A PARAMETRIC MODEL OF THE PORTUGUESE *NAU*

A Thesis

by

CHARLES JUSTUS COOK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Visualization

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Approved by:

Chair of Committee,	Frederic Parke
Committee Members,	Luis Filipe Viera de Castro
	Carol LaFayette
Head of Department,	Tim McLaughlin

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ABSTRACT

A Parametric Model of the Portuguese *Nau*. (December 2011)

Charles Justus Cook, B.E.D., Texas A&M University

Chair of Advisory Committee: Dr. Frederic Parke

This interdisciplinary research project combines the fields of nautical archaeology and computer visualization in order to create an interactive virtual reconstruction of a Portuguese *nau*. Information about the shipbuilding process is gathered from 16th and 17th century treaties by Fernando Oliveira and João Batista Lavanha, as well as from Dr. Filipe Castro (Texas A&M Department of Anthropology). Eight registered tonnage formulas from the 15th to 17th century are used to estimate the cargo capacity of the *nau*. Using this information, I develop an algorithm that creates a parametric computer model of a *nau* hull and calculates its registered tonnage. This parametric model allows the user to choose between the Oliveira and Lavanha hull shapes, adjust parameters to fine tune the hull shape further, and save the information about the hull shape for future editing. The eight registered tonnage estimates are compared to the volume of the parametric hull model below a generic waterline.

The process I use to adapt the information provided by the two shipbuilding treatises into an algorithm determines the hull shape of a *nau*. This allows for projects in the

future to introduce other shipbuilding approaches and information as it becomes available to this parametric model.

ACKNOWLEDGEMENTS

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I would also like to thank my friends and colleagues, as well as the faculty and staff in the Visualization Department at Texas A&M University for making my undergraduate and graduate experiences memorable ones. I would like to acknowledge Carla Rahn-Phillips for providing critical data relating to this project.

Further, I would like to thank André Thomas for recognizing the joint interests of A&M's Visualization Department and Nautical Archaeology Program through this research and the awarding of the Thomas Family Scholarship.

And finally I would like to thank my family. They were supportive throughout my college career, and I couldn't have done it without them.

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CHAPTER I

INTRODUCTION

There are two goals for this project. One is to create a parametric model of certain aspects of a 16^{th} century *nau* by utilizing information from two shipbuilding treatises, and Dr. Felipe Castro's knowledge of the *nau* to obtain a better understanding of *naus* and how they were constructed. The second goal is to compare the actual volume of the parametric model to the volumes that were calculated for a *nau* by shipwrights in the 16^{th} century.

Computer Aided Modeling in Archaeology

Prior to the use of computers, the archeological reconstruction of a given object was created by hand to produce a physical representation. While these representations could be completely accurate, problems could occur during their reconstruction. If mistakes were made during reconstruction, the process might have to start over. Large scale objects such as cities had to be scaled down to a manageable size. However, with the introduction of the computer these objects could be modeled virtually. Utilizing computer models, the dimensions of the object no longer constrained the reconstruction. Also, virtual object models can easily be changed and iterated until satisfactory results are obtained.

This thesis follows the style of *IEEE Computer Graphics and Applications.*

Since the 1980s, the use of computer aided modeling has expanded in the field of archaeology. This is largely due to the fact that computer processing power has increased rapidly, and computer aided modeling programs have become easier to use and more widely accessible [1].

Computers have become a tool widely used by archaeologists today. They have been used to recreate and preserve artifacts of all kinds. Objects ranging from vases to bodies of ancient mummies, to whole cities have been reconstructed with the aid of computers and powerful software.

Some objects can be laser scanned to record actual surface details. Others, such as the remains of an ancient trade vessel underwater, can be measured with various tools and the information gathered entered into a data base for later use. Data gathered by a variety of means could then be interpreted and used to generate a three dimensional (3-D) model or virtual representation of the object.

Parameterized Modeling

An advantage of using computer modeling is the ability to create parameterized models. A parameterized model uses a set of parameters to determine the shape of a 3-D model. The parameters used generally correspond to major features of the object the model represents, such as the width of the human nose. One of the first parameterized models was developed by Parke in 1974 [2]. His model used parameters to create and animate virtual human faces. A set of parameters were specified for the face's structure and expression, and when these parameters were changed the face's shape also changed.

In 2007, Kasap and Magnenat-Thalmann created a parameterized model of the human body for use with real time animation such as video game characters. They divided a template model of a human into many sections. Details of these sections could be changed to create variations of the template quickly and efficiently [3].

Parametric models offer many advantages over conventional 3-D models. In general, 3-D models represent only one specific example; however, a parametric model can be used to explore variations of a given model. By utilizing a parametric model in this project, multiple hull shapes were created and their cargo capacities calculated. By carefully choosing parameters for the model of the *nau,* my interactive parametric model approximates the shape and volume of these vessels, just as the Kasap, Magnenat-Thalmann, and Parke parametric models represent different human bodies and faces. By comparing the parameters changed in each hull variation, we can begin to better understand the relationship between parameters and hull shape and capacity.

CHAPTER II

BACKGROUND

Virtual Archaeology

Virtual reconstructions of ships have been produced in the past. In 1994, Saul developed the reconstruction of a 17th century Dutch ferry. She then created an animated fly-through sequence of the ferry [4]. Haslett analyzed ship building treatises and virtually reconstructed a *nau* piece by piece from a list of timbers dated to around 1590 [5]. In 2008, Wells created a virtual reconstruction of a *nau* from the 1600s. She made a low-polygon model that could be interacted with in real-time. One purpose of her reconstruction was to see how cargo may have fit within the hull of the vessel.

Evolution of Hull Shapes

Nowacki discussed four stages in the evolution of hull shapes. The first stage was used by Portuguese shipwrights to build *naus*. The shipwrights of this stage used an approach known as the Mediterranean method. During this time in history shipwrights constructed ships with “a single master mold …, a planar template made of wood, which defined the frame shapes of the whole skeleton throughout the ship length” [6, p.31]. Castro has conducted research into the algorithms, or formulas, and proportions that shipwrights referred to when constructing the hulls of Portuguese *naus*. He found different ways that the shipwrights may have made the guides or templates used in the construction process [7].

The Portuguese *Nau*

In the 16th century, the *nau* was the primary ship used on the India Route. The Portuguese word *nau* simply means *vessel*. The India Route departed from Lisbon, journeyed south and west until reaching the coast of Brazil, then around the Cape of Good Hope, and across the Indian Ocean to the Indian peninsula. This voyage was known as the *Carreira da India* to the Portuguese people and was a yearly occurrence. "Sixteen to eighteen months later, the ships returned laden with spices, fine textiles, precious gems, exotic animals, and other trade goods " [8, p.22]. The English often referred to the *nau* as a *carrack,* from the Italian designation of large merchant ships*,* or more commonly *Indiaman* because of the route it sailed.

The *nau* was a large vessel, capable of carrying crew, passengers numbering in the hundreds, and several hundred tons of cargo. Designed for long periods at sea required for the journey, the *nau* had three or four masts and the same number of decks. After the 16th century, the Portuguese hold on Asian trade was challenged by Dutch merchants and began to weaken. [8].

Shipbuilding Terminology

To better understand this project, some terms need to be defined. The keel is the backbone of the ship upon which all other hull frames or timbers are mounted [9]. The term *frame* refers to the ribs which support the hull and are perpendicular to the keel. The master frame, also known as the midship, is the widest frame of the ship and divides the fore and aft of the ship [9]. The beam is the widest part of the vessel at the master frame. A *flat* is the horizontal or quasi horizontal portion of a ship's bottom. Traditionally, ship's sections were looked upon as having a bottom (flat), sides (with near vertical tangents to their curves), and a transitional zone in between called *the turn of the bilge* [10]. As the frames get closer to the bow and stern of the vessel, the turn of the bilge rises above the keel and gets closer to the keel horizontally. This is commonly referred to as the *rising* and *narrowing* of the bottom of the vessel.

Timbers that make up the rear or stern of the vessel also need to be explained. The *sternpos*t is the timber attached to the aft or rear end of the keel. The *transom* and *fashion* pieces are attached to the sternpost at the rear of the ship. The transom is the timber placed atop the sternpost while the fashion pieces form the sides of the stern [10].

The front of the ship, or bow, also has a few term to define. The *stempost* is the timber scarfed or attached with "an overlapping joint used to connect two timbers" to the keel at the bow of the ship [9]. The sides of the bow are attached to the stempost. *Tailframes* is a somewhat confusing term. They are not the frames of the tail or stern area of the ship. The tailframes are the foremost and aftermost full frames. The frames in front of the master frame are called the fore tailframes, while those in the rear are the aft tailframes. The frames beyond these tailframes are either part of the bow or stern frames. The weather deck is the top deck of the vessel exposed to the elements. All other decks are beneath the weather deck. Figure 1 is a graphical representation of the shipbuilding terms mentioned above.

The *block coefficient* denoted as *Cb* of a vessel gives us an indication of hull's aerodynamic qualities. This is calculated with the following formula:

$$Cb = \frac{HV_w}{T_w * L_w * B_w} \qquad (1)$$

In the formula above HV_w is the hull's volume under the waterline; T_w or draft refers to the distance from the waterline to the bottom of the hull; L_w is the length of the vessel at the draft; B_w or beam at the draft. Large cargo vessels, like modern oil tankers, have a high block coefficient, while faster vessels, like sailboats, have a low block coefficient.

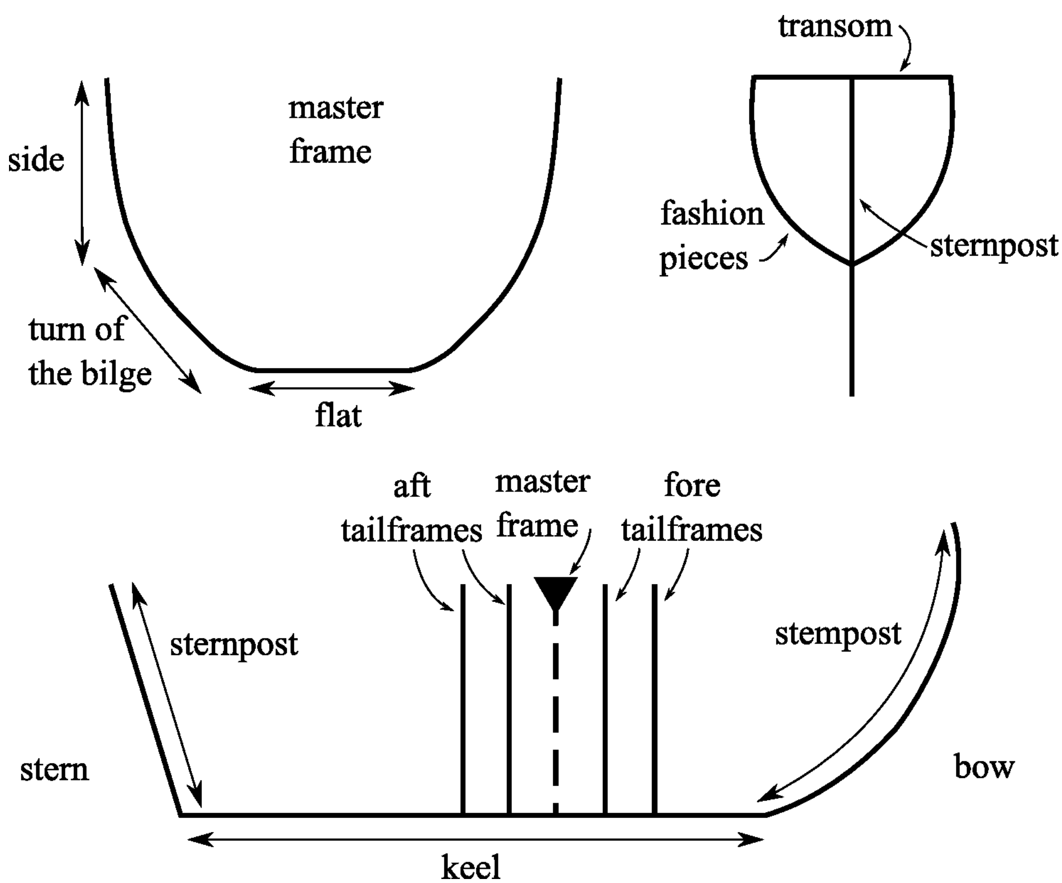

Figure 1. Terminology for components of a *Nau* vessel. Image showing parts of the *nau* that are referred to in this text.

Shipbuilding Treatises

Several shipbuilding treatises related to the *nau* have been discovered. The earliest of these was written in the 16th century, and most recent in the early 19th century. These treatises originated in various regions of Europe and were the shipbuilding manuals used by shipwrights of the times. Two of these treatises have been study extensively by Castro.

Fernando Oliveira, “a Portuguese clergyman, [and] military theorist,” wrote the first shipbuilding treatise discussed [11, p. 172]. It is commonly accepted that Oliveira wrote his *Liuro da Fabrica das Naus* in 1580 [12]. His manuscript defined a number of basic dimensions the proposed standard India Route *nau* based on proportions relative to the ship’s keel length. The second treatise discussed, *Livro Primeiro de Arquitectura Naval,* was written around the beginning of the 17th century by João Batista Lavanha.

Lavanha was a well-educated man, prominent mathematician, and talented draftsman [13]. This manuscript was an opportunity for Lavanha to describe a more scientific approach to ship building. Until this time, most ships were built with knowledge passed down from shipwright to shipwright [14]. Lavanha’s text began with his general thoughts on architecture of the time, chiefly naval architecture. Lavanha also provided details regarding the type of wood that should be used. This manuscript is unfinished. However, it provided enough information to fully reconstruct a 17th century carrack to the first deck and to approximate the shape of the hull [14].

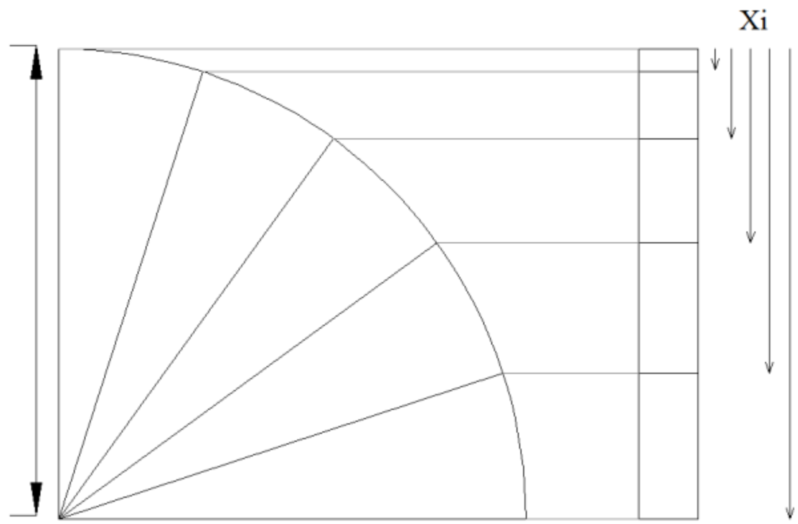

Figure 2. Example of a *graminho.*

Lavanha's approach is the more complex of the two. He describes many of the shapes of the *nau* with compound arcs, while Oliveira's shapes were only composed of one arc and possibly a straight line segment. Similarities exist in their approaches; both utilize a *graminho* to find the rising and narrowing for the fore and aft tailframes (see Figure 2). The tailframes are the foremost and aft full frames [10]. The further the frame is from the tail frame the higher it is vertically and closer to the keel horizontally. A *graminho* was a "gauge with… incremental values" usually drawn in the shape of a half or quarter circle [7, p.149].

Ship Tonnage

Information about the sizes of ships from before the 16th century is hard to come by. Often the records that have been recovered provide units of measure that are no longer used. To better understand the accuracy of these records, it is necessary to investigate the means by which a ship's cargo capacity has been measured over the course of history.

Various formulas, based on vessel measurements, were used to calculate the registered tonnage. Early registered tonnage calculations referred to the weight of the cargo; however over time, the meaning of this measurement has changed to refer to volume. But, acquiring these measurements themselves was often a flawed process. The precision of the tools used by the shipwrights when constructing a vessel had a major influence on the accuracy of the records kept for the vessels. Though there was a standard unit length on record, the shipwrights often used crude gauges for measurements. Units of measure changed over time and varied in different geographic locations. Whether vessels were measured from the inside or outside on the planking of the hull is another issue that must be considered when gathering the measurements needed for the formulas.

The tonnage formulas require measurements of the vessel. These measurements include the *eslora*, *manga*, *puntal*, and the *plan* (see Figure 3). The *puntal* or draft is distance from the waterline or specific deck to the bottom of the hull. The *eslora* is the overall length of the ship at the *puntal*. The maximum beam at the *puntal*, or width of the ship, is referred to as the *manga*. A few of the formulas also require the plan or flat or the length of the keel. All of these measurements are taken at the first, second, and third decks, as well as, the waterline.

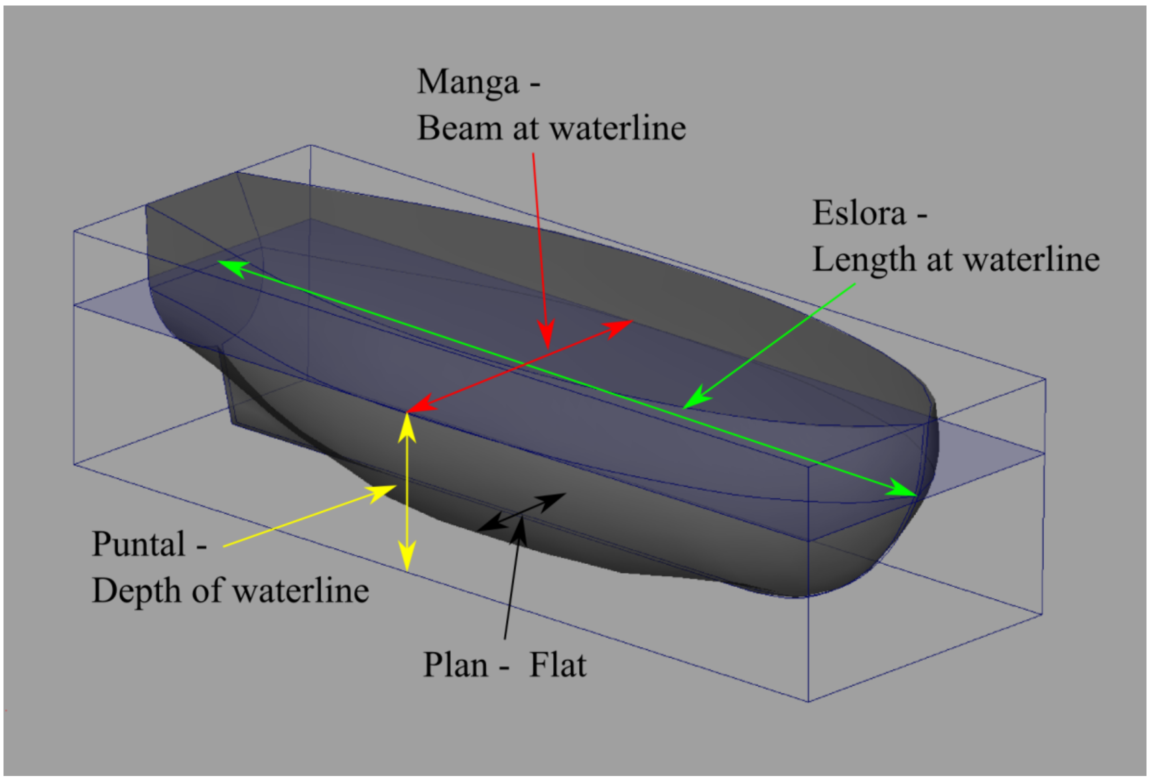

Figure 3. Measurements needed to calculate registered tonnage.

