

The CoSMoLUP Project for the Improvement of Fishfarm Pen Design Using Computational Structural Modelling and Large-Scale Underwater Photogrammetry

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ABSTRACT

The paper presents results from a collaborative *CRAFT* action under the European Union's *BRITE/EURAM* programme. The aim of the presented research programme was to improve the structural performance of the net systems used in fishfarm pens. In particular, it is hoped that the level of pen volume loss due to current can be reduced, as well as improving resistance to sea mammal predation. Both these goals will be of significant economic benefit to the entire European fishfarming industry. A key element of the project is the measurement system for determining the underwater 3D geometry of the pen nets. A underwater CCD camera system and the photogrammetric software package *PICTRAN* are used. The various topics and special problems of underwater photogrammetry such as hardware choice, camera calibration, and working procedures are described. The project is being executed in a series of sequential stages; evaluation of the functionality and suitability of the components, and acquisition of geometrical data for the actual computational modelling calibration and design improvement in the final stage. The statical analysis suite of the *EASY* light-weight structure design system is being used for the computational modelling.

BACKGROUND INFORMATION

Objectives and expected results

The ultimate aim of the research programme is to improve the structural performance of the net systems used in fishfarm pens. Given the comparative lack of scientific research directed at this problem, significant improvements can be expected. In particular, it is hoped that the level of pen volume loss due to current can be reduced, as well as improving resistance to sea mammal predation. Both these goals will be of significant economic benefit to the entire European fishfarming industry. Figure 1 shows a diagrammatic view of a typical fishfarm pen. Such a pen is typically clustered in multiple units when used industrially.

A main part is the measurement system for determining the underwater 3D geometry of the pen nets. The photogrammetric system *PICTRAN* is used, which reconstructs the 3D data from multiple 2D images.

The specific project goals are,

- To measure underwater cage net geometry using 3D photogrammetric reconstruction.
- To develop and calibrate a non-linear computational model capable of predicting the structural behaviour of pen systems.
- To propose modifications to existing pen designs which improve structural and economic performance.
- To propose completely novel pen systems with improved structural and economic performance.

Economic and Industrial Benefits

Over the past decade, the development of fish farming in Europe has been spectacular. In particular the north-west of Scotland, Shetland and Ireland have experienced very large levels of investment in salmon farms. The European industry is, however, not restricted to Atlantic salmon and extends to the commercial cultivation of species such as trout, bream and sea bass in areas including the Aegean. Experimental farming of fish such as halibut is also currently being investigated.

