Group Discussion B.1: Model Manufacturing and Accuracy

Group Discussion Chair: Mr. Tony Randell (IMD-NRC)

SUMMARY
by Tony C. Randell
IMD-NRC, St. John's, NF, Canada

Short description of contributions

Mr. Jan Holtrop
MARIN, Wageningen, The Netherlands

A brief introduction to a four-page handout written by Jan de Boer of MARIN. The paper describes upgrades and improvements to the model manufacturing operations at MARIN that have taken place over the past several years.

Dr. Jin-Tae Lee, *Director-General*
KRISO, Daejon, Korea

KRISO (Korea Research Institute of Ship and Ocean Engineering) recently installed two 5-axis Numerically Controlled machines for ship and propeller models, respectively, with powerful CAD/CAM software. They not only improved the accuracy of manufacturing, but also saved manufacturing time dramatically, by adopting the new manufacturing process using the NC system.

Eng. Lanfranco Benedetti, *Head*
Model Manufacturing and Measurement Equipment Laboratory, INSEAN, Rome, Italy

With use of the industrial software, INSEAN, the Italian Ship Model Basin, achieved a fully 3D model description for design and manufacturing with 3- and 5-axis CNC milling machines. The presentation describes the procedure for model construction manufacturing, inspection and finishing.

Dr. Yoshitaka Ukon, *Head*
Ship Performance Design Group, Advanced Maritime Transport Technology Department, National Maritime Research Institute, Tokyo, Japan

NMRI manufactured three of KCS models (prepared for the CFD Workshop in Gothenburg in 2000) with the same size but different methods, and the inspection on each model was made using three-dimensional digitisers. The resistance tests were performed on three models with several runs. The comparison of five runs of resistance tests results on three models are presented. Uncertainty analysis on the resistance test was partly performed but has not been fully accomplished yet.

Mr. Tony C. Randell, P. Eng., *Leader*
Design and Fabrication, National Research Council, Institute for Marine Dynamics, St. John's, Newfoundland, Canada

The methods for manufacturing models and related apparatus using CNC machining is described as wellas methods of measuring model accuracy.

LIST OF ATTACHED DOCUMENTS

[1] Dr. J. de Boer: Modernisation of the Manufacturing of Models at MARIN. [*paper* and *slides*]

[2] Dr. J.-T. Lee: New CAD/CAM Manufacturing Systems for Ship and Propeller Models at KRISO. [*slides*]

[3] Eng. L. Benedetti: Model Fabrication at INSEAN. [*slides*]

[4] Dr. Y. Ukon, Dr. J. Fujisawa, Dr. T. Yanagihara, Dr. H. Takeshi, Dr. K. Kume: Manufacture Accuracy of Three KCS Models and Resistance Tets Results. [*paper* and *slides*]

[5] P. Eng. Tony Randell: Model Manufacturing Technology at IMD. [*slides*]

MODERNISATION OF THE MANUFACTURE OF MODELS AT MARIN

Jan de Boer (MARIN, Wageningen, The Netherlands)
e-mail: J.deBoer@MARIN.nl

In 1997 the management of MARIN decided to upgrade the production of both ship and propeller models. Reasons for this upgrade were:

- Need for better quality and accuracy,
- Cost efficiency,
- Retirement of qualified propeller and ship model makers,
- Difficult to get new skilled craftsmen for the propeller and model production

Up till then the models were mostly handmade, although for the ship model production a hand-operated Kempf and Remmers milling machine was used. For the propellers a kind of NC milling machine has been in operation, leaving the finishing by hand.

The whole production process has been updated, starting at the design of the models using 3D-models, instead of the 2D-drawings, like a linesplan for cutting the ship models. In the workshops it meant that the models had to be produced by CAD-CAM and CNC machinery.

3D models

The first step was to introduce 3D models. For the propellers a program was developed which transforms the shape of the blades as defined by the sections at the various radii, given in the traditional tabular format of the database of the MARIN propellers, to a NURBS surface description of the propeller blade. This program delivers an IGES file with the 3D surface model of the propeller blade. The IGES-file is read into a CAD program and then other details and the hub are added.

For the ship models MARIN first performed a market study into the use of CAD programs for hull form design, like NAPA and Fastships. For several reasons, but mainly because of sharing geometry data with other software in use for CFD, ship motions, etc, MARIN decided to develop its own hull form design program based on NURBS surfaces.

Production techniques

The next step was to decide the best way to produce the models. The propeller models are made as CP propellers. The individual blades are milled on a standard high-speed vertical milling machine added with a fourth rotary axis. The material for the propellers can be brass, bronze or aluminium. The blades are fitted to a hub and in the case of a fixed-pitch propeller the openings between the blades and hub are soldered. The CAM program uses the 3D model from the previous step to make the programs for the milling machine. MARIN took special care to find the right milling strategies to inhibit vibrations of the propeller blades while milling.

In the case of the ship models it was decided to use a five axis gantry milling machine for the model. The material continued to be wood. MARIN investigated the use of foam but strength requirements and the price difference between wood and foam forced to continue the use of wood (obeche). After a long market search MARIN found a new, innovative, design milling machine for its purpose. The hull shape as given by the hull form design program is used by the CAM program to make the programs for the milling machine. On average, it takes about16 hours to mill a complete ship model.

Implementation

In 1998 MARIN started to produce its model propellers using the new milling machine. The time needed to produce a propeller was reduced by 75%. More work is now needed at the CAD-CAM department, despite a dramatic staff reduction in the propeller workshop. With this milling machine also all kinds of model parts are made like pod housings, shaft brackets and rudders. A typical blade of a 250 mm propeller takes about 2 hours' milling time and one day to finish the complete propeller model.

In 1999 MARIN started to produce the ship models with the new five-axis milling machine with the same results. On average it takes about one extra day after the 16 hours of milling to finishthe ship model by hand.

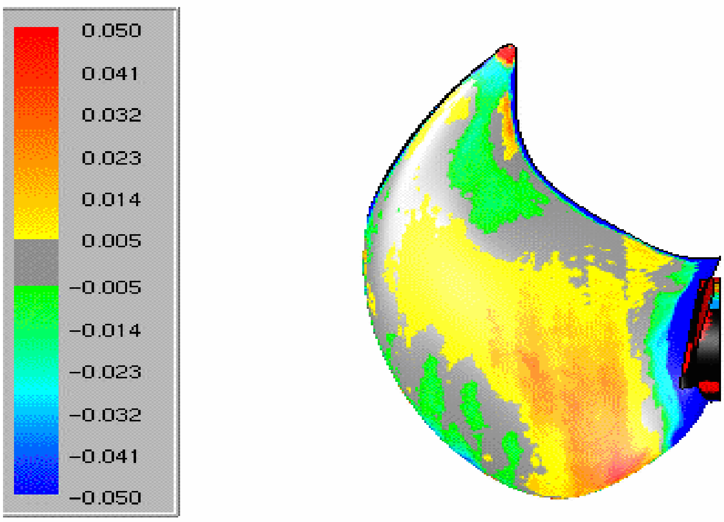
Model size

Using these new production techniques for propeller and ship models, the maximum model sizes are:

- Propellers < 450 mm
- Ship models < 13 * 3 * 1.5 m

Quality Control

For the propeller quality control the traditional propeller measuring machine is used, together with a blade edge microscope. The propeller measuring machine was initially based on the ISO 484/1 standard. In its current state the machine proved to be less accurate than the milling machine. Therefore, it has been renovated and now the accuracy of the measuring machine is ±0.003 degrees in angular sense and ±0.01 mm for the radius, the pitch and the blade thickness. Occasionally, blades are inspected using a laser scanner and compared with the CAD model. An example is shown in the next figure.



From this example it can be concluded that the differences are less than 0.050 mm. MARIN uses no CMM for blade inspection. The accuracy of the milled blade edges is well within the resolution of the blade edge microscope.

The main differences in geometry of the propeller are found in the blade root and the tree-trunk region. This is due to the fact no unique description of these regions are available from the propeller designers. These regions are handfinished according to the craftsmen's interpretation.

Experience with cavitation experiments on propellers manufactured by the new production methods has indicated that the variation in cavitation inception conditions between the various blades has diminished.

For the quality control of ship models and other large objects MARIN uses a FARO measuring arm with an accuracy of ± 0.127 mm. The Krypton systems which are used for measuring 6 DOF motions in the seakeeping and offshore basins can also be used for inspection of large objects, MARIN has not used this option yet.

The accuracy of the ship models proved to lead to deviations which are less than 0.5 mm, comparing a finished ship model and the CAD model.

The main differences in geometry of the ship models is due to the paint and local changes in geometry by the craftsmen. Often the hull design shows local humps and hollows which are "repaired" by the craftsmen. There is a need for good tools to judge the quality of the hull design on the computer.

Another problem with the models is caused by the material. Wood expands or shrinks due to temperature differences and absorption of water and this leads to internal stresses in the model which deforms the model. MARIN has measured op to 5 mm deflection of large models due to these stresses.

Summary table

Name of the equipment	Vertical milling machine for propeller production,	5-axis milling machine for ship model production
Date of completion	1997	1999
Material used	Brass, Bronze, Aluminium	Wood, Foam
Method	CNC-milling	CNC-milling
Geometry data handling	NURBS-surface description Transfer between CAD and CAM: IGES	NURBS-surface description Transfer between CAD and CAM: IGES
Accuracy	Difference between model and CAD-data <0.020 mm	Difference between model and CAD-data <0.5 mm
Max. model size	Diameter = 0.450 m	Length * Breadth * Height = 13 * 3 * 1.5 m
Time to mill and hand finish	Milling: 2 hours/blade Handfinish: 1day/Propeller	Milling: 16 hours (8 m model) Handfinish: 8 hours

New CAD/CAM Manufacturing Systems for Ship and Propeller Models at KRISO

23rd ITTC Group Discussion 2B

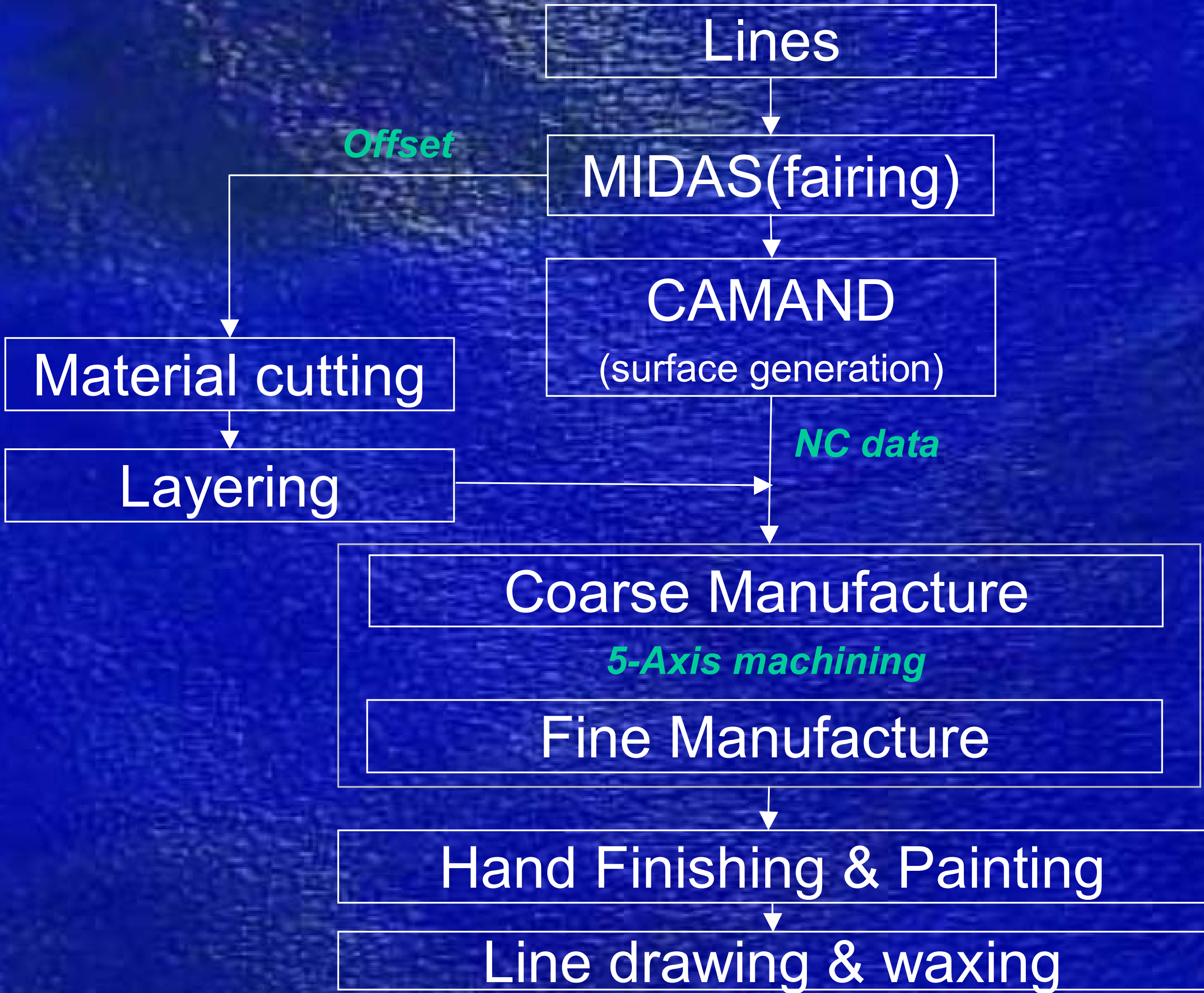
Model Manufacturing and Accuracy

Jin-Tae Lee

Korea Research Institute of Ships and Ocean Engineering (KRISO / KORDI)

New tools and equipment (CAD software, CNC machines) for Manufacturing of Ship Model

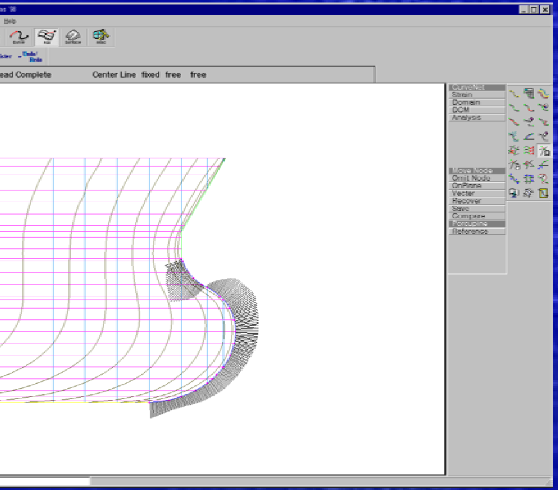
odel Ship Manufacture Process



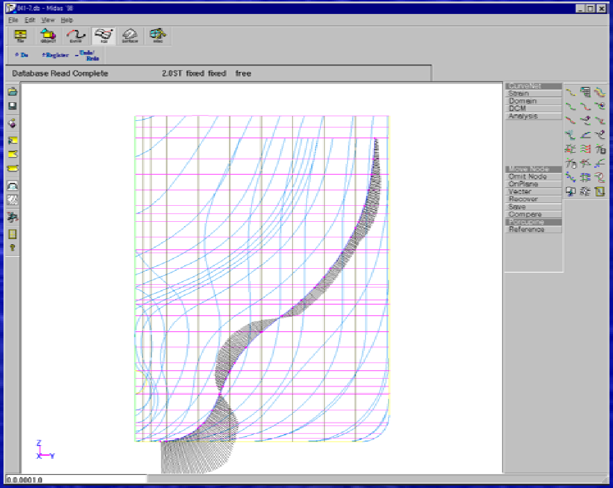
Manufacturing Accuracy: less than 0.1mm

AD Modeling-MIDAS(Pukyong National University)

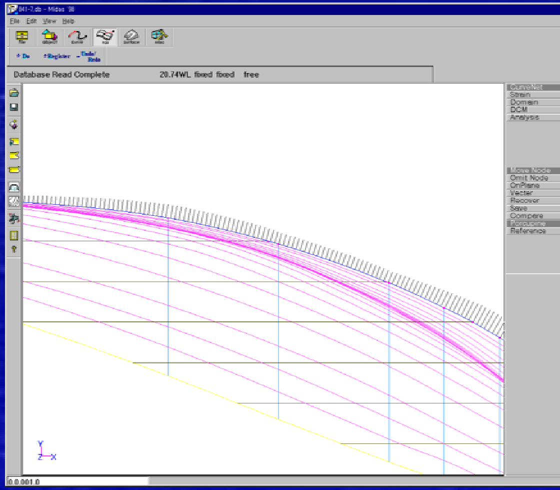
- Modeling Program (MIDAS software)
  - Lines fairing
  - Generation of offset data for production



Buttock Line



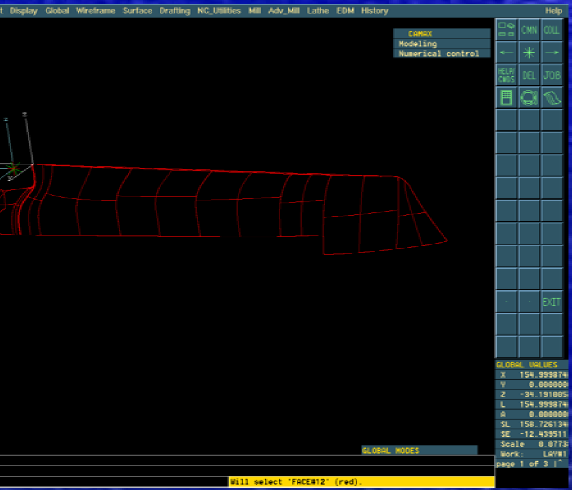
Frame line



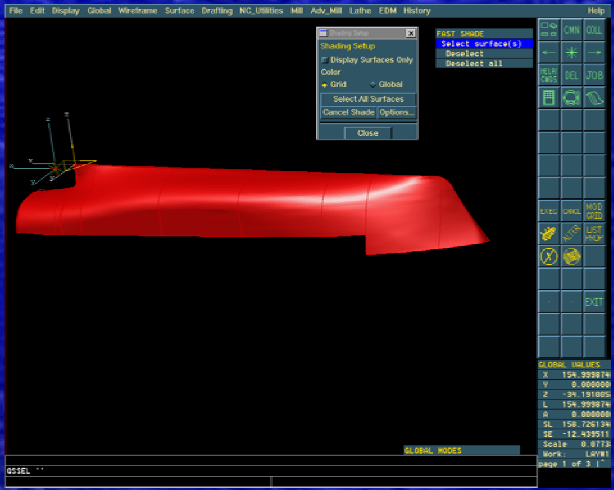
Water line

AD Modeling-CAMAND(CAMAX)

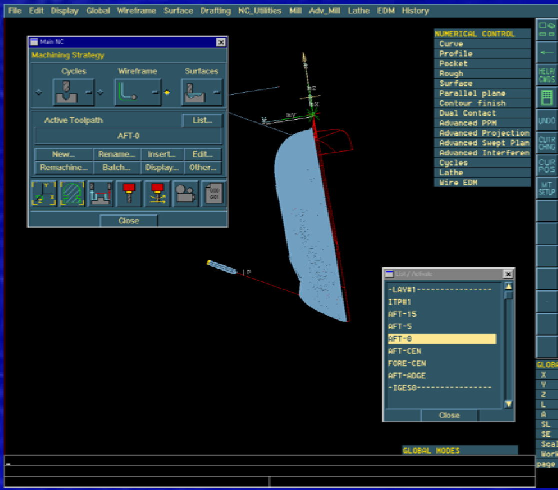
- Modeling Program (CAMAND software)
  - Robust, accurate data exchange
  - Unsurpassed manufacturing
  - High speed tool-path generation
  - Industry leading universal postprocessor
  - Unique NC program simulation
  - Graphic NC verification
  - Rapid design to market turnaround
  - Powerful modeling capabilities
  - Realistic visualization



Line data



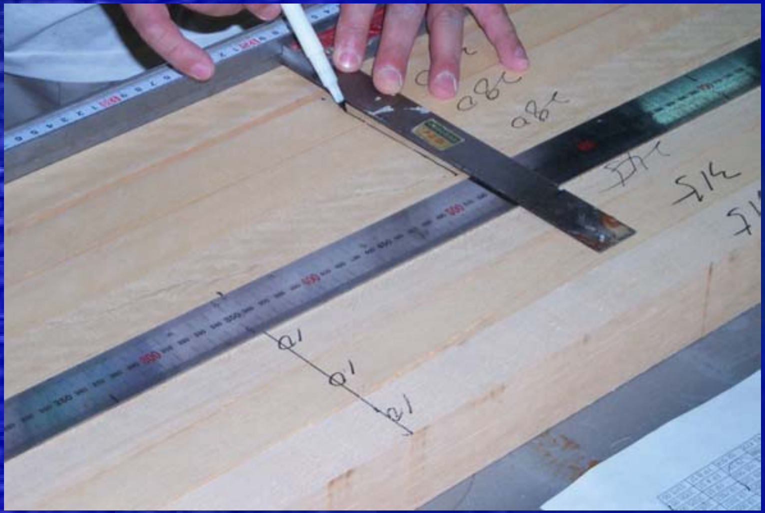
Surface generation

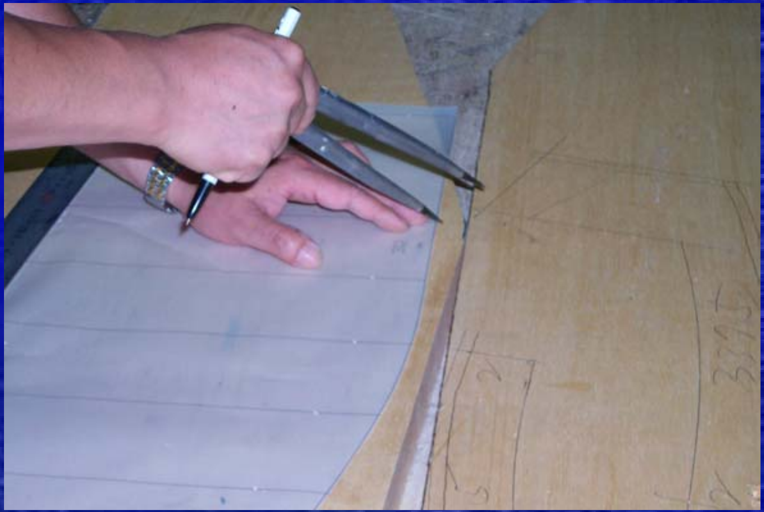


Tool path check

aterial Cutting

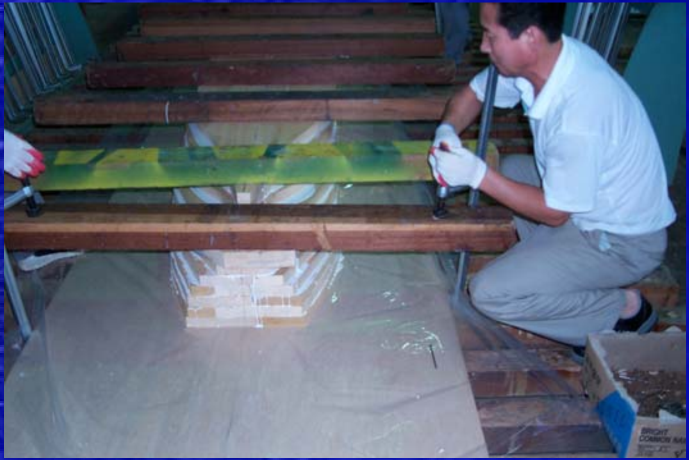
- Round hull drawing
- Parallel hull drawing
- Shape cutting





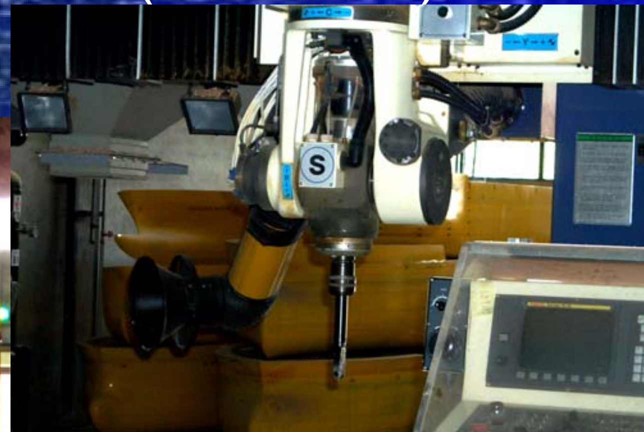
yering

Wood layer with adhesive & nail
Compression with clamp



axis NC milling machine

Model No.: CNC GGE-112A (GIGONG)

