digitally fabricated assemblies, ease of customization and iterative improvement of serially produced vessels us AM, reduced cost through the elimination of moulds and handicraft labor, and improved worker safety through the reduction of exposure to hazardous substances. The purpose and significance of the project are related to these issues as the study aims to improve existing shortcomings of small marine vessel manufacturing through the application of automated AM processes.

The conceptual framework identified two primary challenges that must be addressed in the study: 1) Additive Manufacturing is a broad term that describes a variety of different ways to manufacture objects. As such, AM can be applied to marine manufacturing in a variety of different ways, in different phases of the manufacturing process, and to different extents. 2) Building boats is a complex process that presents specific problems that must be addressed in any automation solution. As such, various kinematic approaches must be investigated, evaluated, and analyzed.

A review of AM technologies and processes included discussions of hardware, materials, and the conceptual underpinnings and limitations of standard laminar 3D printing logic. The concept of MBAM was introduced as a potential solution to these limitations that could be applied to automate marine manufacturing. MBAM is a printing method that uses toolpaths moving along multiple axes through the surface of a complex topological manifold such as the hull of a marine vessel. A discussion of robotic systems introduced six distinct kinematic approaches with a focus on their relative suitability for MBAM marine manufacturing.

The primary challenges that were identified in the research are: 1) Selecting an appropriate AM process for this application; 2) Identifying a material system that is compatible with AM methods and marine manufacturing standards; 3) Developing a kinematic system that can achieve the desired MBAM results; 4) Developing a toolpath generation method that can support the unique requirements of this printing method; and 5) testing the process in a manufacturing research facility.

A series of case studies examined five methods of application of AM to small marine vessel manufacturing: componentry, mould-making, direct printing of hulls, printing of cores and components for cold-moulding, and automated fiber placement (AFP). This discussion laid out a series of options for extruders, material systems, and kinematic solutions that could be applied to the project of AM marine manufacturing. However, the investigation also revealed that supplementary applied research is clearly needed to fully realize a solution.

The methodological approach relied on Qualitative Analysis to evaluate the efficacy and viability of the case studies with discussions of the benefits and shortcomings of the various material and hardware configurations investigated. The combination of a review of the current state of the technology and the discussion of case studies informed the design of a manufacturing process for constructing small marine vessels including recommendations for an extruder, a material system, and a kinematic solution. This line of inquiry suggested that applied practical testing of this manufacturing method could bolster the study with proof-of-concept results.

The reference vessel *Secret,* designed by Francis Sweithguth, was selected as an appropriate case study for applied manufacturing testing, and several excerpts of the hull were identified that represent distinct manufacturing challenges for testing in a lab using AM processes. This required the iterative design and development of a prototype extruder. A Design-Based Research method was used to develop, refine, and test the manufacturing tools and processes including 3D modeling, toolpath generation, and robotic AM testing using the prototype extruder. While not ideal for marine manufacturing, thermoplastic was selected as a suitable material for toolpath testing.

Five extruders were built with off-the-shelf components and custom-designed parts using DBR to refine the printing tool and the method for printing complex MBAM toolpaths. The final extruder system used a 1 mm bead Massive Dimension thermoplastic pellet extruder with a purpose-built ad hoc control board for manually adjusting extrusion rate and temperature settings, and a custom-designed wrist attachment and pellet hopper. Meanwhile a software workflow was developed to generate robotic movement programs from a 3D model of the reference vessel using Rhino, Grasshopper, and KukaPRC. Several hull excerpts were printed to demonstrate the benefits and shortcomings of this AM manufacturing method.

CONCLUSIONS

The results of the study indicate that the optimal approach for marine vessel manufacturing is CSFRPAM, a continuous strand fiber reinforced thermoset plastic extrusion / pultrusion method (Harris et al, 2017; Arrabiyeh et al, 2021). In response to this conclusion, a tool was designed that can serve as a preliminary step in continuing the research on MBAM toolpaths using thermoset resin with continuous glass or carbon fiber roving. The MAMBO project by MOI Composites serves as a definitive proof-of-concept application of this material extrusion / pultrusion method with continuous strand FRP (Loibner, 2021), but applied research with MBAM toolpaths using this material system remains incomplete (Mason, 2019). Moreover, the issue of material consolidation remains unexplored.

