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Block Construction of Small Ships and Boats Through Use of Developable Panels

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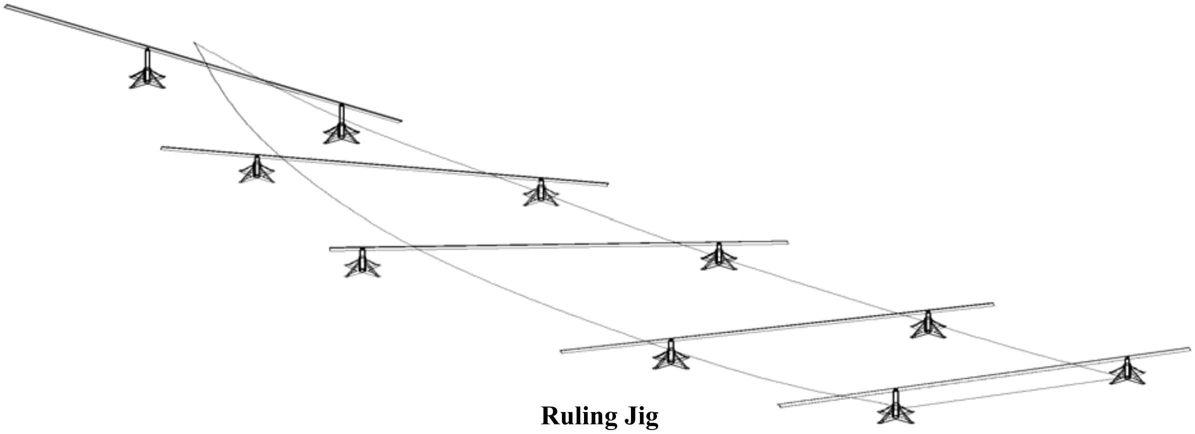

Ruling Jig

ABSTRACT

The authors propose a simple method to improve productivity for construction and subsequent outfitting of typical hard chine boats. This method uses CAD/CAM definition of the structure to manufacture the bottom and sides, decks and bulkheads of the boat as independent panels. The system divides such craft into construction modules by surfaces instead of by blocks as in standard shipbuilding practice. Since all of these panels are developable, an adjustable jigging system supports them essentially horizontally on their rulings. Transverse stiffeners are then welded to the panels. The system and details are optimized for maximum use of down hand welding and weld pacers. This system, however, requires specialized software to develop piece parts and to efficiently derive these modules from the product model.

The developable panels can be outfitted with machinery, foundations, piping, wiring and insulation. Bottom and side panels can be tipped up, joined and more outfit installed in stages optimized for lifting and ready access. The deck is built and outfitted inverted, and then joined to the open hull. The bulkhead details and deck framing are also optimized to allow ready outfitting and subsequent joining of the deck as a unit. The easy access to the panels also allows effective, low cost surface preparation and painting, so this system has benefits for both steel and aluminum construction.

The views and opinions expressed herein are those of the authors and are not to be construed as official policy or reflecting the views of the U. S. Coast Guard or the Department of Transportation.

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INTRODUCTION

Small ships and boats such as crewboats and fishing vessels are frequently distinguished by two contrasting factors relating to producibility.

First, they are often developable hull forms. This reduces forming labor and allows neat plate cuts without having to account for or control a distortion process for forming the plates. This saves labor.

However, advanced outfitting techniques frequently are not used for these vessels, especially smaller ones. They are often "stick built" as one single block or module, or at most two, the hull and deckhouse, and are generally structurally complete prior to any outfitting, or perhaps even any painting. This, unfortunately, costs a great deal of extra labor.

Though Leake and Calkins (1996) and others have advocated more extensive use of block construction for small ships, it is still relatively rare, especially for vessels under about 30 meters or so.

The authors decided to develop a technique for constructing developable hull forms that will enable easily accessible block construction, painting and outfit using what, in retrospect, are the obvious places to divide the ship into blocks; the chines and other joints between the surfaces. The outfitting of these "surface blocks" is a natural option, since in most cases machinery and outfit in small ships is mounted on one of these surfaces rather than in the self-standing internal blocks found in large ships.