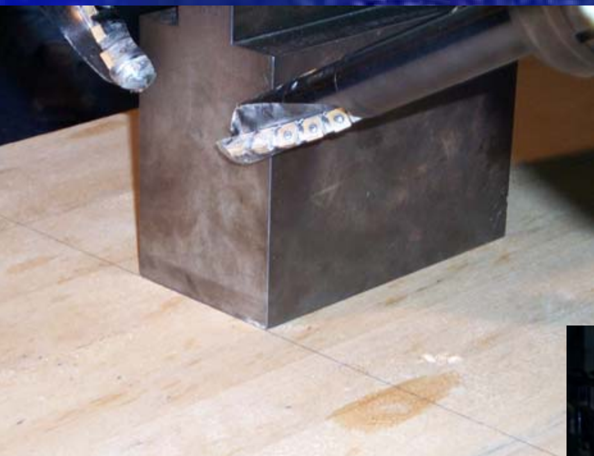


Maximum stroke	Controllable a
x-10,050mm	Master-5axis
y-2,060mm	Slave- 5axis
z-1040mm	

Accuracy (mm)			
Base table		Tool	
axial	0.02/300	position	0.01/300
transverse	0.01/300	repetition	0.005/total len
final model	less than 0.1		

NC cutting

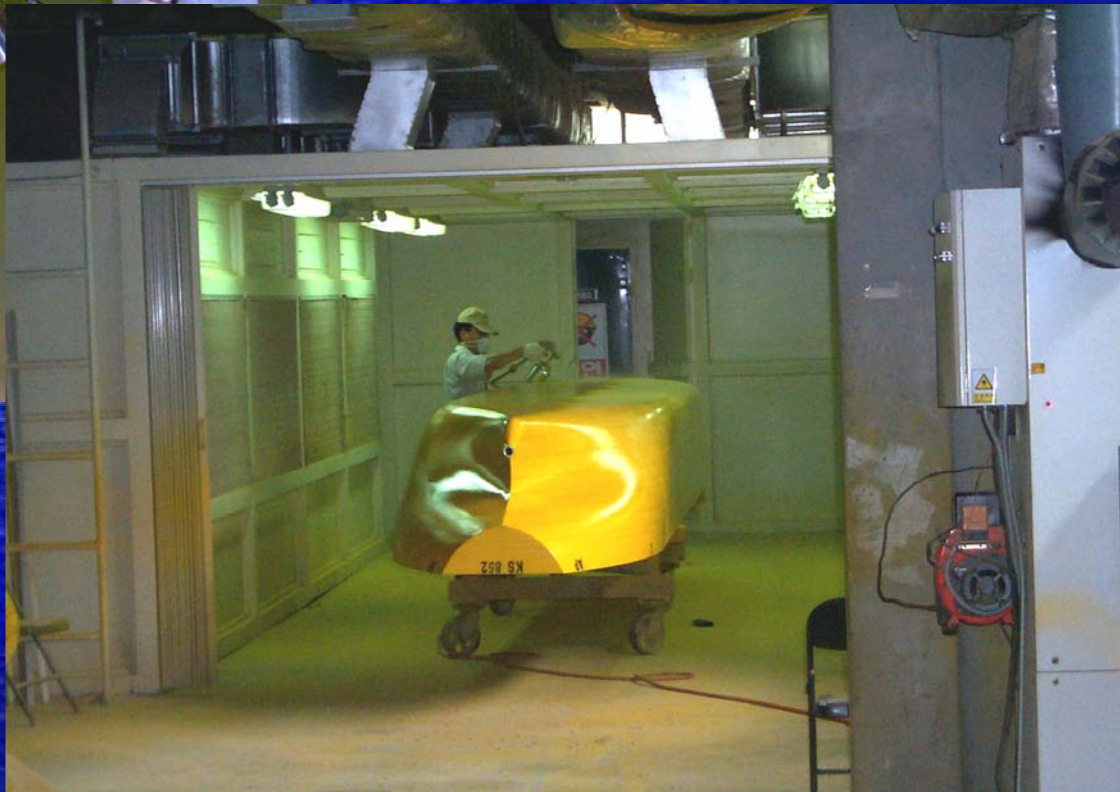
cnc



NC cutting

nd finishing & Painting

ne marking & final painting



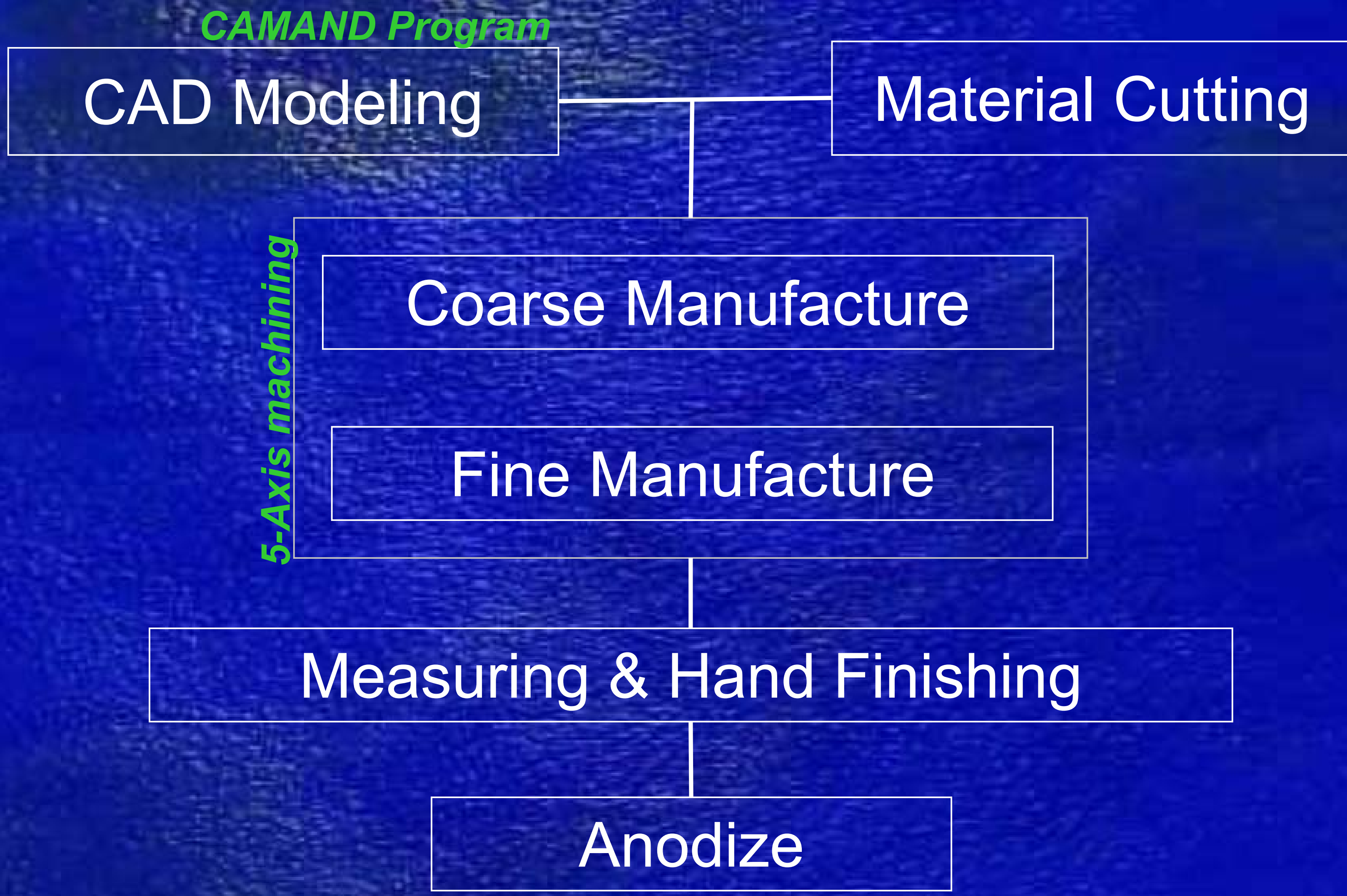
erall process (movie)

Summary

- **Smoothness over ship model is guaranteed.**
- **Carpenter's hard working time of 3 days is saved**
- **Templates for every square stations are not necessary.**
- **Accuracy Improvement**
- **Allowance of error : +/- 0.1 mm at model scale**
- **Working time for one ship model** : 10 days

New tools and equipment (CAD software, CNC machines) for Manufacturing of Propeller Model

odel Propeller Manufacture Process

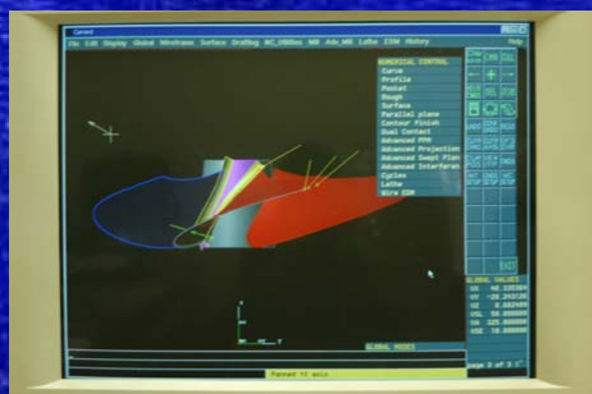


Manufacturing Accuracy: 0.05mm

AD Modeling

- Modeling Program (CAMAND software)
  - Robust, accurate data exchange
  - Unsurpassed manufacturing
  - High speed tool-path generation
  - Industry leading universal postprocessor
  - Unique NC program simulation
  - Graphic NC verification
  - Rapid design to market turnaround
  - Powerful modeling capabilities
  - Realistic visualization

Line Data

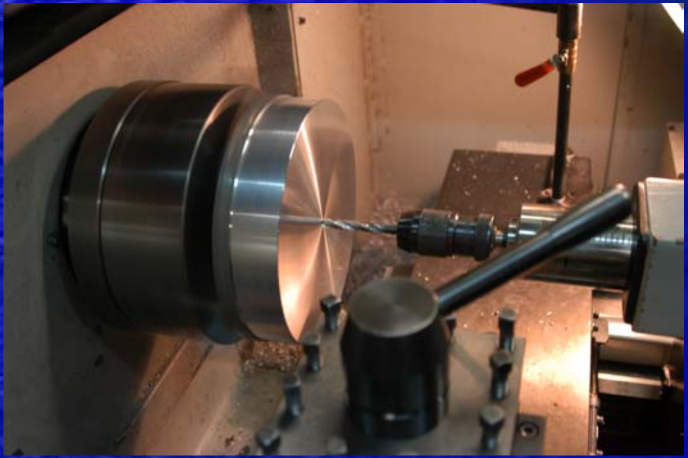


Surface Generation

Tool path Check

aterial Preparation

- Round bar cutting
- Shaft hole drilling
- Blade shape cutting



axis Vertical Machining center

- Model No.: ACE-V500 (Daewoo)
- Main Spec.
  - Main spindle speed: 10,000rpm
  - Repeatability: ± 0.005mm

Machining center (movie)

asuring & hand finishing

- Measuring of propeller offset points
  - Measuring Accuracy : 0.01mm
- Hand finishing
  - Scrapping
  - Sanding

odize

- Protecting of surface corrosion
- Better cavitation observation

Summary

- Efficiency Improvement
- Working Time Saving : 3 days
- Accuracy Improvement
  - Smoothness over propeller model
  - Allowance of error : +/- 0.02 mm at model scale
- Working days for one propeller model : 8 days

Thanks for your attention

MODEL MANUFACTURING AT INSEAN

Lanfranco Benedetti

INSEAN

THE ITALIAN SHIP MODEL BASIN

Istituto Nazionale per Studi ed Esperienze Architettura Navale

C A D

We started cutting a model surface in many parallel slices in space by using a 3-D design software

Cut the slices as much as you can eat

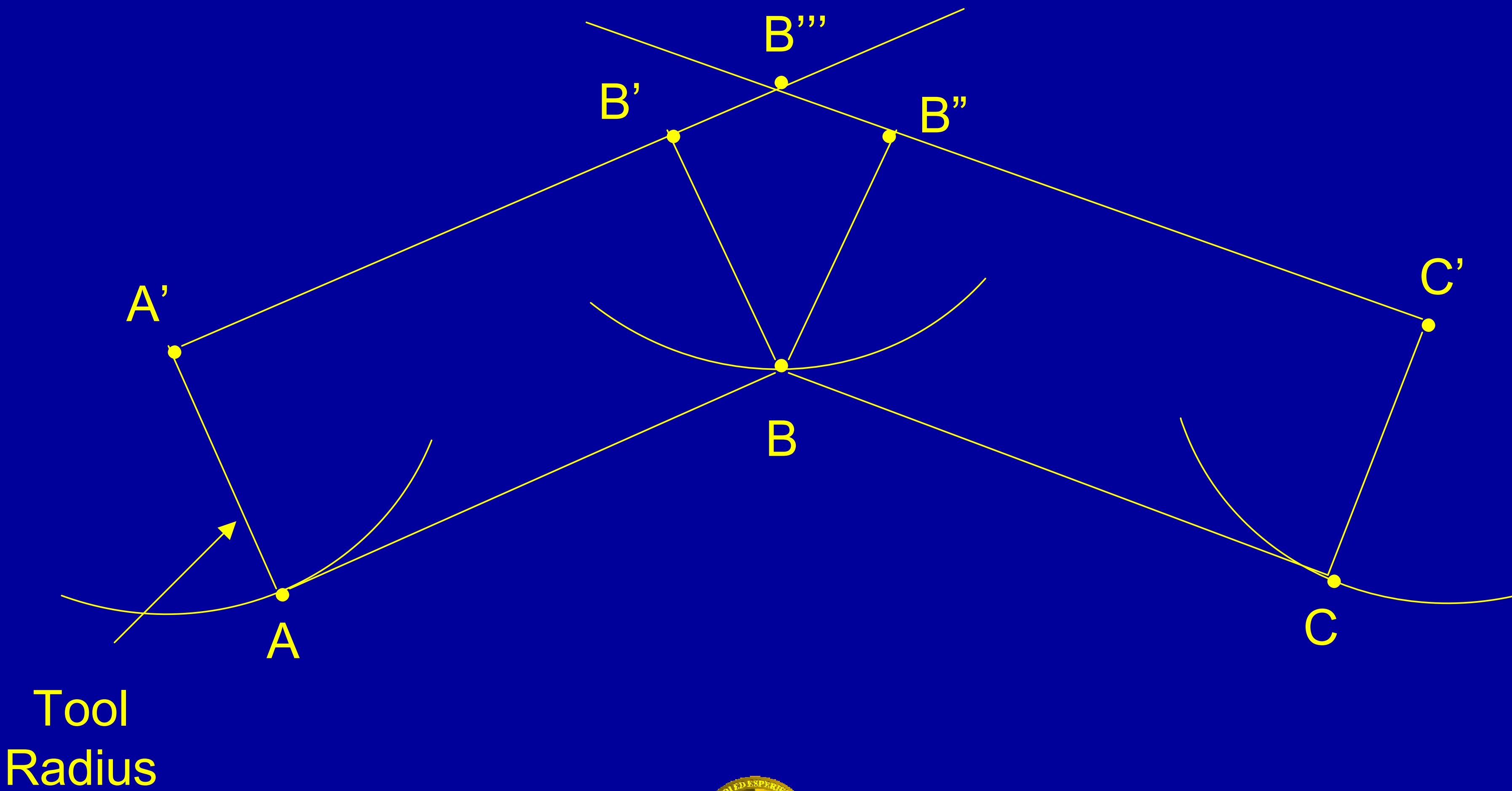
We get a cloud of points; each set lying on a slice.

Very Cloudy

Then we solved the CAM problem

1. Find the straight line passing in AB (two consecutive points on a slice);
2. Find the straight line orthogonal to A;
3. Find point (say A′) lying on the orthogonal straight line in which place the tool centre;
4. Find the straight line orthogonal to B;
5. Find point (say B′) lying on the orthogonal straight line in which place the tool centre;
6. Find the straight line from A′ to B′;
7. Repeat from point 1 to point 6 to find B″ and C′;
8. Then find the intersection between line A′B′ and line B″ C′ and so find point B‴;
9. Now move the tool from A′ to B‴;
10. Repeat from 1 to 8 to find C‴ and so on.

C A M



OK! It works very well.

But….it’s also very poor algorithm

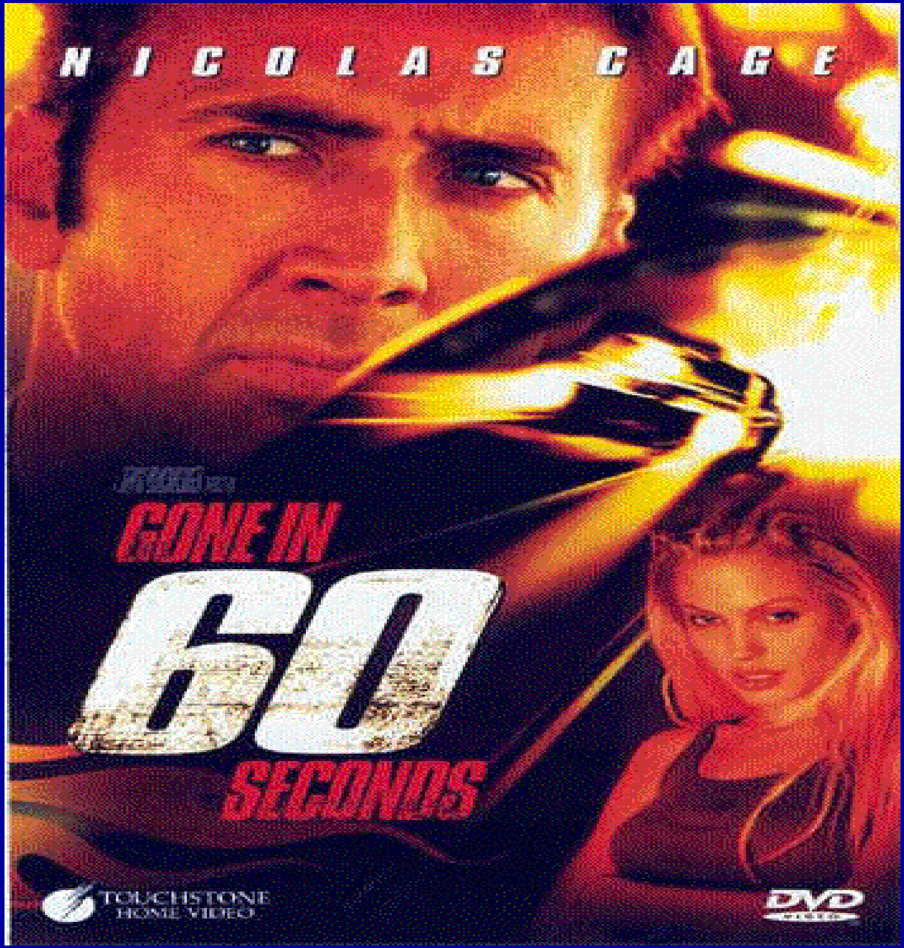
e have to work on skipnot and remove them

Then we have to take in account the tool geometry to collision avoidance;

It takes some months to do this automatic code but….

Then we have to take into account ……..
something else, again and again.

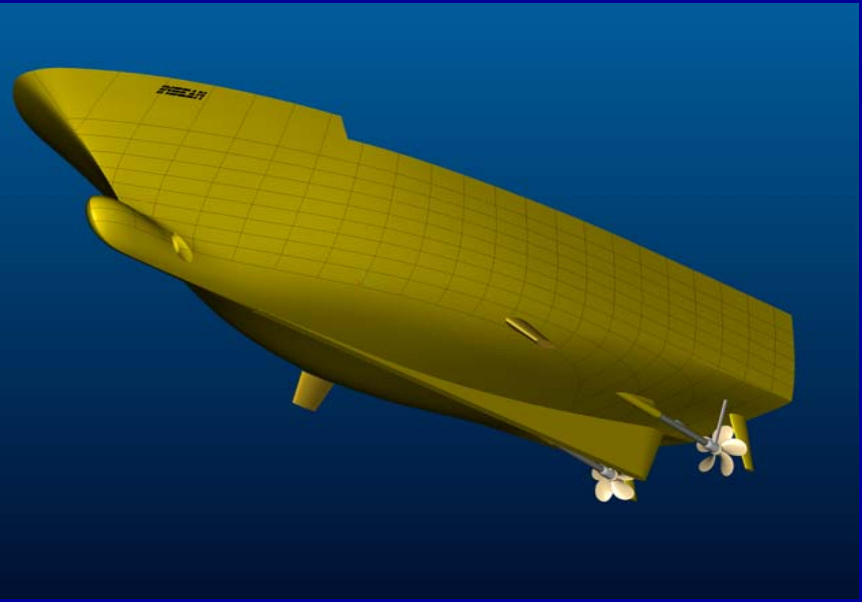
Far form heaven!