The first three formulas were discovered by historian José Luis Casado Soto and required measurements in *codos de ribera* units, each equal to 57.5 cm. The resulting tonnage from these calculations was in *toneles machos*, each equal to 1.521 m^3. Each formula uses common ship measurements. In the following formulas, L = Length overall; B = Beam; K = Keel length; H = Draft height; and F = Flat.

Below is the first formula discovered by Casado Soto [10], [15]:

$$\text{Tonnage} = \frac{19}{20} \text{ x L} \left[\frac{\frac{B}{2} + H}{2} \right] \frac{2}{8} = \frac{19}{640} \text{ x L} \left(\frac{B}{2} + H \right) 2 \qquad (2)$$

The second formula dates to circa 1560 and was in use in Seville and Cadiz, requiring values in *codos castellanos* units (55.7 cm) and yielding values in *toneladas de carga* (1.382 m^3) [10], [15]:

$$\text{Tonnage} = \frac{2}{3} \text{ x K x B x } \frac{H}{8} = \frac{1}{12} \text{ x K x B x H} \qquad (3)$$

The third formula was also used in Seville and Cadiz, between 1570 and 1590, and also used *codos castellanos* and *toneladas de carga* [10]:

$$\text{Tonnage} = \text{L} \left[\frac{\frac{B}{2} + H}{2} \right] \frac{2}{8} = \frac{1}{32} \text{ x L} \left(\frac{B}{2} + H \right) 2 \qquad (4)$$

The Spanish Navy underwent a major reorganization in the 17^{th} century. A number of regulations were issued in the *Ordenanzas para la fábrica de navíos de guerra y merchantes* in 1607, and revised in 1613 and 1618. The *Ordenanzas* did not introduce new formulas, but tried to standardize how and where measurements were taken. It set some standard measurements for varies ship parts, and specified thirteen classes of vessels of varying tonnages. One new measurement was for the *eslora* and *manga.* These measurements were taken from inside the planking, but measured at the weather deck. The maximum beam should be taken at that deck and not above. The *puntal* was a measurement taken from the ceiling of the lowest deck to the upper surface of the weather deck [10].

In 1611 Tomé Cano, a well-connected and respected Spanish shipper, published a treatise titled *Arte para fabricar, aparejar naos de guerra y merchante*. The treatise proposed some changes to both merchant and warships and also contained a formula for tonnage [10], [16]:

$$\text{Tonnage} = 0.95 \text{ x } \frac{B}{2} \text{ x H x } \frac{L}{8} = 0.95 \text{ x B x H x } \frac{L}{16} \qquad (5)$$

Three months later an addendum titled *Regla del arqueo* acknowledged the complaints of many shippers, Spanish and foreigners, pertaining to the ways of calculating tonnage. The addendum called for major changes, abolishing all older formulas and introduced three new ones. These new formulas incorporated the flat of the master frame in the tonnage calculation, but only half the depth of the hold.

$$\text{If F} = \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[B \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8}$$

$$\text{If F} > \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[\left(B \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right) + \frac{F - \frac{B}{2}}{2} \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8}$$

$$\text{If F} < \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[\left(B \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right) - \frac{\frac{B}{2} - F}{2} \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8} \qquad (6)$$

Another formula provided in the *Regla del arqueo* was similar to the first, but gave a new measurement for the maximum beam depending on its width [10]:

$$\text{If F} > \frac{B}{2} \rightarrow \text{B1} = B + \frac{\frac{B}{2} - F}{2}$$
$$\text{If F} < \frac{B}{2} \rightarrow \text{B2} = B - \frac{F - \frac{B}{2}}{2}$$

$$\text{If F} = \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[B \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8}$$

$$\text{If F} > \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[B1 \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8}$$

$$\text{If F} < \frac{B}{2} \rightarrow \text{Tonnage} = \frac{\left[B2 \text{ x } \frac{H}{2} \text{ x } \frac{L+K}{2}\right]}{8} \tag{7}$$

The final formula introduced in the *Regla del arqueo* did not compare the width of the flat and the beam [10]:

$$\text{Tonnage} = \frac{\left[\left(\frac{3}{4B} + ½ \text{ F}\right) \text{x} \frac{H}{2} \text{x} \frac{L+K}{2}\right]}{8} \tag{8}$$

The final formula was created by Matthew Baker, who was appointed Master Shipwright of England in 1572.

$$\text{Tonnage} = \frac{\text{L x B x H}}{100} \tag{9}$$

CHAPTER III

METHODOLOGY

Goals

The methodology of this study is to develop and evaluate a software implementation of a parametric virtual *nau*. Though making a virtual *nau* is not a new concept, creating a parametric model of a *nau* is. To make this parametric model work, I needed to understand how a *nau* was built. I gathered information regarding the *nau's* construction process from treatises written by Oliveira and Lavanha, as well as, information from Dr. Castro. Dr. Castro aided me greatly in understanding the shipbuilding process in general in addition to the similarities and differences in the two shipwrights' approaches.

To achieve the second goal of this project, I needed to understand how the shipwrights determined the tonnage or volume of a *nau*. Dr. Castro provided me with eight different formulas that were used for this purpose. After acquiring a better understanding of how a *nau* was constructed, I developed my parametric model. Every week or so I met with Dr. Castro to either ask questions related to a particular treatise or to show him progress on my model. He and I would determine what changes or additions were required to make the models more accurate, and I would make those corrections. If the corrections were satisfactory the following week, I added more to the model. If more work was needed, I would continue to correct the shortcoming. With Dr. Castro's approval, after I had finished a particular part of the *nau*, I would continue with the next component. This process continued until I completed a model that both he and I felt was satisfactory. I also iterated on the implementation of the tonnage formulas. I worked with Dr. Castro to ensure correct results.

Dr. Castro provided me with an article related to how tonnage was determined for ships in the 16th and 17th centuries [10]. The article contained eight different formulas that were used during that period to approximate the capacity of ships like the *nau*. I applied these formulas to the model parameters which my algorithm used and determined how well they matched the actual volume of the hulls my model created.

CHAPTER IV

IMPLEMENTATION

For this project I chose to use Autodesk Maya and wrote a parametric algorithm using the Python programming language. Maya is an industry standard 3-D modeling, animating, and rendering program that has all the tools and operations required to create a parametric *nau*. My algorithm is contained within a Maya Python script and requires a Maya scene file to be manipulated by the script.

Dr. Castro analyzed both shipbuilding treatises or recipes to help me determine the proportions needed to create the major components of the *nau*. This type of ship was characteristically built with the aid of simple proportions and rules of thumb. The parameters used in this project were taken from references in texts on shipbuilding, which had recipes to determine the basic dimensions as cross-section shapes.

When a proportion needed for creating the *nau's* hull model was not described or discussed in a treatise, Dr. Castro referred to data collected from shipwrecks to determine a plausible value. For instance, the determination of the positions of the tailframes for Oliveira's recipe was obtained by measuring the actual space occupied by all the tailframes in a certain ship and then transforming these into proportions relative to the keel's length. Most often these were determined by taking a specific measurement given in the treatise or another source and dividing it by the keel length. This resulted in a proportion relative to the keel that could be used for my algorithm. The following tables contain the proportions that were used to determine hull shape.

Table 1. Oliveira's proportions.
The information needed to generate the shape of a vessel hull according to Oliveira's treatise. Specific dimensions given in various measurement units and also stated as propositions relative to keel length. The waterline is for a ship with loaded cargo. Developed by Dr. Felipe Castro.

Basic Dimensions	Ref.	Meters	Proportion formulas	Proportions relative to K
Beam [1]	**M**	13.32	K/2>M>K/3	0.481
Flat [1]	**F**	4.62	M/2>F>M/3	0.167
Transom [1]	**T**	6.66	M/2	0.240
Keel [1]	**K**	27.72	K	1.000
Length [1]	**E**	39.27	L2+K+L1	1.417
Height Stern [1]	**H2**	9.24	K/3	0.333
Rake Stern [1]	**L2**	2.31	K/12	0.083
Height Bow [1]	**H1**	9.24	K/3	0.333
Spring Bow [1]	**L1**	9.24	K/3	0.333
Z Fore tailframe [2]	**FTF**	25.97		0.937
Z Master frame [2]	**MSF**	17.33	5K/8	0.625
Z Aft tailframe [2]	**ATF**	8.69		0.313
Y Fore tailframe [2]	**Hf**	0.48		0.017
Y Master frame [2]	**Hms**	0.00		0.000
Y Aft tailframe [2]	**Ha**	0.72		0.026
X Fore tailframe [2]	**Nf**	3.08		0.111
X Aft tailframe [2]	**Na**	3.08		0.111
Run [2]	**R**	3.08	K/9	0.111
Entry [2]	**E**	1.23		0.044
Depth in hold [1]	**Pmax**	8.21		0.296
Depth @ 3rd deck [3]	**H2**	8.21		0.296
Depth @ 2nd deck [3]	**H1**	6.16		0.222
Depth @ waterline [3]	**Plwl**	5.25		0.189
Depth @ lower deck [3]	**P**	4.10		0.148

[1] Proportion of the keel length obtained from recipes
[2] Calculated and transformed into a proportion to the keel length.
[3] Values obtained by adding the ergonomic heights defined in Oliveira's treatise.

Table 2. Lavanha's proportions.
Hull component sizes and determined proportions relative to keel length for a *nau* from Lavanha's treatise. Developed by Dr. Felipe Castro.

Basic Dimensions	Ref.	Meters	Proportion formulas	Proportions relative to K
Beam [2]	**M**	13.86		0.514
Flat [1]	**F**	5.54		0.206
Transom [2]	**T**	6.93		0.257
Keel [1]	**K**	26.95	K	1.000
Length [1]	**E**	39.10	L2+K+L1	1.451
Height Stern [1]	**H2**	10.78		0.400
Rake Stern [1]	**L2**	3.08		0.114
Height Bow [2]	**H1**	13.48		0.500
Spring Bow [2]	**L1**	8.98		0.333
Z Fore tailframe [2]	**FTF**	20.47		0.759
Z Master frame [2]	**MSF**	17.97		0.667
Z Aft tailframe [2]	**ATF**	15.47		0.574
Y Fore tailframe [2]	**Hf**	0.09		0.003
Y Master frame [2]	**Hms**	0.02		0.001
Y Aft tailframe [2]	**Ha**	0.09		0.003
X Fore tailframe [2]	**Nf**	5.45		0.202
X Aft tailframe [2]	**Na**	5.45		0.202
Run [2]	**R**	4.49		0.167
Entry [2]	**E**			0.000
Depth in hold [3]	**Pmax**	7.70		0.286
Depth @ 3rd deck [3]	**H2**			0.000
Depth @ 2nd deck [3]	**H1**			0.000
Depth @ waterline [3]	**Plwl**			0.000
Depth @ lower deck [3]	**P**	3.59		0.133

[1] Proportion of the keel length obtained from recipes
[2] Calculated and transformed into a proportion to the keel length.
[3] Values obtained by adding the ergonomic heights defined in Lavanha treatise.

Table 1 represents proportions used by Oliveira and Table 2 the proportion used by Lavanha. The proportions that were created are used as parameters for the *nau* model. Though Dr. Castro provided me with a list of over thirty proportions, only 17 were actually used. Some proportions were not represented in the model, for example the beam width for a particular deck. I used the maximum beam of the vessel from which the other beam measurements could be calculated.

Graphical User Interface

An important step in my implementation was to create a Graphical User Interface, or GUI, that would control the parameterized *nau* model. The GUI allows the user to set a variety of variable values. The first variable to be set determines which recipe or treatise will be used to produce the hull shape. This was important because the shape of the hull varied between the two recipes used in this study. A set of radio buttons of which only one can be chosen at a time, allows the user to choose the hull shape recipes. The choices given are “Oliveira”, “Lavanha”, “Custom Oliveira” and “Custom Lavanha” (see Figure 4). If a custom button is selected, the parameter sliders in addition to the keel length that control the proportions that create the hull shape become available for the user to manipulate the hull shape.

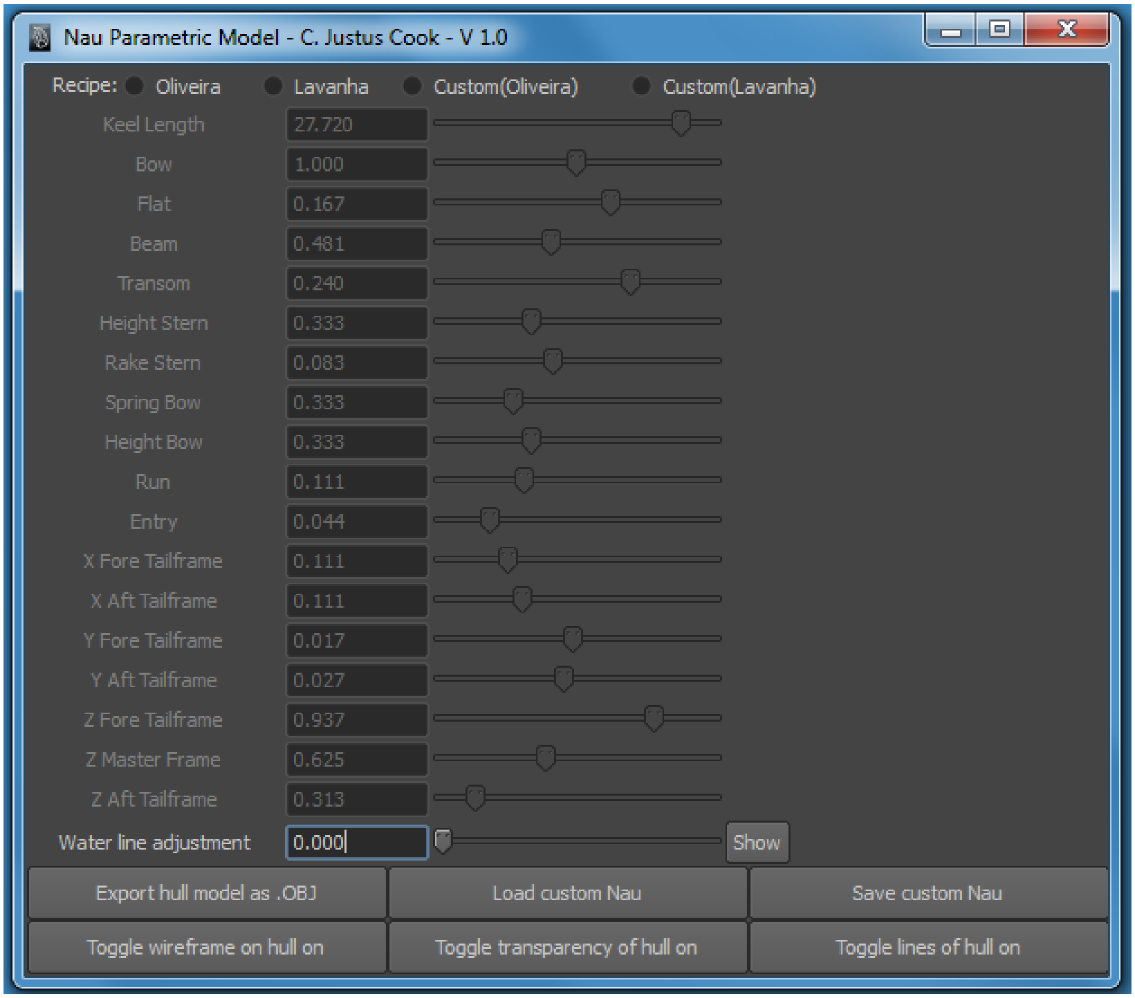

Figure 4. Image of GUI.

The primary variable is the length of the keel. A slider control, a knob that can move between a minimum and a maximum value, allows the user to set the keel length in meters. An input field can also be used to enter a precise value for the keel length. The minimum allowed keel value is 15.5 meters and the maximum is 30 meters.

In the ‘custom’ versions, there are seventeen parameters that can be changed to affect the hull shape. Slider controls are also used to specify these parameter values. Each parameter controls a proportion used in the ship hull shape creation. Most of the maximum and minimum values for the proportions are between one and zero. The parameters were clamped to a range of values which prevent the user from using unrealistic values for a particular parameter. This limits the user to creating a plausible *nau*. Values that would lead to an implausible hull shape cannot be selected.

Additional buttons at the bottom of the GUI pane are used for exporting and loading the relevant hull data used by the algorithm. The first button, ‘Export the hull model as .OBJ’, exports the hull surface as an OBJ file. OBJ is an open file format originally developed by WaveFront Technologies that has been adopted by many 3-D applications. I chose this format so the hull model could be easily saved from Autodesk Maya and imported into other 3-D programs, including those that are more suited for determining the volume of a 3-D shape. Note that in order to export the hull shape data, the Maya *OBJEXPORT* plugin must be loaded before the export button is clicked.

The “Load custom *Nau”* button will load a previously saved data file to set up hull proportions values and select the recipe used to create a *nau*. The “Save custom *Nau*” button creates a ‘.txt’ file with the information needed to recreate the current hull model. In addition to the information that is saved about the proportions, information is also saved for the tonnage calculations based on the formulas discussed earlier.

The buttons on the last row of the GUI are used to change the display of the hull geometry. The ‘Toggle wire frame on hull’ button hides or displays the edges of the polygon mesh of the *nau* hull. With the wire frame of the model visible, the user can see the resolution of the mesh. The ‘Toggle the transparency of the hull’ changes the transparency of the hull geometry to opaque or transparent. The ‘Toggle hull lines’ button allows the user to see the cross-section curves from which the hull geometric shape is derived (see Figure 5).