While Automated Fiber Placement (AFP) appears promising for marine applications (Gardiner, 2018; Tekinalp, 2014), there are substantial issues with this manufacturing method that may hinder its application to the marine industry. 1) Exotic polymer high-temperature thermoplastics remain prohibitively expensive (Neser, 2017), 2) Consolidating the material to reduce voids and ensure material strength requires the use of a heated mandrel or mould (Kumar et al, 2020; Kaill et al, 2021), contradicting one of the primary considerations in the problem statement. 3) These materials have not been subject to a rigorous review process for their suitability for use in marine environments either in terms of long-term durability or toxicity for marine ecosystems (Dokos, 2013; Wan & Takahashi, 2014; Raji et al, 2019; Bel Haj Frej et al, 2021).

Analysis of kinematic systems that have been used for large-scale AM applications in marine vessel manufacturing point to a hybrid approach: using gantry-mounted robotic manipulators to position extrusion tools on highly maneuverable 6-axis robotic manipulators. This allows the AM fabrication of larger objects such as a hull with more sophisticated toolpaths than have thus far been demonstrated in any practical applications to marine vessel manufacturing (Post et al, 2018; Dini et al, 2015). This method harnesses the capacity for building large objects demonstrated by Big Area Additive Manufacturing (BAAM) research projects at the Oakridge National Laboratory which have use both gantry systems and revolute robotic manipulators to build moulds for marine vessels (Post et al, 2019). The integration of external axes was also suggested to expand the reach and work envelop of the robotic manipulators.

Both MAMBO and the Livrea 6.50 project support the conclusion that 6-axis robotic arms are a suitable kinematic solution in terms of maneuverability and positioning of a tool (Mason 2021; Nasso et al., 2018), but Thermwood's LSAM method and the University of Maine's 3Dirigo project point to the scale and expandability of gantry systems for large manufacturing projects (Thermwood, 2017; UMaine News, 2018). While practical testing of this specific configuration was not tested in this research project, toolpaths were developed that can easily be expanded with additional axes. Moreover, practical testing for similar scale applications is widespread (Association for Advancing Automation, 2010).

The research revealed an area of robotic AM toolpath generation that remains underdeveloped. Toolpath generation for AM currently relies on laminar slicers that are not optimized for the loading conditions and technical requirements of more complex non-planar, multi-bias, 3-dimensional assemblies such as marine vessel hulls (Gardner et al, 2018; Zhao et al, 2018; Mitropoulou et al, 2020). The research used the 3D modeling tool Rhinoceros with Grasshopper and KukaPRC plugins to transform excerpts of surface topology from the reference vessel into a series of oriented points and movement instructions that can be incrementally fed to a robotic manipulator using a Pointloader system. This allows the relatively inadequate computing resources and memory, typical for robotic controllers, to process long-string toolpaths incrementally, rather than becoming overloaded with more data than they can handle.

Movement programs from Grasshopper and KukaPRC were used to produce three excerpts from the reference vessel representing distinct AM challenges for manufacturing marine vessels with a prototype thermoplastic extruder system. While additional applied research will be required to develop an effective CSFRPAM extruder and to refine methods for efficiently generating complex 3-dimensional MBAM toolpaths, the research proposed a method of manufacturing small marine vessels that was ultimately effective for producing representative excerpts from a reference vessel.

INTERPRETATION

The results of this research study point to a method for manufacturing small marine vessels (typically produced with a moulded FRP) using robotic AM with a modified FFF extrusion process. Limited toolpath generation and 3D printed excerpts from a reference vessel suggest that it may be possible to print complete marine vessel hulls using this process thereby eliminating the need for moulds. These conclusions are limited in several distinct ways that will be discussed below using the following categories: 1) Materials, 2) Consolidation, 3) Surface Qualities, 4) Structural Integration, 5) Kinematics, and 6) Toolpath Generation.

Extruded Glass Fiber Reinforced Plastics: The ideal material for 3d printing marine vessels requires the following characteristics: impervious to ultraviolet light and water or ability to easily bond to UV and water-resistant coatings; relatively light weight by volume so as to not significantly increase displacement; retain dimensional stability at a broad range of temperatures; exhibit stiffness, shear strength, and puncture resistance; and ideally lend itself to low waste and end of use recycling. At the same time, this material should be low cost and easy to work with to meet the profit margins typical for smaller marine vessels. In the near term, GFRP thermoset is the best candidate material to satisfy these criteria (Harris et al, 2017).