GOALS

Our goals in developing this technique were:

- Maximum pre-construction and shop construction of structural components
- Maximum use of Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC)
- Maximum use of automated welding techniques
- Maximum use of downhand welding
- Maximum use of advanced outfitting
- Minimum use of large scale special equipment

It is important to emphasize the early work, both in terms of maximizing shop construction and advanced outfitting. Shipbuilding theory says that productivity decreases 40% for each standard construction stage a task is delayed. This is because early stage work in shop conditions is usually done in better conditions, requires less travel for the workers, tools, and materials to get to and from workstations, requires less staging and other preparation and because work aids including both automated machinery and lifting and positioning equipment are more available and productive. Early work also allows increased parallel and out of sequence work. Parallel work allows more workers access to the work without adversely impacting productivity. This in turn allows faster construction, which reduces delivery times, allows better productivity of capital and improves market agility. Out of sequence work allows workers to pre-make components that may not be required until later. Though this may increase the capital invested in the boat at an early stage, it reduces the workload fluctuation, eliminating the need to lay off workers or hire them. Shop construction also allows for better environmental controls and improved worker safety and health. It is also worth noting that virtually by definition almost all welding is down hand in this system.

The authors would like to note that their experience is in the AutoCAD environment using the Ship Constructor system (which includes ShipCAM as a primary hull definition tool). This paper discusses some specific techniques in terms of this software and its nomenclature as an example, but the authors recognize that other packages have similar features and capabilities.

BACKGROUND

This system evolved from a technique common in the US Pacific Northwest, "free-forming". Free forming is simply building the boat "outside in", without lofting. The bottom shell plate is cut to a shape that the builder assumes will result in an acceptable hull shape, generally by use of small cardboard models. The two bottom plates are set in a "deadrise" jig, consisting of a series of wood vees set to the deadrise at each station and the keel joint is welded up. The plates are pulled and pushed until they "look right". Internal framing and the subsequent side plates and deck are templated off the hull. The resulting boat is not exactly the shape that was originally intended, but is generally "close enough for fishing".

Some builders in the Pacific Northwest switched directly from this "no-lofting" process to Computer Aided Lofting/Numerically Controlled Cutting, beginning in the early 90's with increasing levels of sophistication (measured by the amount of precut material).

Victoria Ship Yards, Victoria, B.C., Canada is one such builder, and recently built a series of three 22 feet patrol boats using the CAD/CAM free forming method. The parts manufacturing was done with a CNC high speed milling method, with all parts derived from a 3D product model, including the developed shell plate and substantial amounts of non-metal material for outfit. None of the parts had any allowance for trimming.

The parts were assembled without the use of jigging. The bottom shell plates were joined at the keel starting from the aft end. While doing so the plates naturally form the correct shape because the 3D model was a nearly true developable surface, and the desired shape represented the minimum energy solution for the cut plates when constrained on the keel and chines. Installing longitudinal stringers, frames, hull sides, and decks at the marked positions follows this stage. The entire hull was tacked together, stitch welding was performed in selected places to lock in the shape and the hull was welded out. A comment by Victoria Shipyards foreshadowed the next step: “This approach to engineering and manufacturing will also work well in larger programs where modular construction is used”.

DEVELOPABLE SURFACE BLOCK CONSTRUCTION

The proposed system is as follows:

- All parts are precut using standard Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC) techniques.
- The boat is subdivided into blocks, each comprising a major surface, i.e. the port bottom plate, the port side plate, etc. Some grand blocks are also designated, mainly the two bottom plates together, the entire hull below the deck and the entire hull.
- A jig is made of angles set up on jackstands for each surface. The angles run along selected rulings of each surface determined during the lofting process. Other jigs are built for the deck and other flat surfaces.
- Other small jigs can be developed as required for assemblies (such as edge stiffened webs) to be installed on the surface blocks
- The developed plates are set on the ruling jig, and the longitudinal and transverse stiffeners are installed.
- Foundations and brackets for outfit that will be connected to that surface are installed.
- The welded out surface is blasted, primed and optionally finish painted.
- Outfit components are mounted on the surface blocks up to limits implied by the need to lift and tilt the block.
- The bottom surfaces are joined to the form the first grand block and all machinery bearing on the bottom is installed as convenient. Appropriate parts of the bulkheads can be installed at this point and subsequently.
- The sides are joined to the bottom and appropriate outfit and bulkhead parts are installed.
- The pre-outfitted deck is installed.
- The pre-outfitted deckhouses are installed.

DEVELOPABLE SURFACES

Since this system depends on developable panels, (as does much boat and small ship construction) it is worthwhile to review these surfaces. This has become especially important with the use of CAD/CAM, because although computers can find mathematically developable surfaces, they may not be the surfaces we desire.