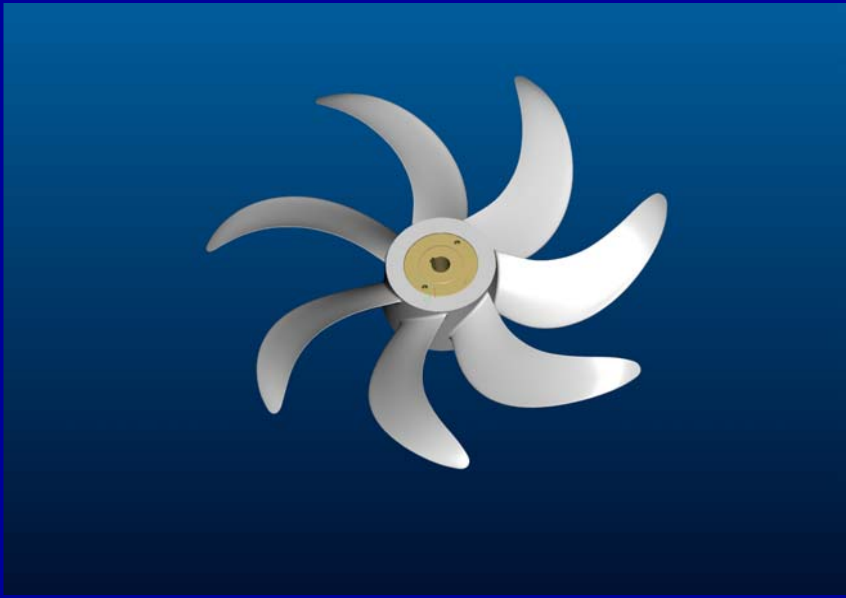


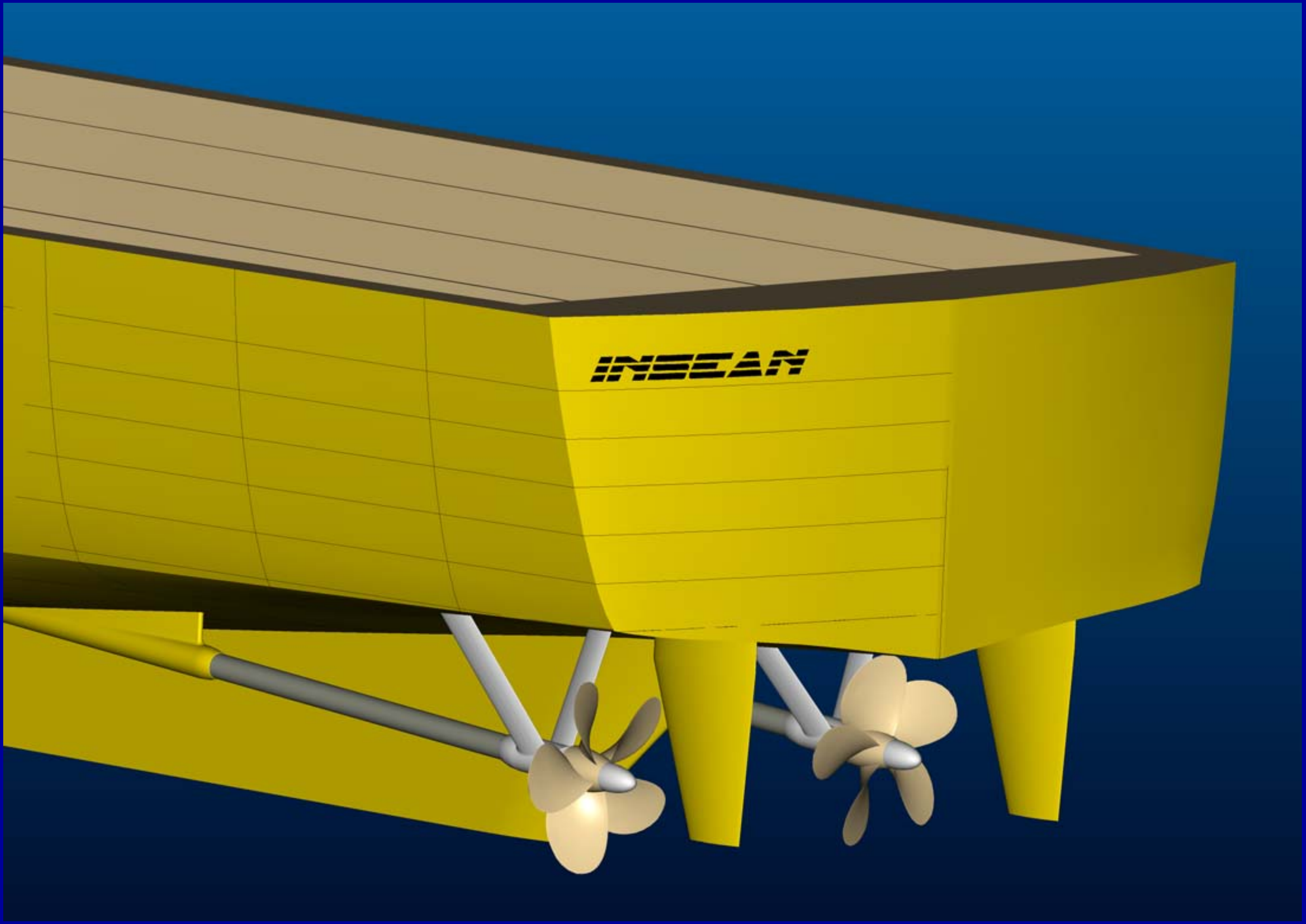
in the General Manager room
to convince him to buy
an industrial CAD/CAM/CAE Software

H E A V E N F I N A L L Y

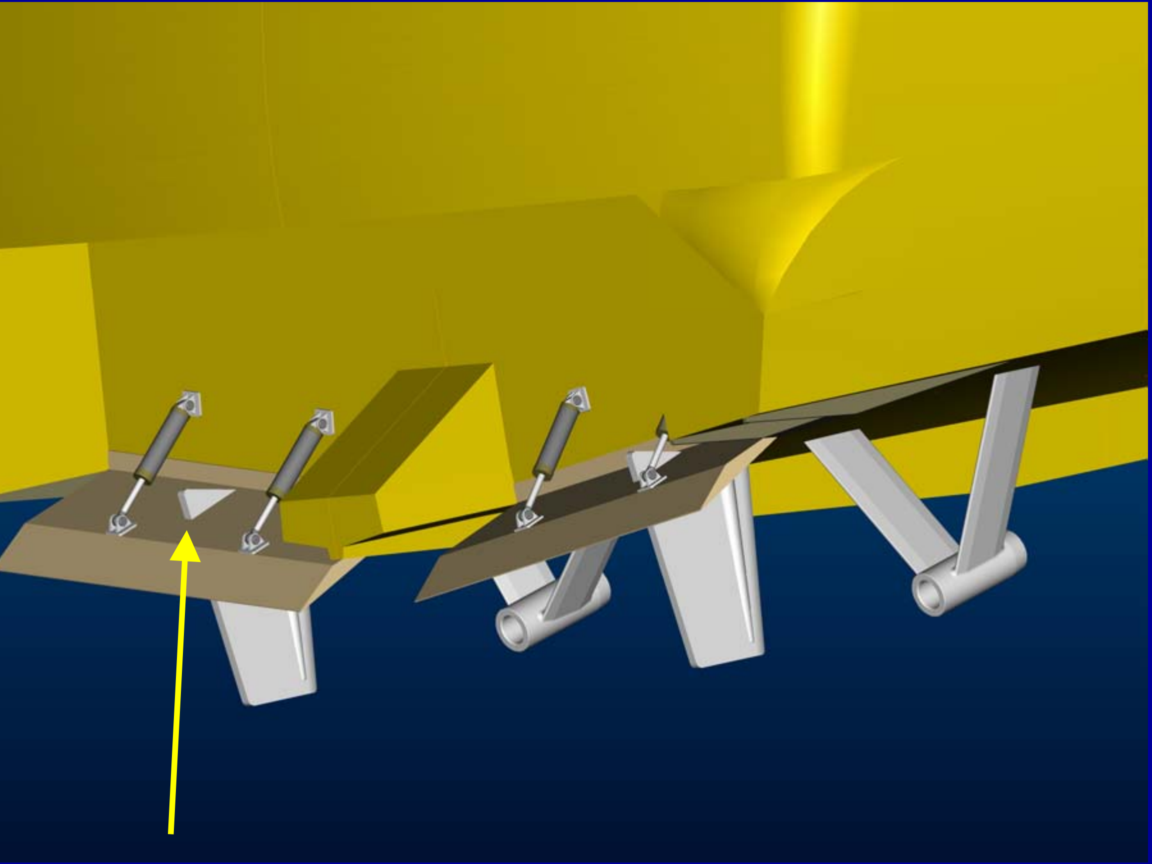
Now we can work freely in 3-D space on ship hull, propellers, appendages and whatever we need



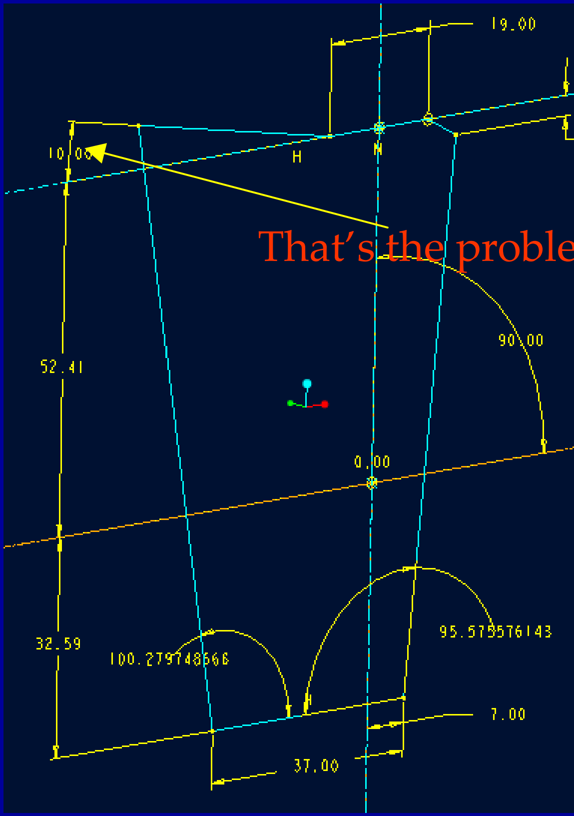



INSEAN

We can assemble and check models before constructions in workshops

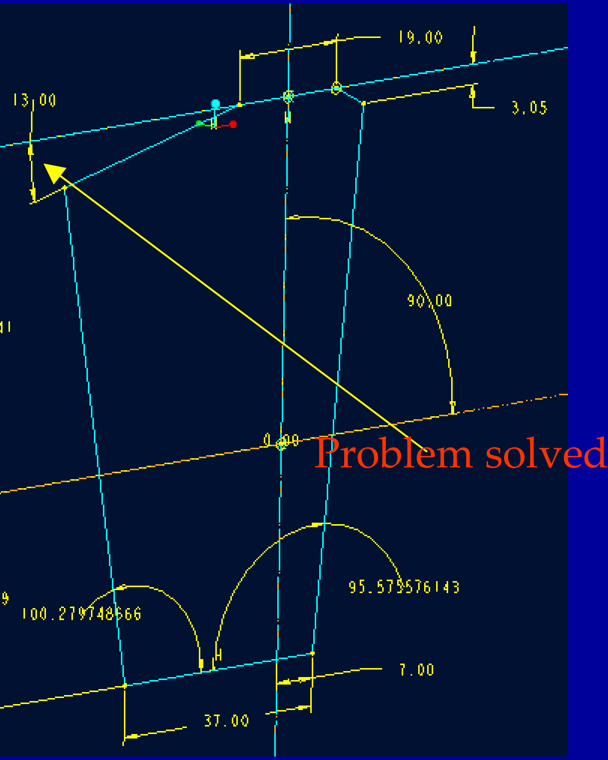


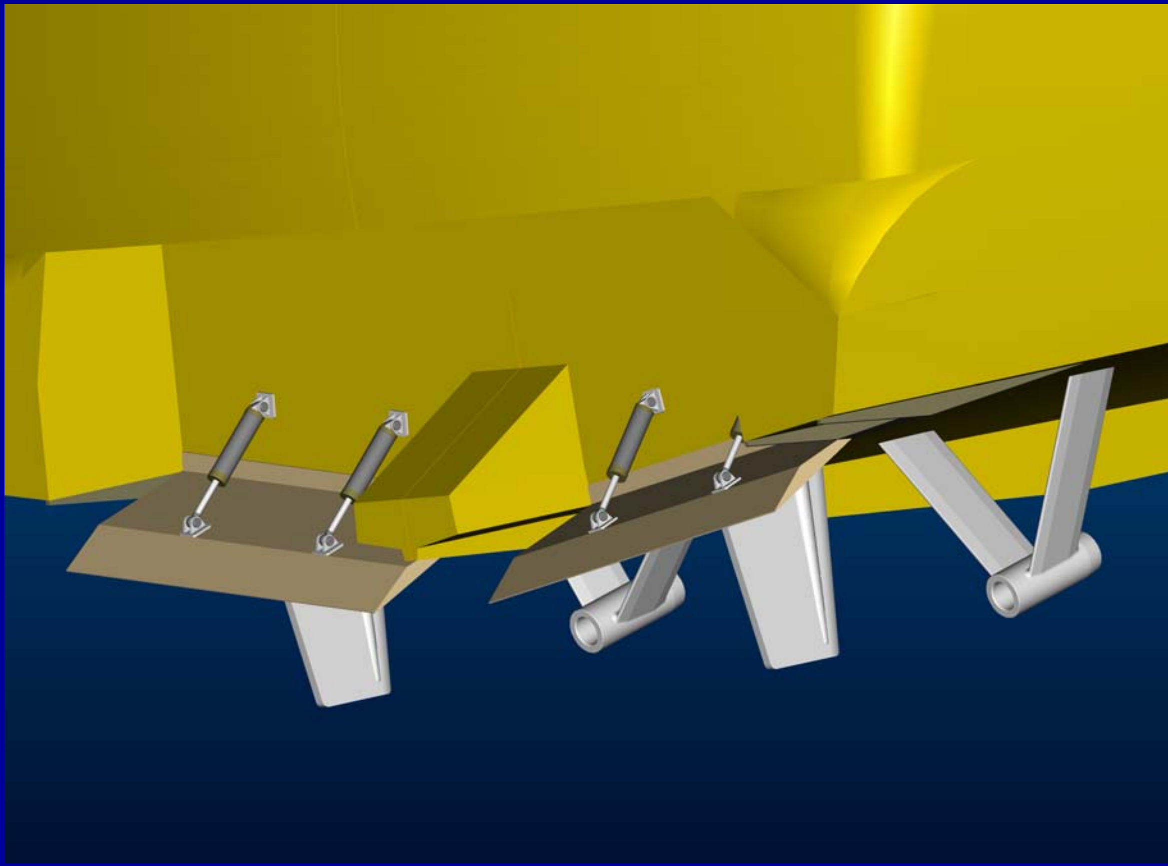
Interference between rudder and flap
(Customer data)



Rudder section

Call customer and modify

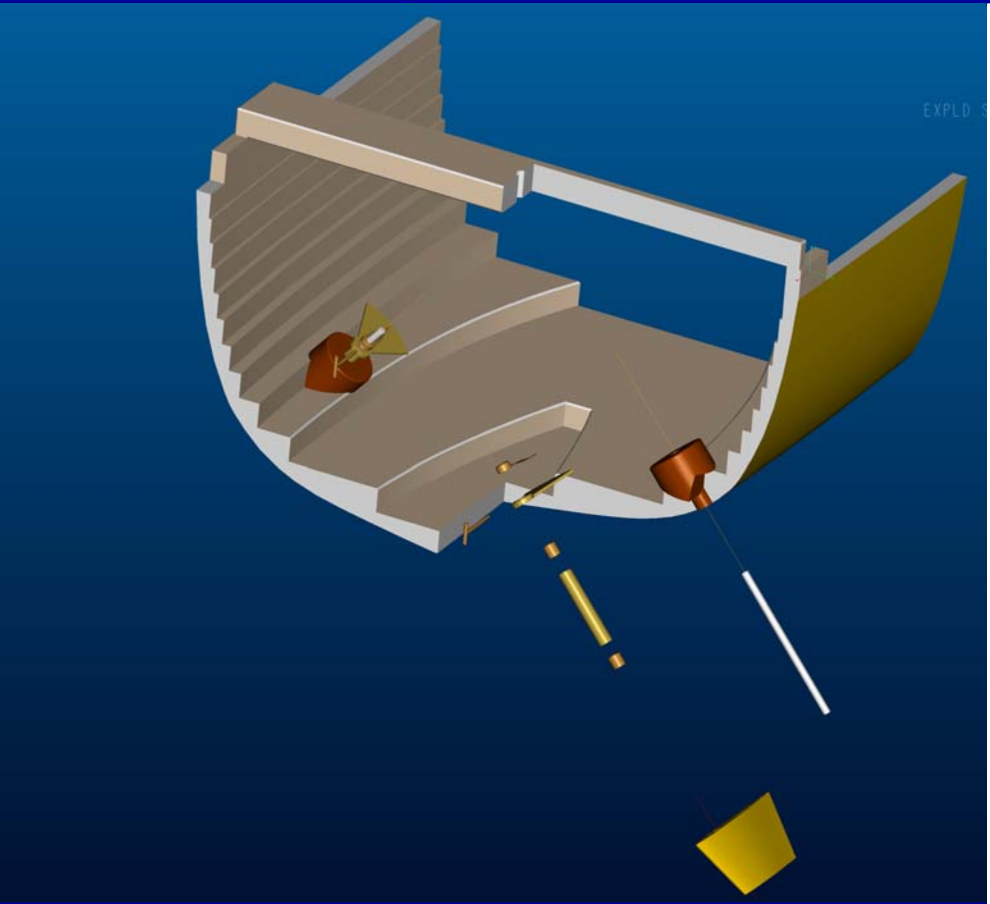


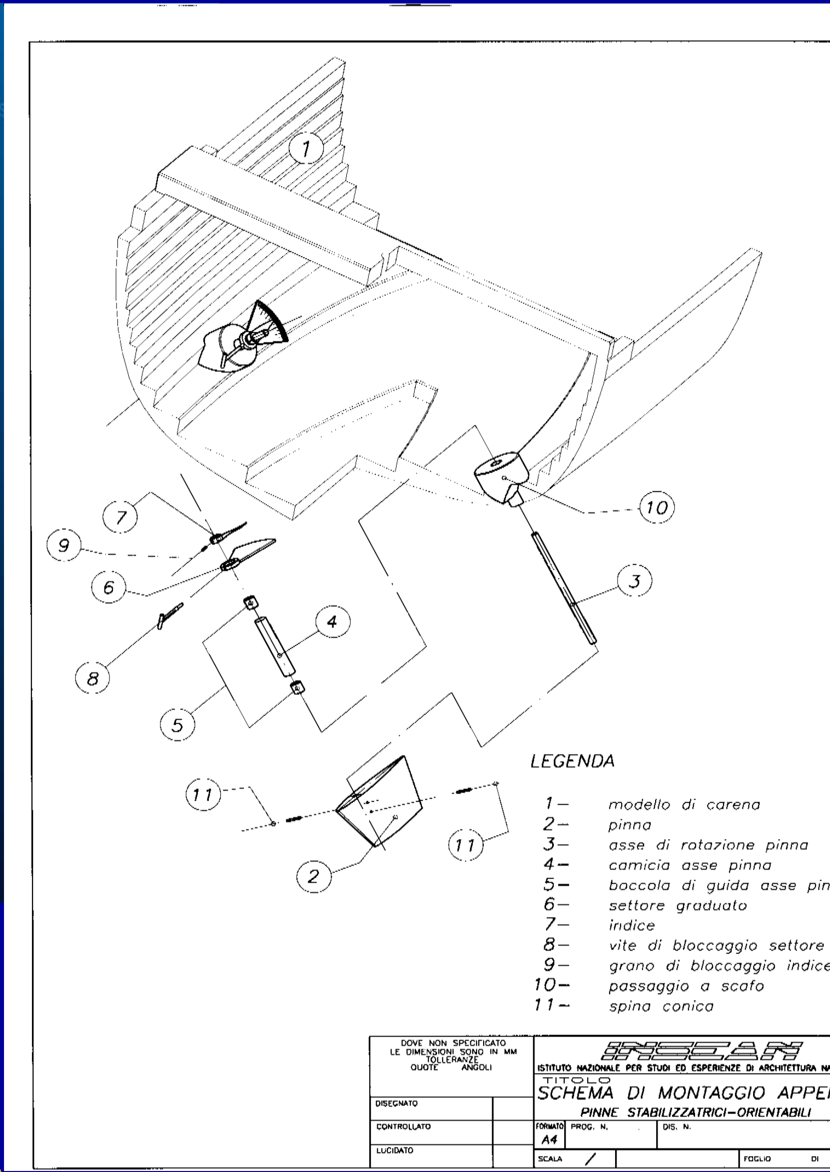


odify the rudder shape

Final check

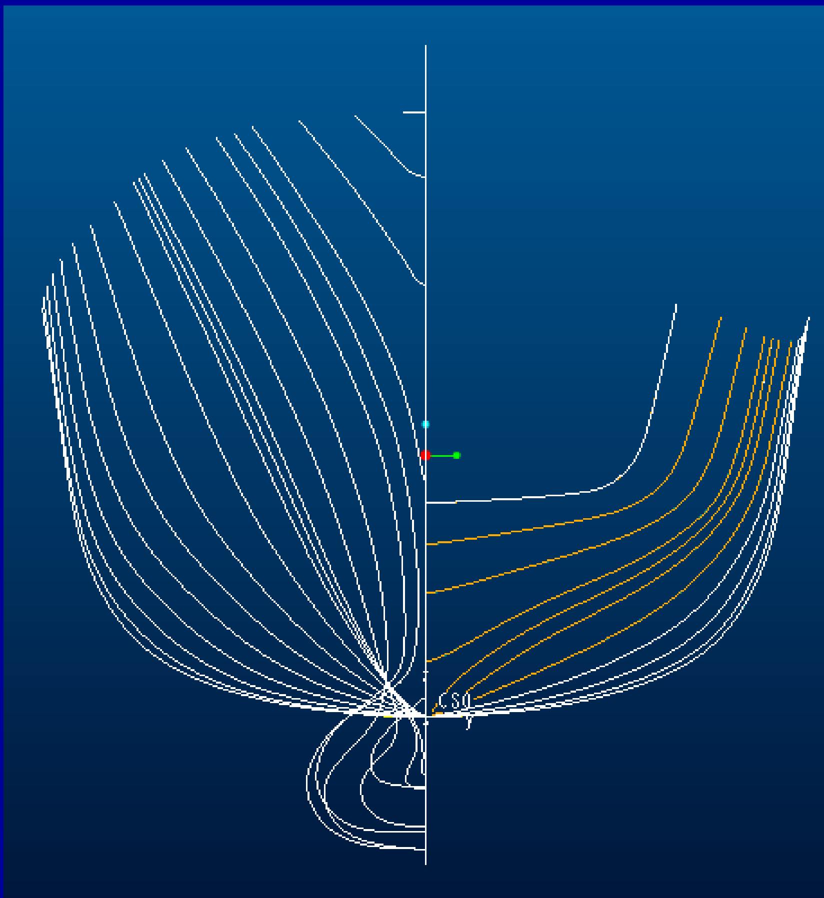
Send everything in workshops for production