Assuming that continuous fiber reinforced composites present the optimal material solution for deploying additive manufacturing to small marine vessel manufacturing, the technology will need to be scaled up to accommodate the relatively large size of yacht hulls. Currently, there are no examples of commercially available large-scale composite additive manufacturing tools that can make an entire full-size hull as one piece using a continuous strand AM process (CSFRPAM) (Godec et al, 2022). While MOI Composites has conducted an interesting demonstration project with MAMBO, printed using a robotic arm and continuous glass fiber strands impregnated with thermoset resin, the project was produced as 50 smaller parts that were later joined together in a cold-moulding process (Mason, 2021). The toolpaths used for this project were built from simple planar slices demonstrating that the hull parts were non-structural core shapes with minimal inherent structural properties. Structural integrity of both the surface manifold and the vessel as a whole was provided almost entirely by FRP hand lay-up on both sides of the printed core shapes (Andreae, 2021).

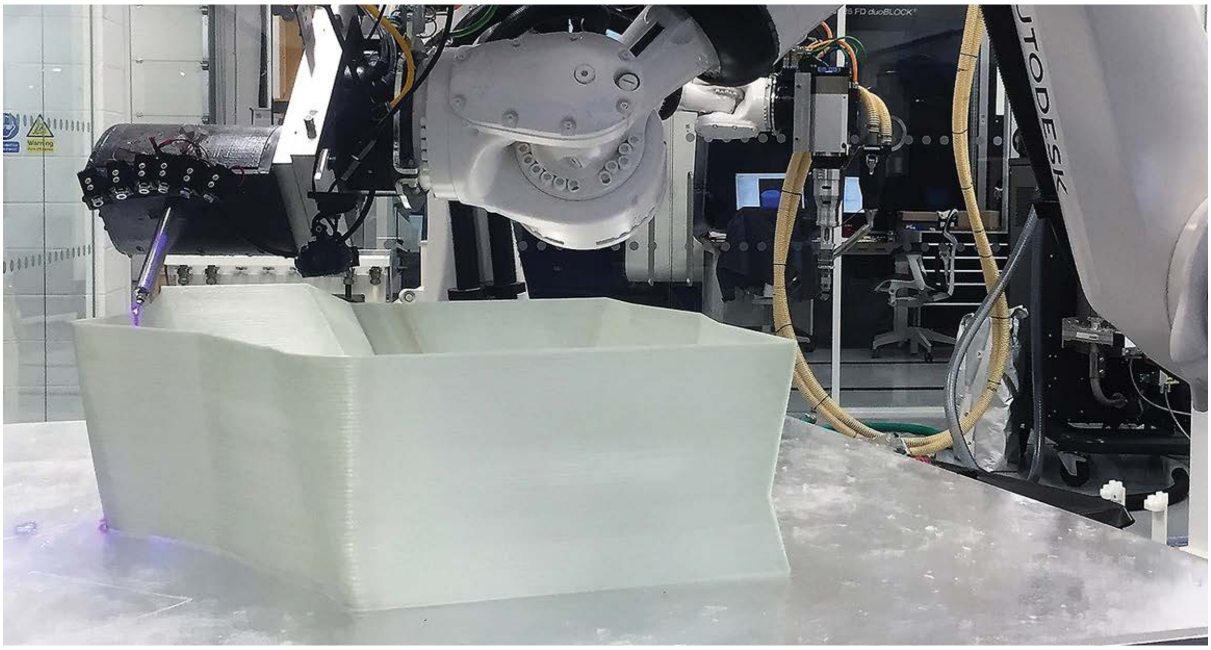


Image courtesy of Gabriele Natale showing the fabrication of a portion of the Mambo project (Andreae, 2021).

Vessels printed without the need for cold moulding will require MBAM toolpaths and larger kinematic systems for their production. It is likely that large scale additive manufacturing tools that can print continuous strand composite materials will become commercially available within the next decade (Mason, 2019).

Image courtesy of University of Stuttgart showing long-span structural integrity using MBAM (University of Stuttgart, 2021).

Meanwhile, a series of pavilions built as proof-of-concept computer assisted manufacturing projects at the University of Stuttgart Institute of Building Structures and Structural Design demonstrate that large-scale objects can be constructed with robotic arms weaving continuous strand fiber reinforced composite structures that span modest distances without appreciable deflection (University of Stuttgart, 2021).