A developable surface has “zero Gaussian curvature” (Faux and Pratt, 1981). That is, the product of the greatest curvature and the least (the principal curvatures) is zero. This implies that at least one of the two curvatures is zero, a straight line. These straight lines are the rulings in the surface and connect the two defining edge curves (chines) of the surface. (Note that “chine” is conventionally used both to mean any edge of a developed surface as well as specifically the joint between the bottom and the side.) However, containing rulings is not sufficient for a surface to be developable. The rulings have to be one of the principal curvatures. A hyperboloid of revolution is a useful example. This surface is formed by connecting evenly spaced points on two coaxial circles such that the points are not coplanar with the mutual axis. There are rulings at every point on the surface. The greatest curvature at any point is the hyperbola formed by a section through the surface containing the axis, but the least curvature is the circle in a plane perpendicular to the section, not the rulings. It has a (numerically) large negative curvature. The Gaussian curvature is thus non-zero. Non-developable surfaces containing rulings are “warped” and have negative Gaussian curvature. In order to be developable, any two adjacent rulings must be co-planar. We can convince ourselves of this by putting three rubber bands on two parallel pencils. If we twist the pencils relative to each other, note that the bands at the two ends stretch more than the middle, despite the fact that the surface is composed of rulings. This stretching violates a practical definition of developability: A surface that can be plated from flat sheet material without stretching the material.

If two lines are co-planar, they define a plane and thus must either be parallel or intersect. The latter condition gives rise to the name “conical surfaces”, and the former is a general cylinder. In the latter case, it is important to note that it is only necessary that each pair of adjacent rulings intersect.

Most computer programs use a different process, however. If we take two rulings, we can test them for co-planarity by taking the vector cross product of the ruling and the line connecting one end of the ruling with the adjacent end of the other ruling (i.e. the next point along the chine). The result is a vector that is perpendicular to the plane formed by these two lines. The similar vector cross product at the other end of the ruling also forms a perpendicular to the plane containing these two lines. The vector cross product of these two vectors in turn should be zero if these two vectors are parallel. If this is the case, both of the previous planes are also parallel, and since both contain the ruling, they must be the same. If they are not parallel, the warp angle between the two rulings is simply the arctangent of the absolute value of the cross product divided by the dot product.

A computer program for finding developable surfaces seeks a minimum warp angle at each of a series of many points along each chine, generally by simply trying each possible pair of rulings. This process can be duplicated easily with a spreadsheet program such as Excel and can be instructive. Nolan (1971) discusses this process and gives a typical search algorithm to find the ruled surface.

One problem occurs when there is no absolutely developable surface between two proposed chines, which is often the case. Fortunately, in practice, metal can stand a warp angle on the order of six degrees or so. Standard strength analysis methods can be used to calculate the tensile stress resulting from a given warp, but a six degree warp generally is approaching the yield of most aluminum alloys and requires a force of a couple of hundred pounds or so on one corner of the plate. However, admitting any amount of warp other than zero means that the quasi-developable surface is no longer unique. Though there is at most one true developable between two chines, there are an infinite number of warped ones. We can see this by returning to the example of lines between two circles. The true developable is the cylinder, with all rulings parallel. However, by allowing warp, even if we require constant skew angle, there are an infinite number of more or less wasp-waisted hyperboloids between the two circles.

Algorithms that simply seek a minimum amount of warp will generally produce some sort of dihedral surface. Looking at the simple case of two skew lines, a surface with zero warp is two sets of rulings, one set originating at the end of one line radiating fanwise to points distributed along the length of the other line, and the other set of rulings forming a similar fan from the opposite end of the other line. The resulting surface is two flat planes joined by a corner along the diagonal connecting the opposite ends of the lines and is certainly not fair.

Another problem for computer algorithms occurs when one chine is “shorter” in the sense that it contains less of the developed surface that the other. The simplest example of this is two co-axial arcs with one subtending a smaller angle than the other. The true developable is a portion of a right circular cylinder. However, the rulings beginning at the larger arc don’t all end on the smaller arc. Some end on a partial helix connecting the two ends. Unless this helix is defined and designated as part of the shorter arc, the algorithm will either fail, (end the surface with a fan from the short arc) or produce a partial hyperboloid instead of a partial cylinder.