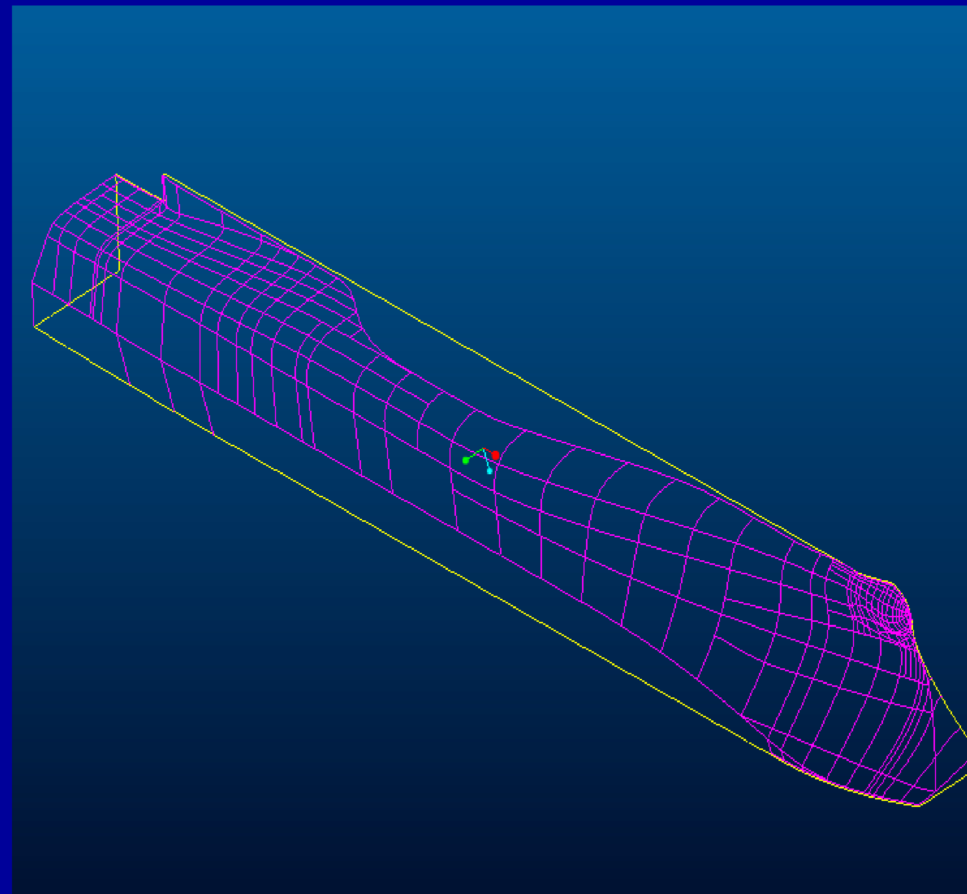


e can build up a reverse engineering process based on customers data forma

From curves or points

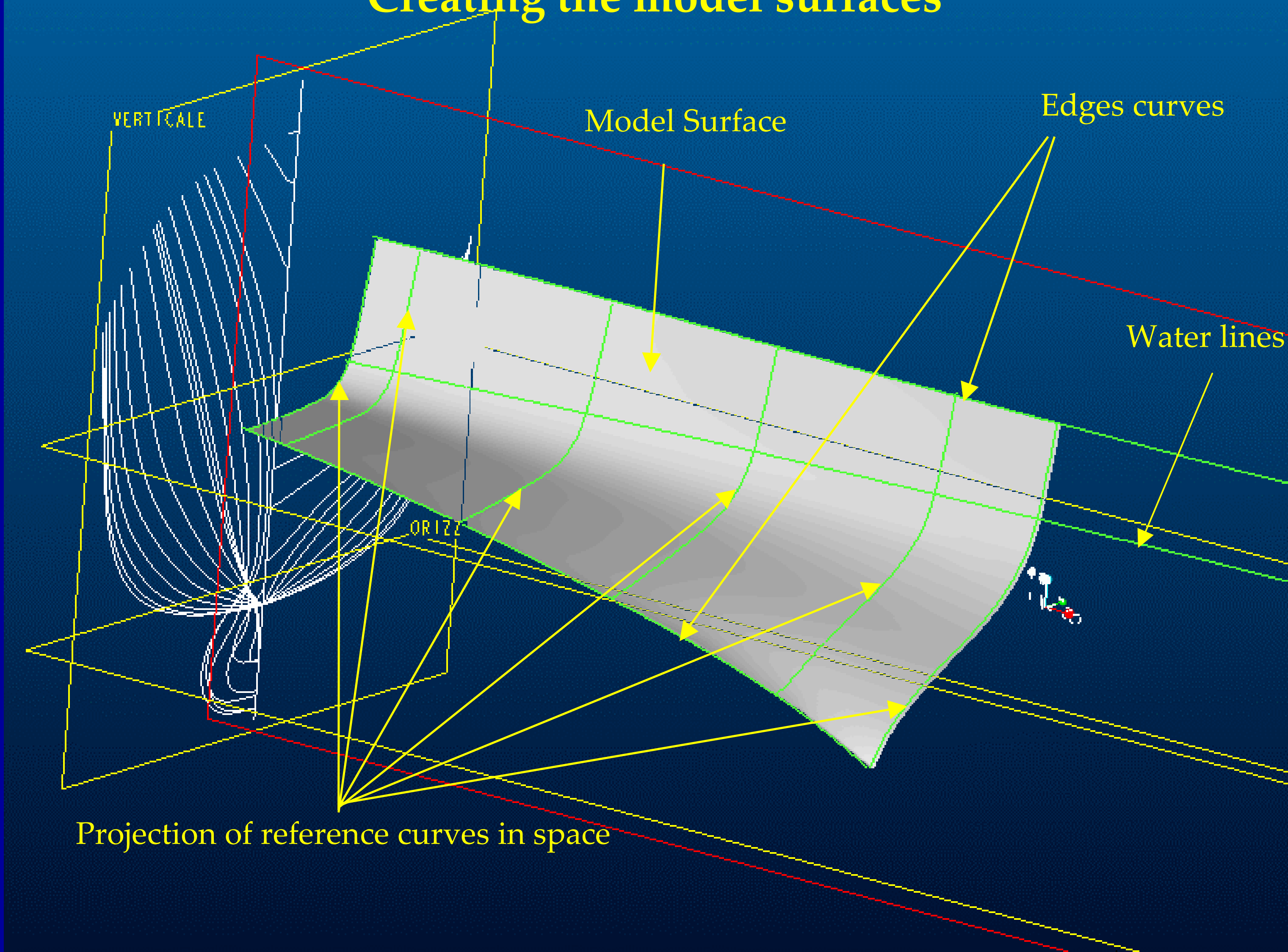


From surfaces



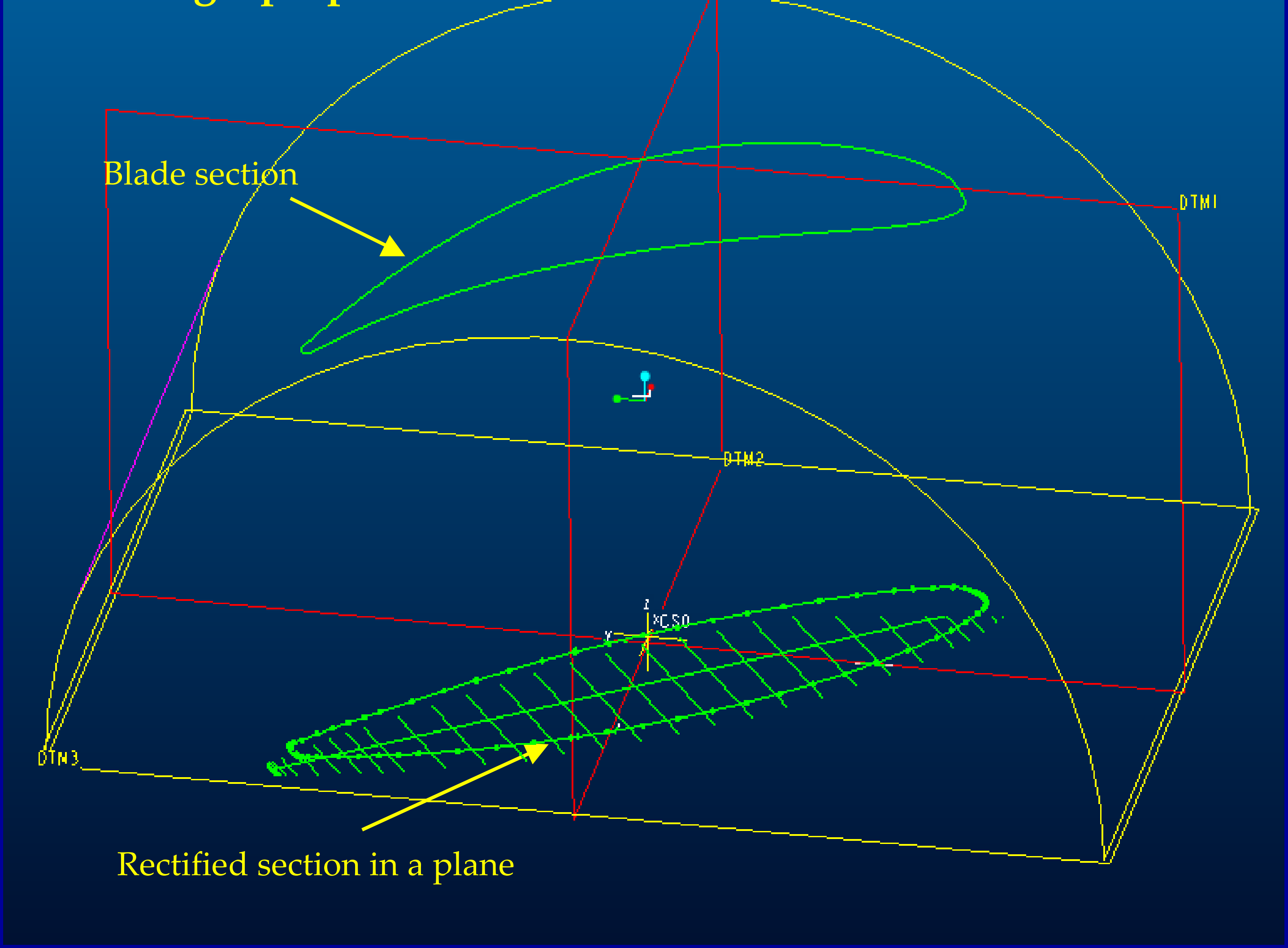
Ship hull

Creating the model surfaces



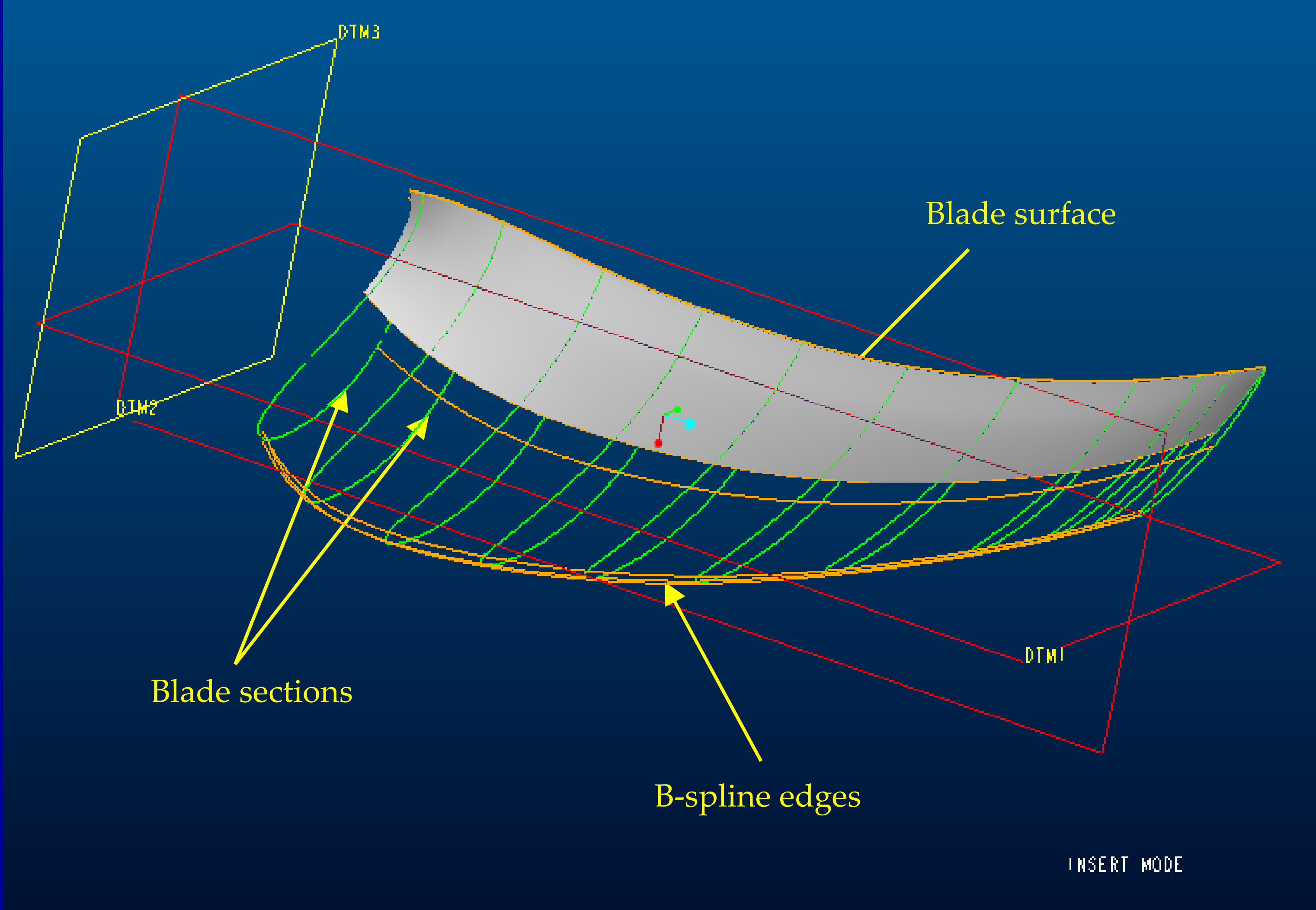
Propellers

Creating a propeller section from conventional section draw



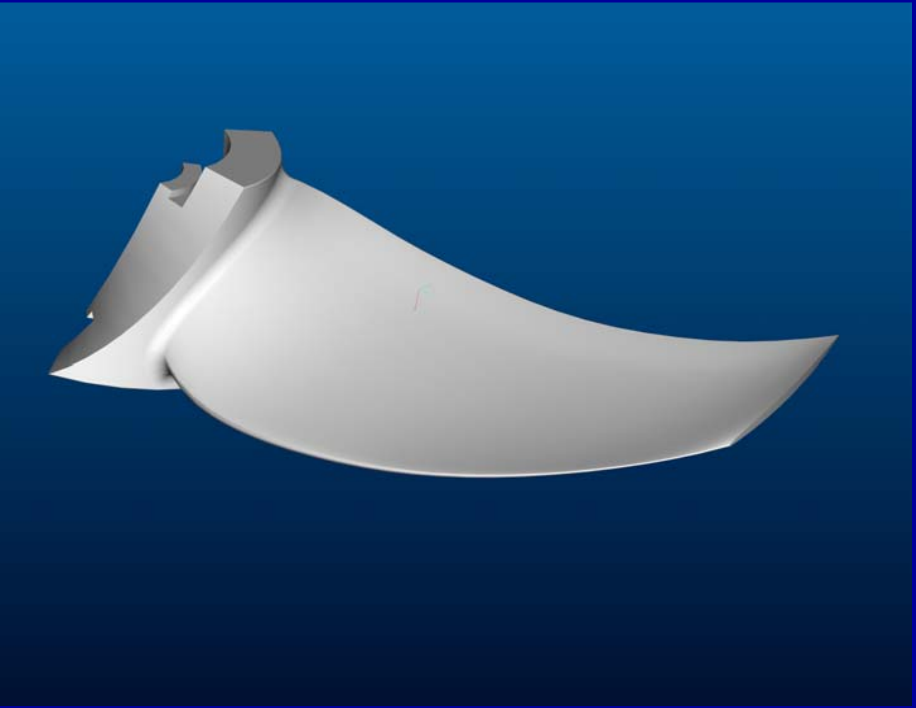
Propellers

Creating the model surfaces



Propellers

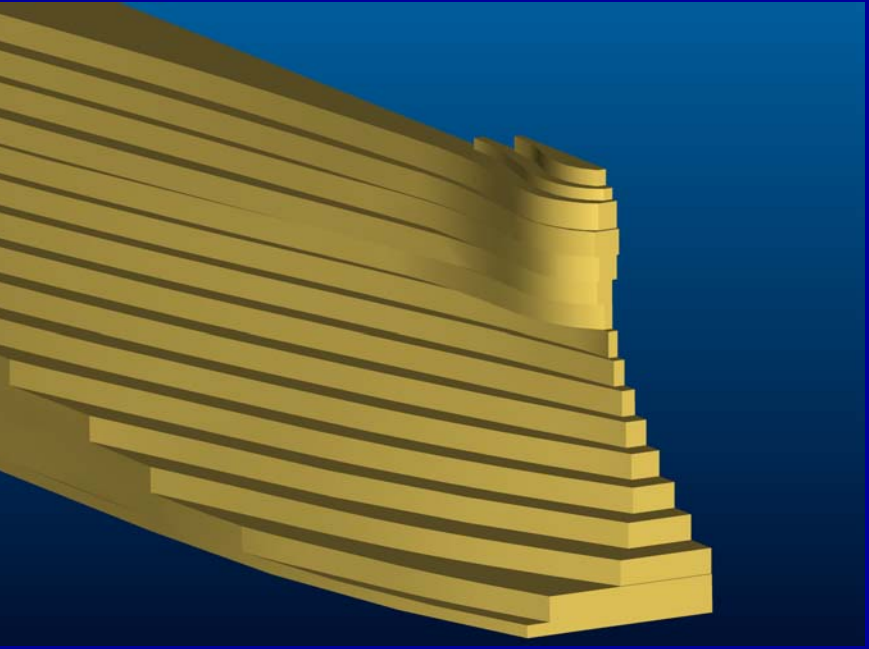
Creating the solid from surfaces for CAM and CAE