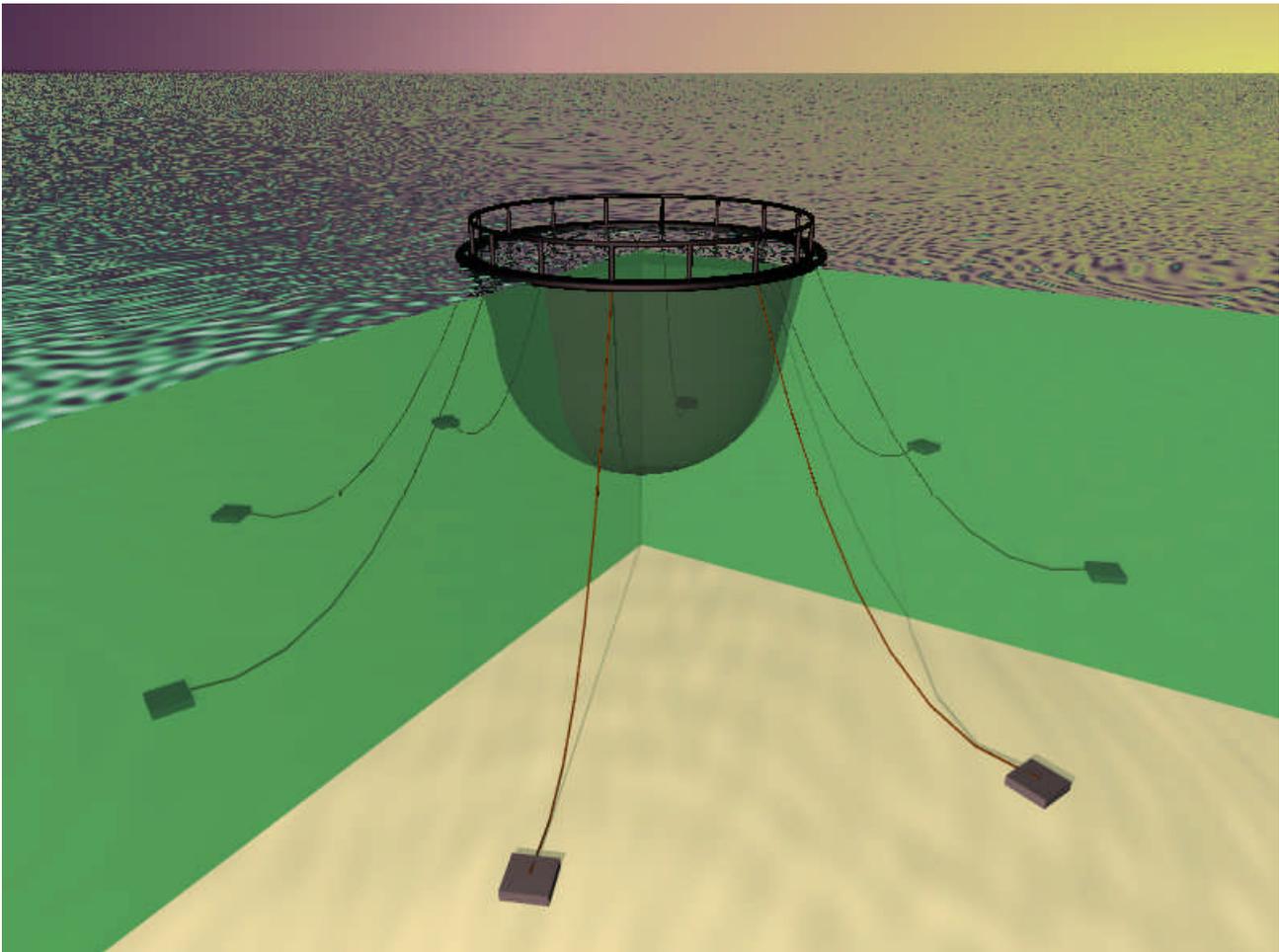


Figure 1 Configuration of a typical individual fishfarm pen.

At present the salmon industry is experiencing a period of slump due to short term overproduction causing low prices. European producers have traditionally specialised in the production of premium quality produce. Consequently, damaging though this price slump is, the producers are still able to export to the many world-wide markets which recognise their high quality. Due to the continual and catastrophic decline in wild fish stocks, and the corresponding chaos in the hunter fishing industry, it is clear that the future of European fish farming looks promising.

In addition to the basic need to maintain structural integrity under extreme weather conditions the following problems with existing pen systems can be identified.

- From an economic perspective, it is clear that for a pen collar of a particular size, it is desirable to maximise the available volume within the pen net. It is important therefore that the volume achieved does not decrease significantly under the effect of tidal current. The problem of volume loss due to current also occurs when stocked pens are towed from one site to another. At present such manoeuvres are only performed when absolutely essential due to the extreme problems involved and the stress caused to the fish. Towing must be performed at speeds of less than two knots and requires perfect weather conditions. Currently towing is mostly performed to avoid problems with algal blooms, though if increased current resistance is achieved, it would be possible to move farms away from oil pollution incidents such as the recent disasters of the *Braer* in Shetland or the *Sea Empress* in Wales.
- The problem of wild animal predation on farmed salmon has been endemic throughout the industry. Stock loss to birds has been largely solved by covering the pens with either large mesh netting, or else a similar system of string. Predation from seals has, however, proved significantly more troublesome.
- Under particularly violent sea conditions it is possible that stock damage can occur due to the pen sides impacting with the fish.

By gaining a better understanding of the most effective ways to stiffen net systems, each of these problems can be reduced. It is believed that through the exploitation of state-of-the art computational modelling, existing tensioning practices can be greatly improved. In particular, by increasing the stiffness due to geometric rather than purely elastic factors, significant economic benefits should be gained. Pen volume loss will be reduced giving farmers greater flexibility in their stocking density. This will in turn allow them to keep fish from the market during periods of overproduction. If, as expected, the tensioning improvements result in a reduction in fish scale damage due to dynamic wave action, the product's premium value will be preserved. By reducing the effectiveness of seal attacks, the economic losses due to both stock destruction and net damage will be lessened. Additionally, since farmers will resort to shooting seals much less, the negative environmental image associated with this practice will be disassociated from the industry.

State of the Art and Innovation

The original response to seal predation was the installation of secondary defensive nets outside the main stock nets. Despite this measure, it was found that predation was still a serious problem, resulting in the shooting of large numbers of seals. Since the use of anti-predator nets involved considerable cost, both capital and operational, a more effective alternative strategy was sought.

It was found that if tension could be maintained throughout pen nets, predation was mitigated. Accordingly, a variety of techniques were developed to apply prestress to the nets. With small to medium sized square pens, it was found that the introduction of a semi-rigid frame at the pen base proved effective. Such a strategy was found to be too unwieldy for the larger square pens, however, due to the very much larger steel tubes required. The tensioning system developed to cater for these larger pens has since been applied to many smaller systems due to its simplicity and cost effectiveness. Several implementations exist, but the general principal behind them all is to suspend heavy weights from the pen collars, and then tension the nets from these weights. This system, like the semi-rigid frame system can not be effectively applied to round pens. Despite the pen tensioning approaches already taken, existing systems are still susceptible to predator and other loading induced problems.