Although these are pathological cases, computer programs commonly produce similar bad surfaces, especially with lower speed boats with chines non-parallel to the keel. The desired surface for such craft usually has some curvature in the sections aft, and though it is developable, it must generally be forced.

Software must allow user control of the search process to get the desired surface. One program, ShipCAM, has user set controls on maximum allowable warp and maximum allowable fanning. This latter value essentially expresses the angle between the first ruling originating at a point and the last.

To develop a surface, the surfacing algorithm begins a ruling search at the beginning of a designated chine comprising a large number of points. Let them be designated as i_1 through i_n on one chine and j_1 through j_n on the other. The user has already determined the number of points comprising the chines and their distribution along the chines. The first ruling connects the two adjacent ends of the designated chines i_1 and j_1. There are three possible following rulings; i_1 to j_2, i_2 to j_1 and i_2 to j_2. The “best” next ruling is found by examining these three possible rulings and some subsequent ones. Based on the warp angle and the fanning angle, the algorithm selects one of the three and repeats the process down the length of the chine.

Increasing the “fan” setting increasingly inhibits the algorithm from selecting several rulings “fanning” from the same point, (i.e. the series j_1-i_1, j_1-i_2, j_1-i_3, etc.) and setting the fan high enough forces the algorithm to always connect the j_{nth} point on one chine to the i_{nth} point on the other. If a ruling cannot be found that satisfies the fanning criteria and does not exceed the warp limit, the algorithm selects the best fit, designates that portion of the surface as “warped” (by changing the color of the rulings) and proceeds to the next point.

The user must often try various combinations of fan and warp settings to get the desired surface. In addition, the user can change which end the algorithm starts with and the density and distribution of points on the chines (the program can place more points in areas with tight curvature). In the common case of a short chine as above, the chines can be arbitrarily extended. By adjusting parameters, the bad fans can be forced onto the extended portion of the surface. This portion can be trimmed away, or the curve forming intersection of the surface and the desired end can be added to the short chine. (This also requires that the software be able to add a hard breakpoint that the search algorithm can span where the short chine meets the new curve.)

Despite this, it is still common to be unable to find a satisfactory surface. This is especially the case when the designer has not preserved the rulings and desired sections, butts, and waterlines are depicted. (Here, the authors would like to make the case for preserving ruling data in contract drawings. It not only makes life easier for the lofter, but also preserves the designer's intent.) In this case, old-fashioned techniques can be used to help find a good surface; though use of 3D CAD makes the old fashioned techniques much easier.

What is often called "Rabl's Method" (1958) is based on the fact that if two rulings intersect, they are by definition co-planar. There are two variants of Rabl's method. In the "conic" case, all rulings intersect at a single point. In the other "multi-conic" method, each ruling only intersects the adjacent one. In this case, the first ruling and second will intersect at one point, but the third will intersect the second at a different point along the second. Many lofting and design texts give details of these techniques for two-dimensional drafting, but they are very simple in any three dimensional CAD system, since the tedious projection of intersections and rulings from one view to another is eliminated. The exact techniques will vary according to the software in question, but, for example, note that AutoCAD will allow the user to drag a whole series of rulings at one intersection point by using the "grips". In the conic method, this speeds up the process of repeated guessing at a single intersection point that produces the desired surface.

If a desired hull form has been designed with sections, waterline and butts, the approximate rulings for a multiconic development can be found by trial and error in three dimensions. Assume a ruling from a chine to a point on a section, waterline or butt, and then extend it to meet the other chine. It will probably miss, but when it is close enough, it is a local ruling. Repeat the process for another ruling and then extend them to meet each other. Again, if they are close enough, the surface is approximately developable.

Another technique is a three-dimensional variant of the Kilgore (1967) method. In orthographic, two-dimensional drafting, the details are quite tedious, but the core of the method is simple: The tangent line at a point on one chine is found and a plane containing the tangent is assumed. Then the other chine is examined to determine where it is tangent to the plane. In practice, the chines are faired in ShipCAM and transferred to AutoCAD in 3D. Once in AutoCAD, select a point on one chine and assume a ruling. Place a User Coordinate System (a coordinate system located and oriented as desired) with the X-axis along the ruling and a point adjacent to the selected point in the XY plane (this is the "3 point UCS" option). This is a plane containing the ruling locally tangent to the chine. Rotate the UCS 90 degrees around the Y-axis. This places the ruling in the Z-axis with the local tangent to the chine on the X-axis. Change the viewpoint to "Plan". This results in a view looking down the ruling with the local tangent either exactly vertical or exactly horizontal. The actual point on the other chine, which is tangent to the originating chine, can generally be found by inspection. Then draw a ruling from the local UCS origin to the tangent point. It is wise to repeat the process on the new ruling to ensure that the change of viewpoint doesn't change the tangent point, but the actual process takes about twenty seconds.