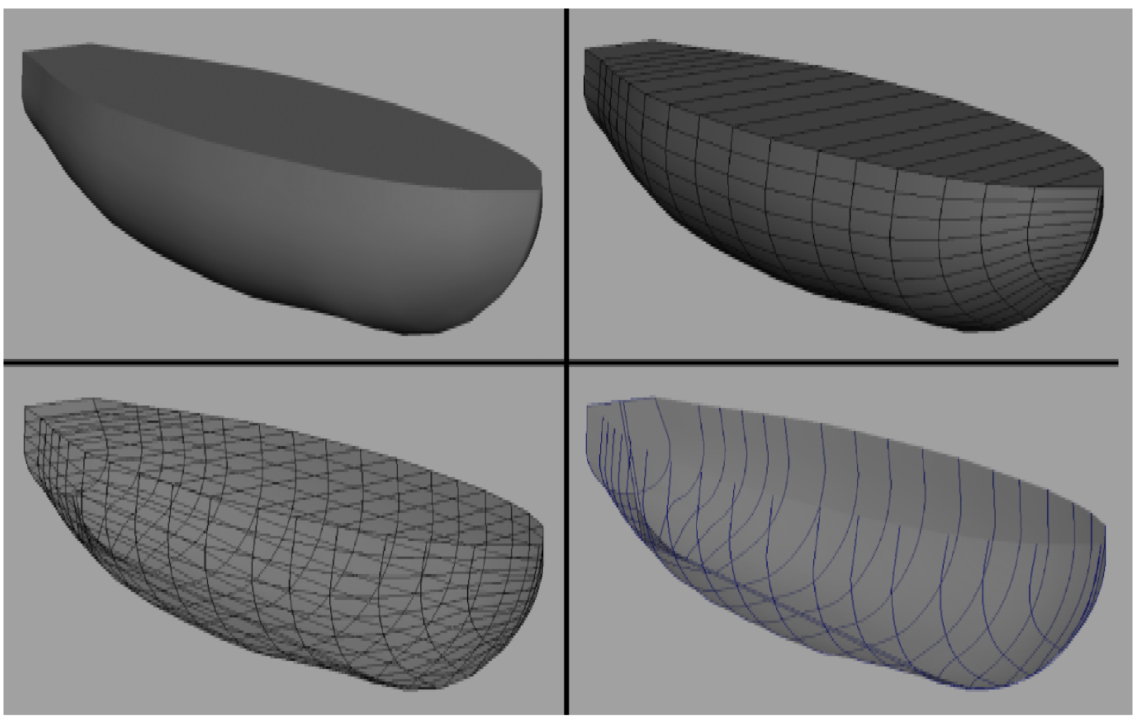

Figure 5. Display modes for *nau* hull geometry in Maya. From left to the right, top to bottom: Default model, Wireframe on with opaque hull, Wireframe with transparent hull, and Hull line with transparent hull.

Creating the Parameterized *Nau* Hull

My approach to implementing Oliveira's and Lavanha's *naus* as three dimensional models was heavily influenced by their design process. They created 2-D drawings that were used as templates to make the frames needed for their vessels. These drawings were the section and elevations of a *nau* hull. By adding a third dimension and using the 2-D sections and elevations to create a surface in 3-D space we begin to see the shape of the vessel and the volume of space it contains. After analyzing Oliveira's and Lavanha's line drawings, I decided to create 3-D curves as elevations and sections of the *nau*. Once these curves were created I used them to drive the shape of a polygonal mesh. This defined a 3-D volume that was determined by the elevation and cross-section curves.

I will use a set of drawing created by Dr. Castro when describing my implementation of Lavanha's method. I created a similar set of drawings to illustrate Oliveira's approach.

The construction process of the *nau* was influenced by the tools used by the shipwrights of the time. They used many simple tool such as straight edges, simple hand tools, and compasses. The use of the compass was very common as demonstrated by the number of arcs both Oliveira and Lavanha used in their designs.

Coordinate System Used

To understand the 3-D space in which my parametric model was created, the coordinate axes must be defined. I used a Y-Up right handed coordinate system. This means the keel is created along the negative Z axis. Looking down the Z axis, the positive X axis is to the left, and the positive Y direction is up (see Figure 6). The keel, stempost and sternpost components are connected and lie in the defined YZ plane.

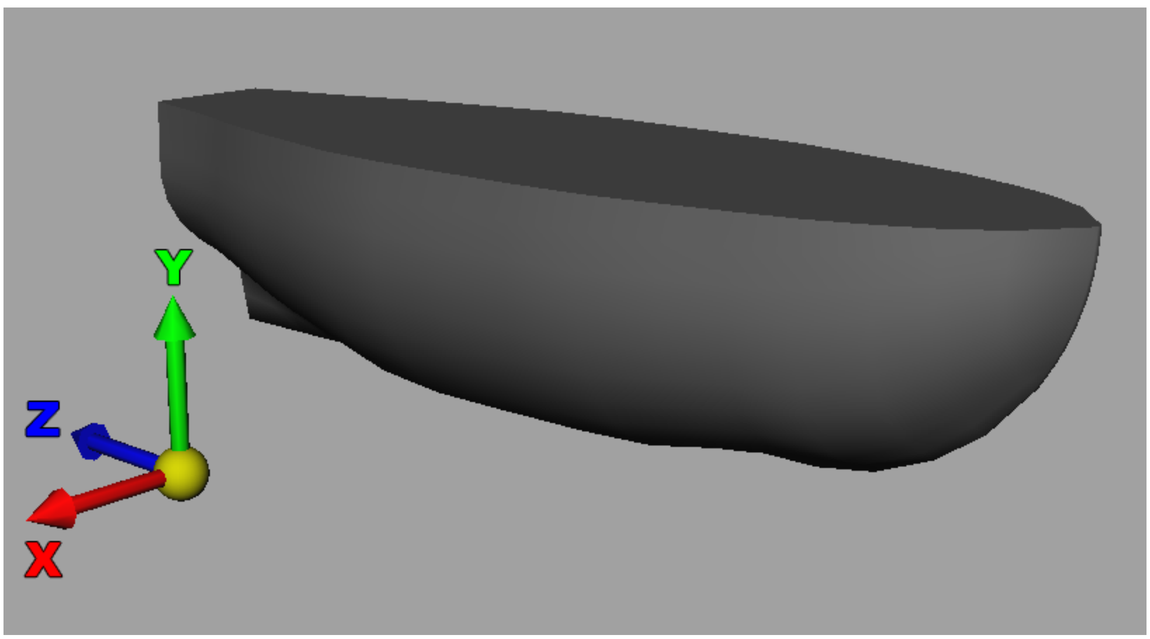

Figure 6. *Nau* hull and axis.

The rest of the frames, the structural support timbers of the vessel, are attached to keel, sternpost, or stem post. My algorithm does not try to recreate all the frames that a real vessel would require. It instead approximates the shape of the hull with vertical cross-sections along the keel in planes parallel to XY plane. Some of these cross-sections correspond with actual vessel frames, for example the master frame. I chose 17 cross-sections, a number that is close to the number that Dr. Castro used in his reconstructive drawings of the *nau's* hull. Since I am using the same polygon mesh to represent the hull shape for each shipbuilding approach or recipe, the number of cross-sections is the same for both. This allows me to reuse the same polygonal mesh in Maya and not have two separate objects representing the hull for each recipe. It also allows for the introduction of additional recipes in the future if they use the same cross-section approach.

The Keel

The first step in creating the *nau* is to create the keel. Since the keel is just a single straight timber for both Oliveira and Lavanha designs, it is represented by a line the length of the keel from the origin in the negative Z direction (see Figure 7). Lavanha's manuscript described a specific size *nau* with a 105 *palmos de goa* long keel. *Palmos de goa*s, also referred to as palmos, were a common unit of measure in Portuguese shipyards in the 16^{th} century, and were equivalent to 25.67 cm [10]. For illustrating Lavanha's method, I will describe the construction for a ship of the size described in his manuscript.

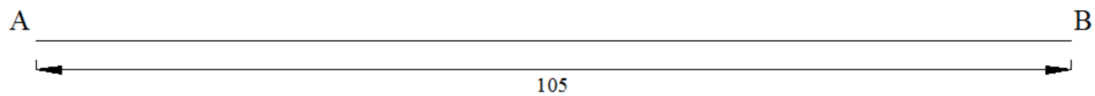

Figure 7. Drawing of keel [14].

Figure 8. Drawing of sternpost based on Oliveira. This image shows the keel and the sternpost.

To represent the keel for both recipes, my algorithm creates a line whose length is the value specified using the GUI keel length slider. This line is offset by 0.5 *palmo*, 12.835 cm, in the positive X direction. This line is then reflected across the YZ plane to represent the total width of the keel timber.

The sternpost is calculated next. For an Oliveira *nau*, the height of the sternpost is one-third the length of the keel and the rake of the sternpost is equal to one-twelfth the keel length (see Figure 8) [12].

The sternpost for a Lavanha *nau* is similarly calculated, and but with slightly different proportions. This is done by drawing a line AC that is two-fifths the length of the keel, or 42 *palmos*, and a line CD of 12 *palmos* representing the rake of the sternpost. Then the AD line is drawn which is the sternpost line (see Figure 9).

To determine the sternpost for either recipe, I used values proportional to the keel length for the rake and for the height of the sternpost. The algorithm takes these two values and multiplies them by the keel length to determine the points defining the sternpost line. This line is then offset and reflected across the YZ plane representing the thickness of the timber.

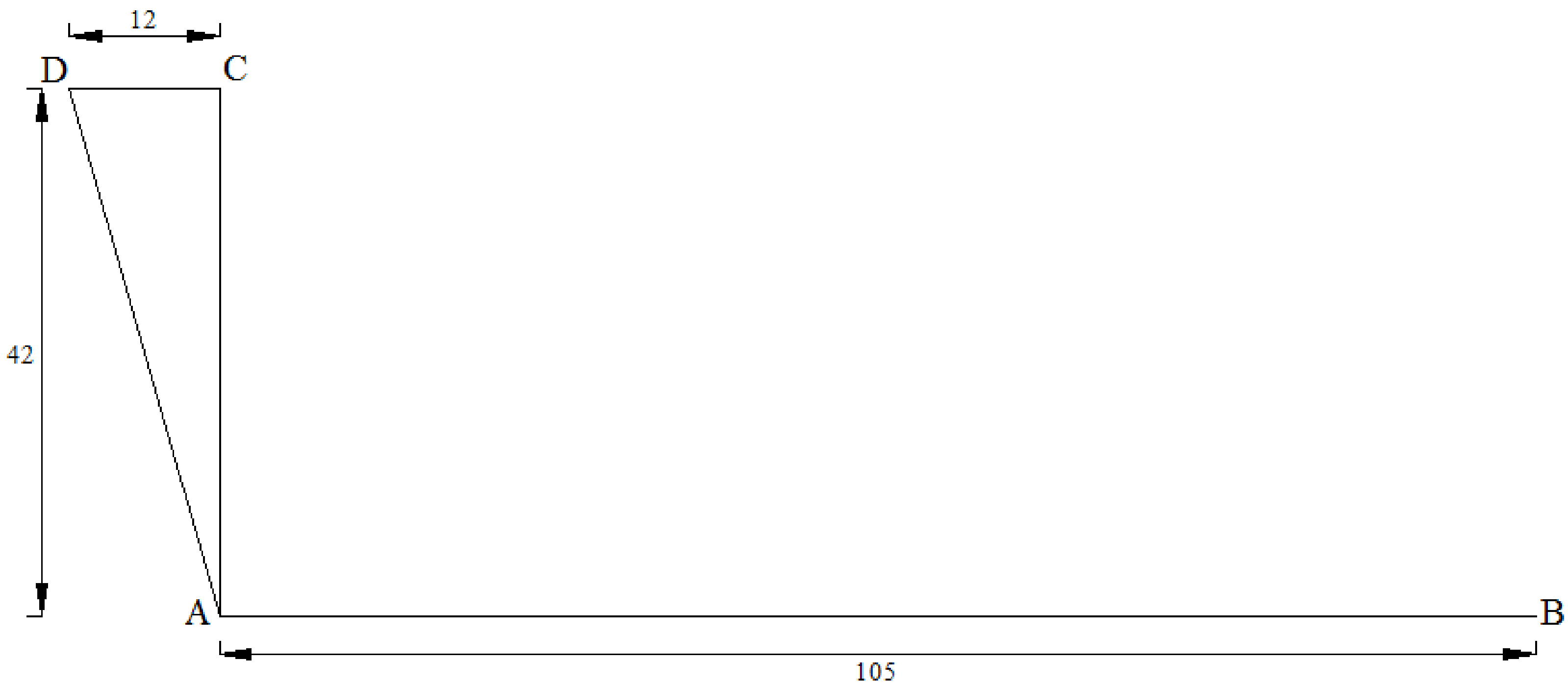

Figure 9. Drawing of sternpost based on Lavanha [14].

The stempost is determined very differently for each recipe. Oliveira created the curve of the stempost with a simple arc (see Figure 10). The center of this arc is one-third the length of the keel above the fore end of the keel. Its radius is equal to the height of the center point and is swept 90 degrees counterclockwise [12].

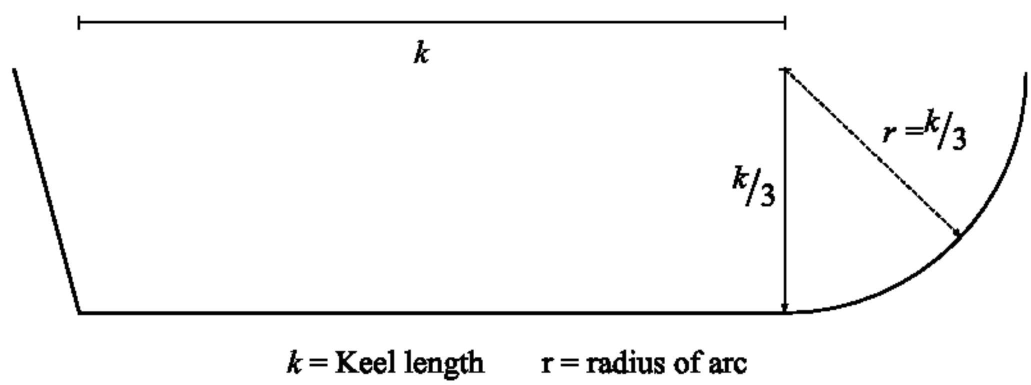

Figure 10. Drawing of bow based on Oliveira.

Lavanha's stempost is determined with a compound curve. The *spring* of the bow, or the horizontal distance from the end of the keel to the tip of the stempost, which is one-third of the keel, or 35 *palmos*, and the height of the bow, which is one-half the keel length or 52.5 *palmos* must be determined before the arc of the stempost can be created.. The spring is represented by line BE, and the height of the bow by line EF (see Figure 11).

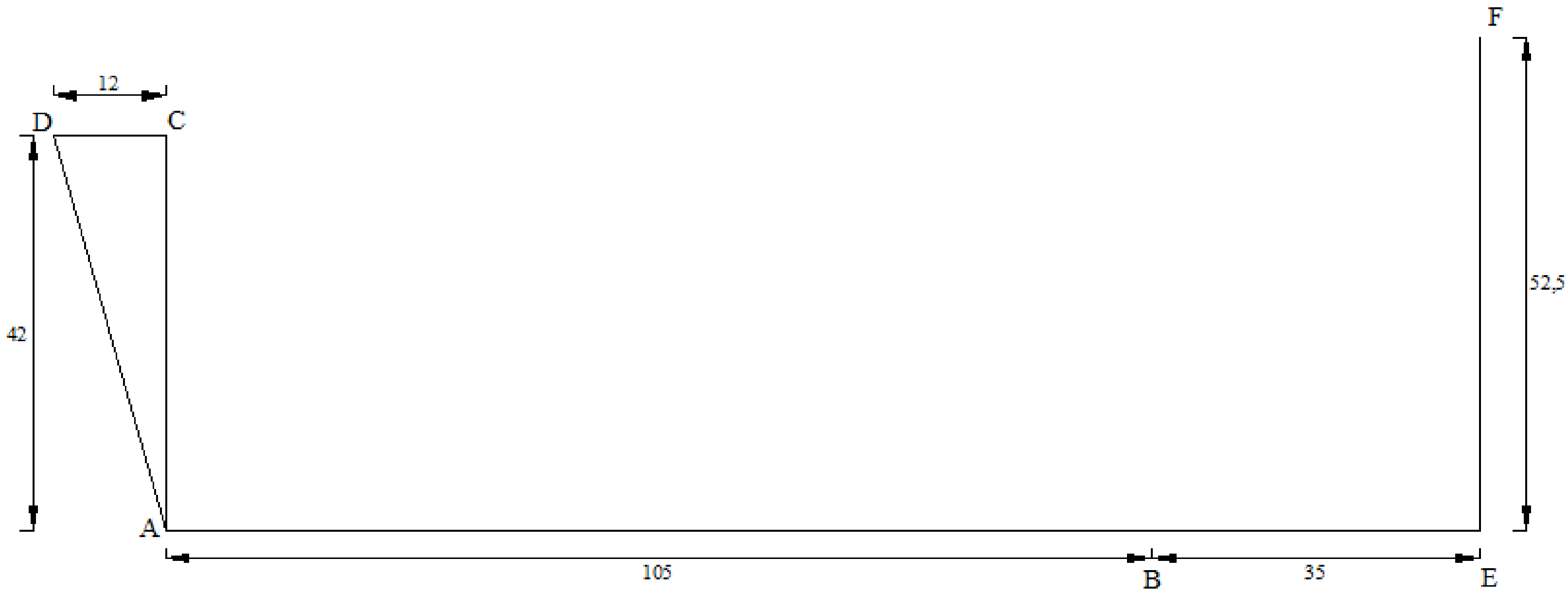

Figure 11. Initial steps in drawing of stempost. Points E and F are defined based on Lavanha [14].

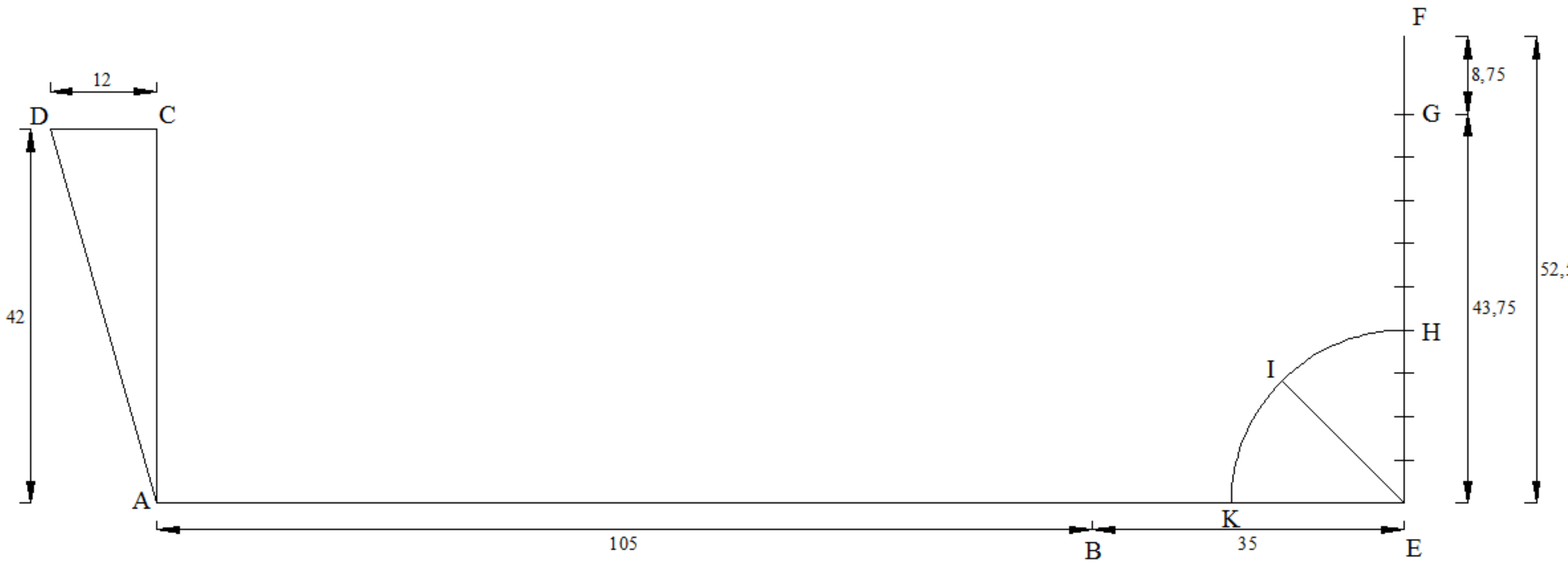

Figure 12. Additional steps in drawing of stempost. Point G and arc HIK are added based on Lavanha [14].