Material Consolidation: In modern FRP manufacturing of marine vessels using the VARTM process, vacuum-bags allow a precise regulation of the ratio of resin to glass fiber (Rigas et al, 2001; Dae et al, 2003). In the hand layup process, a worker manually regulates this ratio using a roller and a wiping tool (Marsh, 2003; Scott, 1996).

Image courtesy of Gabriele Natale showing the rough poorly consolidated example of extruded FRP (Gardiner, 2018).

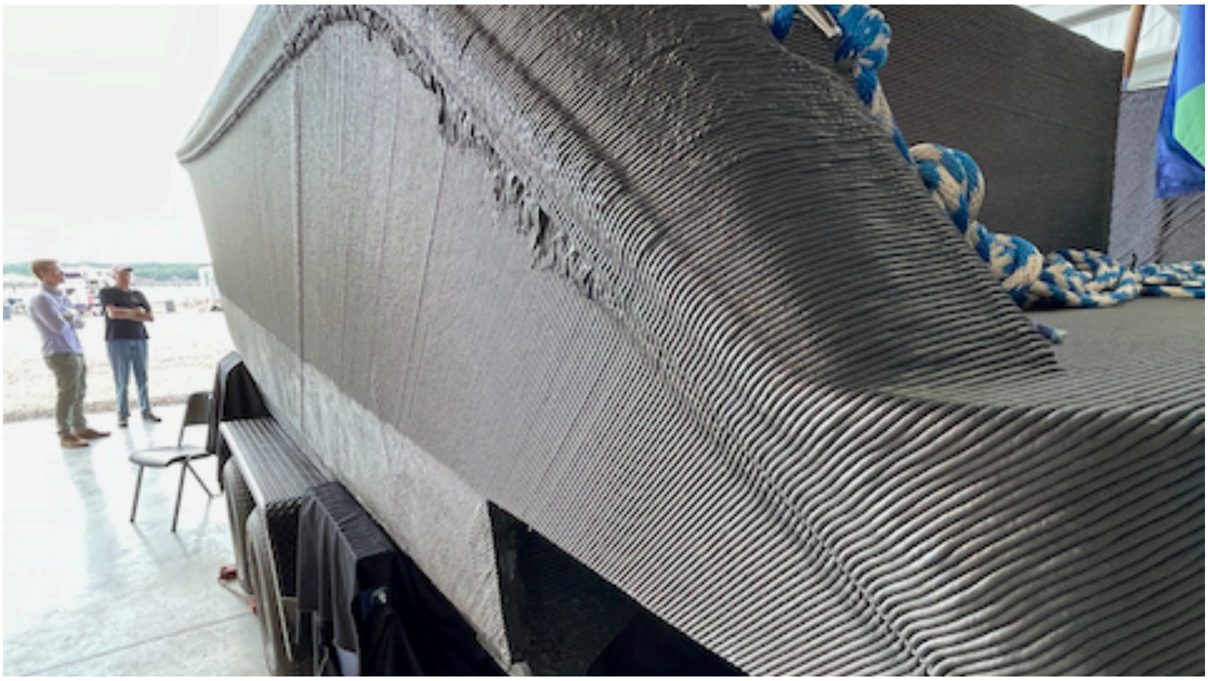
Thermoset FRP parts built using a continuous strand extrusion / pultrusion process tend to exhibit a rough stepped appearance with conspicuous voids and irregularities indicating a high plastic/void to fiber reinforcement ratio. A process for regulating this ratio is necessary. It remains unclear how well the ratio of resin to reinforcing fibers can be controlled using CSFRPAM with thermosetting plastics. The lack of control over material consolidation is not a minor or insubstantial issue, but rather a serious shortcoming that can have serious impacts on the structural integrity of parts made using FRP (Scott, 1996; Lundström et al, 2010; Dodiuk, 2021). The AFP manufacturing process featuring in situ consolidation described in Case Study 5 solves the consolidation problem using a mandrel and roller, essentially combining the material winding process with an integral compression assisted annealing process (Gardiner, 2018). In order for CSFRPAM to achieve similar consolidation, a wiper or roller may be required to be integrated into the design of the extruding tool. Additional research in tool design and fabrication testing will be required to find solutions to this challenging problem.