Once several approximate rulings are found, they can be transferred into ShipCAM and used to break the chines into segments. Since each segment will begin and end on a desired ruling, the algorithm will (perhaps with a bit of prodding with warp and fanning) find a good developable surface close to that intended.

RULING JIG

The ruling jig (frontispiece) comprises a series of angles, pipes or other stock straight components set on vertical supports. The actual design of the components is very flexible. The author's conceptual design is simple tripod jackstands with telescoping pipe stanchions.

The stanchions end in a trailer hitch ball and the pipes are set by passing a pin through holes in the pipes. The holes are set at vernier spacings. That is, on one pipe the holes are set with, for example, six holes per foot and on the other, seven. Various combinations of holes allow continuous spacing variations at a minimum interval of the difference between the spacing. The ball can also be set in a threaded hole to allow further fine-tuning. The jackstands would sit on a concrete floor and be held down by chains and turnbuckles connected to threaded steel inserts cast in the floor. Setting angles heel up clamped to the hitch balls would form the ruling lines.

There are numerous schemes for setting the location and height of the stands. Standard laser surveying equipment with witness marks cast in the floor would yield a straightforward procedure. Another scheme could use a water level for height and two distances from preset points for location. The concrete slab could also be permanently marked along predetermined axes.

Note that the vertical supports do not necessarily have to be on the ends of the rulings (provided the clamping arrangement allows for this). They can be under the surface or beyond the edges, so they can be placed at fixed positions in one axis if desired.

FRAMING AND BULKHEAD DETAILS

Longitudinals

Longitudinals should be pre-formed to the correct curvature before they are installed on the plates. In many small shipyards, longitudinals are flat plate, cut to the correct "hard way" curve, and this is the easiest way to implement this process. (Note also that the ability to vary the depth of the flat plate long at will, may be of some advantage for structural optimization.)

If shapes such as angle are used, the longs must be bent to shape first. The desired shape can be shown either by numerically cutting "roll set" templates out of flat stock or by marking inverse curves on the shapes. (Inverse curves are curved on the straight stock. When the stock is formed to the desired curvature, they are straight.)

Obviously, edge cut flat plate longitudinals are cheaper, so if it is structurally possible they are preferable. If more section modulus is required than is feasible in a flat long, an alternative to shape is welding a bulb on the flat section. Other advantages of bulbs have been extensively discussed elsewhere, but in this case, the main advantage is that the bulb is relatively compact, and bends readily. The bulb could be GMAW welded onto the flat bar at a machine that feeds bar and bulb together over a non-consumable ceramic backing. Induction welding or other processes are applicable to this process as well. A relatively small number of standardized bulbs should be devised to make a range of stiffener section moduli. The bulb should also be designed to provide good weld prep inherently, to provide a consistent surface for the non-consumable backing, and to keep the weld near the neutral axis of the welded section to avoid distortion. There is not a wide range of such bulbs available in steel, though they are becoming more common, but a custom extrusion of this type in aluminum is quite feasible. The authors got a bid of $600 for the die charges on such a bulb a couple of years ago.

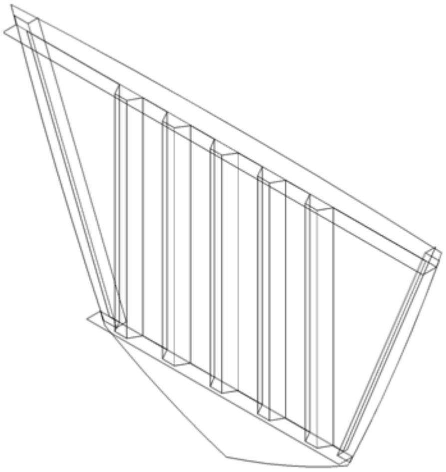
Transverse Frames

Transverse frame design would not be affected by this system. Flanged transverse frames, lapped at the joints between surfaces, would probably be easiest to connect when joining the modules, and because it eliminates welding the flange and possible distortion, many small shipyards prefer it. (Flanging is sometimes seen as a problem in small shipyards because high capacity general-purpose press brakes are normally used. However, a specialized machine that can only bend flanges is an alternative. General-purpose press brakes are costly because they can place a bend in the middle of a large panel. A machine that only flanged could be designed to have a very limited bend depth and be cheaper, and possibly, shipyard made.)