Point G is defined on line EF at a height of five-sixths EF. Point H is defined at four-ninths of GE, and an arc HIK is drawn with I being the arc midpoint and a radius equal to the length of line HE (see Figure 12).

Arc BIG is drawn next. To find the center of this arc, line BI and IG are drawn. The midpoint of each line is found, and a perpendicular line is drawn from each line. The point at which the perpendicular lines drawn from lines BI and IG intersect is the center of arc BIG and is labeled M. To draw the upper arc, LG, of the stempost, point N is drawn directly below point M at the same height as point G. N is used as the center of arc LG, NG being its radius. The arc is swept until its height is equal to that of point F (see Figure 13).

Lavanha then offset inside all the previously drawn axes to the inside by one palmo to represent the height and shape of the timber that would be used to create them (see Figure 14).

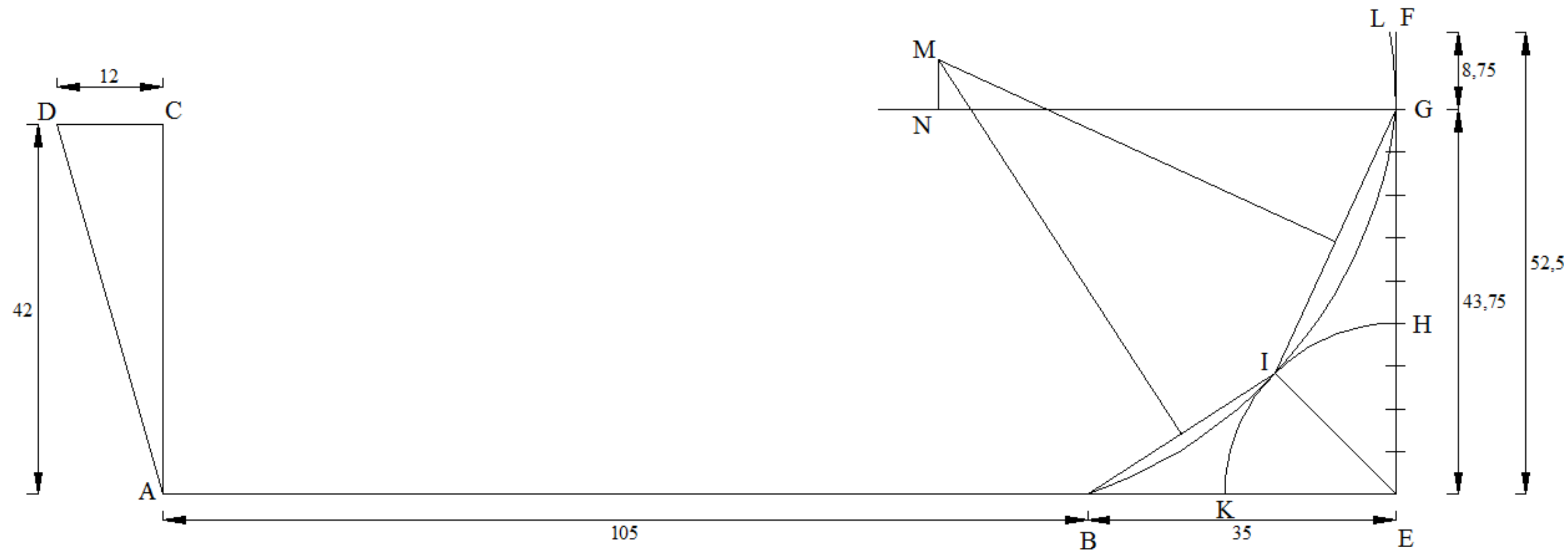

Figure 13. Drawing of arc of stempost. Arc BIG and LG are added based on Lavanha [14].

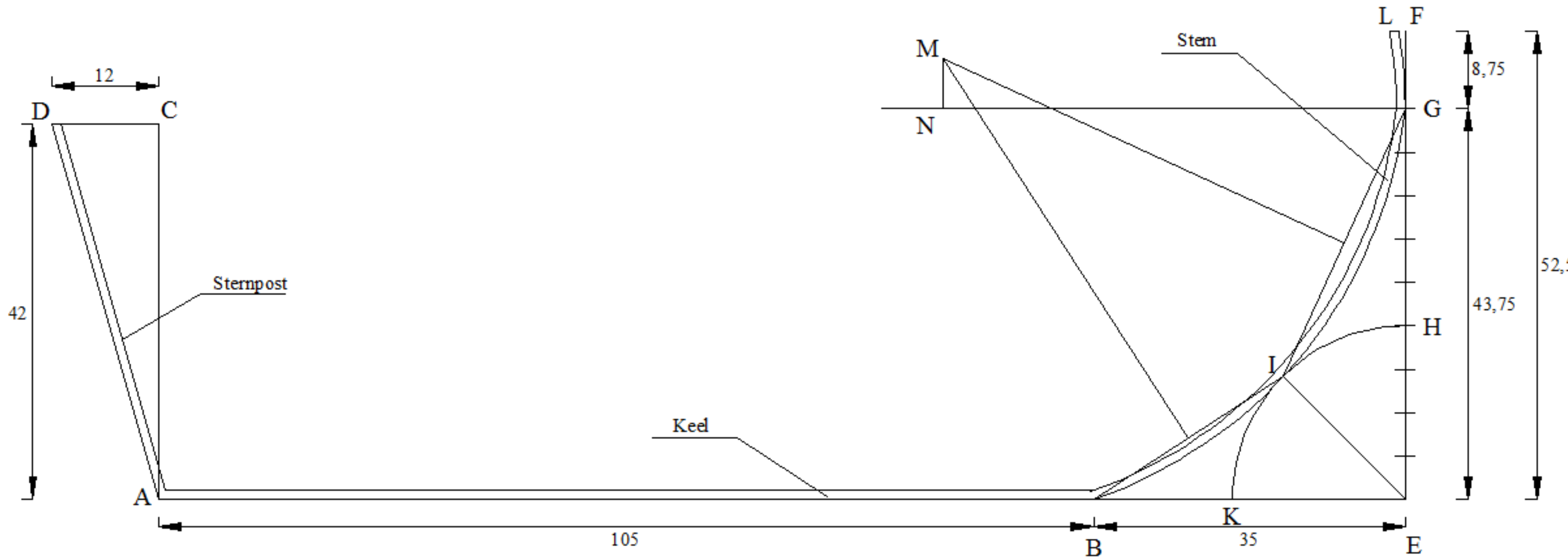

Figure 14. Complete drawing of *nau* profile based on Lavanha [14].

For the stempost, my algorithm calculates the point coordinates just as Lavanha did. My model does differ from Lavanha's drawings here slightly. Lavanha's stempost continues past the height of the sternpost; however the weather deck or upper deck, is also at the sternpost height. The weather deck is the main deck of the ship that is exposed to the elements. All other decks are below the weather deck.

My model determines the cargo capacity of the vessel under its weather deck, therefore I do not account for the stempost curve past point G. The vertical offset to account for the thickness of timbers used by Lavanha is also ignored by my algorithm. This is because I want to know the volume inside the outer planking of the hull, were cargo would be stored. The planking of the vessel is applied to the outside of the frames to create a water tight hull. I only offset in the X direction by 0.5 *palmo*, or 12.835 cm, for the timber width, then reflect the line across the YZ plane [10].

Master Frame

The master frame, also known as the midship, is the widest frame of the ship and divides the fore and aft sections of the ship [17].

For an Oliveira *nau,* a line that marks the center of the master frame is created. Then the width of the beam and height of the master frame is determined. Oliveira states that the beam and the height are one-third the keel length. Next the flat is drawn with a width equal to one-third of the beam (see Figure 15) [10]. The frame radius is determined by finding the height of the center of the arc that will represent the sides of the master frame. This height is described by Oliveira to be two-thirds the width of the beam, or two-ninths of the keel length. Point C is drawn at that height above the flat as the center of this arc. The radius is the distance from the center of the arc to the edge of the flat. A compass would have been used to create this arc with the appropriate radius.

The radius can also be found with the Pythagorean Theorem. The radius is the hypotenuse of a triangle with the base being the flat of the vessel and the height of the center of the arc being the length of the other side.

The sweep of the arc stops at a predetermined height which is three-fourths the width of the beam or one-fourth the length of the keel. At the point that the arc intersects this height the rest of the master frame is just a straight line that is tangent to the arc that ends at a height which is one-third of the keel length (see Figure 15) [12].

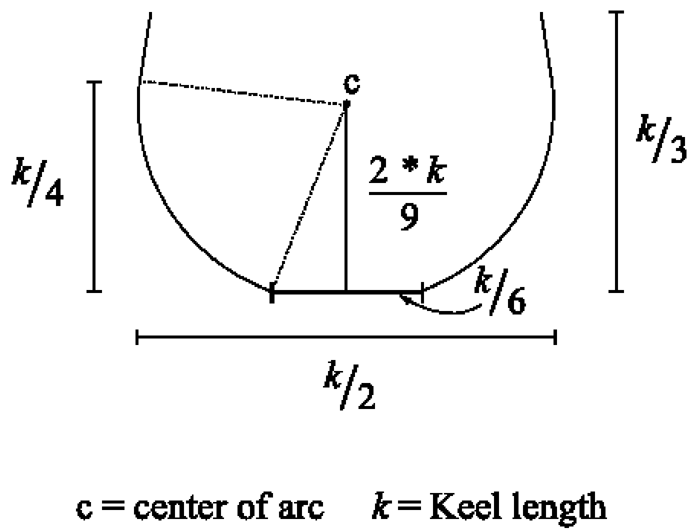

Figure 15. Master frame based on Oliveira.

Next the position of the master frame along the keel is determined. The mast step is at the center of the keel. The master frame is then placed fore of the mast step by $1.5 * \frac{K}{18}$ (K = Keel length) [12] (see Figure 16).

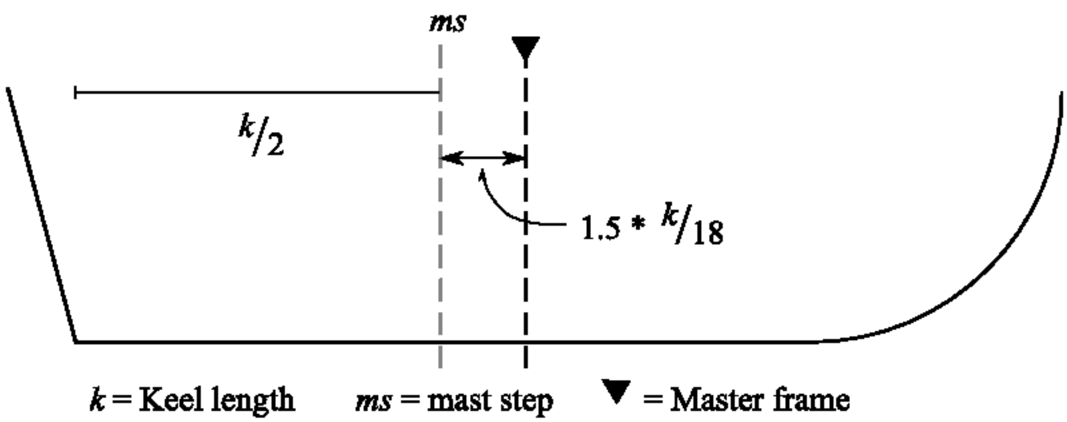

Figure 16. Placement of master frame based on Oliveira.

To create the master frame for my model, I followed the same steps as Oliveira. I also reflected the curve offset for the width of timber.

Lavanha's approach used a compound curve for the master frame, just as he did for the stempost. To find the width of the master frame, the *eslora* or the overall length of the vessel must be determined [14]. This length can be found by adding the rake of the stern post, the length of the keel, and the spring of the bow (see Figure 17). This calculation results in 152 *palmos*.

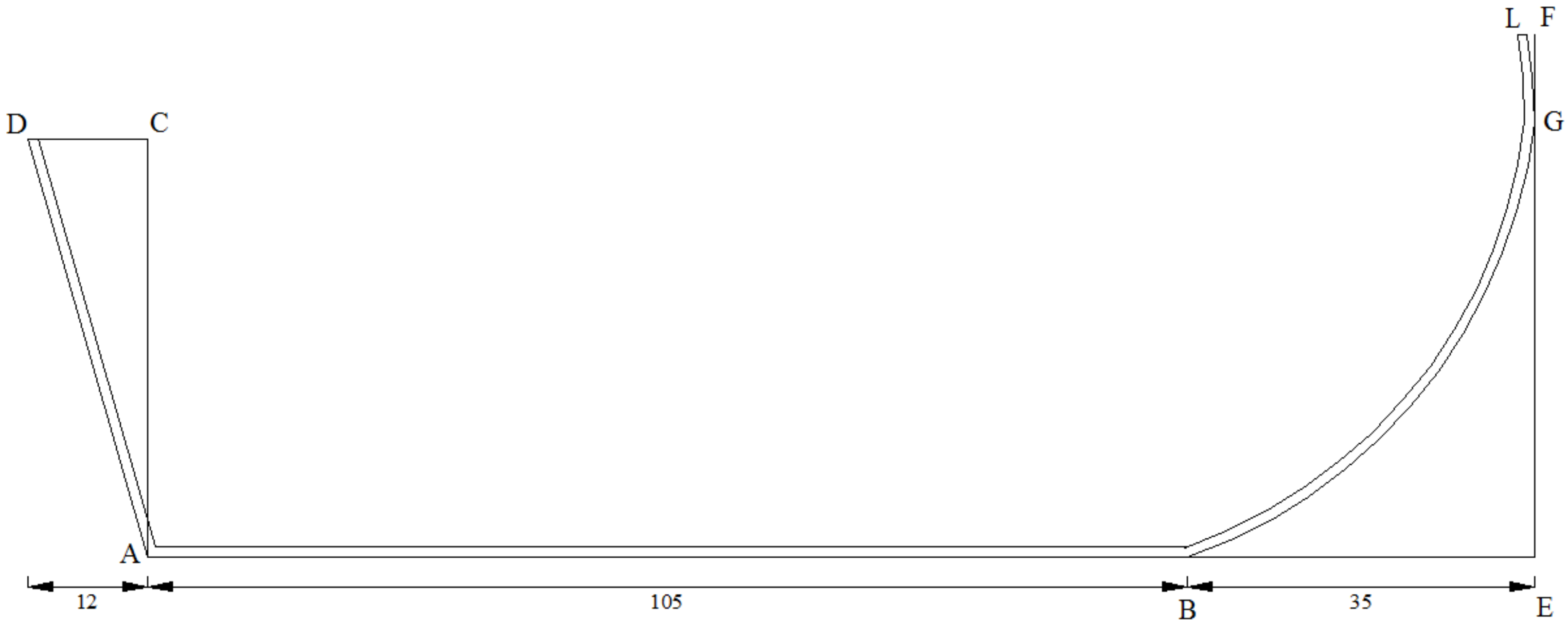

Figure 17. *Eslora* of *nau* based on Lavanha [14].

A mistake on Lavanha's part is revealed at this point. He used an *eslora* of 153 *palmos* as he continued to produce his drawing. He should have used 152 *palmos*. Small errors such as this appear in other ship building treatises of the time.

Lavanha described the maximum beam of the vessel as one-third of the *eslora* plus the radius of the spring of the bow. Again Lavanha made a mistake is arithmetic, he used 54 *palmos* for the maximum beam, derived from adding the *eslora* he calculated, 153 *palmos*, plus 9 *palmos* for the spring of the bow, yielding 162 *palmos*. When 162 is divided by three the number 54 *palmos* is given for the maximum beam. When the correct value for *eslora*, 152 *palmos*, and 9 *palmos* is added then divided by 3 used the resulting maximum beam is 53.6 *palmos*. For the master frame, a width of 54 *palmos* will be used and is represented by the line AB in Figure 18.

To determine the height of the master frame, Lavanha used the sum of the height of the decks and the hold. Each deck is one-fifteenth of the keel, or 7 *palmos*, and the depth of the hold is 14 *palmos*. The thickness of the decks, two-thirds *palmos*, and the floor, 1 *palmo*, as well as the thickness of the bulwark are all added to the height of the decks and hold; giving 34.5 *palmos* as the height of the master frame (see Figure 18).

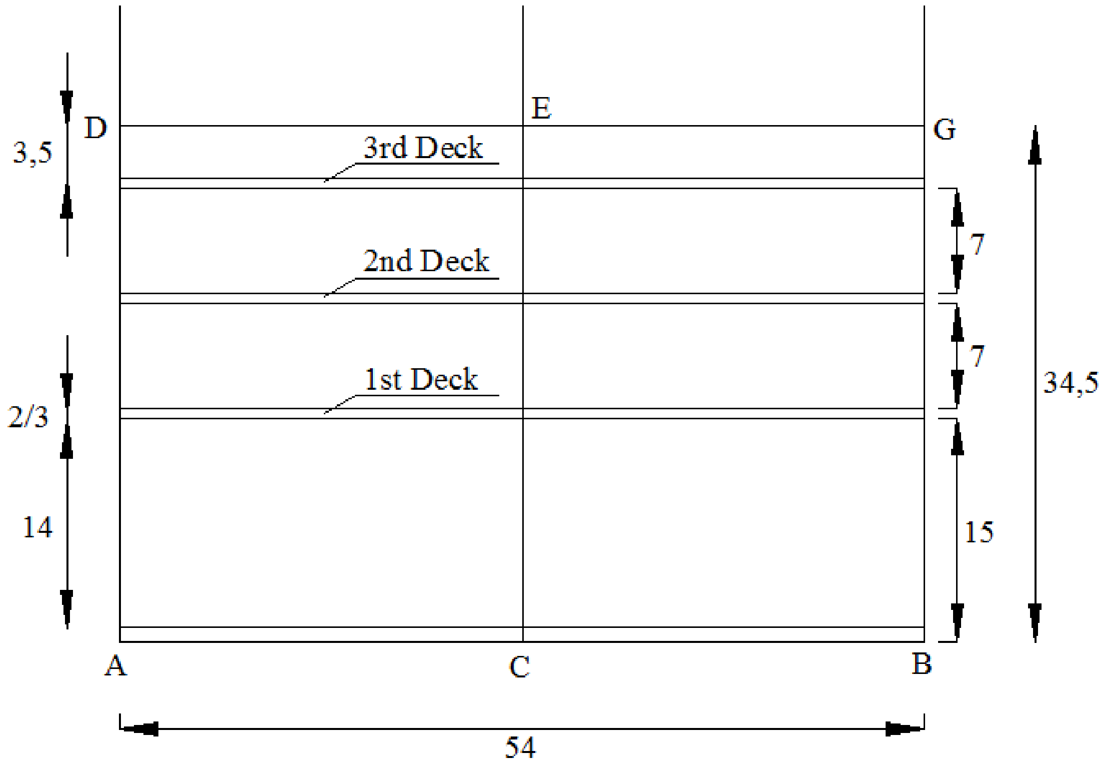

Figure 18. Drawing of master frame with decks based on Lavanha [14].