The expected design improvement proposals are based on an extension of the existing tensioning technology, as well as completely new strategies. The key element among the technological developments is the underwater net geometry measurement system. To date no data exists on the accurate shape adopted by fishfarm nets, and no system has been available to address this need. Without such data it is impossible to calibrate the computational structural models required to evaluate design improvements. With respect to the completely novel design proposals, two specific areas which look particularly promising are the use of curvilinear net cutting patterns and reinforcement with sleeved flexible splines.

In order to determine underwater net geometry, 3D photogrammetric reconstruction techniques are applied to networks extracted from digitised video data.

PHOTOGRAMMETRIC DATA ACQUISITION

The main goal of the early on-site tests was the evaluation of the functionality and suitability of the components. On the basis of the feedback from the first tests the system configuration was finalised. The later tests proceeded to test the systems capability in progressively more demanding situations. There are different topics and special problems of photogrammetric data acquisition in the underwater environment. In the following we outline the problems and describe the chosen solutions.

Object Preparation

The net must be marked to highlight specific key points. Control points must be attached to the pen structure, which is difficult in the unstable underwater environment.

It is not possible to use natural points on the nets due to the weak visibility conditions. Retroreflective targets cannot be used because the plankton will drift to the light source and reflect the light so that the visibility will be even worse. Also, retroreflective targets exhibit strong directional bias. It is therefore difficult to illuminate all targets satisfactorily. Active lights must be used to identify the net points and control points. We used strings of 10 W halogen lamps which can be easily attached to the net by cable clips.

The whole pen structure consists of different parts, which can move slightly with respect to each other while the pen is floating in the water. It is impossible to have totally fixed control points on the object. Some points (lights) are attached to vertical steel pipes which are fixed to the pen structure. During the photogrammetric image capturing nobody is allowed to be on the pen so that the movement will be reduced to a minimum and

these points can be used as fixed points. Distances between the fixed points are measured to obtain a correct scale. Distances from the fixed points to the water surface are measured to level the coordinate system. The x and y directions of the coordinate system are chosen arbitrarily.

Hardware System

The underwater imaging system must provide high resolution and sensitivity. Due to the fact that the target points are not labelled, a continuous video is appropriate to track the points through the different images.

The system is composed of the following components:

- Underwater CCD video camera with good low-light sensitivity (*Micro SeaCam 1050*, focal length 2.8 mm (air), fixed focus, wide angle, depth of field 10 cm to infinity, 1/3 inch CCD sensor (537x595 pixels), 8bit grayscale).
- Cables to carry power and video signals between camera and surface (2 x 40 m).
- S-VHS Video recorder unit (*Panasonic AG-4700E*).
- Video frame-grabber (*Cameron CamDrive*, PAL Video Signal, 800x600 pixels, PCMCIA).
- Portable computer (*Design-Notebook*, 486DX4-100).

Camera Calibration

The focal length of the camera in water is different to the focal length in air because of the different optical densities. The optical density varies due to the influence of salinity, temperature and water depth. Therefore an on-site camera calibration in seawater has to be performed. There are parameters for linear (scale difference a_3 and non-orthogonality a_4) and radial distortion (a_1 and a_2) as well as the principal point (x_0 and y_0) and the focal length (c) (Krzystek, 1995).

A flat test field with a large number of points (See Figure 2) is used for the calibration. The point measurement can be done automatically by least squares template matching for most of the points. Some are disturbed by reflections and had to be measured manually. In the following bundle adjustment the calibration parameters are applied. The calibration results are shown in Table 1; the distortion vectors are shown in Figure 3. The calibration results lead to corrected image coordinates with an accuracy of 3 μm (1/3 pixel).

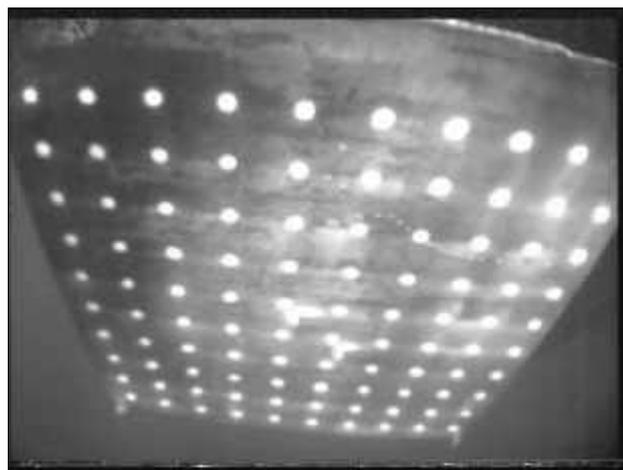


Figure 2 Calibration plate with point grid.