Web frames with face bar flanges can also be used in this system. The joint in the face bar (at least for aluminum) should not align with the joint in the web (which would probably be a corner mitre). Thus the radiussed portion of the face bar could be added later or overhang either the bottom or side web. The accuracy requirements for placement and angle of this type of frame is the same as for flanged frames, and it would actually be a little easier to adjust the web alignment (prior to welding on the flange) than to adjust the alignment of flanged frames. The accuracy of the mitre joint has to be good, but this is a numerically cut part, so adequate accuracy is feasible. The mitre joint could also be a backed seam. The one drawback to face bar web joints is that there will be a small amount of difficult welding connecting the radiussed corner of the face bar to the web.

Bulkheads

Bulkhead design has to keep in mind the need to be readily divided, with natural, convenient joints between the parts mounted on each surface. Corrugated bulkheads are a natural concept for this system. The outer boundaries of the bulkhead would be more or less frame like, and the middle portion would be corrugated. This reduces welding and distortion, and may allow weight reduction if elimination of welding allows lighter material to be used. Labor savings depend on the relative cost of corrugating and welding. (And again, a specialized corrugating machine may be more economical than a general-purpose brake. It would only have to be rated for light material and the width of the bend would be limited to about eight feet.) If flanged frames were used, then the bottom portion and the top portion would be flanged in the same direction as the corrugations. One face of the corrugation would be aligned at the molded surface of the frames with the corrugations vertical and over the flanges. The corrugations would be welded to the flanges. A flat portion of the corrugated plate, outboard of the



Corrugated Bulkhead Divisible Across Panels

corrugations, would be lapped to the side frames.

Penetration farms are designated areas for multiple penetrations. This is preset and precut in the bulkhead, and is oversize. After the penetrations are accurately located, an insert, either a commercial penetration block or a doubler plate with penetrations welded into it, is set in the farm after all of the required penetration locations and sizes are determined. A profitable location for penetration farms is spanning the joint between the bulkhead and the deck, so they are easily installed.

Deck beams

Deck beams have to be designed to allow cableways, pipes and so forth to be installed when the deck is inverted. Designers are reminded that openings in deck beams should be near the neutral axis of the beam, which is close to the deck. This may allow a penetration to be comprised of a scallop in the beam, rather than a hole, which may allow more efficient outfitting subsequently. (Especially on aluminum, which does not have to be coated. Cables and pipe could be installed prior to welding down the beams.) It is also worth noting that penetration-reinforcing rings are a worthy target for standardization, and possibly for farming out to a specialist fabricator.

AUTOMATED WELDING TECHNIQUES

Obviously, this system achieves the stated goal of maximizing downhand welding, but it also facilitates low cost welding automation. Weld pacers are the least costly means of automation, both in terms of first cost and in terms of programming cost. A weld pacer (often called a "Bug-O" based on a common trade name) is simply a pair of motorized wheels that clamp on one member to be welded or a track and a controller/manipulator that carries a GMAW torch. Such a device would be very useful for welding longitudinals. (The number of interruptions in the transverses would probably make automating these welds with pacers uneconomical as the move and setup time would be excessive compared to the weld time.)

Another such device should be set up on a track over a permanent non-consumable ceramic backing to seam plates (prior to setting them on the jig). A setup comprising a single longitudinal welder setup and a seam welder setup would only cost about ten thousand dollars or so (not counting the welding torches and power supplies themselves).

More sophisticated systems are also possible. These would comprise robot arms running on tracks in the ceiling above the jig. These units can be costly, but their cost is rapidly coming down. The effort of programming these devices is also being reduced because many of the CAD/CAM packages generate weld path data from their 3D structural database.