<u>*Surface treatments:*</u> For smaller marine vessels traditional FRP moulding allows the production of durable, lightweight, and highly polished finished hull surfaces integral to the manufacturing process (Scott, 1996). On the other hand, the finished surface of 3d printed objects is often quite rough, suggesting that additional surfacing applications or polishing procedures may be required to achieve surface qualities required for boat hulls (Loibner, 2021).

Image courtesy of Livrea Yachts showing a section of their cold moulded hull using an open AM core.

The problem of surface roughness was addressed in several of the case studies using a cold-moulding process. Livrea Yachts used a bidirectional carbon fiber skin over their assembled hull core elements in the production of the Transat 6.50 (Jamie, 2017; Moruzzi, 2017). While this skin can be understood as both a structurally reinforced manifold surface as well as a surface treatment it is clear that AM will need to address the issue of surfacing (Alsharhan et al, 2017).

The University of Maine 3Dirigo project, printed as a series of laminar toolpaths oriented to a single plane with wood fiber reinforced composite extruded in a wide 3mm bead (UMaine News, 2019) features an exceptionally rough surface. While some effort has been made to improve surface smoothness below the waterline, it is clear why the vessel has not been tested in open waters. In the near term, it is likely that cold moulding may be the optimal method to ensure surface smoothness of marine vessels produced using AM methods. Increased stiffness and watertightness serve as ancillary benefits of cold moulding (Hastak, 2004; Scott, 1996).



University of Maine 3Dirigo features a rough stepped surface typical of wide-bead laminar FFF printing process.

<u>*Structural integration and support for the hull during manufacturing process:*</u> As previously discussed, yacht hulls are not purely composite FRP, often relying on wood, foam, or metal structural components that may be encased, chemically bonded, or mechanically affixed to the interior portions of the hull (Steward, 2011; Garden, 1999, Scott, 1996). In FRP construction structure is typically integrated using a tabbing process whereby structural elements are cut to fit and affixed to the hull using multiple applications of hand layup glass fiber roving (Junhou & Shenoi, 1996). If these elements are themselves non-structural (such as foam or other lightweight materials), or if they are intended to remain submerged in water, the hand layup wrapping these elements provides dimensional stiffening as well as waterproofing (Dodkins, 1995). Integrating structural elements in the AM process may present serious challenges for automating marine vessel manufacturing.

In order to join separate parts and incorporate structural elements into the hull of the MAMBO project MOI Composites had craftsmen manually add a series of foam elements tabbed into the aggregated hull components (Andreae, 2021). Using hand layup methods, the hull was integrated with a structural system using a tedious handicraft process. Simultaneous cold moulding of aggregated components on both the inside and outside of the emerging hull provided additional stiffness (Mason, 2021). It is hoped that the integration of structural elements in AM marine vessel manufacturing projects might be at least partially automated in the future. One can imagine a hybrid process whereby a large-scale 3d printer builds integrated pockets, channels, or brackets into the hull. Printing might pause while rigid elements or grid-structures are added, after which printing could resume directly atop these elements to tab them into the hull. This might require a low profile or slender extrusion head mounted on an articulated robotic arm with enhanced maneuverability to reach into tight spaces.

A hull section of MOI Composites Mambo project shows the integration of structural reinforcements. (Mason, 2021)

An additional consideration for 3D printing large objects is the potential need for either permanent or sacrificial support structures to buttress the emerging hull. These may be either compression structures under overhanging surfaces to keep them from sagging (3Dirigo), tensile structures to keep surfaces from separating from one another (Livrea Transat 6.50), and shear structures to provide stiffness and maintain the shape of the manifold surface as it emerges MAMBO). Research in desktop 3D printing can serve as an excellent resource for addressing this particular issue (Kantaros & Piromalis, 2021; Godec et al, 2022; Duty et al, 2019; Fernandez-Vicente et al, 2016).

<u>Kinematics:</u> The issue of kinematics for robotic marine manufacturing is largely solved, awaiting only an application that accommodates large-scale AM. Over the past several decades marine vessel manufacturers have increasingly adopted robotic manufacturing techniques that have become commonplace. For example, the Sea Ray manufacturing facility in Palm Coast, FL uses robotic manipulators attached to a linear track for precise router cutting operations that were previously performed using electric hand tools. Meanwhile, at the Grand Banks Manufacturing Facility in Malaysia a pair of 8-axis robotic mills create plug moulds and other 3-dimensional forms. At various steps in the manufacturing process these two marine vessel manufacturers have introduced robotic tools that can perform tasks far faster and with greater accuracy than manual labor without exposing workers to potential hazards (Vatalaro, 2016; Lind, 2018).