Line AB is divided into five equal segments, defining points M, O, R and P. Using a compass, an arc is drawn with point A as the center, and the line AM as the radius; the same is done on the other side using points B and R. These result in arcs MTS and RZV, T and R being the mid points of each arc respectively. Lines AS and BV are perpendicular to the line AB. The width of the second deck is one twenty-seventh *palmos* less than the maximum beam on both sides, placing points H and I slightly inside of points D and G (see Figure 19).

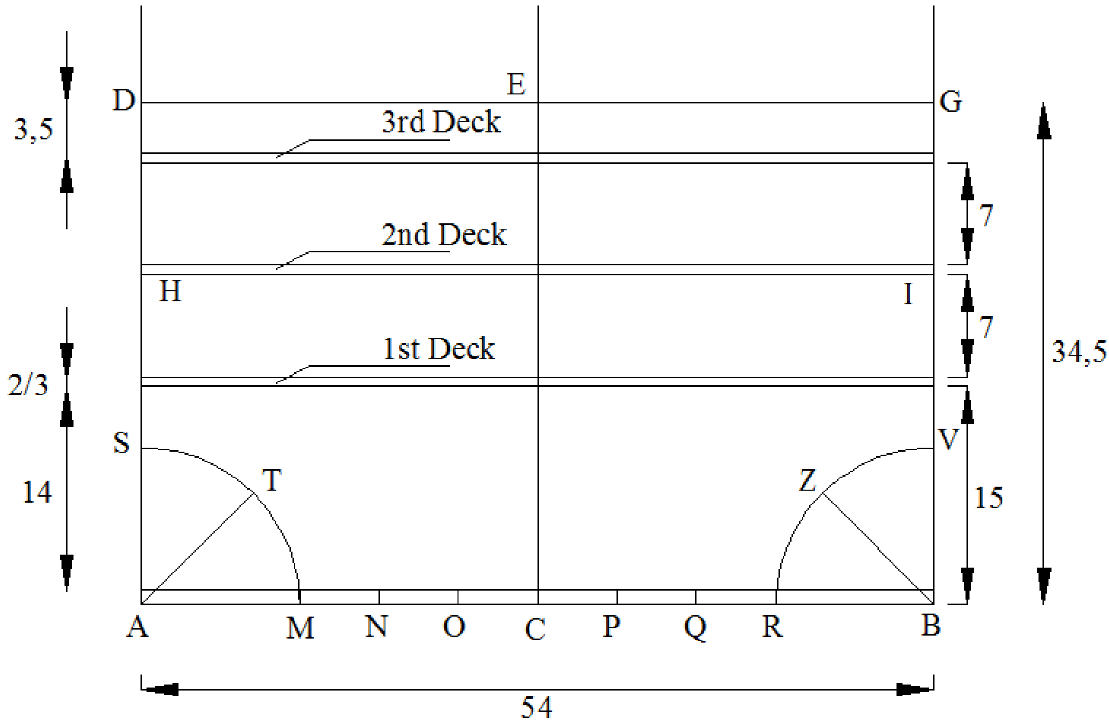

Figure 19. Defining point for arcs based on Lavanha [14].

Arc NTH is drawn by finding the lines perpendicular to NT and TH. Where these perpendicular lines intersect is the center of the arc and is labeled point X. To determine the center of arc MHD, line MH and HD are created. Then the midpoint of both lines is found, and perpendicular lines are drawn. Where these lines intersect is labeled Point Y and is the arc MDH's center (see Figure 20).

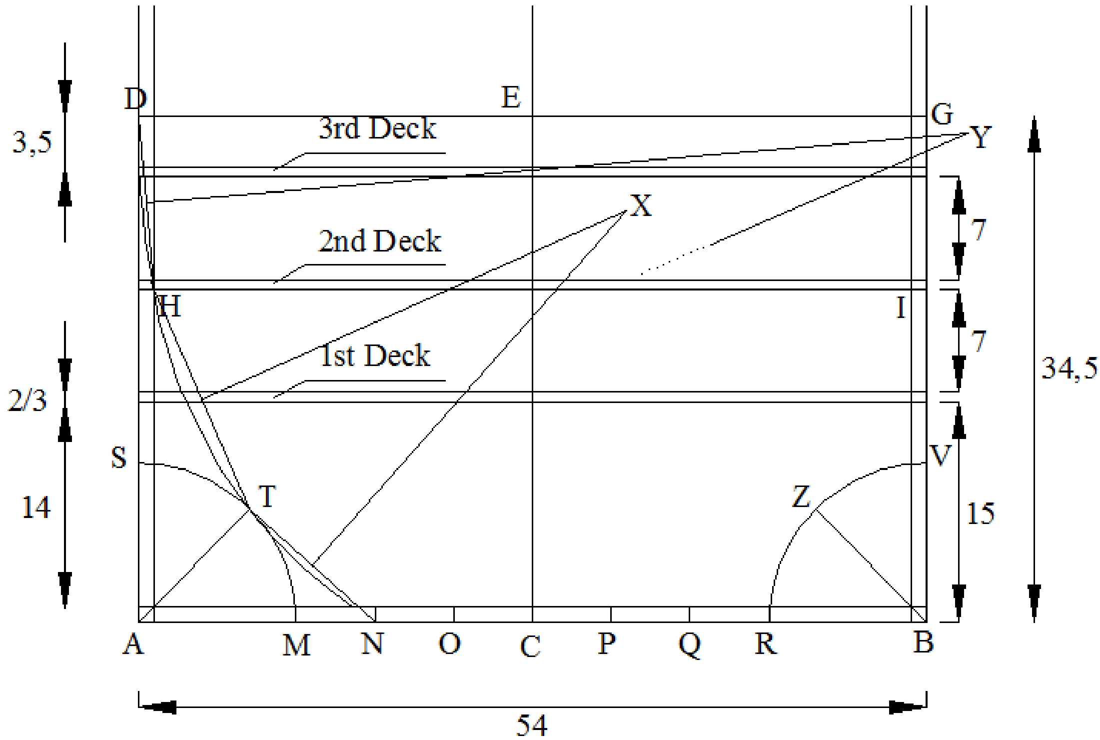

Figure 20. Drawing of master frame arcs based on Lavanha [14].

The other side of the master frame is created the same way; by creating arc IZQ with center at point c and arc GI whose center is point b (see Figure 21). To draw the turn of the bilge, or *côvados*, points i and h, are located 7 *palmos* from the center of the master frame. Then points d and e are added where the arcs NTH and IZQ intersect the offset for the thickness of the master frame. Vertical lines are drawn 3.5 *palmos* to the left and right of points d and e respectively (see Figure 21). Points f and g are placed where these vertical line intersect arcs NTH and IQZ respectively.

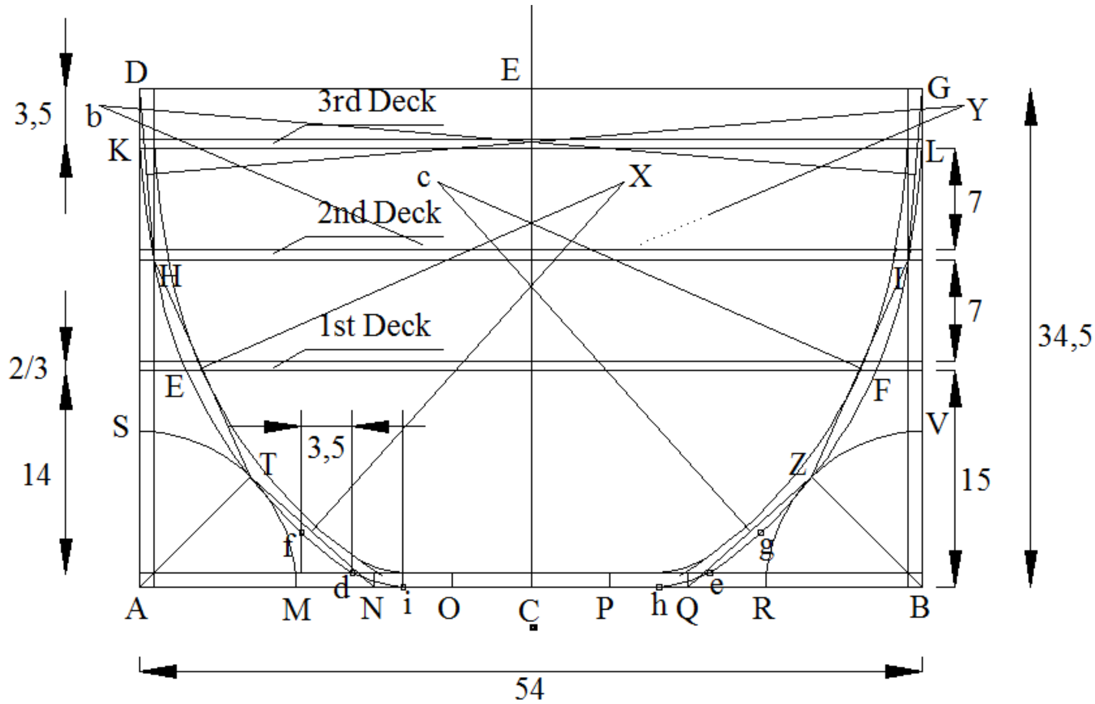

Figure 21. Drawing of turn of bilge at master frame based on Lavanha [14].

After consulting with Dr. Castro about the *côvados* refinement, I decided not to include it. The resolution of the hull mesh is fairly low, and this added detail would have little effect on volume calculation.

My algorithm calculates the points to determine the curves for the master frame according to Lavanha's rules. I do not include a vertical offset for the thickness of the timber, but I do include a horizontal offset. The curve is reflected across the YZ plane. The final step for the master frame is positioning it along the keel. It is one-third of the keel length aft of where the bow begins.

The transom which also varies between Oliveira and Lavanha is drawn next. With Oliveira's approach, I found an error. His manuscript called for the width of the transom to be equal to half of the maximum beam or a quarter of the keel length. However, I found that if I adhered to other proportions given, mainly the run proportion, the transom width was less than two-ninths of the keel length, slightly narrower that Oliveira's transom width of one-forth. The run is the height of the base of the transom and fashion pieces. I discussed this discrepancy with Dr. Castro. We determined it was more important to maintain the run proportion than the width of the transom and fashion pieces.

The only information given for the transom and fashion pieces was the width of the transom and the run height, which is the starting point of the fashion pieces. According to Dr. Castro, the fashion piece shape should be almost identical to the master frames shape, except that the radius of the arc for the fashion pieces would be much smaller.

The centers of the arc for the fashion pieces are placed at the same height as the centers of the master frame arcs or two-ninths of the keel length. The points where the fashion pieces arcs begin, known as the run, were determined by multiplying the keel length by the run proportion of one-ninth. The radius of the arc is equal to the distance between the center of the arc and the run or one ninth the length of the keel. The arc is drawn clockwise until it reaches a height of one-fourth of the length of the keel. Then a line is drawn tangent to the arc from the end of the arc to the maximum height of the sternpost, one-third the keel length. I reflect the fashion piece across the YZ plane and draw a line from the end of one fashion piece to the other to represent the transom (see Figure 22).

For Oliveira's approach, my algorithm calculates the lines of the transom and fashion pieces as described above, adding the offset of the thickness of the sternpost.

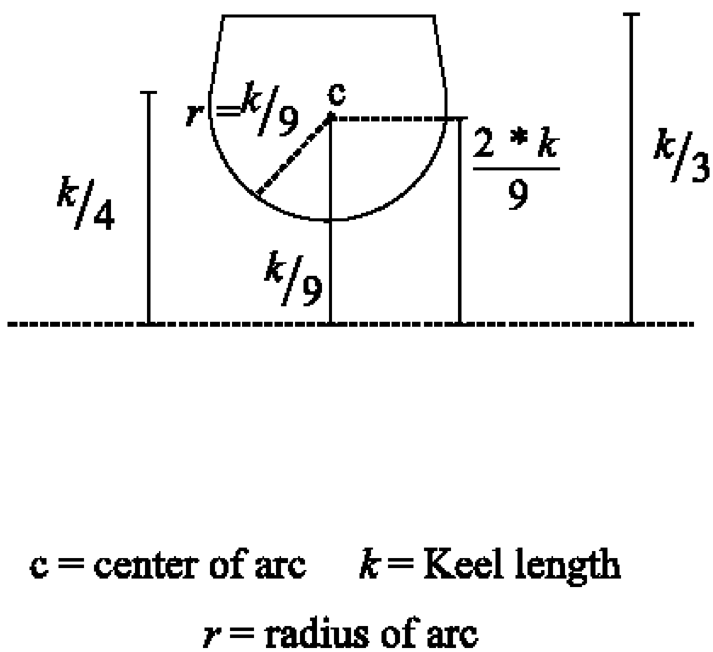

Figure 22. Drawing of transom based on Oliveira.

Lavanha described the form of the transom and fashion pieces in greater detail than Oliveira. In Figure 23, Line AB is drawn with a height of two thirds of the length of the keel or 42 *palmos*. To represent the width of the sternpost, a line CD is offset by one *palmo*. The transom timber is drawn atop the sternpost with a width equal to half of the maximum beam, or 27 *palmos*, represented by line EF, and offset 1 *palmo* adding line GH.

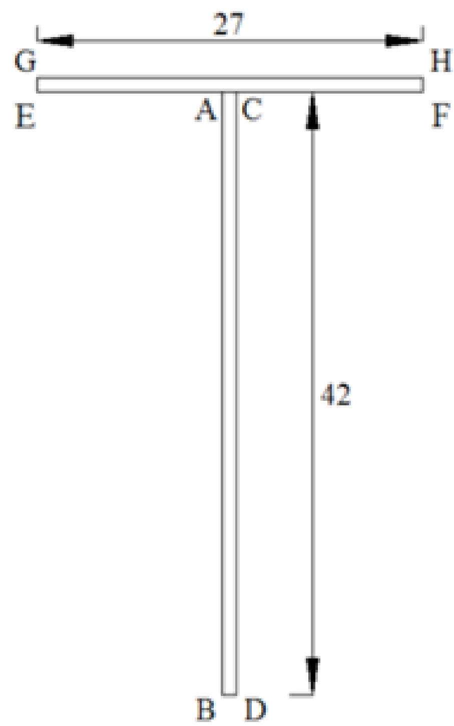

Figure 23. Drawing of transom timber and sternpost based on Lavanha [14].

As shown in Figure 24, points I and K are added at a height of 17.5 *palmos*. At the midpoints of lines IA and KC, points L and M are added. Points P and R are then added 1 *palmo* inside of points E and H. Directly below points P and R points N and O are added at the same height as points L and M. Next to determine the center point that will be used for arc INE, lines are drawn perpendicular to lines IN and NE at their respective midpoints. Where these perpendicular lines intersect, point S is created. An arc is then created using point S as the center point, and passing through points I, N, and E. The same process is used with arc KOR with point T as the center.

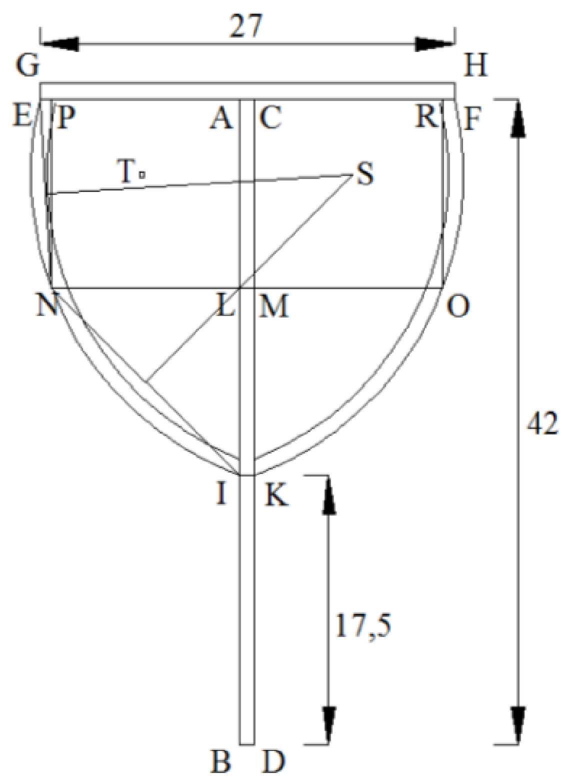

Figure 24. Drawing of fashion pieces based on Lavanha [14].

My algorithm calculates these curves based on Lavanha's approach described above. Once the transom and fashion pieces are create they are skewed to match the slope of the sternpost. Although Lavanha draws a second curve to represent the thickness of the stern pieces, I am only interested in the outer curves because they affect the volume of the hull.

Both *nau* treatises give information on the set of frames that are placed fore and aft of the master frame. The number of frames and tailframes, the total amount of rising and narrowing of the tailframes frames, and the frame spacing along the keel is different for each of the two approaches.

Oliveira called for 18 frames spaced evenly over a distance equal to $\frac{37.5}{108} * K$ (*K* = Keel length) in both directions away from the master frame [12]. Once the position along the keel is determined for each frame, the rising and narrowing needs to be calculated. The 'rising and narrowing' refer to the horizontal 'narrowing' and vertical 'rising' (see Figure 25). To find the amount each frame is offset in either the X or Y direction a g*raminho* is used. The X direction is the narrowing, and the Y direction is the rising of the frames. Oliveira used a *graminho de besta*, and Lavanha used a *graminho de meia-lua.* A *graminho* is drawn by creating a quarter circle with radius equal to the total rising or narrowing distance. The quarter circle is then divided into equal slices (see Figure 2). The number of slices is the number of frames that will be used. Where the radii used to make these slices intersect the circle, a height measurement is taken from the base of the circle. The resulting heights are then used to determine the rising or narrowing of the tailframes (see Figure 25).

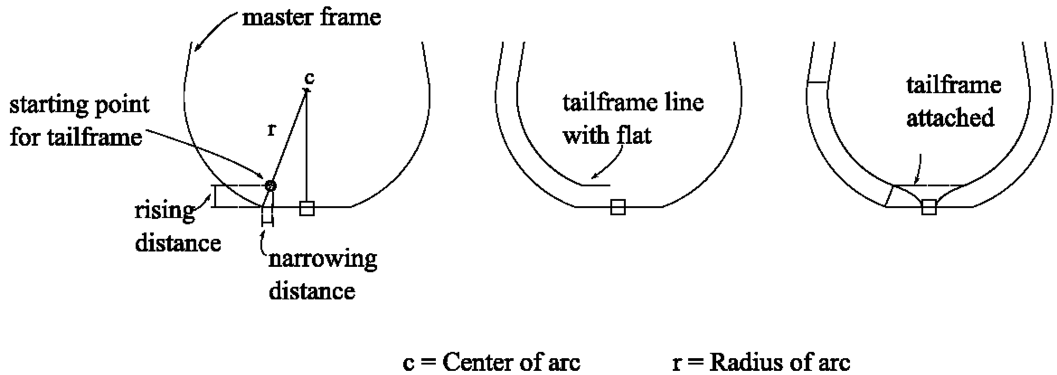

Figure 25. Drawing of rising and narrowing based on Oliveira.