POKE YOKA AND ACCURACY CONTROLS

Poke yoka are features, either permanent or temporary, numerically cut into parts that provide accurate location and alignment of parts. Naturally, the parts will all have fiduciary marks placed when they are numerically cut. Another obvious feature is brackets cut into plate longs that correctly locate the transverse frames. Numerically cut templates can also be cut to ensure proper fit between two surface blocks. These would be simply plates that fit along the chine and provide marks or hard alignment features for components. The same template would be used on both joining surface blocks to ensure accuracy. The assembly drawings generated by packages such as ShipConstructor also provide means for accuracy check dimensions. Also, the plates themselves should be marked with the jig ruling end points, and the ruling bars should extend far enough so that the plate alignment on the jig can be checked by comparing plate marks with jig bars. Finally, the exact orientation of the plate with respect to vertical is well known and precise. Thus levels, possibly combined with precut alignment tools, can be used to check alignment of most parts.

Finally, discretion is the better part of valor. At least until accuracy is well controlled, it would be wise to leave a few joints, such as the transverse – plate joint from the last long to the plate edge, unwelded, to allow for final alignment. This should be accompanied by a statistical accuracy control program and related measures such as that used by Bernhard (1993).

ADVANCED OUTFITTING TECHNIQUES

Despite its proven success, block oufitting is not common in small vessels. The arguments against block construction and advanced outfitting of such small boats and ships include:

- The resulting blocks would be too small, and would be almost as difficult to access as the complete vessel, so that the additional effort in joining the blocks would not pay off in reduced labor to build them.
- Advanced outfitting requires too much engineering effort, especially up front. This is costly and a schedule problem. (Piping and wiring is often field run in these ships, usually to schematics rather than piping and cable arrangement drawings.)
- Small ships are often built very fast and machinery and components are often available too late.
- Manloading concerns can conflict with block outfitting.

Clearly, the fact that the units are completely open makes them easily worked. Lighting and lifting is quite easy, and just the fact that parts do not have to be held overhead or against the side will reduce labor. Builders using the traditional free-forming technique often leave off the transom and lazarrette bulkheads during outfitting, just to eliminate the time workers spend climbing over the side. This suggests that there will be savings from improved worker access. Improved ventilation may not be quantifiable in terms of productivity, but just the difference in heat induced productivity loss will probably save a lot of money.

The added cost of engineering can be addressed in two ways. First, interfaced CAD/CAM software is radically reducing the cost of high quality 3D models. Such models not only produce accurate data for construction, but perhaps even more important, they produce accurate bills of material, thereby reducing material cost and eliminating delays to obtain unanticipated material. Small shipyards frequently outsource engineering. It is thus a cost rather than a profit center, but by working closely with one design firm for the long run, and possibly even sharing profits, standards and other process can be developed. These will reduce the risk and cost of engineering as well as improving its effectiveness.

Second, use of mock components can be profitable as well as addressing component delivery schedule issues. These are simple wood or metal cutouts, like paper dolls, that present the interfaces in the right locations. Use of mocks is common in small ship overhaul, especially re-engining (Does, 1997). They can also be cheaply made. Note that a CNC wood router with a four-foot by eight-foot working envelope is as cheap as $4,000 and many vendors provide CAD drawings on the Internet. These mock components can be placed on the units, and pipe and cable can be field run if desired. Use of these mocks will also allow components to be mated up prior to the actual arrival of the real part. A lightweight mock of an unwieldy part could also be used to set up connections while still allowing it to be removed for good access to other areas. Use of mock engines is especially convenient in this respect. (Note though, at some point, all of the components of the ship will have to be serviced. Advanced outfitting is a good excuse to make access on the delivered vessel a nightmare for the owner. This should be avoided.)

Schedule concerns relating to manloading are actually minimized by any type of advanced outfitting and block construction, because work is more efficient, hence faster, and because work can be done in parallel. Admittedly though, this system does require potentially more floor space than conventional construction, and this might impact schedule.

Right of Way is an important design technique for any type of advanced outfitting. Right of ways are spaces for components and runs assigned to each system, usually to the designer of the system. As long as all components stay within the right of way, they can be located without concern that they may interfere with other parts. In this system, it is also wise to add structural interface surfaces to the right of way assignment so that hangers can be co located.