Multi-axis manipulators on separately controlled linear axes perform precision manufacturing tasks at the Sea Ray manufacturing facility (Vatalaro, 2016).

In these robotic applications at Sea Ray and Grand Banks, it is easy to see how AM could be deployed with minimal modification to existing kinematic systems.

A pair of 8-Axis robotic mills at the Grand Banks manufacturing facility in Malaysia. (Lind, 2018)

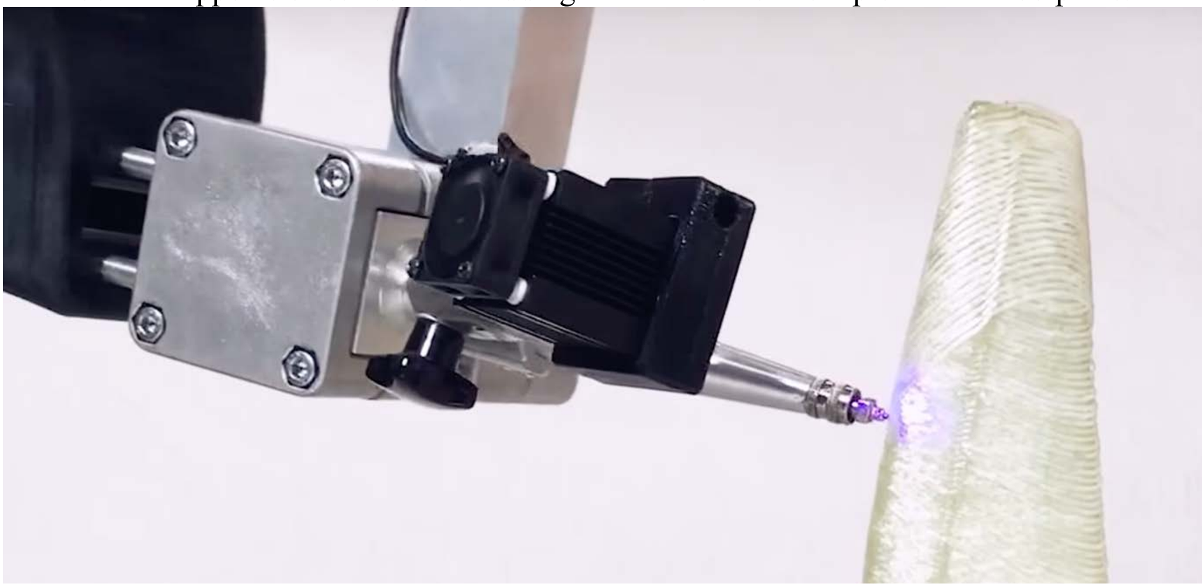
Toolpath Generation: MBAM toolpaths for large-scale marine manufacturing are complex and difficult to produce. The process remains tedious and inefficient because slicers are not optimized for multiple bias printing (Šljivic et al, 2019) and boat hulls are very large, requiring long string movement commands. At the same time, robots are not optimized for extremely long-string movement commands so complex toolpaths must be incrementally managed in a dynamic process.

This research relied on Rhino and the visual programming plugins Grasshopper and KukaPRC. While this method for defining toolpaths, is relatively straightforward for programming and simulating robotic movement paths, the method is optimized for simple geometric forms. Calibration of multiple parameters including motion speed, offset distance between extrusion layers, and orientation of the tool to the work surface is uncomplicated. However, as the number of points increases the visual scripting software becomes increasingly unstable. The interface also becomes increasingly complex to navigate as the graphic user interface is not well-optimized for large numbers of points and long-string movement commands that are typical for manufacturing a marine vessel using AM. Ultimately, software will need to be developed for setting up toolpaths that can be derived from Finite Element Analysis (FEA) of marine vessels. This is a project that is currently under development at the University of Maine to expand their AM marine vessel manufacturing capabilities.

RECOMMENDATIONS

Continued research will be required to address the myriad challenges of Robotic Additive Manufacturing for automating the production of marine vessels. The areas requiring continued research include 1) Hardware development for CSFRPAM printing, 2) Software development for MBAM toolpath generation, and 3) Assembly testing for various marine applications.