For Oliveira's approach, my algorithm approximates the tailframes shapes. Instead of creating a cross-section for each of the 18 fore and aft tailframes that Oliveira called for, I chose to represent only three of the fore and two of the aft tailframes. While Oliveira would have drawn a *graminho* to determine the rising and narrowing values, I use an equation. The rising or narrowing is determined for any particular frame with the following equation [17]:

$$X_i = (1 - \sin \alpha_i) * T \tag{10}$$

Xi = rising or narrowing amount, α_i= Angle, T = Total rising or narrowing

In Equation 10, "α_i is the angle of the radius of point i on the quarter of the circle" of the *graminho* [7]. Once the algorithm finds Xi, it is multiplied by the total rising or narrowing to find the correct offset value. By doing this multiplication the resulting values will be a fraction of the total rising or narrowing. These rising and narrowing values are used to find the starting point of the frame line.

The radius of the frames arc is determined by finding the distance from the frame's base point to the center of the arc. The remainder of the curve continues as for the master frame (see Figure 15). Then the portion of the frame that corresponds flat of the master frame is modified to curve downward and attach to the keel. The curve is modified by moving the end point of a Catmull-Rom spline that is used to create the curve to the keel (see Figure 25). Once the curve had been created, it is placed on keel at the correct distance from the master frame (see Figure 26).

To determine the placement of each tailframe along the keel, I used a proportion value to find where the aft most or fore most tail frame should be placed and divided that distance by three for the three tailframe cross-sections.

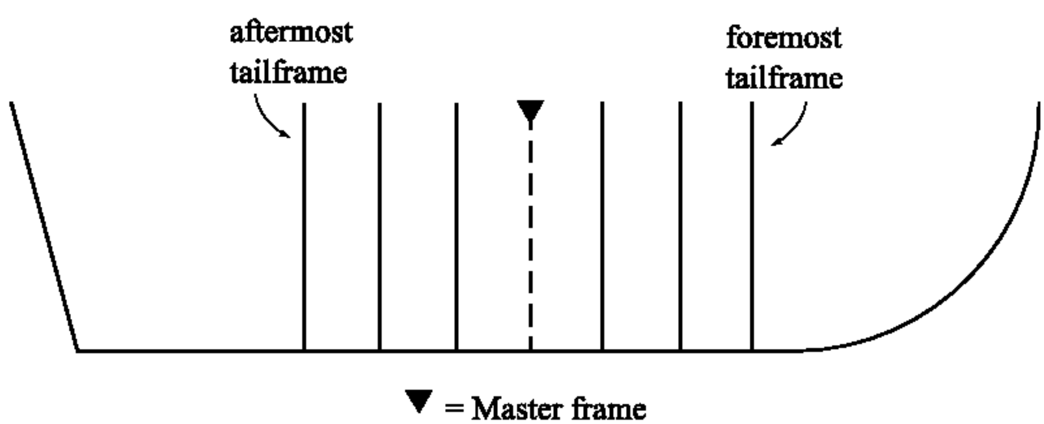

Figure 26. Placement of tailframes based on Oliveira.

To determine the shape of Lavanha's tailframes, my algorithm calculates the points on the curve in the same way as the master frame. First the rising and narrowing is found. Then a curve that is a copy of the master frame curve is offset so that point N, which is at the end of the flat where the turn of the bilge begins, corresponds to the rising and narrowing values calculated for that tailframe. The line is then cut off where it extends above the height of the sternpost, and point C is moved so that it attaches to the keel, as shown in Figure 27. The shape of the curve from point N to C is determined using a Catmull-Rom. This spline passes through the control points that define the curve and smoothly interpolates between them.

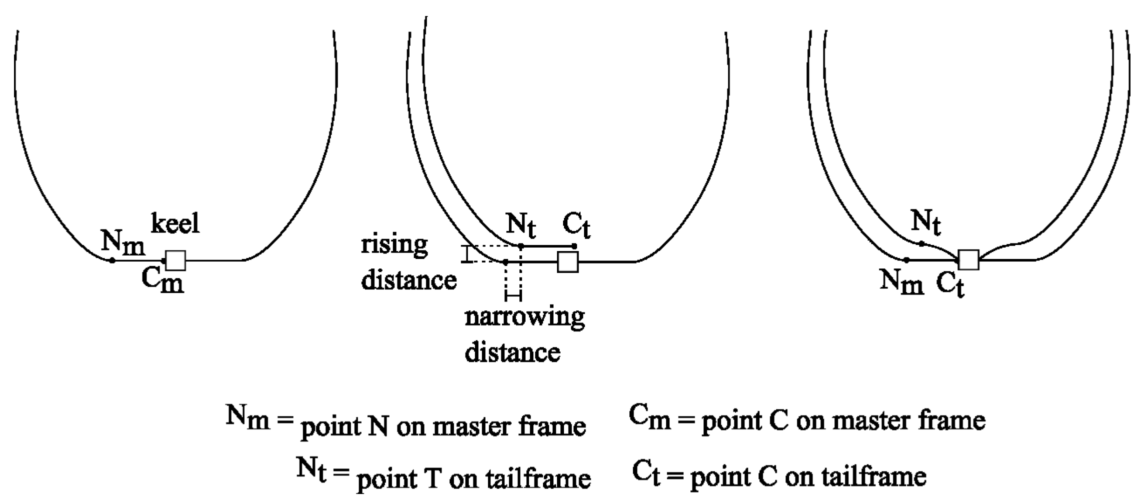

Figure 27. Rising and narrowing of Lavanha *nau*'s tailframes.

The hull from the fore tailframes forward and from the aft tailframe to the transom is not described in detail in either treatise. However, there was adequate information given in the treatise and discovered by Castro to create an educated guess as to the shape of these portions of the vessel.

For the bow, Dr. Castro provided me with the height of the *entry* which is the foremost part of the stempost that is underwater [10]. For the stern, Dr. Castro provided the height of the run which is the height of the base of the fashion pieces. These measurements were used in determining the shape of the bow and stern of the hull (see Figure 28).

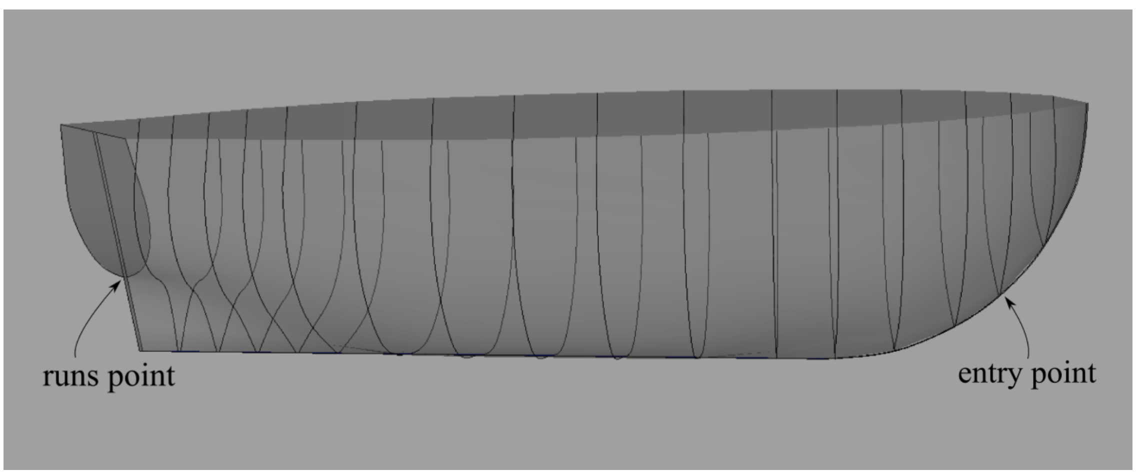

Figure 28. Run and entry points based on Oliveira *nau* hull.

For the bow of Oliveira's *nau,* Dr. Castro explained, "we would have to determine the shape by eye, but the shape of the cross-sections should be very similar to the tailframes and the master frame." I decided to represent the bow using five cross-sections. My algorithm finds the point on the stempost at the height of the entry. This point defines placement of one of the bow cross-sections. Another is placed fore of the entry cross-section, half way between the entry cross-section and the foremost point of the stempost. The remaining three cross-sections are evenly placed from the last fore tailframe to the entry cross-section. Once the placement of the cross-section along the stempost, the Z position is determined the curves of the frames that would be at a cross-section can be calculated.

A radius is needed for each of the three cross-sections between the foremost tailframe and the entry cross-section curve. To calculate these radii, the starting points for the arcs of the bow cross-sections and center of the arcs must be determined.

To determine the placement of the starting points for the arcs of the bow, the equation of a line from the starting point of the foremost tailframe to the entry point is found. This equation is used to find the X position of the starting points of the bow cross-section curves by inputting the Z values of the bow cross-sections into the equation. The Z position of starting point for the bow cross-sections curves is determined by placing them equidistant along the line (see Figure 29). Next the Y values of the bow cross-sections curves needs to be found.

To find the Y coordinates for the bow cross-section starting point, the trigonometric function discussed earlier is used (see Equation 10). The total rising is the vertical distance from the starting point of the foremost tailframe to the entry point. The height for each starting point is shown in Figure 30.

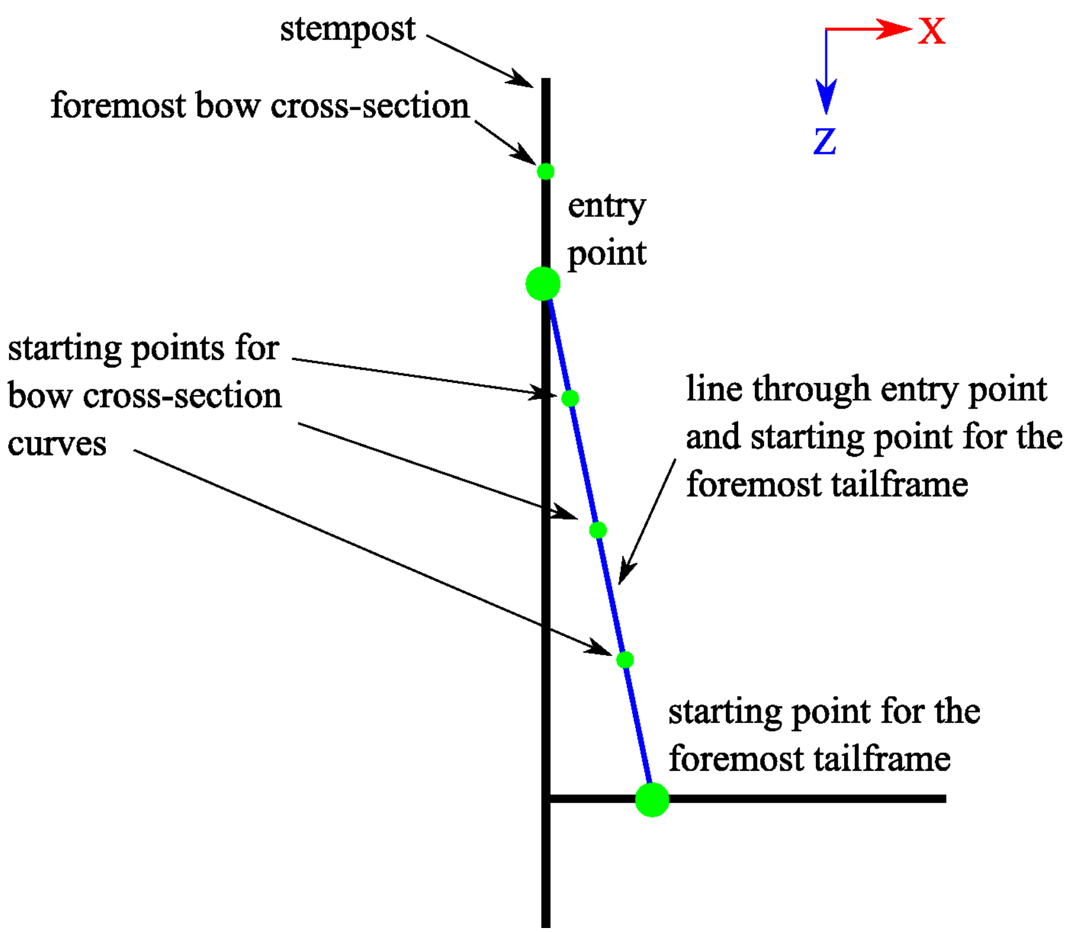

Figure 29. Starting points for bow section curves in X direction. These points are along a line from the starting point of the last fore tailframe to the entry point on the stempost.

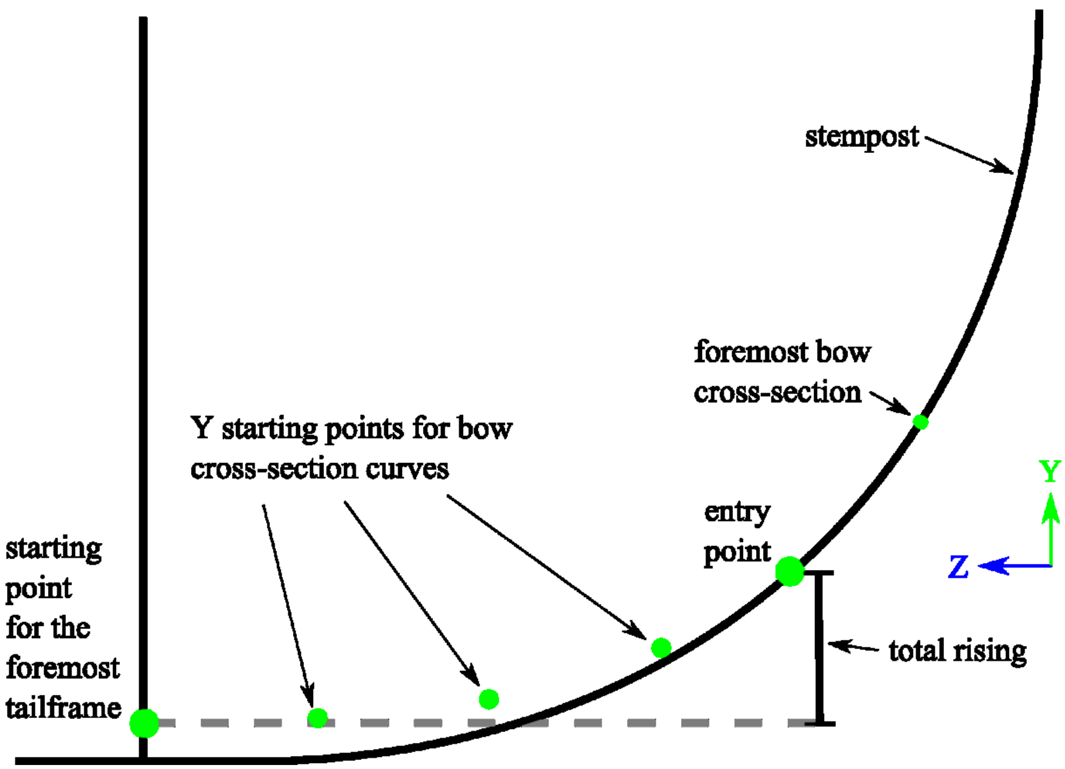

Figure 30. Starting points for bow section curves in Y direction.

The center of the arc for a particular cross-section was adjusted by eye until Dr. Castro felt it created a plausible hull shape. Then the distance from the center of the arc to the starting point of the arc is calculated. This distance is the radius of the arc. A curve is then created with a shape similar to the master frame, but with a smaller radius value. The end point of this curve is moved to lie on the stempost (see Figure 31).

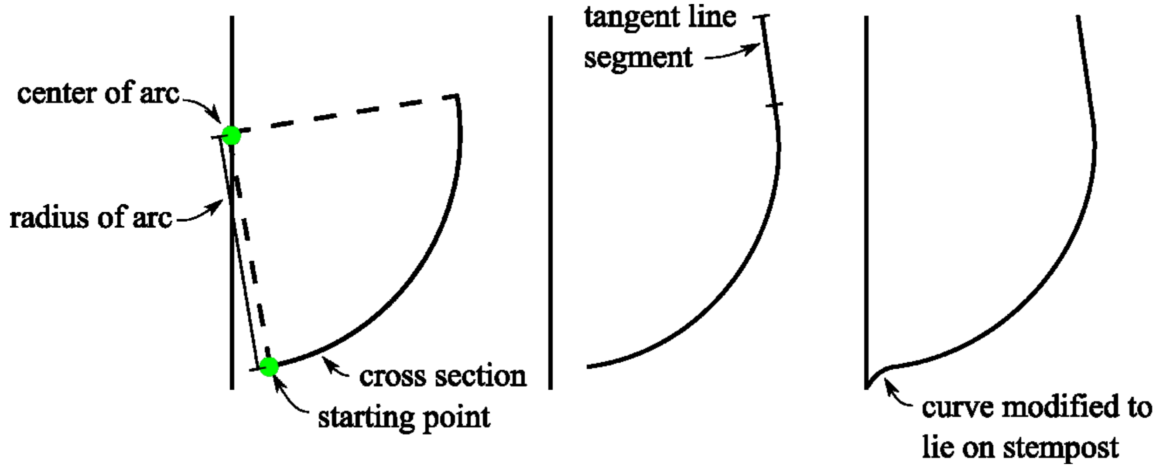

Figure 31. Front view of Oliveira bow aft of entry point.

The Z position of the foremost cross-section of the bow is placed half the distance along the Z axis from the entry point to the end point of the stempost curve (see Figure 30). To determine the radius of the entry cross-section and the foremost cross-section of the bow, the distance from the center of the cross-sections arc to the point at which the cross-section intersects the stempost is calculated. Once the radius value is found, an arc is created from the stempost counter-clockwise until it is perpendicular to the arc's center point. At the end of the arc a line is drawn tangent to the curve ending at the maximum height of the stempost (see Figure 32). Once the curves for one side of the bow were completed, they were offset by the thickness of the keel timber and mirrored.