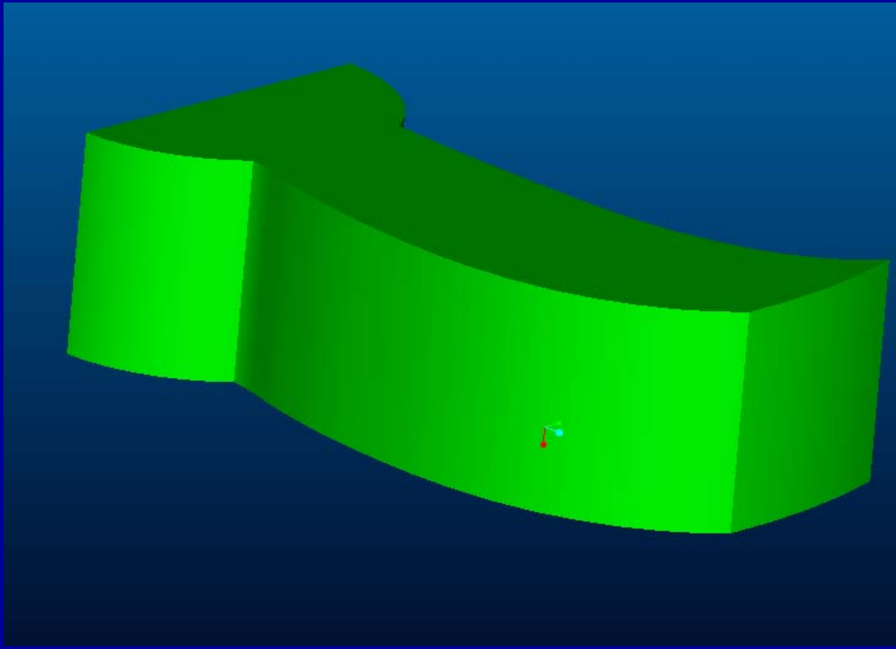
Blade solid model

Blade assembly

We can build up a CAM procedure for manufacturing

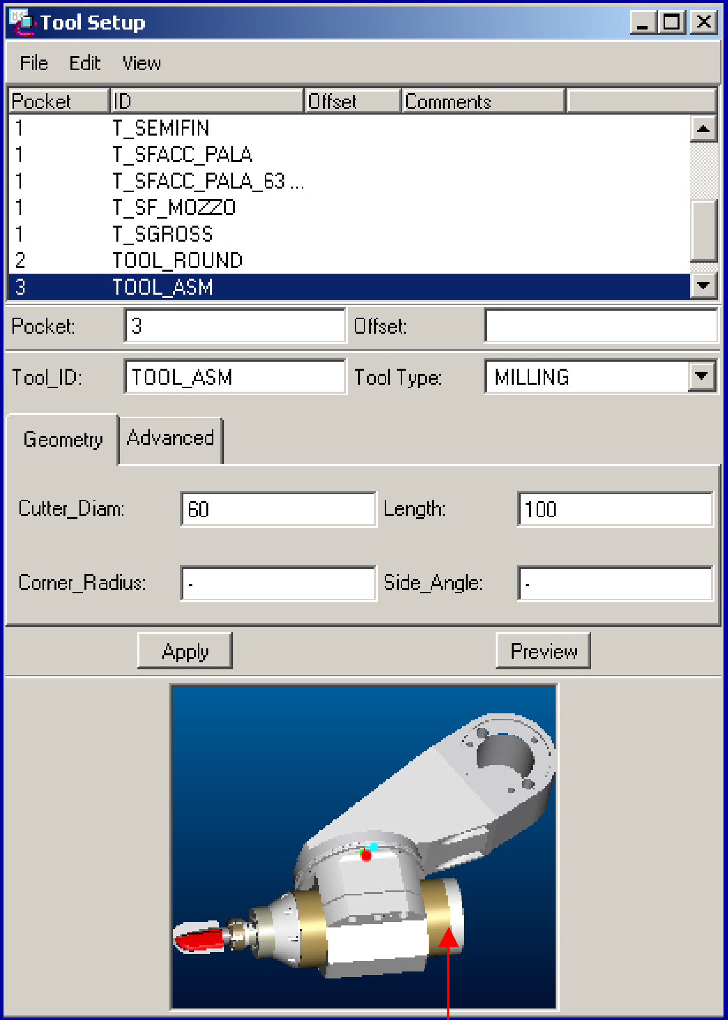


Workpiece for ship hull model

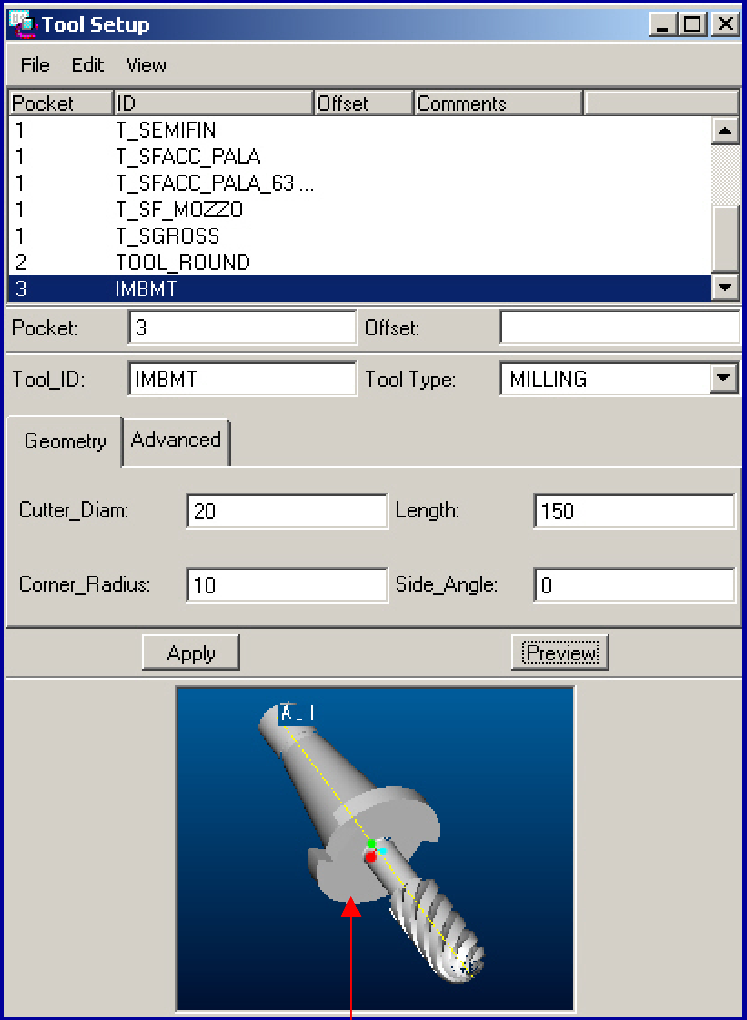


Workpiece for propeller model

Choosing or creating the tools

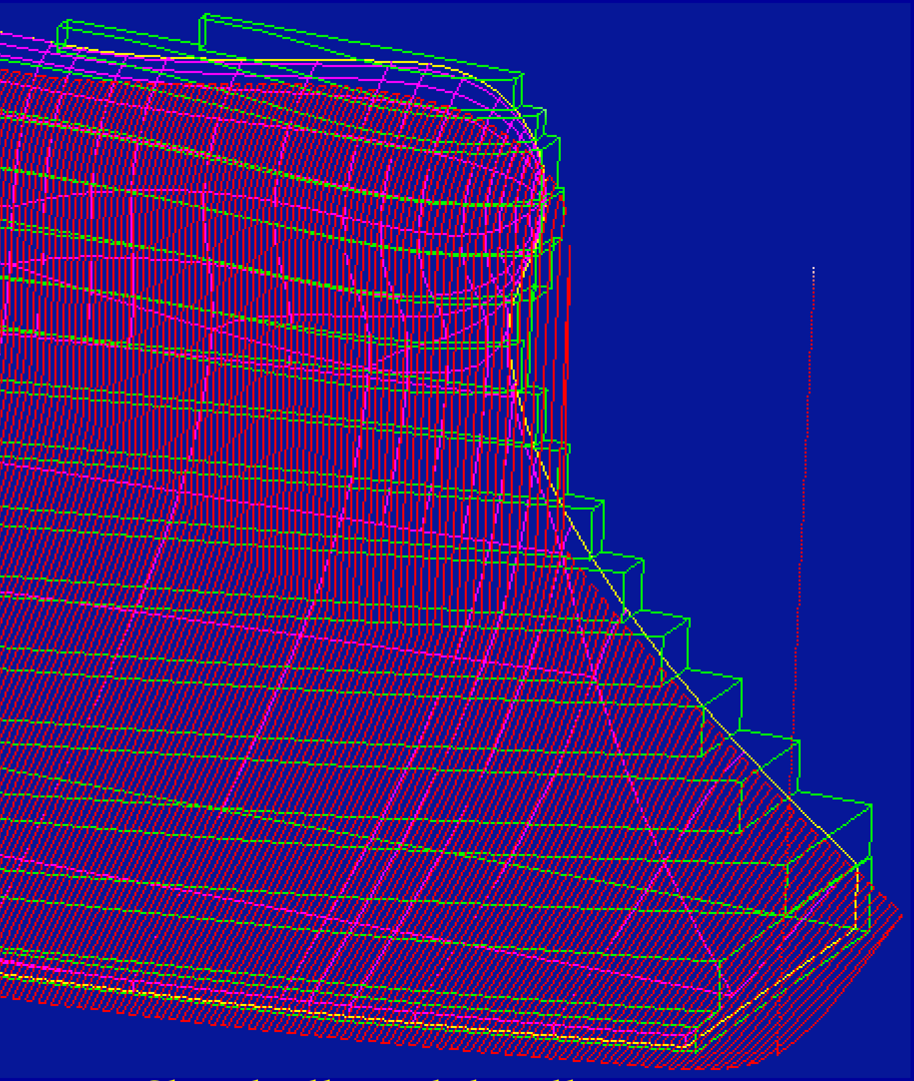


INSEAN designed tool

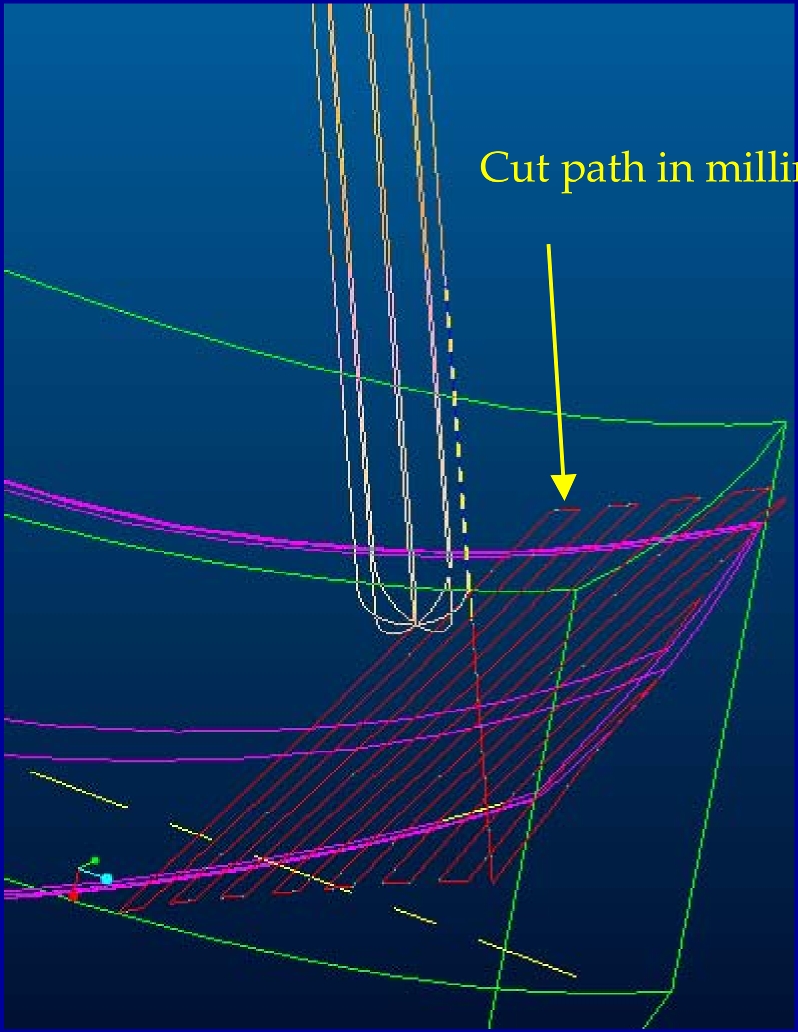


Standard tool

Showing the cut path

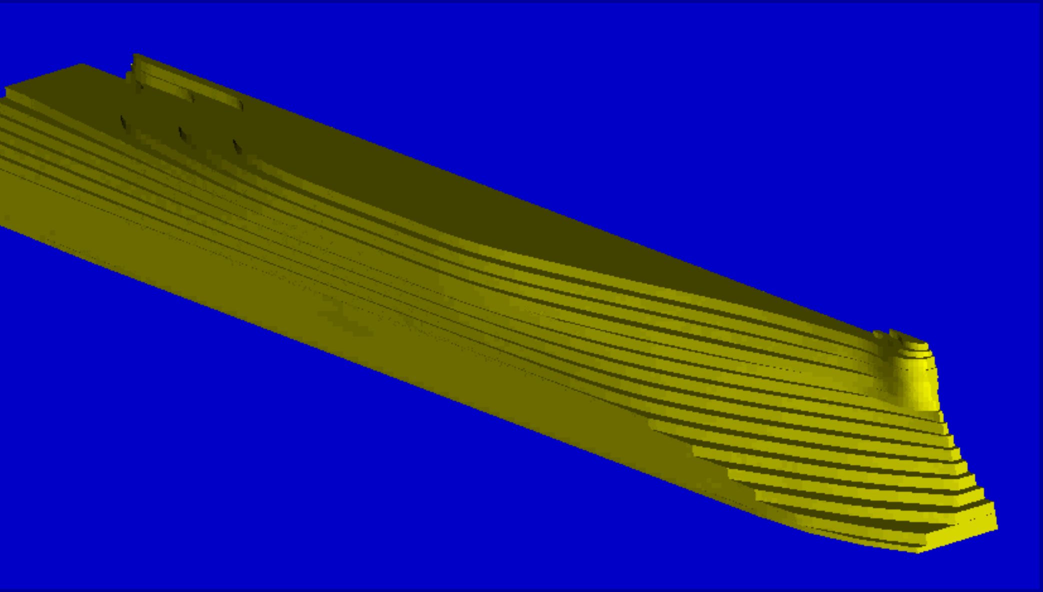


Ship hull model milling



Blade model milling

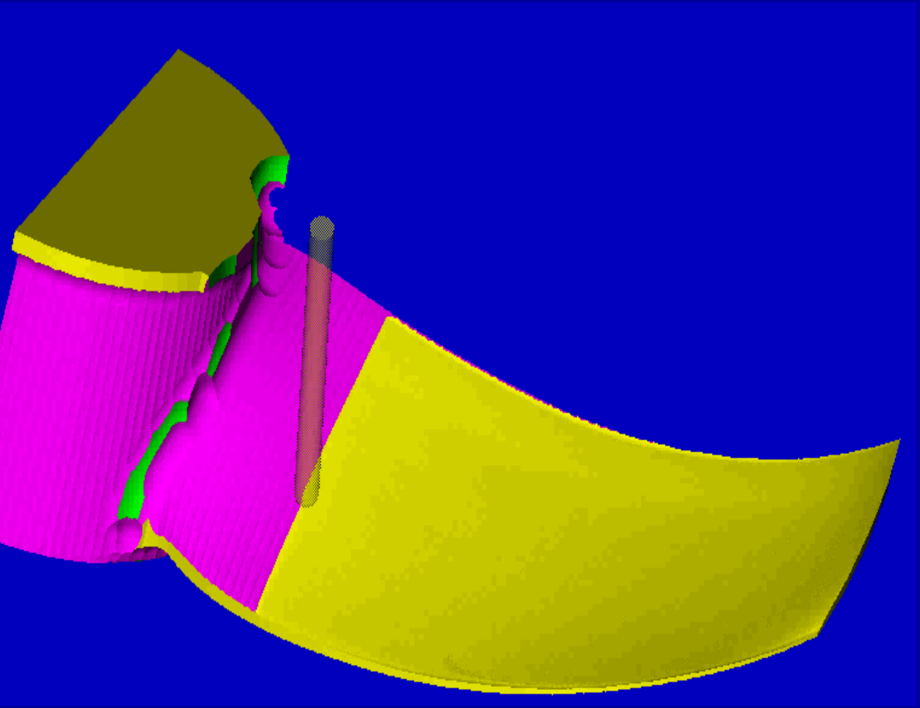
Check the whole cut path → and then the real work on a three axis old fashion milling machi
(10000×1500×1800 mm)

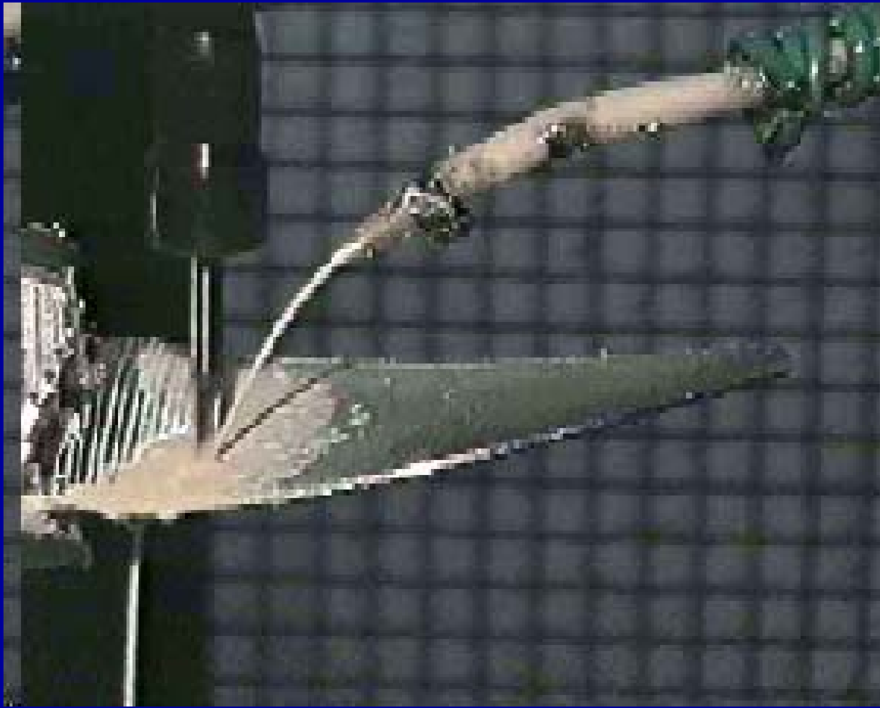


movie

movie

Check the whole cut path → and then the real work on a five axis milling machine (1000×400×400 mm)





movie

movie

CHECKING TOLERANCES

For ship hull model

We use stainless steel plane (8000x2000 mm),
linear gages (1000 mm) and
handmade template based on 2-D model description.
We work the model with a precision
within 0.5 mm in all three space dimension

For propeller model

We use a special checking machine for blade geometry.
We work the model with a precision
within 0.04 mm in all three space dimension

That is what we do daily.
Everything seems to work well but there are still some questions

metimes the CAD model delivered by customers are not so smoo
not dramatically, but within some fraction of millimetre
(they don’t pay much attention to that);
What must we do? Do we modify, smoothing,
or don’t mind to save time?
What do you do?

What are the border on tolerances?

Do all of us need for ship hull model,
suisse watch mechanism tolerances?

How many points we should use to check the model?

How do you measure the final model surface?

Manufacture Accuracy of Three KCS Models and Resistance Test Results

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Maritime Bureau, Ministry of Land, Infrastructure and Transport, Tokyo, Japan

1. Shaping Machine and Model Inspection Device at NMRI Workshop

In the National Maritime Research Institute (NMRI), previously called as the Ship Research Institute (SRI), ship models are mainly manufactured in the NMRI workshop, using a 40-year old shaping machine as shown in Fig. 1(a) [1]. This machine is not numerically controlled by a computer and models are cut by manually tracing the drawing of waterlines. The maximum size of a ship model manufactured by this machine is 12m long, 2m wide and 1m high. Each nominal accuracy of the NMRI shaping machine in three directions under a model shaping condition is expected to be ±2mm to 6m range in the longitudinal direction of a ship model, ±0.4mm to 1m range in the transverse direction and ±0.2mm to 0.5m range in the vertical direction. These values were given when it was installed at the NMRI workshop. A ship model is cut at each waterline usually by around 20mm interval but dependent on the drawing of lines. Finishing is made by hands of skillful technicians, using adjustment gauges in the vicinity of the forward and after ends of the model. As the materials for manufacturing ship models, paraffin wax and/or wood are employed. Wooden models are polished by sand papers and coated with watertight paints repeatedly.

Model inspection is made by a pair of three-dimensional digitizers equipped on the precise model inspection table as shown in Fig. 1(b). The size of the table is 10m in length and 3m in width. The determined roughness of the table is within ±0.02mm. When the probe of the measuring devices touches the surface of a ship model, the buzzer sounds and the measured data are acquired by a personal computer. The nominal accuracy of the digitizer is ±0.08mm.

2. Measured Manufacture Error of Three Models

To comply with the request from the resistance committee of the 22nd ITTC and to provide CFD validation data, the NMRI (SRI) manufactured a ship model of the KRISO Container Ship (KCS) [2] as shown in Table 1 NMRI (SRI) M.S. No.631 was made of the combination of paraffin wax and wood in the NMRI workshop. The drawing of lines was produced by the help of a Japanese shipbuilder, based on the numerical offsets provided by KRISO. The ship model was cut by manually tracing the drawing of waterlines with the NMRI shaping machine. The generated offsets for the lines were modified from the original one by using a shipbuilder's CAD software different from KRISO. The manufacturing time for this ship model was needed twice as usual due to unexpected problems on the data transfer between NMRI (SRI) and KRISO as described above. This ship model was favorably manufactured in spite of the difference in the manufacturing methodology between NMRI and KRISO.

The difference in the half breadth of the model between the target offsets and the manufactured model offsets horizontally measured at each waterline is shown in Fig.2 by a contour map. The relatively big deviated parts from the target offsets are observed around the bottom part between the square station, S.S. 2 and 3 and near the forward perpendicular on both sides, and around the upper part of bulbous bow. The measurement by half of the length only in the horizontal direction exaggerates the error of model manufacture especially in the overhang part of model hull around the forward and after perpendiculars. If the correction is made to these measurements by considering the inclination of hull surface, the difference between the corrected and the given offsets becomes within 0.5mm around the overhang part of the transom stern.

After the first series of the resistance test on this ship model, remarkable distortion of the model was observed. The model was shrunk 3mm in the longitudinal direction of the ship model mainly in the aftbody due to the employed materials and not well established manufacturing technique about the hybrid structure used for this ship model. Totally the ship model length was around 6mm shorter than the given offsets after the all of the measurements. This model was employed for the measurements of local velocity field [3, 4] and hull surface pressure distribution [4, 5].

Then, the same size of ship model, NMRI (SRI) M.S. No. 640 was manufactured one year later by another method to examine the effects of exceptionally distorted ship model NMRI M. S. No. 631 on the same measurements. The ship model was fully made of wood and manufactured by a ship model maker. By using the IGES data provided by KRISO, the numerical lines data for this model were generated by a CAD software, FastShip. These numerical offset data were transferred to the ship model maker but finally used numerical lines data were also modified by its own curve fitting software. The model was cut at each waterline with 7.9mm interval by a numerically controlled (NC) shaping machine at the workshop of the ship model maker. The nominal accuracy of this shaping machine is almost the same as the one in the NMRI workshop mentioned above.

The horizontal difference between the original and the manufactured model offsets measured at each waterline on the second KCS model is shown in Fig.3 by a contour map. This model was manufactured more precisely than the previous ship model except the overhang part around the after perpendicular. The relatively big difference from the given offsets was found around the forward perpendicular and the aftbody in the port side. After the use for the measurement of hull surface pressure distribution, this ship model surface was so roughened around the pressure taps to make us decide to manufacture a new accurate one.

Finally the third ship model, NMRI M.S. No. 702 was manufactured with the same size by the cooperative work between the NMRI workshop and the workshop of the above-mentioned ship model maker. The model was cut by using the previous numerical offset data and the same numerically controlled shaping machine as those employed for NMRI (SRI) M.S. No. 640. Other manufacturing work including preparation and finishing work was made by the NMRI workshop. The materials, adhesives, paints, finishing, polishing and paint coating procedure are different from those employed for the previous model manufactured by the ship model maker.

The horizontal difference between the original offsets and the manufactured model offsets measured at each waterline is shown in Fig.4 by a contour map. On the third ship model, still significant manufacture error is observed around the forward and after perpendiculars near the load waterline.

The comparison of manufacture error among three KCS models is shown in Figs. 5 and 6 determined by a pair of three-dimensional digitizers. The former figure shows the horizontal difference between the measured offsets and the given offsets at each square station expressed by the root mean squared deviation, which is expected to indicate the averaged roughness of a manufactured ship model. The latter figure shows the maximum manufacture error measured in the horizontal direction at each square station.

3. Resistance Test Results on Three Models

For each ship model, the resistance tests were performed twice except NMRI M. S. No. 702 at the NMRI 400m towing tank whose length is 400m, the breath is 18m and the depth is 8m respectively. Fig. 7 shows the wave pattern around NMRI M. S. No. 631 at the design Froude number of the KCS, Fn*=0.2600 based on the L_{PP} and the speed of the ship model, Vm=2,196m/s.

The resistance tests on each ship model were performed during three years. Fig. 8 shows the comparison of the total resistance coefficients converted to the values at 15 deg C among five runs on three KCS models measured at the NMRI 400m towing tank. At the design Froude number Fn*=0.2600, the difference among them is found small except the test on NMRI M. S. No. 631 in October 1999, while remarkable data scatter in the total resistances coefficients is observed with three nodes around Fn*=0.14, 0.24 and 0.30. Less difference on the measured total resistance coefficients between NMRI M. S. No. 640 and 702 is found as shown in Fig. 8, comparing with those on NMRI M. S. No. 631. The models in the total resistance coefficient curves at higher Froude numbers might be related to the interference between bow and stern wave. The sources of the data scatter among these resistance coefficients have not been fully examined yet.

Uncertainty analysis was made by using a standard spreadsheet for documenting uncertainty analysis provided by the resistance committee of the 23rd ITTC. The total uncertainties $U_{CT}^{15\ deg\ C}$ for total resistance coefficient C_T converted to those at 15 deg C on three models, NMRI M.S. No.631, 640 and 702 at Fn*=0.2600 were 1.48, 0. 55, 0.35% of C_T under the statically even keel condition and 0.31% of C_T [6] on NMRI M. S. No. 702 under the dynamically even keel condition [2, 4] respectively.

Fig. 9 shows the comparison of the measured wave resistance coefficients among three ship models. The form factor 1+k was determined to be 1.10 throughout the whole tests for three ship models.

4. Comments on Model Manufacturing and Accuracy

* Manufacture accuracy depends not only on the hardware error of a shaping machine and CAD/CAM software but also on the data transfer interface between a designer and a manufacturer, finishing procedure and time spent, materials including adhesives and paint used for the model, and finally technician's skillfulness.
* Model inspection not only immediately after the completion of the ship model but also after and on the way of the towing tests seem to be more effective to examine the effect of the model deformation on the test results.
* To clarify the correlation between local manufacture error and towing tank test results on resistance including form factor, sinkage and trim, propulsive coefficient, wave profile and pattern, wake and hull surface pressure distribution is one of the most complicated and difficult but important problems.

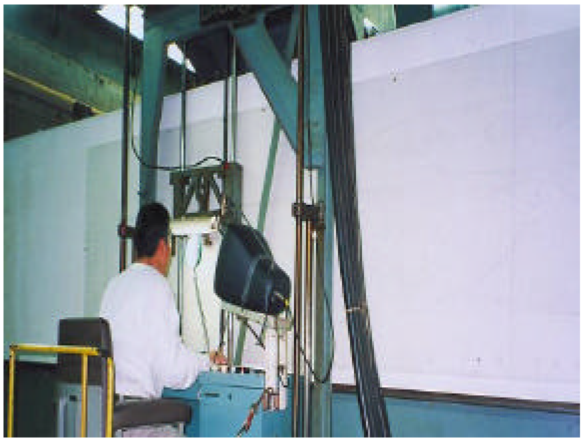
References (*; written in Japanese)

1. Ship Propulsion Division, "On the Mitaka No. 2 Ship Model Experimental Tank of the Ship Research Institute", Report of Ship Research Institute, Vol. 6, No. 4, July, 1969, pp.1~ 104.*
2. Van, S. H., et al., "Experimental Investigation of the Flow Characteristics around Practical Hull Forms", Proc. of the 3rd Osaka Colloquium on Advanced CFD Applications to Ship Flow and Hull Form Design, 1998, pp.215-227.
3. Fujisawa, J., et al., "Local Velocity Field Measurements around the KCS Model in the SRI 400m Towing Tank", Ship Performance Division Report No. 00-03-02, March, 2000.
4. Kume, K., Ukon, Y. and Takeshi, H., "Measurements of Surface Pressure and Local Velocity Field around a KCS Model and Uncertainty Analysis", Proc. of Gothenburg 2000, A Workshop on Numerical Ship Hydrodynamics, Goeteborg, Aug. 2000.
5. Tsukada, Y., et al., "Surface Pressure Measurements on the KCS in the SRI 400m Towing Tank ", Ship Performance Division Report No. 00-004-01, 2000. *
6. Ukon, Y. and Kume, K., "The Standard Form for Documenting Uncertainty Analysis on Total Resistance C_T Filled in by NMRI and Sent to the Resistance Committee of 23rd ITTC", Dec. 2001.

Table 1 Principal Particulars of KCS Model

KRISO Container Ship					
NMRI/SRI M.S.No.	Key	Unit	631	640	702
Manufacturer			NMRI/SRI	Model Maker	NMRI & Model Maker
Length between Perpendiculars	L_{PP}	m	7.2786		
Length at Load Waterline	L_{WL}	m	7.3568		
Breadth (Moulded)	B	m	1.019		
Depth (Moulded)	D	m	0.5696		
Draft (Moulded)	d	m	0.3418		
Wetted Surface Area w/o Rudder	S_W	m^2	9.4984		
Displacement w/o Rudder	Ñ	m^3	0.0741		
Center of Buoyancy from Midship (Backward, +)	l_{CB}	% L_{PP}	1.48		
Blockage Coefficient	C_B	-	0.6508		
Midship Coefficient	C_M	-	0.9849		
Prismatic Coefficient	C_P	-	0.6608		
Manufacture Accuracy of Shaping Machines					
Ship Length			2mm/6m	Similar	
Ship Breadth			0.4mm/1m	Similar	
Ship Depth			0.2mm/0.5m	Similar	
Uncertainty Analysis Results					
Total Uncertainty	$U_{CT}^{15\ deg\ C}$	% U_{CT}	1.48	0.55	0.35

(a) Model Inspection Table and 3-D Digitizer



(b) NMRI Shaping Machine

Fig. 1 Shaping Machine and NMRI M.S. No. 640 on Model Inspection Device at NMRI Workshop

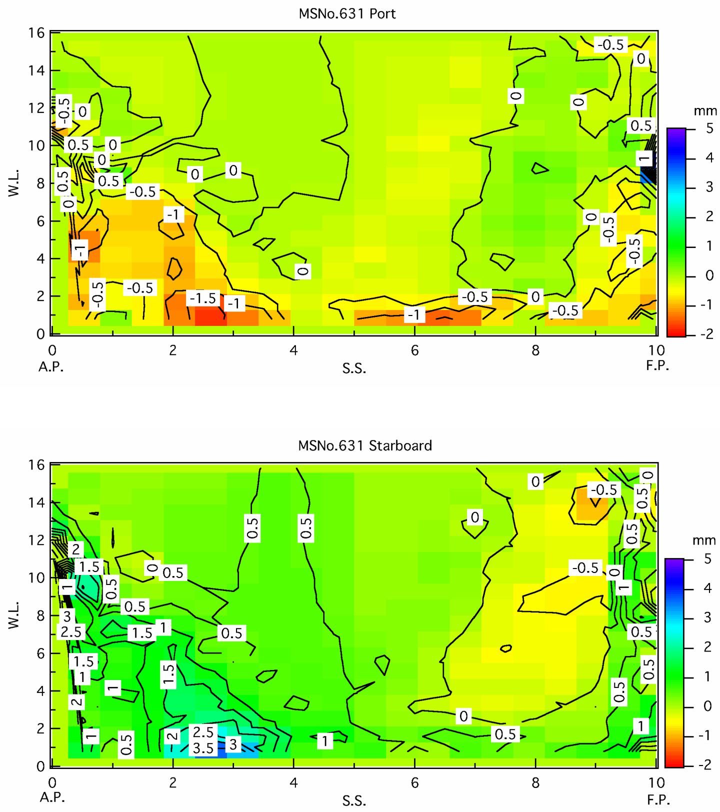


Fig. 2 Horizontally Measured Manufacture Error on Port and Starboard Sides of NMRI M.S.No. 631