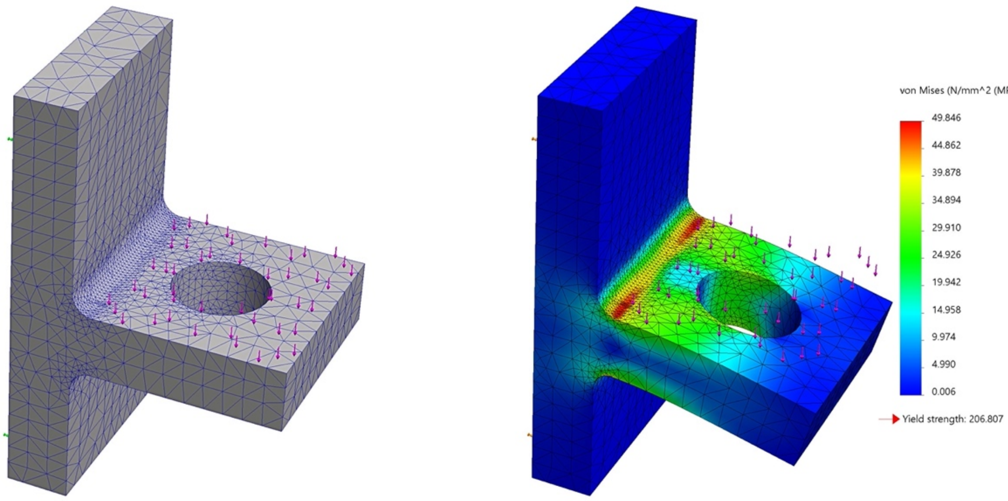
Extruder Design: With assistance from Autodesk, MOI Composites has already developed a FRP tool that appears effective for extruding FRP materials in simple laminar toolpaths.



Continuous Strand FRP Extruder used by MOI Composites (Gardiner, 2018)

However, the issues of material consolidation and surface quality remain challenges that have yet to be solved. Integral processes including an attached wiper or roller should be tested. Moreover, the extruding tool has not yet been extensively tested using MBAM toolpaths which could dramatically increase the strength of complex topological assemblies common in marine vessels which rely on multiaxial stiffening provided by reinforcing fibers oriented in multiple axes. It is unclear how the extruder will behave when following more complex movement patterns and changeable orientations relative to deposited materials. Examination of the AFP with ISC process may prove valuable for developing new extruder and extrusion process designs for FRP materials.

<u>*Software Development:*</u> Software does not yet exist which can easily generate toolpaths optimized for complex surfaces typically found in marine vessels. Ideally software could reduce the volume of decision-making much like CAM and Slicer software automate toolpath generation by reducing the number of choices a programmer need make in regard to the movement of a tool. Until MBAM slicers are available, research and development of multi-bias printing will remain limited in scope. Once MBAM toolpath generation becomes more automated it will be easier to perform manufacturing tests with larger and more complex parts such as marine vessels. Integral FEA analysis with toolpaths generated in response to loading conditions will greatly improve the effectiveness of MBAM slicers. FEA responsive AM toolpath solutions will be invaluable for manufacturing research.



An example of von Mises stress analysis of a simple bracket. (Image courtesy of ASME).

<u>*Assembly Testing:*</u> Very few boats have been built using AM technology. Specific areas of manufacturing research include improving the surface quality of extruded FRP, testing the limits of unsupported overhanging surfaces in the manufacturing process, the use of support materials to assist in large-scale AM, alternative approaches to MBAM such as lofting whereby short multi-layered sections of hull are printed in sequence, and integrating typical marine vessel structures in an automated tabbing process.

<u>*Conclusion:*</u> Additive Manufacturing is a broad term that describes a variety of different ways to manufacture objects. As such, AM can be applied to marine manufacturing in a variety of different ways, in different phases of the manufacturing process, and to different extents. Building boats is a complex process that presents specific and unique problems that must be addressed in any automation solution.

Attempting to build a boat by coaxing a robot to draw individual strands of 1 mm string coated in sticky resin tracing unique 3-dimensional toolpaths through a complex manifold surface is a challenging undertaking. The most valuable tool for manufacturing research in marine vessel AM is published work on boat building projects including projects that fail. As non-scientists, boat builders and researchers in manufacturing and fabrication may undervalue the significance of negative results: there is vanishingly little in the way of published results that are other than successful demonstrations of experimental manufacturing approaches. More published information on failed projects as well as successful ones will be of tremendous value moving forward.

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