COATING

Aluminum has a major advantage compared with steel for pre-outfitted components: It does not need to be coated unless required for cosmetic purposes or anti-fouling. This may seem a minor issue in terms of overall ship production, but it means that there is no internal painting or surface preparation so all painting can be delayed until the boat is finished. (And some exterior painting is often omitted as well.) Structural blocks can be joined without re-prepping and re-coating weld damage, which might damage pre-outfitted components. Use of the proposed technique with steel still requires some problematic paint and prep on joining blocks. However, the vast majority of painting can be done on relatively open surfaces, even after they are structurally complete. Since the panels have open edges, the process of removing spent grit is much easier. This is very laborious on a structurally complete vessel, and if any grit remains, it often compromises the coating system. The joint areas remaining for block joining can be masked if desired and prepped but not coated. Even if weld through primers are used, (which have some issues of their own), touching up weld areas and finish coating the panels flat, before joining still reduces labor.

CAD/CAM SOFTWARE

Effective software for this technique requires special features that may not be available in all systems. The requirement to allow the user to manipulate developable surfaces is discussed above, but bears repetition, because it is mandatory. Computer programs producing developable surfaces will generally produce undesirable surfaces without some level of user intervention, so effective, convenient methods of controlling the surface development are critical. This capability not only requires adjustable search parameters, but the ability to trim surfaces, to force surface breaks in chines, to derive new chine segments from surface-to-line and surface-to-surface intersections, and a reasonably convenient two way interface with your CAD system.

Generalized three dimensional drafting or solid modeling, even with the most advanced tools, is difficult and requires a skill set that is not common in today's drafting and design workforce. In addition, even if solid models are available, most ship parts are planar and the data for cutting parts is generally either two-dimensional or essentially one-dimensional (i.e. stiffener length and end cut type). Finally, some parts like the shell plate exist in two forms, their final form as part of the ship and their as cut form prior to forming. These problems can be handled, but they are tedious, fussy and subject to errors. These details are relatively mechanical so, though not absolutely required, a software solution to this is both feasible and highly desirable. The ShipConstructor system (and other suites) allows designers to retain their customary 2D practices and design in 2 dimensions. The software automatically generates solids from the 2D geometry (as well as providing other tools for standard details and tasks). It also extracts the appropriate geometry and makes it available for subsequent plate nesting and CNC code generation.

The software also has to provide for easily leveling the plate to set up jig data and to readily extract the data. The "pin jig" option (if available) can be adapted for this purpose.

Advanced outfitting requires that the software either includes or be able to readily interface with specialized software for piping, HVAC and so on.

Finally, the software has to be able to conveniently generate assembly documentation that can depict the block panels in their as built condition, laid flat, or combined with one or two other panels. In some cases assembly drawings at several stages are required (as well as drawings depicting in-service arrangements for the owner and regulatory bodies). This can be done with a system of external reference files (drawings that automatically insert other drawings – "xrefs" in AutoCAD) and methods for depicting different views of a 3D model ("paper space" and "layouts" in AutoCAD). However, setting up these systems and enforcing the conventions required to make them work is a big effort. This is also a process readily subject to automation, and suites such as ShipConstructor provide this type of functionality.

CONCLUSION

The authors propose an alternative system for the construction of small ships and boats, which have developable surfaces and have suggested various details to implement it. This system enables many techniques that have improved productivity in large shipyards. This paper is by no means the last word on this subject. Readers of this paper will immediately come up with ideas for and improvements to this system of their own which will further increase productivity. The authors look forward to hearing about these improvements and ideas and hope that this paper will inspire others.

The authors would also like to note that this technique initially grew out of discussions at TQM process improvement meetings at Munson Manufacturing with the design staff, the production manager and trade foremen and leadermen, followed by various informal discussions over several years with many builders in the small ship industry. It is by no means proprietary and anyone who wants to try it is encouraged to do so.

REFERENCES

Bernhard, B. S. 1993, Benefits of Quality Control Techniques in Series Ship Construction by Computer Integrated Manufacturing, *Marine Technology* V. 30, No. 4, October

Faux, I. D. and Pratt, M. J., 1981, *Computational Geometry for Design and Manufacture*, John Wiley & Sons

Kilgore, U. 1967, Developable Hull Surfaces, *Fishing Boats of the World*, V. 3

Does, Lee M. (1997) “Easy Inboard-Engine Installation With an Engine-Pattern Jig” *Boatbuilder Magazine* July/August 1997

Leake, J. M. and Calkins, D. E. 1996, Small Ship Productivity, *Journal of Ship Production* V. 12, No. 2

Nolan, T. 1971, Computer Aided Design of Developable Surfaces, *Marine Technology* V. 30, No. 4, April 1971

Rabl, S. S. 1958, Multiconic Development of Hull Surfaces, *The Planimeter*