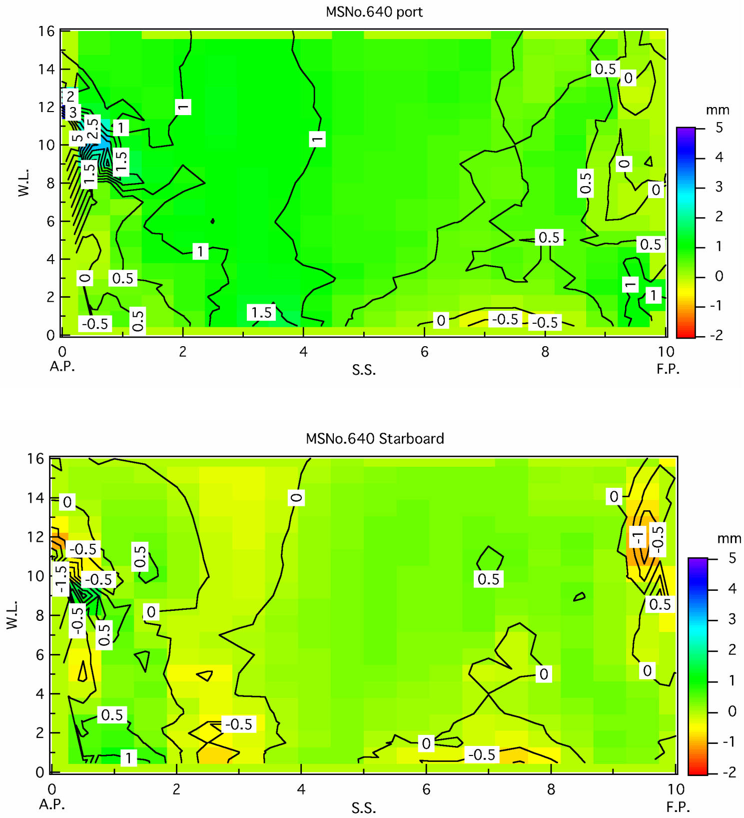


Fig. 3 Horizontally Measured Manufacture Error on Port and Starboard Sides of NMRI M.S.No. 640

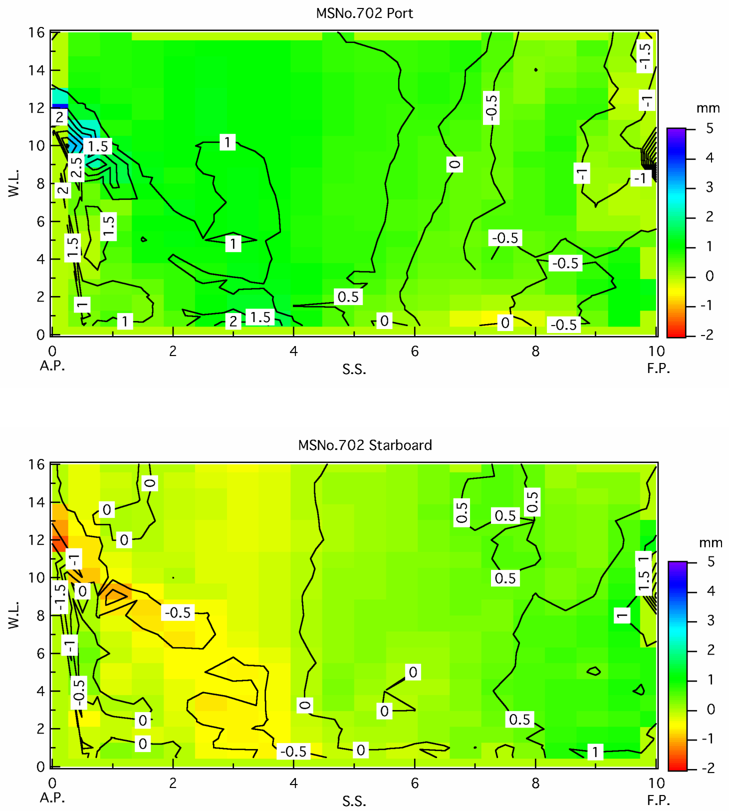


Fig. 4 Horizontally Measured Manufacture Error on Port and Starboard Sides of NMRI M.S.No. 702

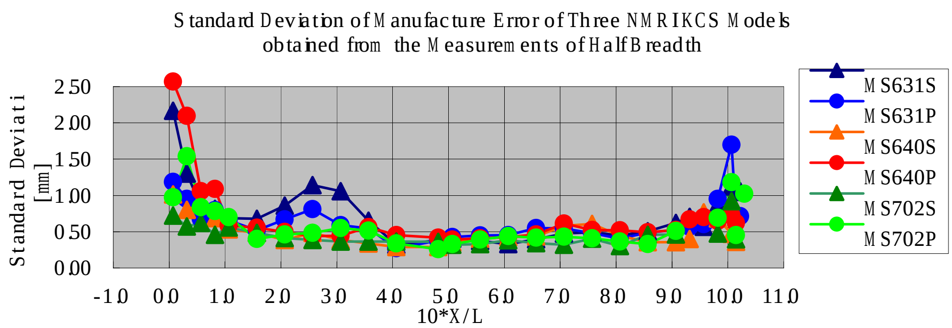


Fig. 5 Comparison of Manufacture Error by Root Mean Squared Deviation at Each S.S. among Three KCS Models

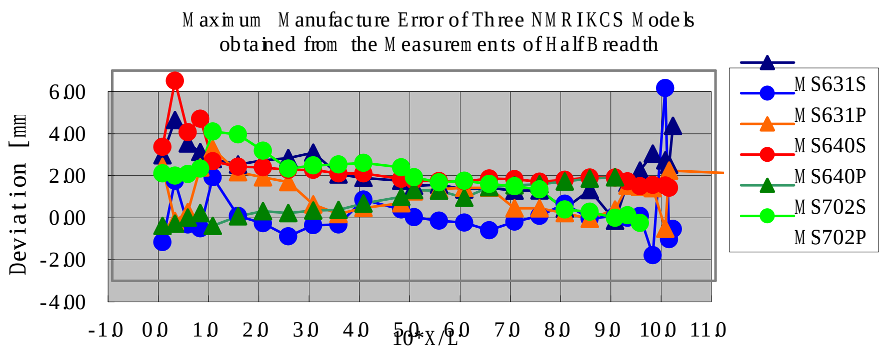


Fig. 6 Comparison of Maximum Manufacture Errors at S.S. among Three KCS Models

Fig. 7 Resistance Test on NMRI M.S. No. 631 at NMRI 400m Towing Tank

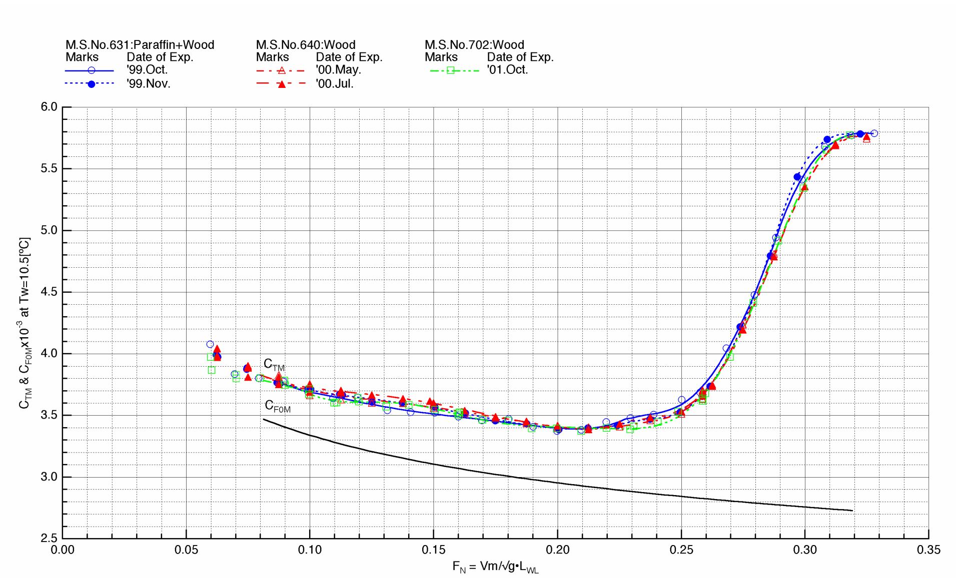


Fig. 8 Comparison of Total Resistance Coefficients C_T among Three KCS Models

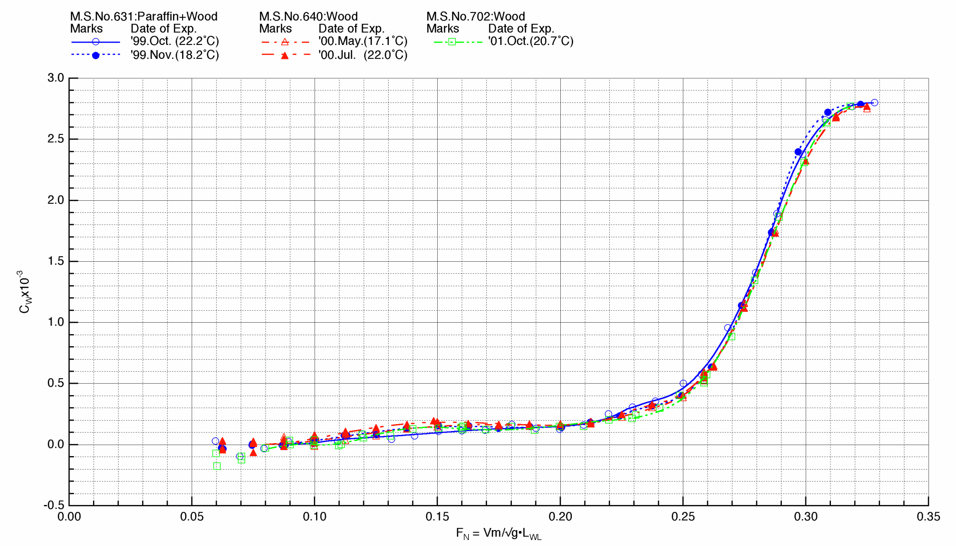


Fig. 9 Comparison of Wave Resistance Coefficients C_T among Three KCS Models

Model Manufacturing Technology at IMD

Tony Randell P.Eng
Leader, Design and Fabrication
National Research Council of Canada
Institute for Marine Dynamics

NRC · CNRC

National Research Council Canada
Institute for Marine Dynamics

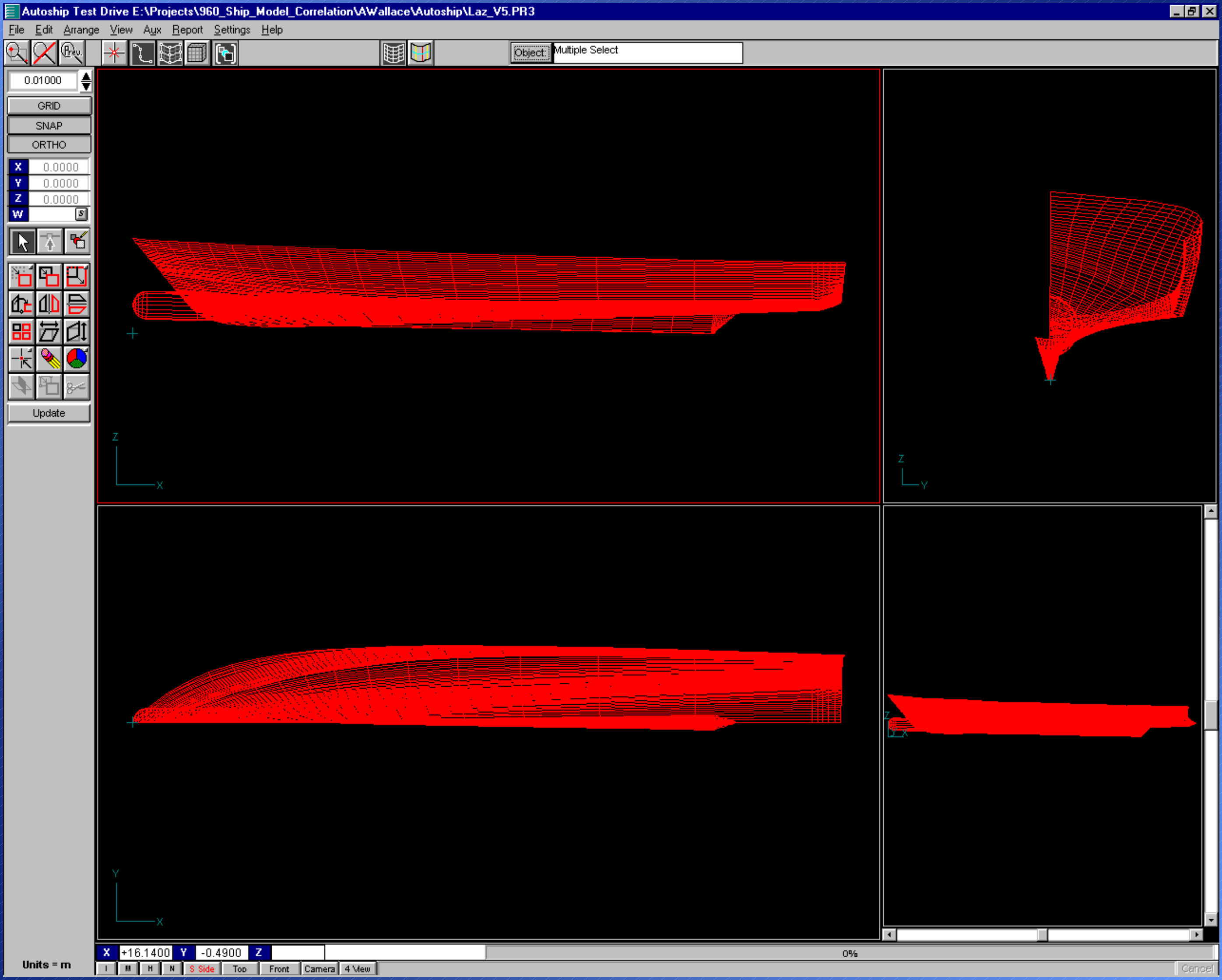
NRC · CNRC

How IMD build Models

CAD software

- Autoship™
- Fastship™
- Blines™
- Cadkey™

Autoship™ Model of Ship Hull



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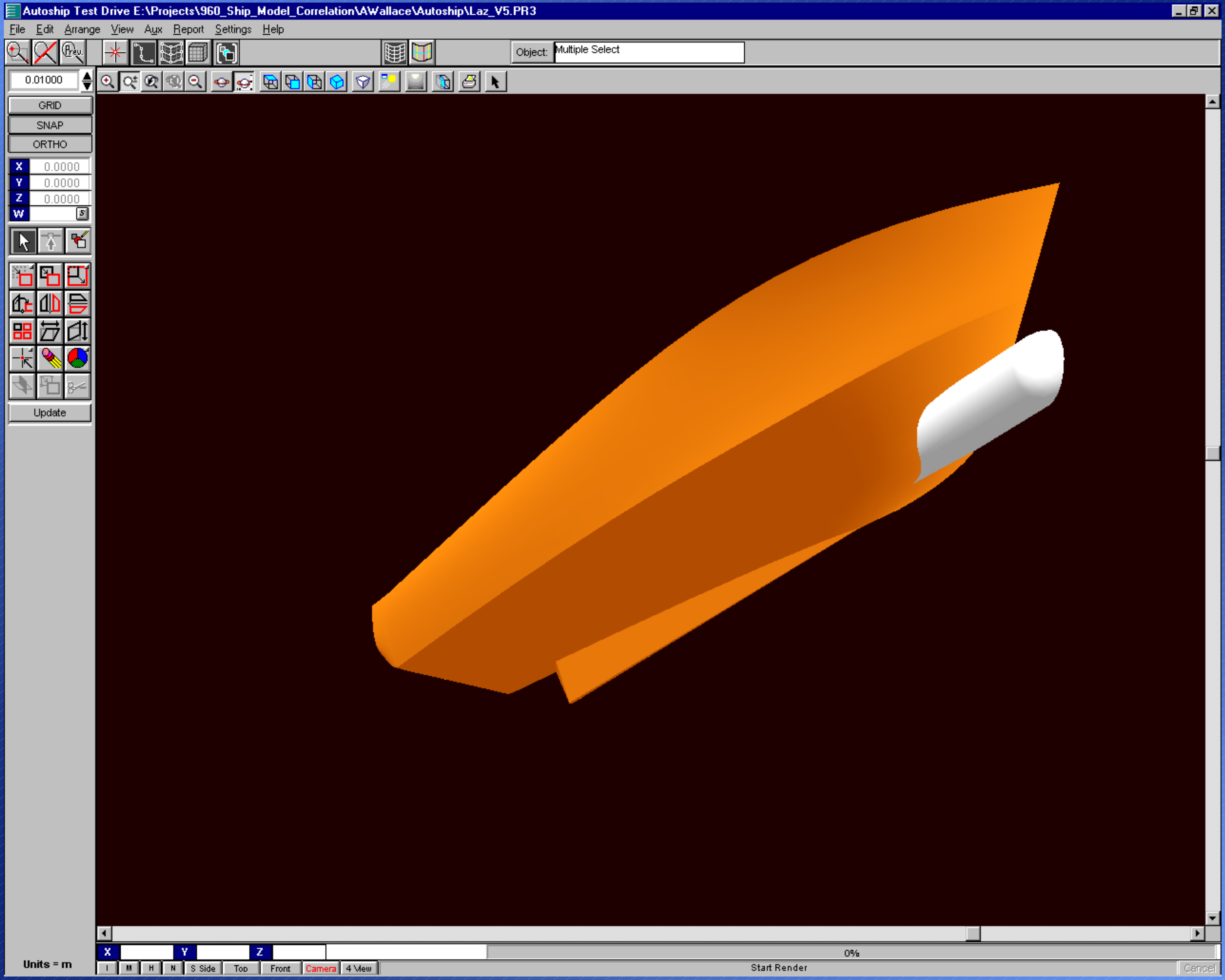
Autoship™ Model of Ship Hull

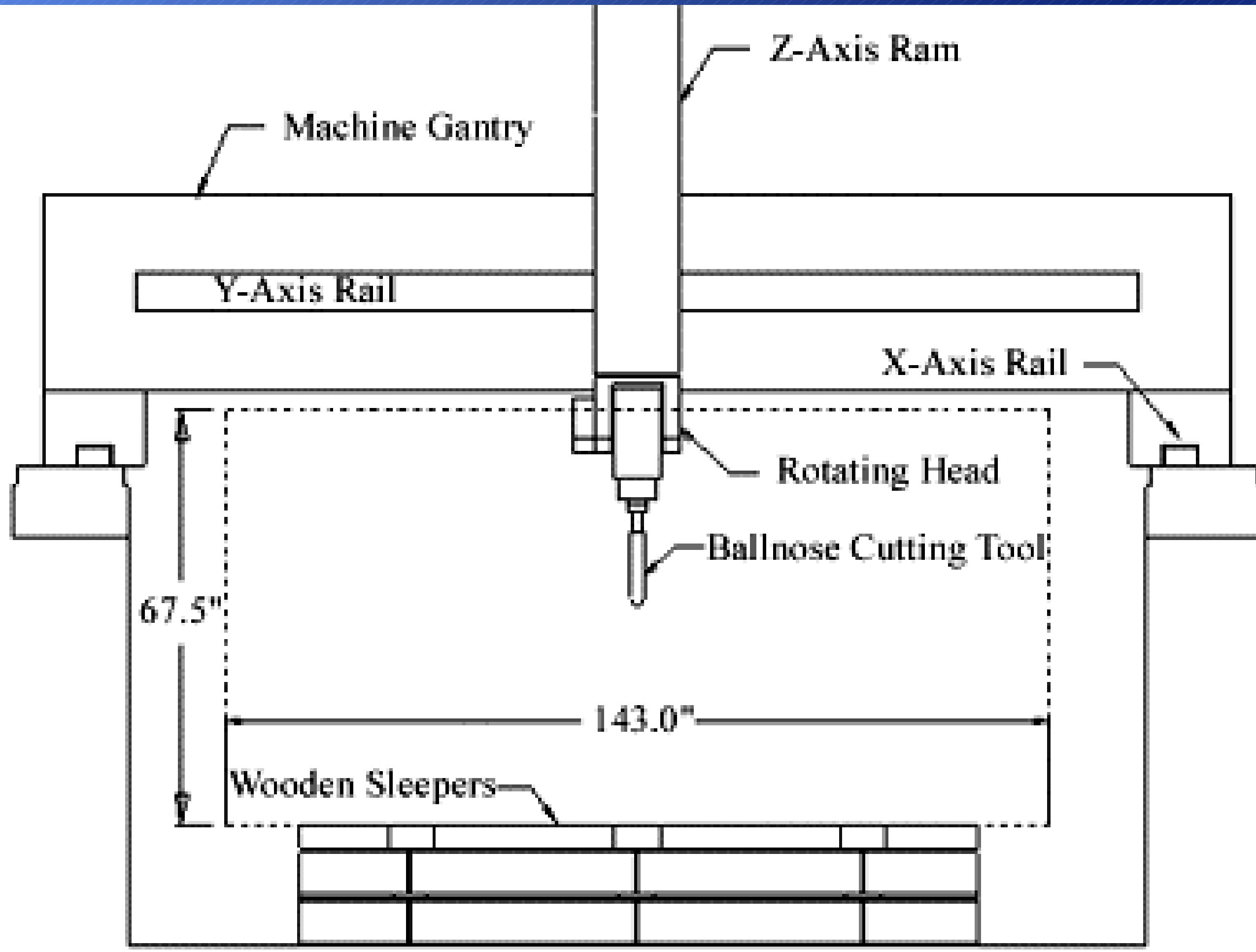


IMD Model Construction Shop

Line CNC Ship Model Mill (1985)

Line CNC Ship Model Mill (1985)

Line CNC Ship Model Mill (1985)