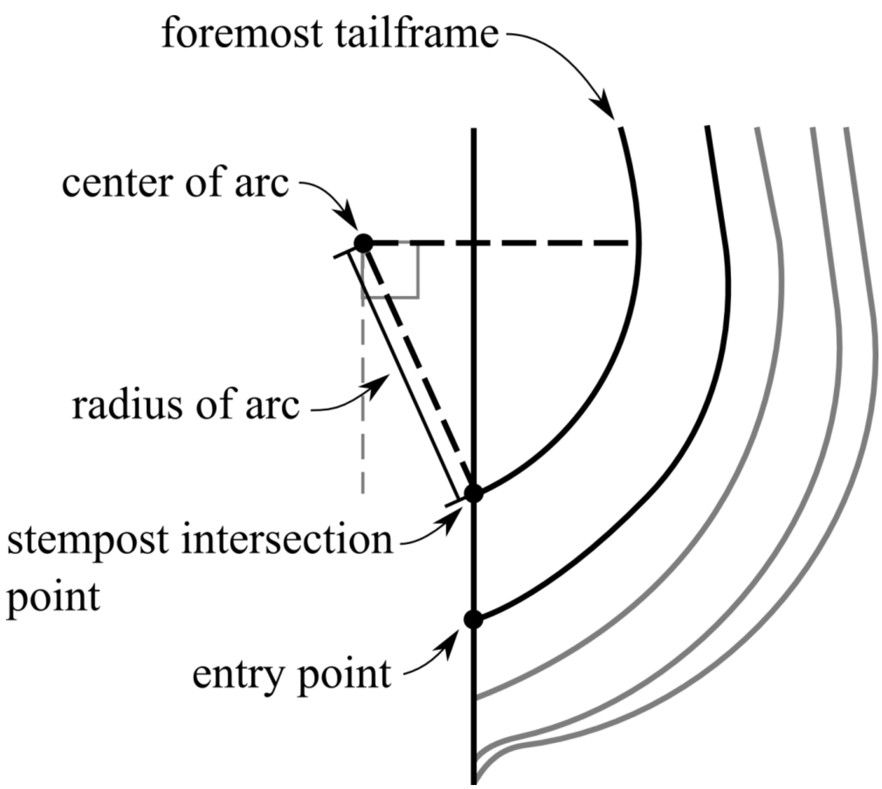

Figure 32. Front view of Oliveira bow fore of entry point. Process used to create the cross-section curve at the entry point and the foremost bow cross-section curve.

For a Lavanha *nau* the entry point is found in the same way. A curve is created from the base point of the fore tailframe line to the entry point on the stempost. This curve determines the offset from the center of the ship similar to the narrowing of the tailframes (see Figure 29 and Figure 30). The height or rising is found with a trigonometric equation (see Equation 10); the total rising being the vertical distance from the fore tailframe base point to the entry point. Once the rising and narrowing are calculated for each cross-section, the points used to create the master frame are all offset so that point N is at the rising and narrowing position, similar to the rising and narrowing of the tailframes (see Figure 27). Finally each cross-section is offset by the thickness of the keel timber and mirrored (see Figure 33).

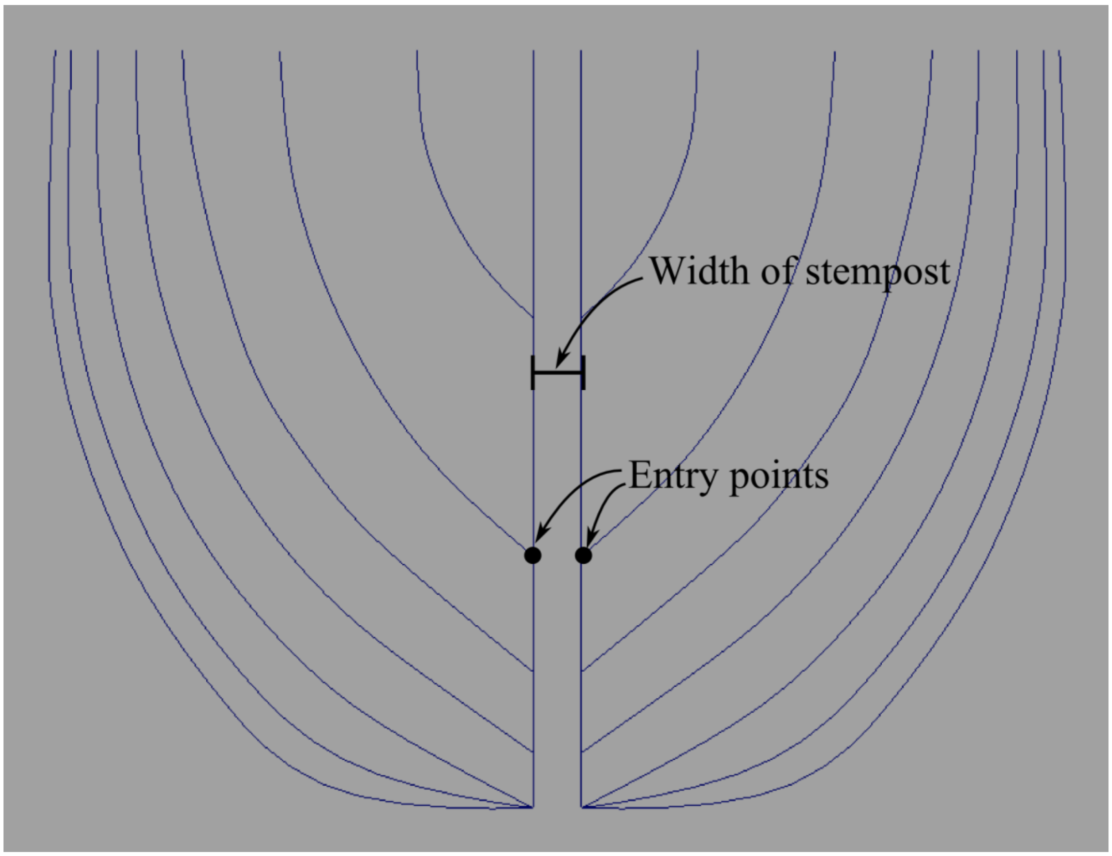

Figure 33. Front view of Lavanha bow section curves attached to stempost.

There are few specifics given for the frames from the aft tailframe to the stern of the vessel. Dr. Castro gave me some advice on how to approach the stern frames based on his knowledge of the *nau*. For Oliveira's *nau*, I used four cross-sections to represent the stern area. These cross-sections were evenly spaced from the last aft tailframe to the aft end of the keel.

I first used an approach similar to the way the bow cross-section was created, find the base point of the frames with a curve from the last aft tailframe base point to the run point, at the bottom of the fashions pieces. Later I decided to use the curve to find only the narrowing of the cross-sections. The height calculations used the trigonometric function, just as for the bow. Once the coordinates for the starting point of the cross-section curve were found, my algorithm calculated the radius of the arc. The radius for the arc of a section was determined by finding the distance from the starting point of the cross-section line to the center of the arc at height two-ninths of the keel's length. This process is very similar to that used for creating the tailframes (see Figure 25). These curves have the same general shape as the curves of the master frame and tailframes, except that they had to be modified to connect to the stempost. This connection was made by moving the end point of a Catmull-Rom spline to meet the stempost (see Figure 34).

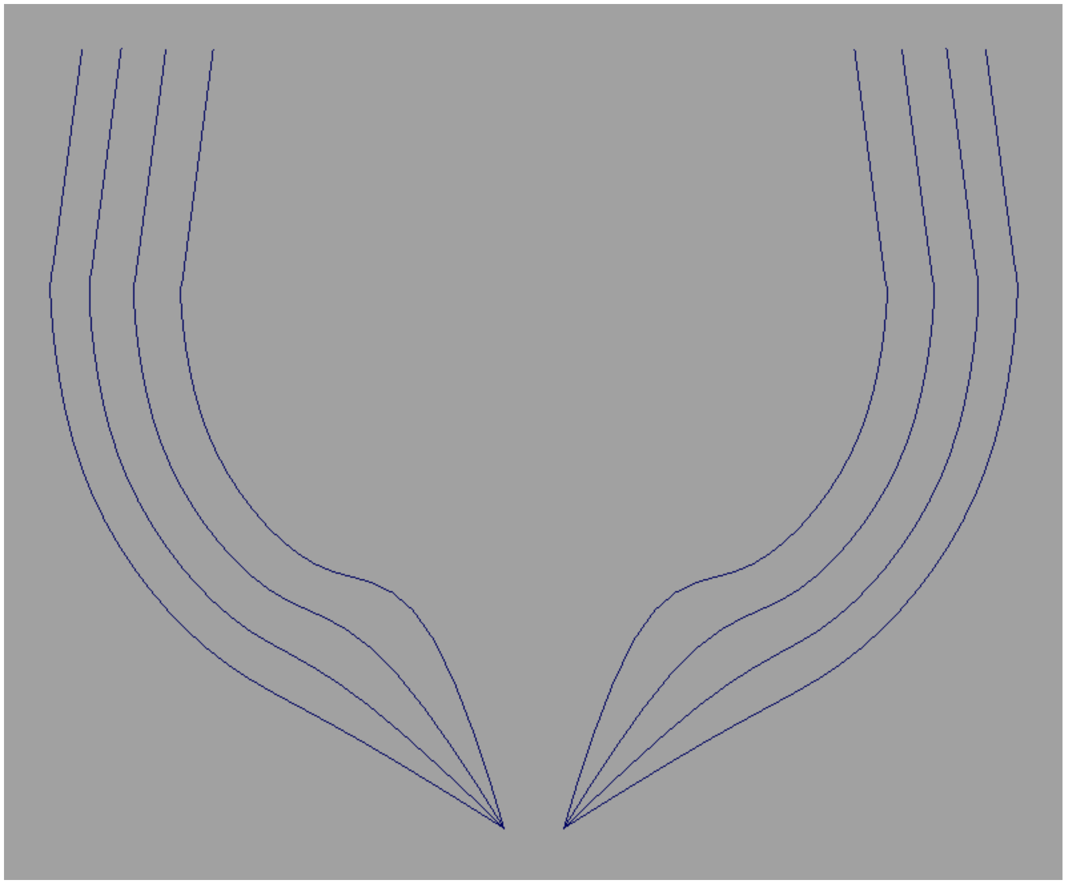

Figure 34. Front view of Oliveira bow section curves attached to stempost.

For the Lavanha approach, the starting points of the cross-sections were found in a similar manner. However, six sections are used. The total rising and narrowing for the cross-sections are from the starting point of the last aft tailframe to the run point. Once the rising and narrowing have been determined, the same points used to define the master frame are translated so that point A is at the starting point of the curve for the cross-section. The cross-section curve is then created just as for the master frame,

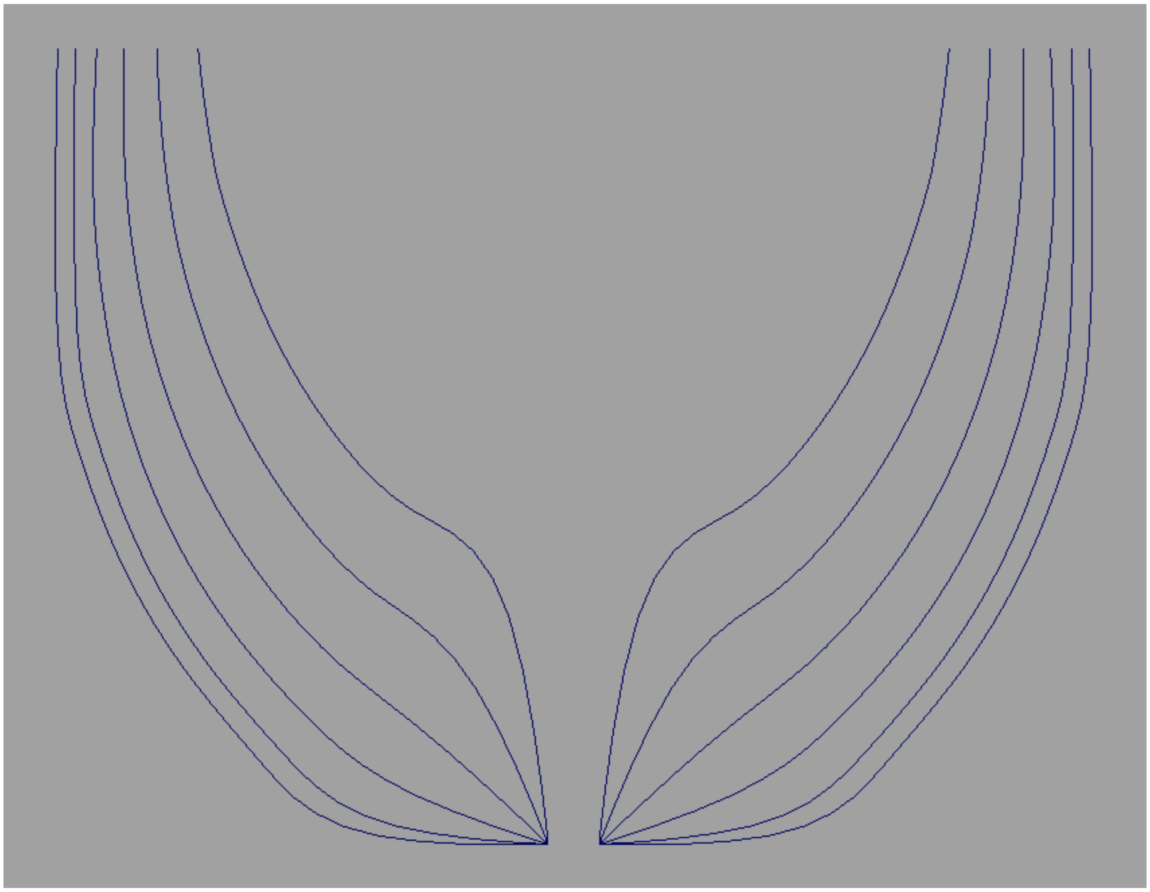

Figure 35. The stern cross-section curves of Lavanha *nau.*

except that it does not extend past the height of the transom, and the bottom portion of the curve is extended to the keel below (see Figure 35).

Hull Mesh

Once all the cross-section curves are completed, 12 points are placed along each curve. Each of these points is a vertex on the mesh that represents the hull's surface. Twelve vertexes on each cross-section were required to create a hull shape with sufficient resolution to give a good approximation to the volume of the hull. Dr. Castro and his colleagues produced the drawings in Figure 36 from their study of Lavanha's text. Figure 37 was produced from Dr. Castro's study of the Pepper wreck I compare my algorithmic model to these drawings.

Though the Oliveira and Lavanha designs are similar, there are a few noticeable differences. Lavanha's *nau* has a sharper transition from the keel to the bow (see Figure 36). The sides of Lavanha's design also do not curve back in towards the center of the vessel, whereas Oliveira's design does (see Figure 37). In general, Oliveira's design tends to create a more rounded hull.

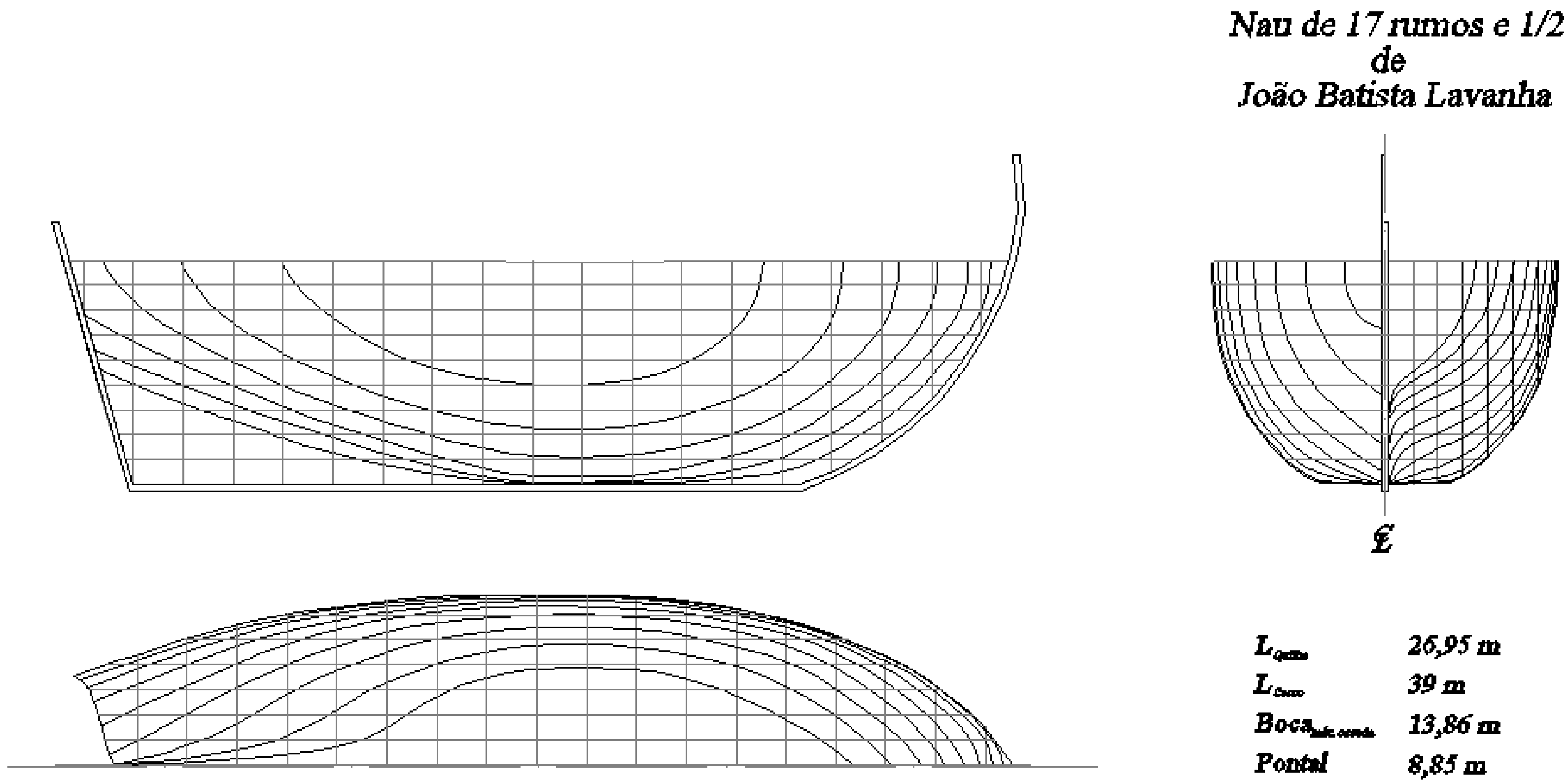

Figure 36. Reconstruction drawing based on Lavanha (Drawing by Tiago Santos) [14].