LINÉ 5-AXIS NC MODEL MILLING MACHINE

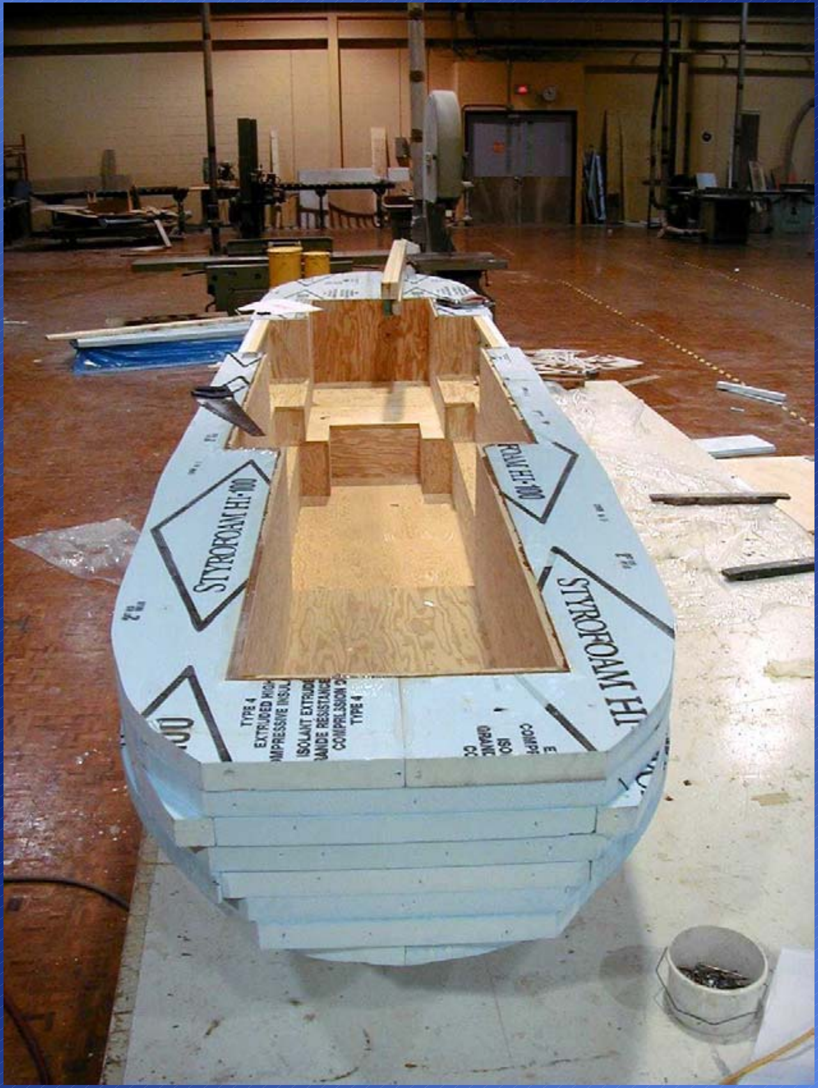
Model Milling tools

Model Plug Laminations

Styrofoam™ Hi100

Plug Internal Box Assembly

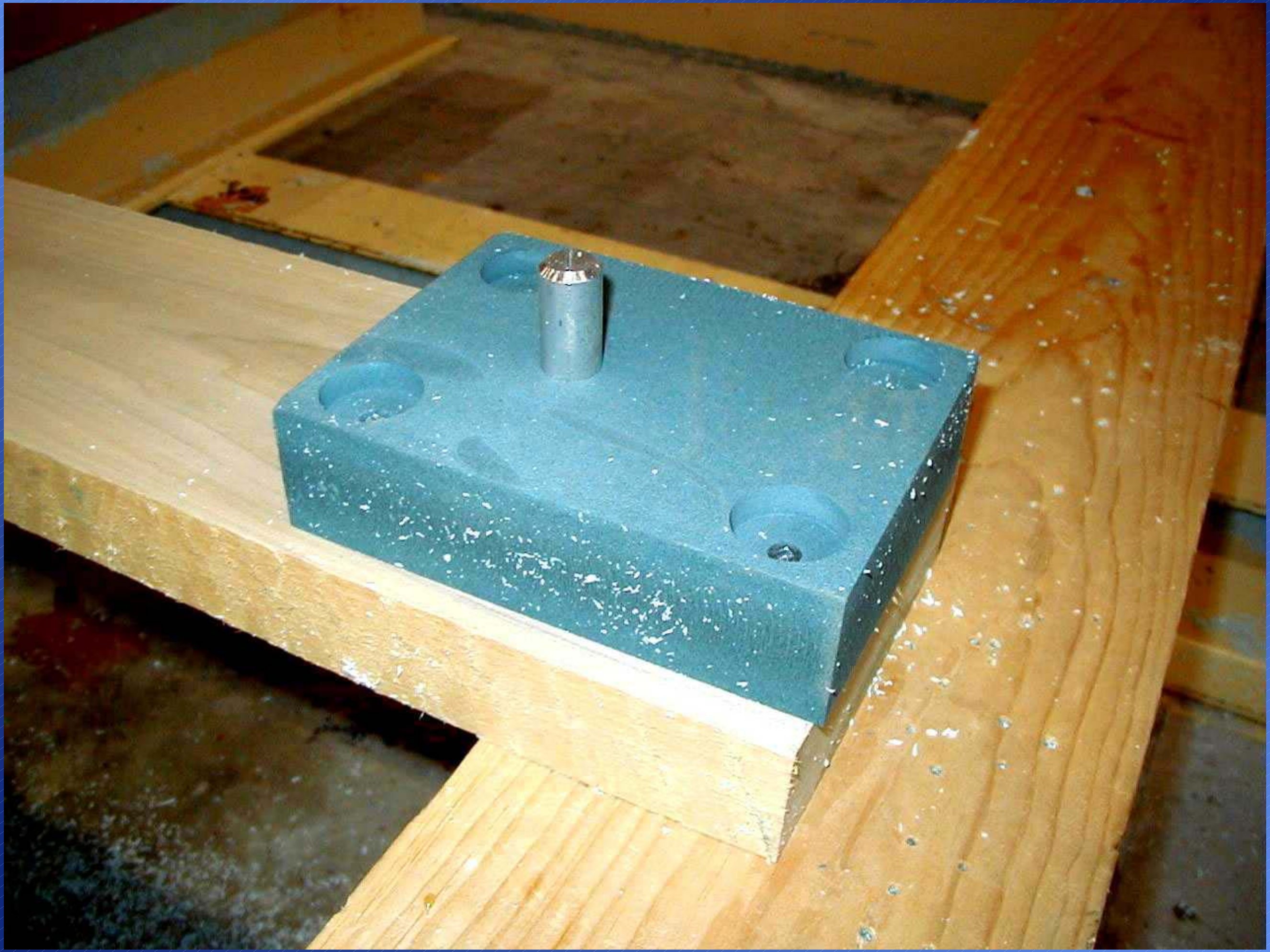
Assembled Model plug



Model Plugged with Glassed Interior

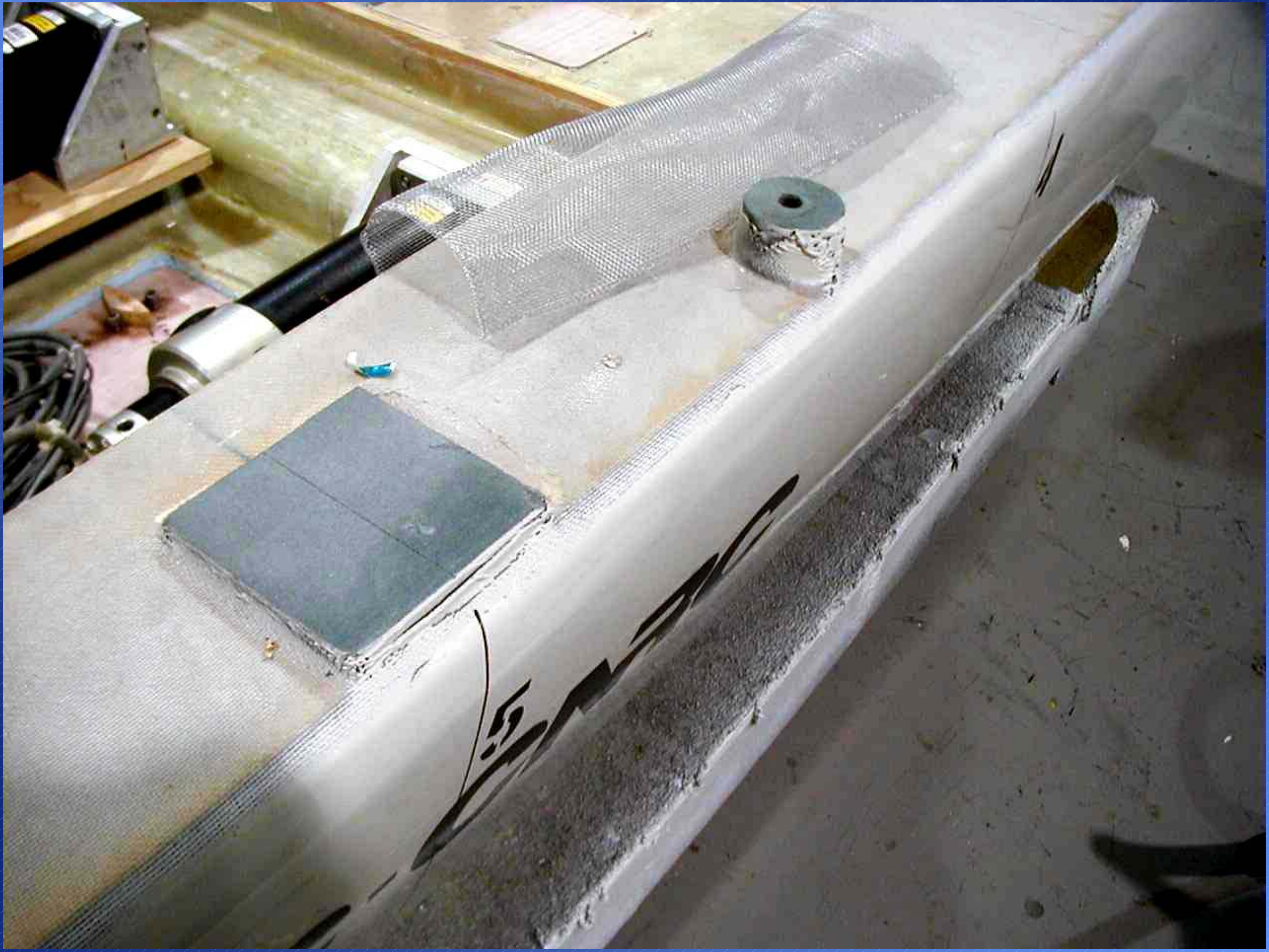
Model plug in CNC Milling Machine

CNC Machined Model Fixturing pads

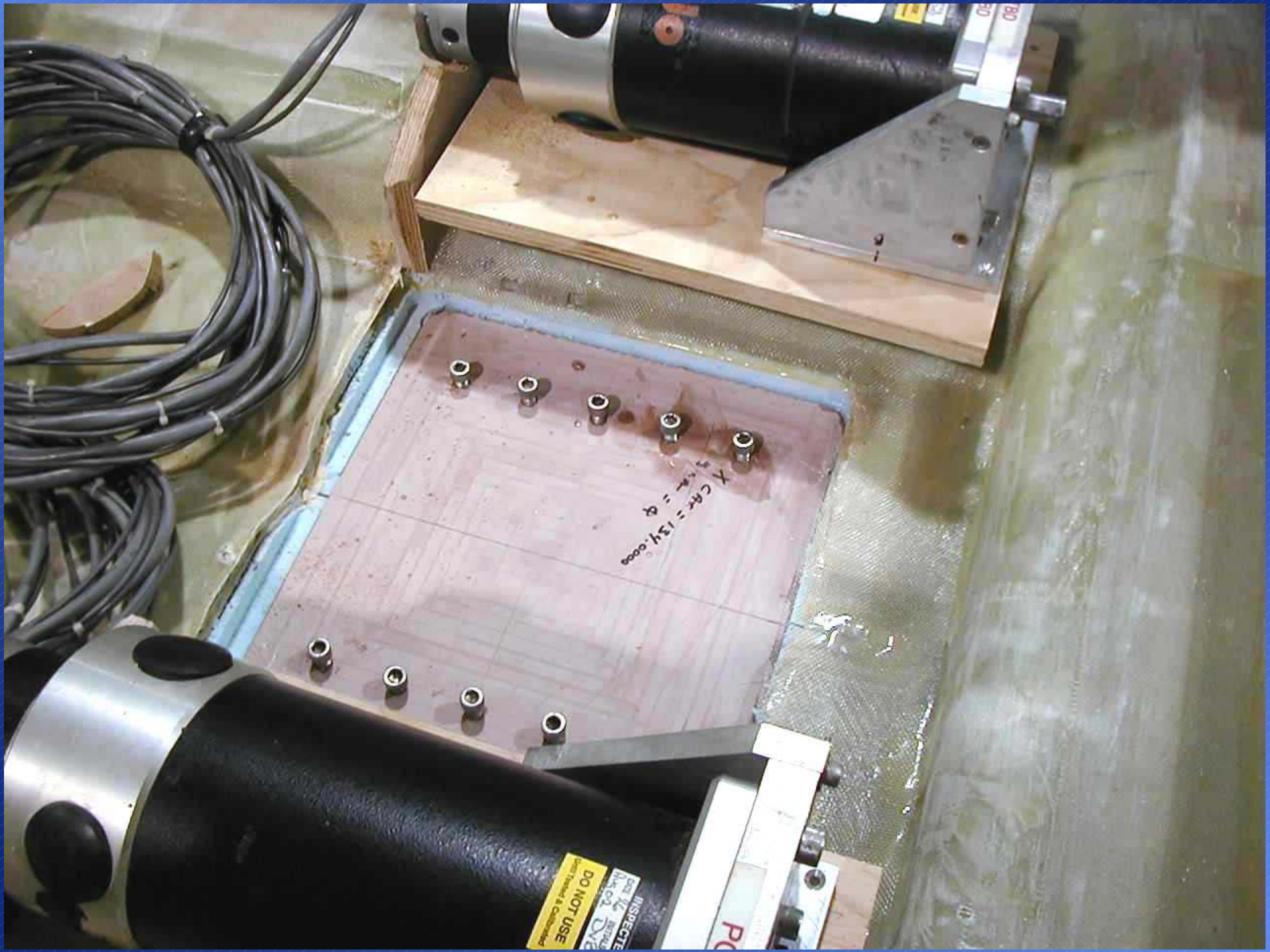


Model Fixturing pads

CNC Machined trim pads



CNC Machined Gimbal base pad

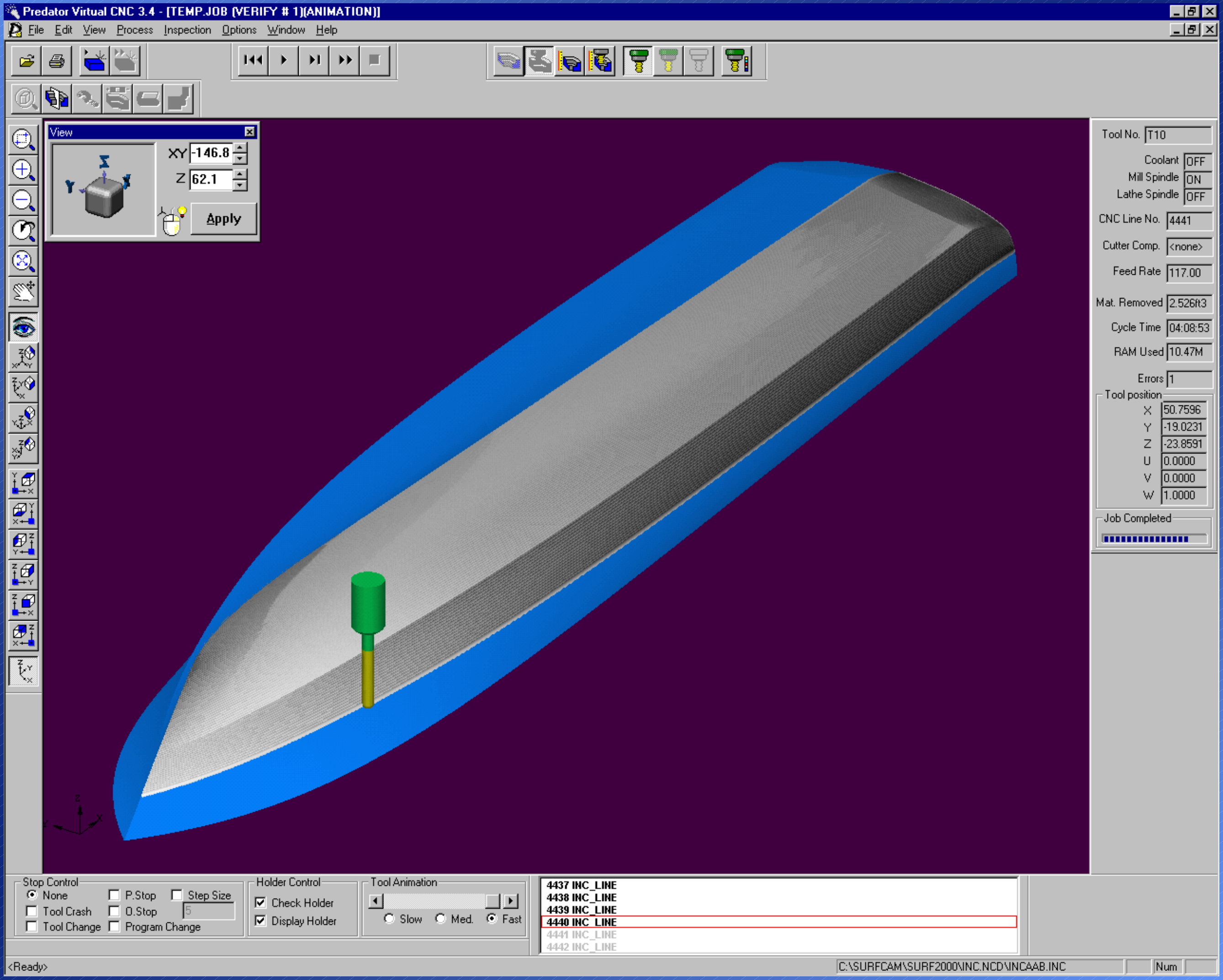


Yacht Model Milling Fixture

CAM (CNC Machining) software

- Surfcam™
- Predator Virtual CNC™
- ICAM™ M5 Post processor
- Greco WinDNC™

CNC Machining Toolpath Verification for Hull



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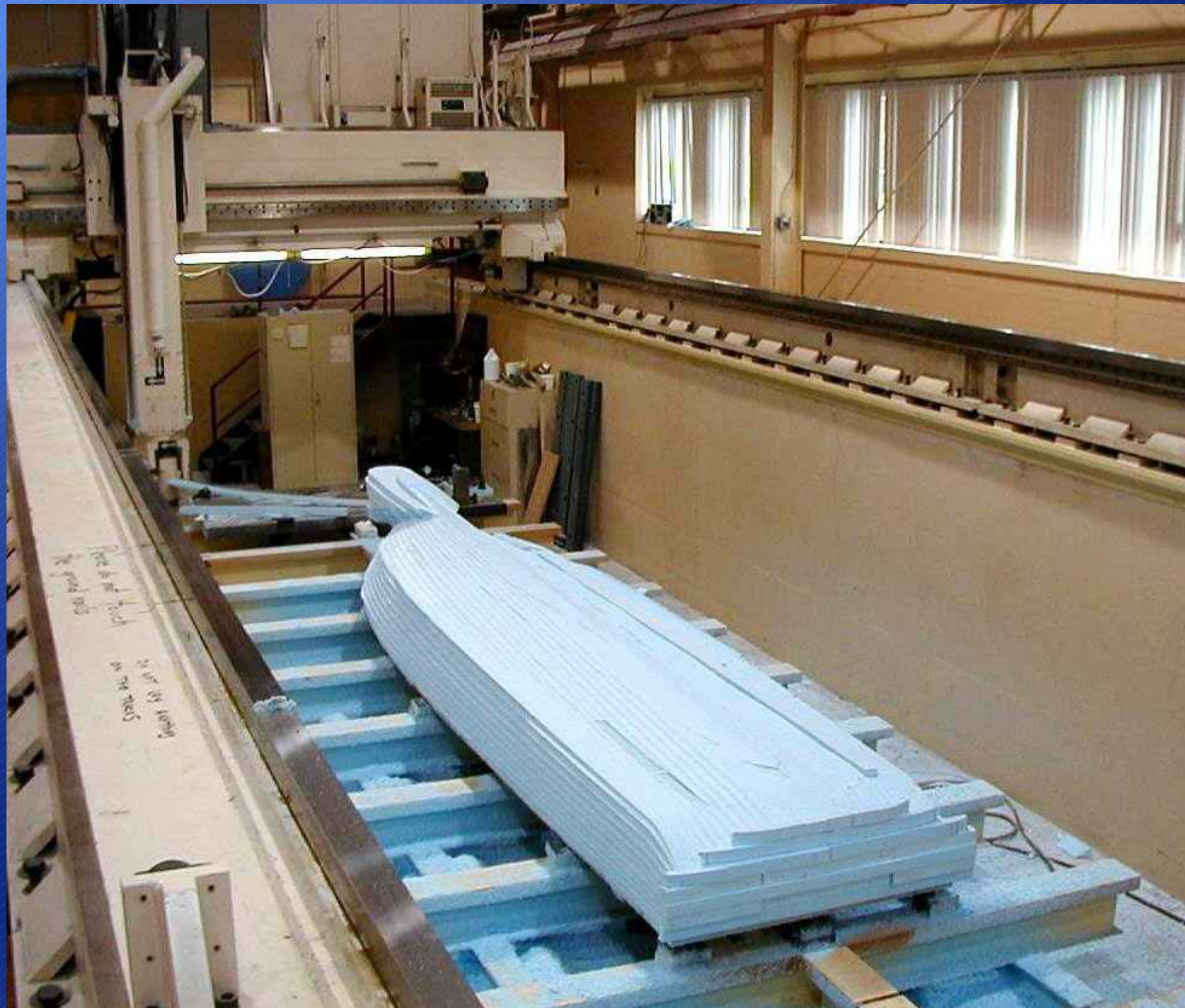
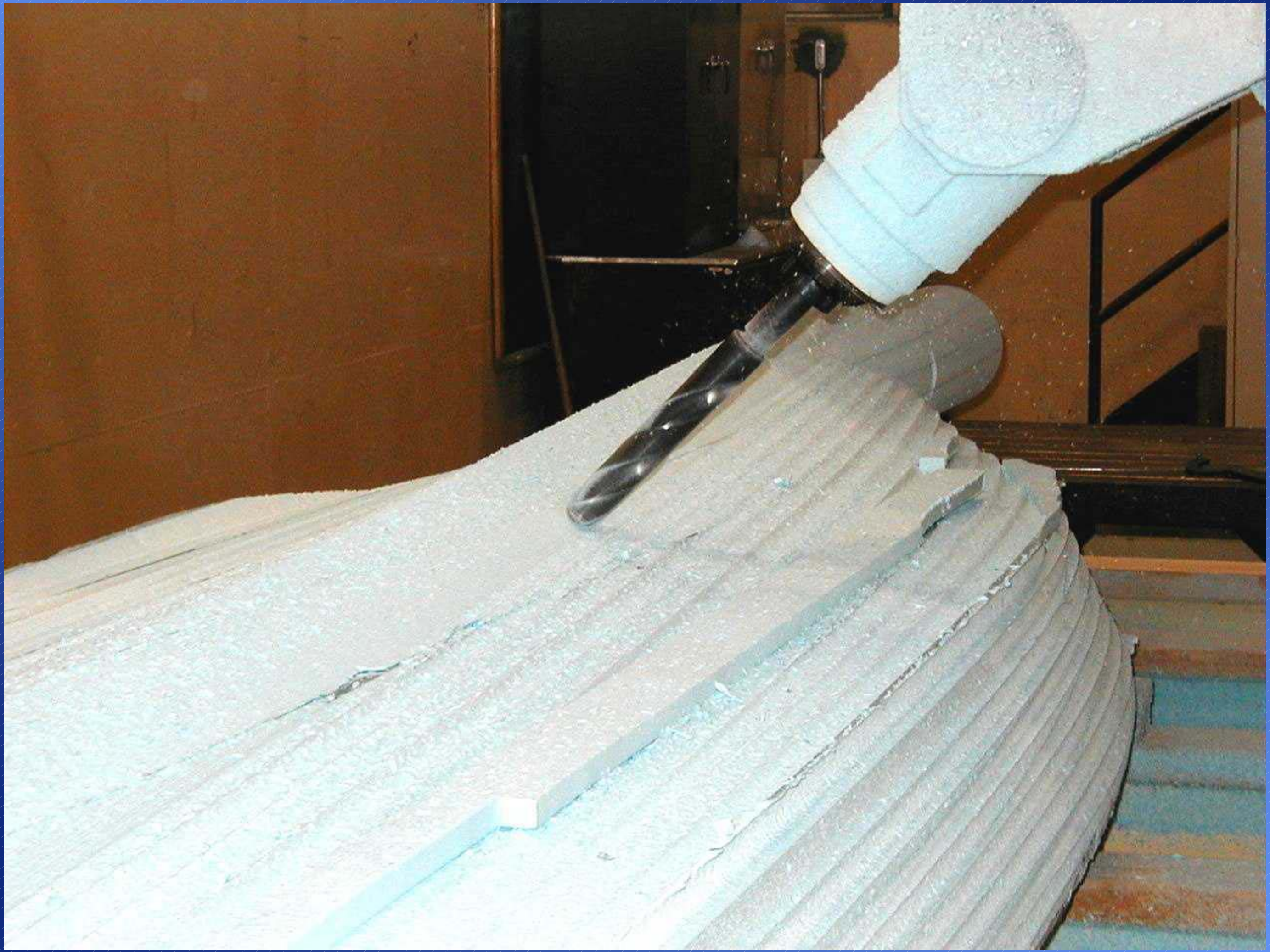
Institute for Marine Dynamics

CNC Machining (roughing pass)

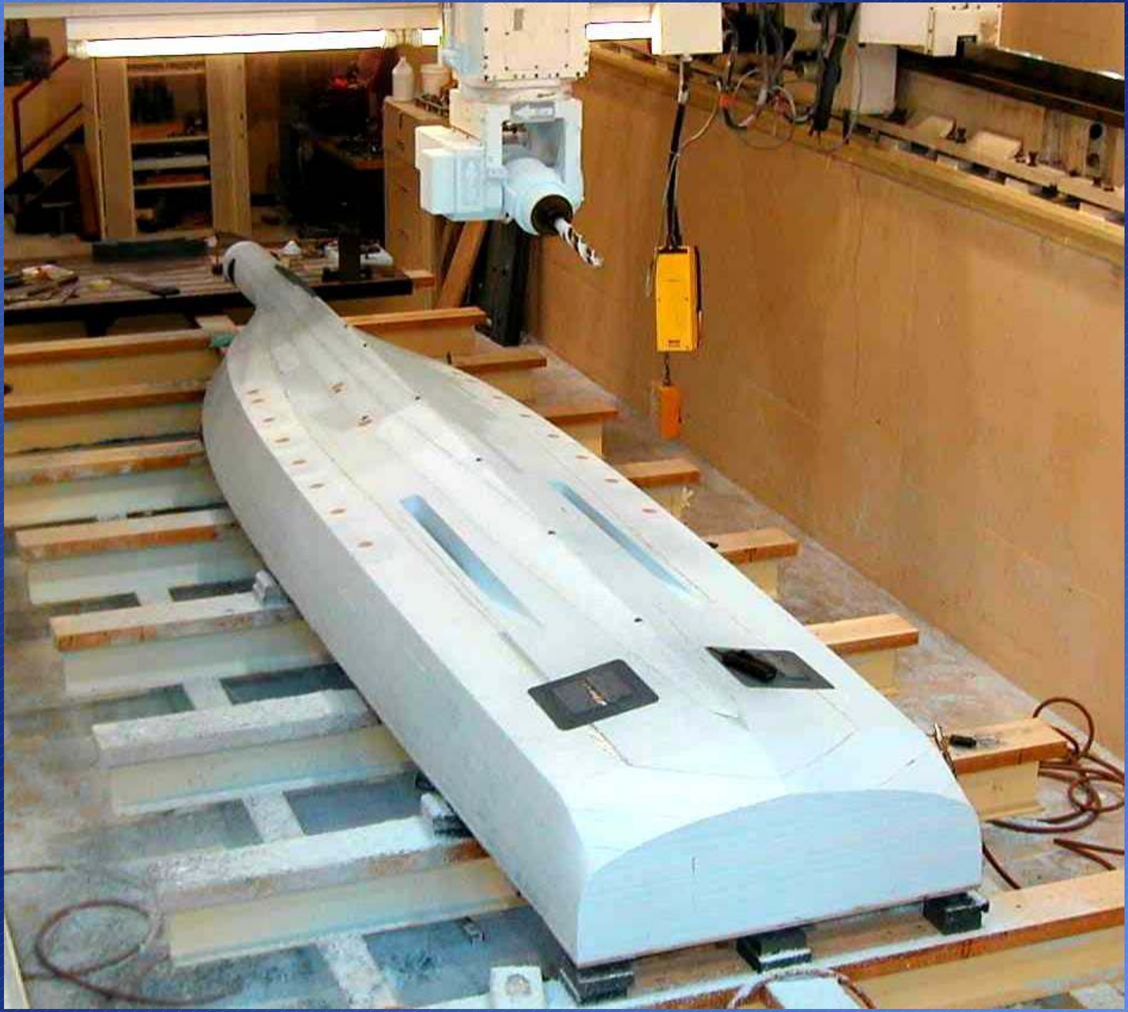


CNC Machining (finishing pass)



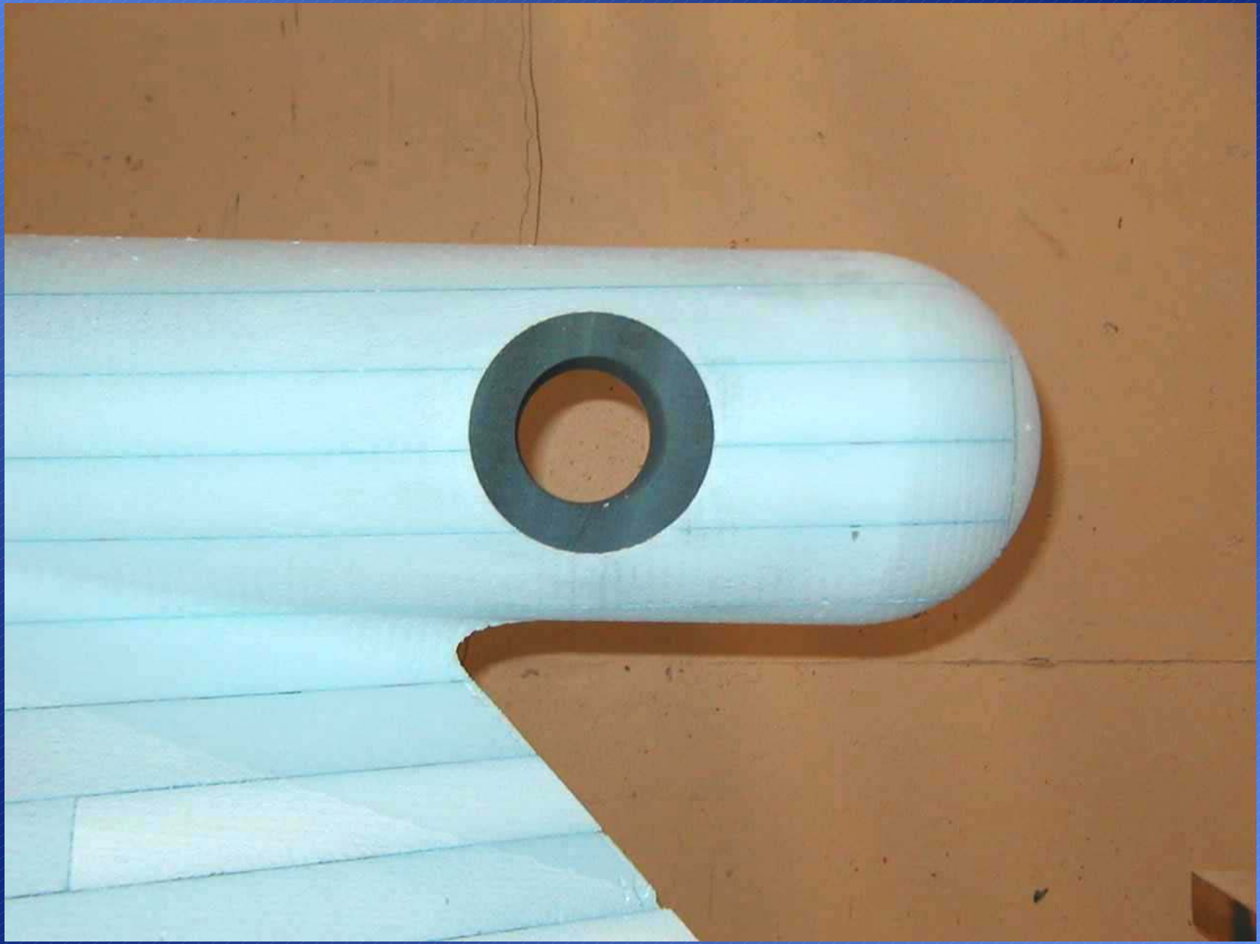
CNC Machining (finishing pass)

Appendages
Rudder, Keel, A-brackets, Thrusters, etc.



Appendage machining
Renshape™ Bilge keel insert

Appendage Machining
Bow Thruster opening



Renshape™ Bow Insert

Mold Insert

Fibreglass Shop

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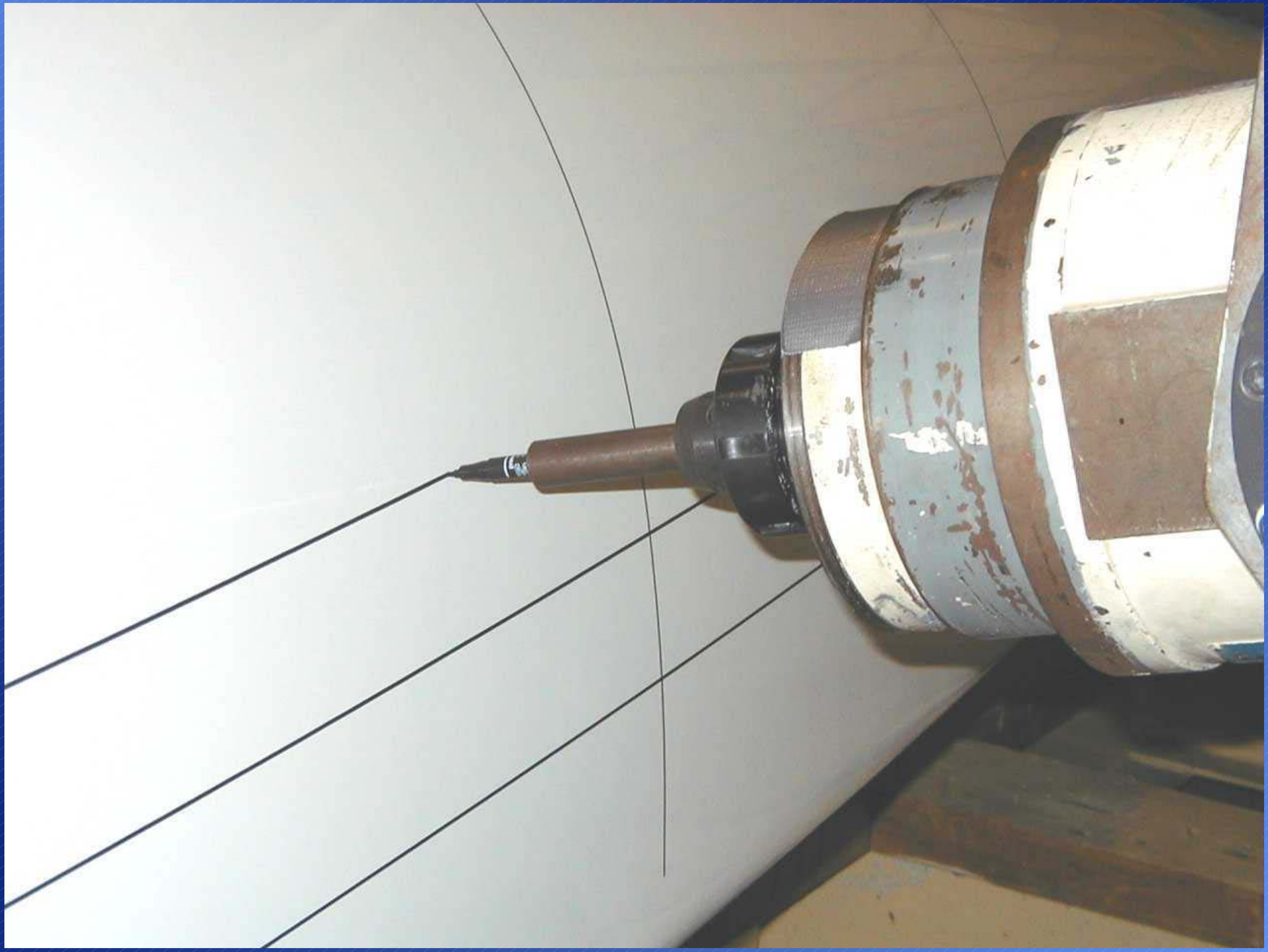
Model with 10oz glass cloth applied

Model with Duratec™

Paint Booth

Marking Model with CNC Milling Machine

Marking Model with CNC Milling Machine



Finished model

Finished Model Topsides

Sources of Error and Distortions

Accuracy / Quality of CAD Model
- Use as supplied surfaces
- Comparison to client sections
- Qualitative Assessment

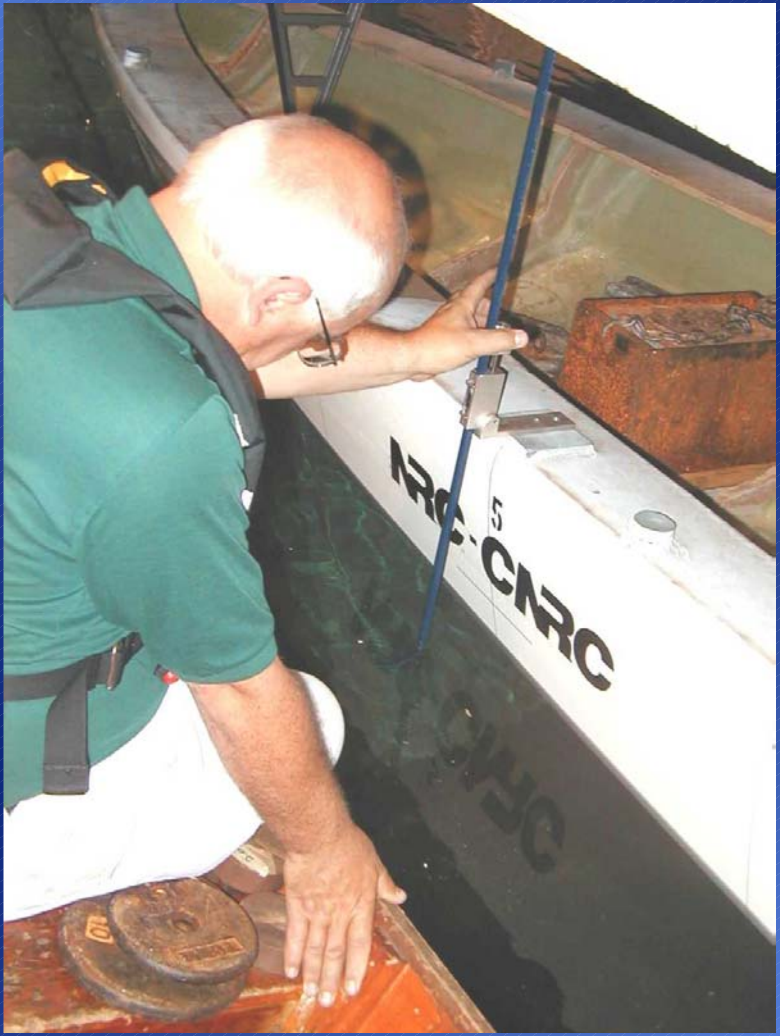
Accuracy of CNC Machine
- alignment
- calibration
- tool measurement

Hand finishing error
- QA templates
- measurement of skin thickness

Material Shrinkage effects
- trim pad setting in tank
- measurement in CNC machine

Model QA templates

Setting trim hooks



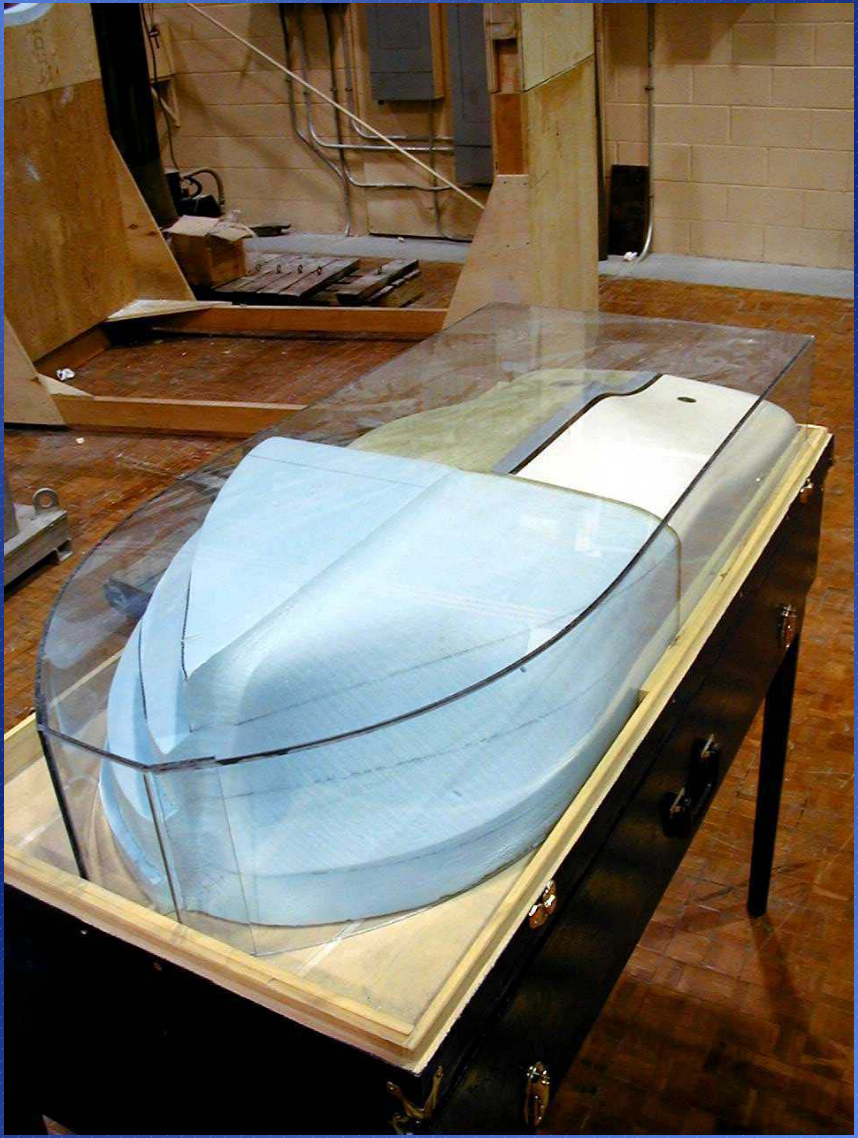
Stress relief bands in Duratec™ coating

Titan CNC horizontal boring mill (2002)

“Ice-breaker” Model

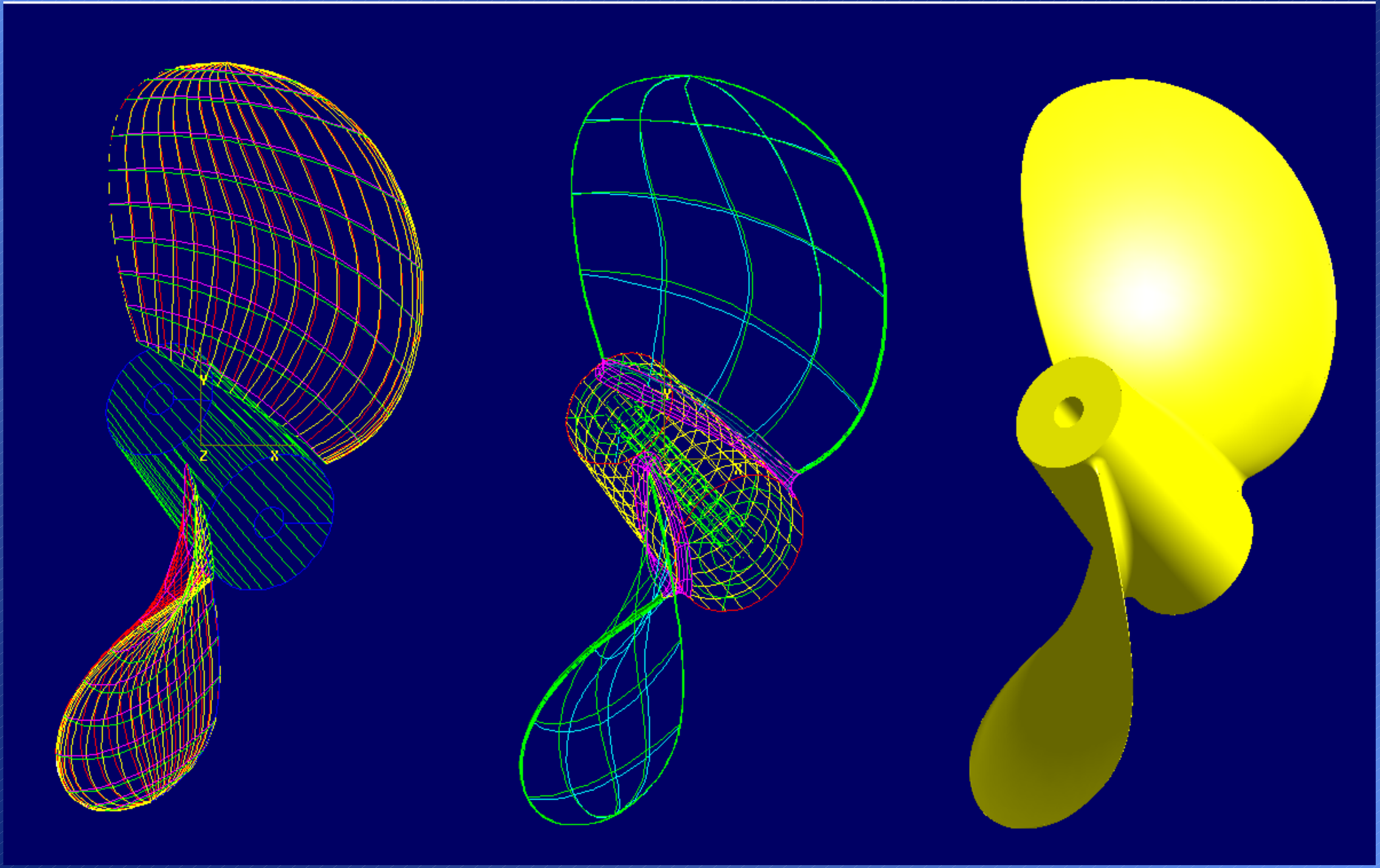
END

Model construction Display



Machine Shop

Propellers CAD Model



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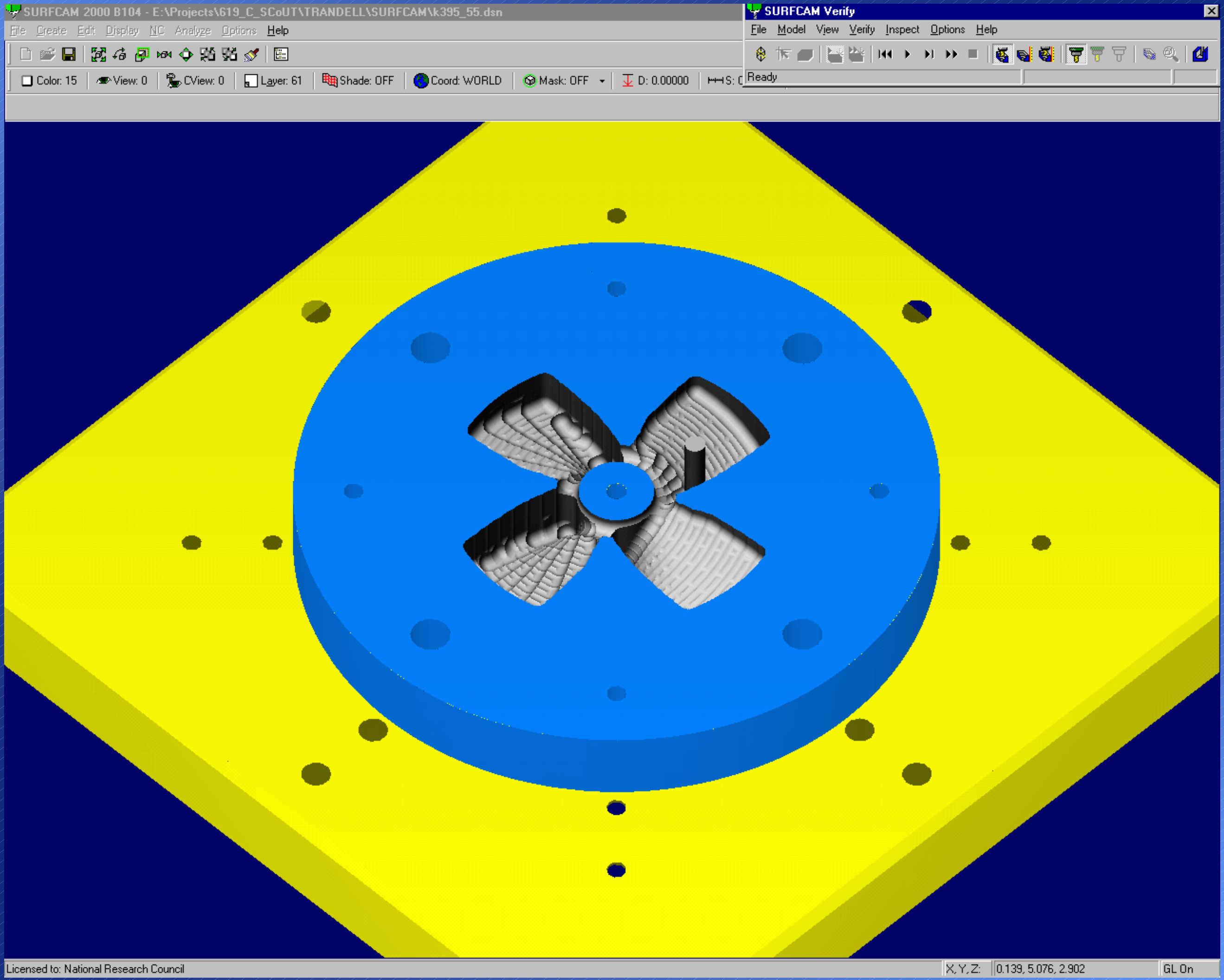
Propellers CNC Machining Verification



Propellers CNC Machining in Lexan

CNC Machined Propellers

A-Bracket Assembly Jig

Finished model shafts

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Actual Hull Shafts

NRC · CNRC