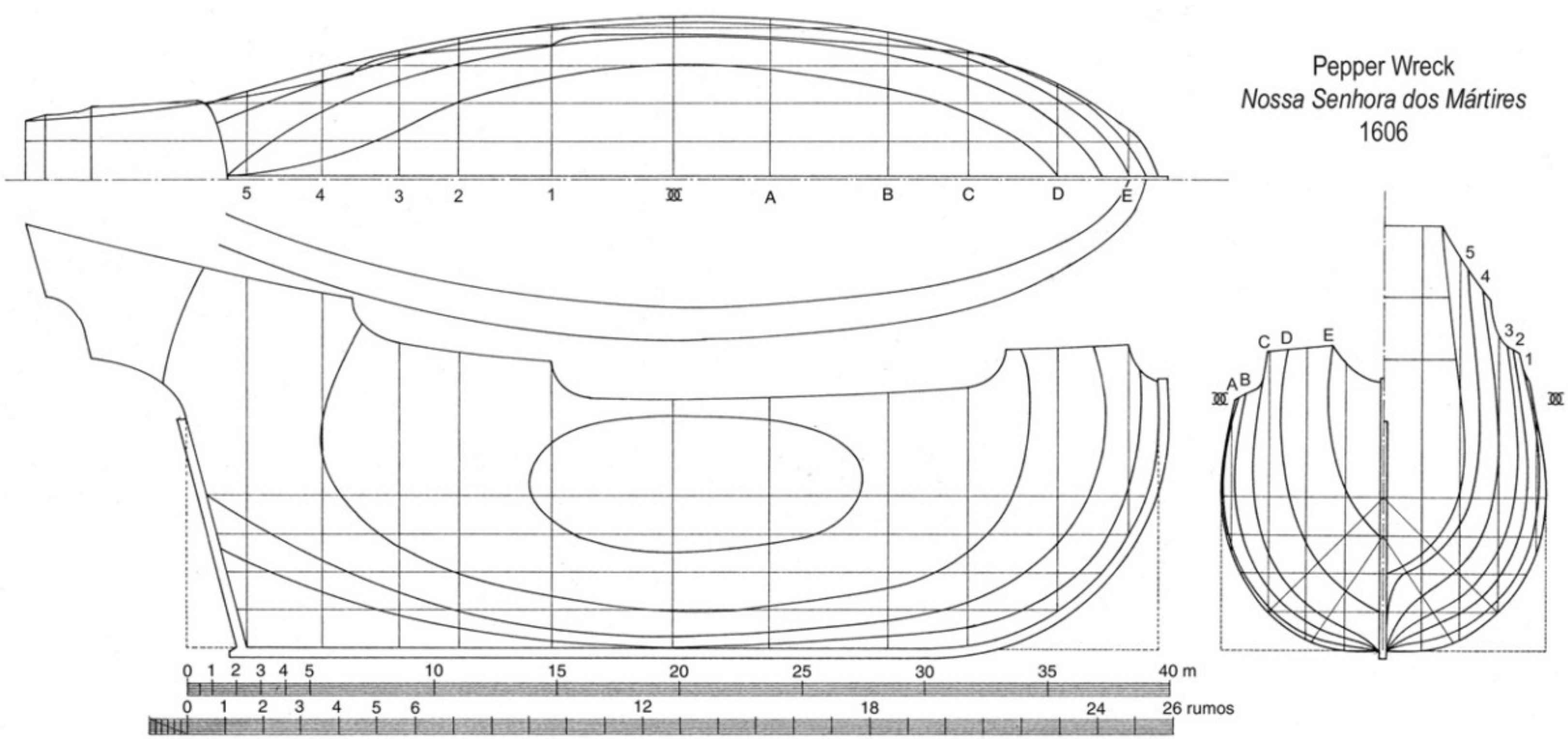

Figure 37. Reconstruction drawing based on Oliveira [18].

Parameterizing the *Nau*

Parameterizing the *nau* was a straightforward process. Many of the GUI parameters are used to change the value of a proportion used in creating the *nau* hull shape when the user selects a 'Custom' radio button. A few of these parameters are only used by one recipe. Each proportion was either a distance a frame was along the keel in the Z direction, above the keel in the Y direction or lateral distance away from the keel in the X direction. As a custom proportion or the keel length changes the cross-sections are re calculated thus changing the shape of the hull.

To understand how each parameter affects the shape of the hull, an explanation of how each is used in the hull shape calculation is needed. The primary parameter is the keel length. The GUI Keel Length slider simply controls the length of the keel for the vessel. Anytime a change is made to the keel length, the 3-D hull shape is recalculated to reflect the new keel length.

The 'Bow' parameter was not derived from either treatise; however, I found that it was needed to help adjust the shape of the hull in some cases. The 'Bow' GUI slider allows the user to set a parameter value which controls the X offset of the center for the bow cross-section arcs. This parameter allows adjustment of the shape of the side of the bow until the user is satisfied. Its default value is 1.0; if it is less than 1.0 the bow is narrower and if its value is greater than 1.0 the bow is wider.

The ‘Flat’ GUI slider is only used when the ‘Custom (Oliveira)’ radio button is chosen. This GUI slider sets the parameter that controls proportion used to determine the width of the flat of the master frame. To determine the width of the flat, the ‘keel length’ value is multiplied by the ‘Flat’ value, resulting in the width of the flat in meters. When changed, the width of the flat of the master frame is recalculated which also changes the radius used to create the arc of the master frame. The flat of the master frame also influences the width of the tailframes frames by affecting the total narrowing calculations. This in turn affects the stern and bow cross-section width.

The ‘Beam’ GUI slider is only used when creating a ‘Custom (Lavanha)’ *nau*. This slider sets the parameter that controls the proportion of the beam relative to the keel. The ‘Beam’ GUI slider is used to determine the width of the master frame by multiplying its keel length. Changing the ‘Beam’ parameter value influences the width of most cross-sectional curves of the *nau* hull, excluding the transom. The flat is also determined as a proportion of the beam width.

The ‘Transom’ GUI slider is unique to the ‘Custom (Lavanha)’ and is used to calculate the width of the transom and fashion pieces. The ‘Transom’ GUI slider sets the parameter that controls proportion used to determine the width of the transom. To determine the transom width, the parameter value is multiplied by the keel length. The ‘Transom’ parameter only affects the shape of the stern of the vessel.

The ‘Height Stern’ and ‘Rake Stern’ GUI sliders are used by both recipes to determine the shape of the sternpost and transom. The ‘Height Stern’ GUI slider controls the parameter that sets value of the proportion used to determine the height of the sternpost. To find this height, the parameter value is multiplied by the keel length. The ‘Rake Stern’ GUI slider is used to set the parameter that controls the proportion used to determine the rake of the sternpost. The rake of the sternpost is found by multiplying the parameter value by the length of the keel. These parameters also control the height and rake of the transom and fashion pieces as they are aligned with the sternpost. The ‘Height Stern’ is also used to determine the height of the weather deck which is also the maximum height for the entire hull shape.

The ‘Run’ and ‘Entry’ GUI sliders can be adjusted for either recipe. The ‘Run’ and ‘Entry’ heights are also determined by multiplying their values by the keel length. The run is placed along the sternpost, and the entry is a point on the stempost. The ‘Run’ parameter changes the shape of the fashion piece at the stern of the vessel and affects the total rising of stern frames, aft of the tailframes. Similarly, the ‘Entry’ parameter is used to determine the height of the entry on the stempost and influences the shape of the cross-section curves of the bow.

The ‘Spring Bow’ and ‘Height Bow’ GUI sliders are only used when the ‘Custom (Lavanha)’ radio button is selected. The ‘Spring Bow’ controls the parameter that sets the proportion used to determine the position of point E for the bow (see Figure 11).

This parameter affects the amount the bow curve juts out past the fore end of the keel. The ‘Height Bow’ parameter sets the parameter that controls the proportion used to determine the bow curve height at point F (see Figure 11). By multiplying these parameter values by the length of the keel, the height or spring of the bow is calculated. The user should not set the ‘Height Bow’ parameter less than the ‘Height Stern’ parameter; however this is not enforced. This is because point F, which is the end of the bow arc, must be at least the same height as the weather deck, which is calculated based on the ‘Height Stern’ parameter.

The ‘X Fore Tailframe’, ‘Y Fore Tailframe’, and ‘Z Fore Tailframe’ GUI sliders all determine the foremost tailframe cross-section positions. The ‘X Fore Tailframe’ sets the parameter that determines the proportion used in calculating the distance of point N from the keel for the foremost tailframe cross-section (see Figure 21). ‘Y Fore Tailframe’ GUI slider controls the parameter that is used in determining height for point N of the same curve. The ‘Z Fore Tailframe’ GUI slider sets the parameter that is used to determine the cross section’s distance from the stern of the vessel along the keel. To calculate these values, parameters are multiplied by the keel length. These parameters are used to set the total rising and narrowing of the fore tailframes and influence the hull shape. The value of the ‘Z Fore Tailframe’ GUI slider is multiplied by the keel length to determine the total narrowing of the fore tailframes. The total rising is obtained by multiplying the value of the ‘X Fore Tailframe’ GUI slider by the length of the keel.

The GUI slider ‘X Aft Tailframe’, ‘Y Aft Tailframe’, and ‘Z Aft Tailframe’ are similar to those used for the fore tailframe. They are used to find the width, height and distance from the stern for the aftermost tailframe. These positions are also calculated by multiplying the GUI slider values by the length of the keel.

CHAPTER V

CONCLUSION

The first goal of this project was to generate a virtual parametric model of plausible *nau* hull shapes. The second goal was to use this virtual model to determine the actual displacement of the hull shape and to compare it with the registered tonnage of the hull according to eight different formulas from the 16th century.

Results

I have developed a parametric model that produces plausible hull shape based on two recipes for the construction of ship type from the 16th century. I can vary the basic dimensions of this model to create plausible representations of hull shapes based on historical documents. My model takes data input using a GUI and produces: (1) the registered tonnage of each hull model calculated according to eight different formulas dating from around 1600, (2) the volume below each deck, and (3) the displacement for a generic water line placed at three-fifths of the total depth of the hold.

Because an intact *nau* shipwreck has not yet been discovered, multiple sources of data were compiled to determine *nau* hull shapes. Dr. Castro created composite drawing of *nau's* hulls that take into account his personal knowledge of the *nau* and the research he had done on both *nau* construction recipes (see Figure 38 and Figure 39). The hull shapes from my model are compared with these drawings.

Evaluation

A primary goal was to make the *nau* hull shapes generated by my algorithm closely match the drawings provided by Dr. Castro. As I worked on my algorithm, I compared the hull shape to these drawings many times and discussed with Dr. Castro how well they matched. Once he was satisfied with the hull shape, I knew my model could then be used to approximate the volume of the *nau*'s hull.

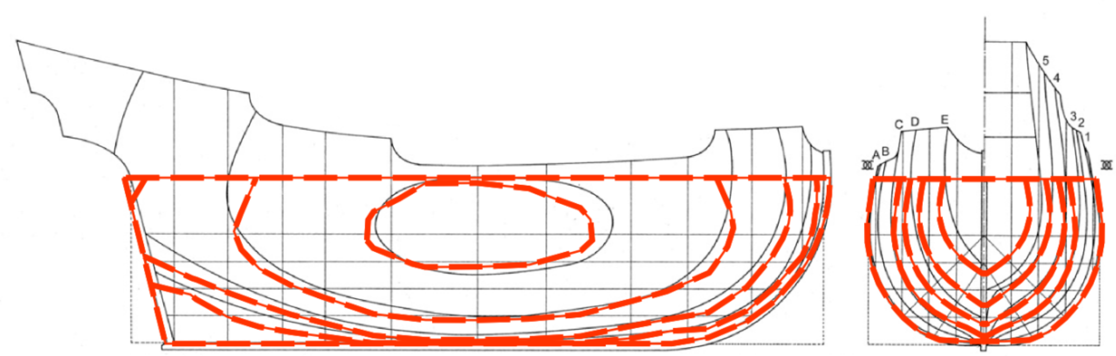

Figure 38. Oliveira hull contours comparison. Comparing the contours of 2-D drawings of Oliveira's *nau* and contours of the 3-D model generated. My contour lines are the red dashed lines, and the black lines are Castro's.

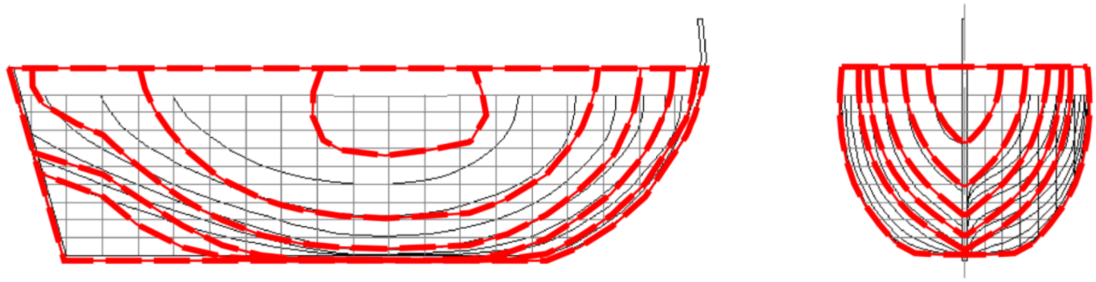

Figure 39. Lavanha hull contours comparison. Comparing the contours of 2-D drawings of Oliveira's *nau* and contours of the 3-D model generated. My contour lines are the red dashed lines, and the black lines are Castro's.

To evaluate the second goal, we decided to use my algorithm to create ten hull shapes. We used data for five vessels taken from historical documents. The measurements used as parameters to create the virtual *naus* were provided by Carla Rahn-Phillips [10], [13]. This information was used to create two hull shapes for each vessel. The hull shapes for each vessel were generated using both the Oliveira and Lavanha recipes. The length of the keel, flat, and beam were used to determine the basic parameters for the *nau*. After this data was entered, I used the GUI to manipulate the other parameters until a plausible hull shape was produced that Dr. Castro approved. Then the registered tonnage was calculated for each of the three decks and at the waterline. Multiple .OBJ files were exported for each hull shape. An .OBJ was exported to represent the volume under each of the three decks, the volume under the vessels waterline, and the total volume of the vessel at the weather deck. The .OBJ files were then imported into Rhinoceros 3D where the volume was calculated in cubic meters.

We have calculated the capacities obtained by the application of each of the formulas for the uppermost deck and compared them with the displacements for a draft of 3/5 of that height.

In the five cases tested, we found that the relationship between actual displacement and registered tonnage were close to 2 to 1, with variations that were influenced by politics. The kings changed the registered tonnage formulas constantly trying to balance the value of the tariffs collected as a percentage of the registered tonnage and the total capacity of the vessel. We found the hull shapes generated with my algorithm had block coefficients between 0.43 and 0.58. These block coefficients and displacements very close to the values found archeologically or described in contemporary documents. Although the displacement obtained by these formulas are plausible and consistent with other known the block coefficients, some of the values obtained for the Oliveira model seem a little high. Dr. Castro believes the difference in the registered tonnage and the volume of the hull was because half the capacity of the vessel was generally used to hold trade goods, and half for the crew and ship equipment. Also, these variations were influenced by politics. The kings changed the registered tonnage formulas constantly trying to balance the value of the tariffs collected as a percentage of the registered tonnage and the total capacity of the vessel.

Table 3. Oliveira *nau* data.
Table of the values gathered for five Oliveira *naus*. 'RT' stands for 'registered tonnage' in the table below.

	Bertandona	Basque whaler 1600's	Pepper Wreck	P. Menendez	Basque 1577
Keel length	17.83	17.83	27.72	17.6	18.98
Displacement	412	464	1528	408	552
RT Formula 1	218	240	826	219	289
RT Formula 2	259	289	979	262	346
RT Formula 3	278	307	1053	279	368
RT Formula 4	259	289	980	262	346
RT Formula 5	141	218	541	153	260
RT Formula 6	210	212	789	201	255
RT Formula 7	175	218	670	188	260
RT Formula 8	325	362	1229	328	434
% of registered tonnage Formula 1	52.9	51.7	54.1	53.7	52.4
Block Coefficient	0.58	0.59	0.57	0.57	0.58

Table 4. Lavanha *nau* data.
Table of the values gathered for five Lavanha *naus.* 'RT' stands for 'registered tonnage' in the table below.

	Bertandona	Basque whaler 1600's	Pepper Wreck	P. Menendez	Basque 1577
Keel length	17.83	17.83	27.72	17.6	18.98
Displacement	349	347	1288	287	439
RT Formula 1	232	232	873	188	299
RT Formula 2	277	277	1039	217	358
RT Formula 3	296	296	1113	240	381
RT Formula 4	278	278	1044	218	360
RT Formula 5	238	238	893	244	295
RT Formula 6	175	175	658	79	240
RT Formula 7	238	238	893	244	295
RT Formula 8	348	348	1308	273	450
% of registered tonnage Formula 1	66.5	66.9	67.8	65.5	68.1
Block Coefficient	0.49	0.49	0.43	0.5	0.48

The information on how Lavanha created the stern portion of his *nau* is very limited. We do not know how shipwrights solved this in the early 16th century. Dr. Castro felt that this lead to values of the displacement being consistently smaller than for an Oliveira *nau* generated by my algorithm. He expected the hull volumes for each recipe to be closer in value than my results demonstrated (see Table 3 and Table 4). For the purpose of this study, the possible error in shape of the stern was considered unimportant because the relations between values of displacement, internal volume, and registered tonnage calculated within each recipe was under analysis, not the comparison of the values gathered between the two recipes.

Future Work

I believe that this project demonstrates a new way to recreate and study the 16th century *nau*. In the future modifications and improvements can be made to make this algorithm more inclusive and powerful. This project may also inspire parametric models in other fields.

This project could be expanded in several directions. One would be to develop a model with greater detail. This could include more than just the hull shape by adding for example the masts, decks, and rigging. Another possible direction would be to include other ship types in the model. Other similar ship types could be created by adapting the algorithm based on other construction guidelines.

Though not all shipbuilding manuscripts are ideal for conversion into a parametric algorithm, there are many manuscripts that could be studied to determine whether they are good candidates. Once algorithms for other ships are developed, they could be compared to my algorithm for the *nau* to help understand the differences between them. This would allow researchers to explore differences in hull shape and group ships together into families of similar hull design. It is hoped that with the flexibility of my model and future findings either from shipwright's construction methods or the discovery of new shipwrecks, an even more accurate depiction of the *nau* vessels will be determined in the future.

Instead of the idea of proportions, one could modify my approach and choose to let the user directly input size and positions for certain parts of a vessel. For example, a shipwreck might be found in which an archeologist could determine the maximum beam of the vessel. If the user could input that width directly into an algorithm, then choose between the recipes, the user could quickly determine if the ship's remains were similar to Lavanha, Oliveira or represents a totally different vessel type. An advantage to this approach is that the size of a given element could be used instead of finding its proportion to the keel.

Another possible modification would be to implement the model with other software. If my implementation had been within a program other than Maya, volume may have been more easily calculated. Currently the algorithm creates a 3-D hull shape file which must be exported from Maya and imported into another program for the volume to be calculated. Implementing the algorithm within a program such as Rhinoceros would allow the user to directly determine the volume.

As it is, my model allows researchers to calculate interiors volume, for hull displacements for different waterlines and hull coefficients.

In future development of this project, it might be possible to reduce the complex surfaces of a hull shape to a small number of equations describing the hull shape. Also, this project could perhaps be extended to evolutionary studies of hull shapes through time.

The idea of a parametric algorithm to define artifact shapes could also be used in other disciplines. This idea could be of interest to archaeologists, historians, and naval architects, as well as professionals in many other fields of study.

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APPENDIX

This appendix contains a description of each file that was used to complete this thesis and is available for download along with the thesis document. The file name is underlined and followed by its description below. Feel free to email me with comments or questions at koocsutsuj@yahoo.com.

README.txt: A text file that gives instructions on the setup and use of the Maya Python script file (Nau.py) and the Maya scene file that it manipulates (Nau.ma).

Nau.ma: A Maya Ascii scene file that contains the hull model of the *nau* and is manipulated by the Maya Python script file (Nau.py). For more information on using this file please look in the README.txt.

Nau.py: A Python script that contains Maya commands that are used to manipulate the Maya scene file (Nau.ma). For more information on using this file please look in the README.txt.

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