	Value	Standard deviation
Focal length [mm]	4.7807	0.0024
Principal point x [mm]	-0.3065	0.0029
Principal point y [mm]	0.1295	0.0024
Radial dist. (a_1)	-0.014216	0.000047
Radial dist. (a_2)	0.000259	0.000002
Scale diff. (a_3)	0.009329	0.000090
Orthogonality (a_4)	-0.000900	0.000098

Table 1 Calibration results; pixel size is 0.008 mm.

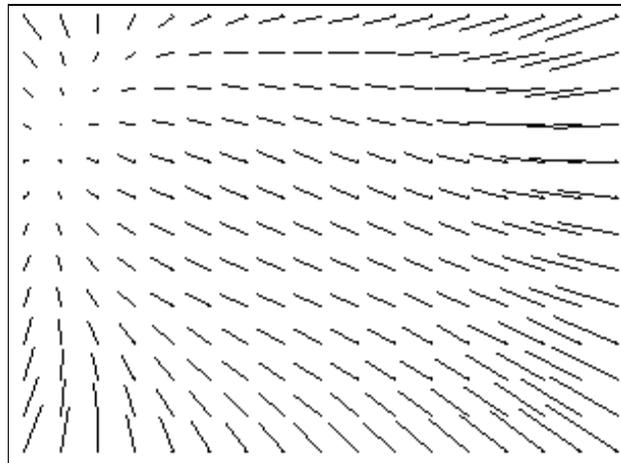


Figure 3 Distortion vectors of the camera.

Procedure

Depending on the pen setup, the recording device is operated from the pen platform or from a boat. The camera is connected to the recorder by a 40 m or 80 m video and power cable. Since we used an off-the-shelf video recorder without special housing, this equipment has to be protected from sea water and bad weather conditions.

The camera is operated by a diver who swims around the pen at different depths and distances, panning the camera left and right as well as up and down. He cannot see the image contents since there is no viewer at the camera. The recording has to be supervised from above, where it can be checked using a TV-monitor. This leads to rather long recording times and should be improved.

The recorded tapes are reviewed and appropriate images are selected by the operator. The images are transferred to the notebook hard disk as 800x600 pixel TIFF-Files (See Figure 4) using the PCMCIA frame grabber. With these images the standard photogrammetric procedures (interior orientation, point measurement, bundle adjustment) are performed.

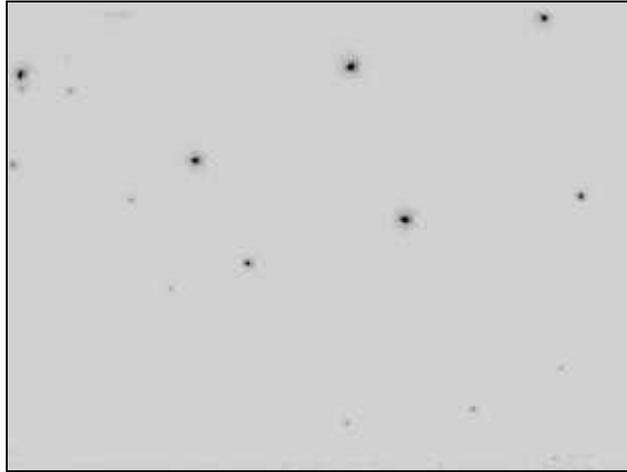


Figure 4 Underwater image with targets; the image is shown as a negative.

Digital Photogrammetric System

The photogrammetric aspects of the *CoSMoLUP* system are based on the *PICTRAN* system's modules for digital photogrammetry. Both systems run on standard PCs under Windows 3.1.

For CCD-cameras the interior orientation is constant; so the transformation from the pixel coordinate system to the image coordinate system can be written to the images directly without using any fiducial marks.

The *PICTRAN* modules offer the opportunity to measure image coordinates of signalised points manually or by using least squares template matching. For most of the points the semi-automatic measurement could be used, others had to be measured manually because of poor visibility (contrast and size).

The integrated bundle adjustment does not need any approximate values for projection centres, image rotations or object coordinates. In a first step the images are oriented by using only a few of the points which can be identified properly (in general the fixed points). Since the points all look very similar and there is no background information in the images it is sometimes very difficult to identify the points. In the second step this preliminary orientation information is used to display the epipolar lines of the measured image points in all of the other images. This helps to identify the same object points in the different images (See Figure 5). After having measured all image points the bundle adjustment was performed again and the object coordinates of all points determined.

Results

Second On-site tests

In order to check the internal accuracy measures, two different operators determined the object coordinates independently - from selecting the images to the object coordinate determination. In this test three different pen types and sizes were measured, but only with a minimum number of points on two sides of the nets (See Figure 6). Net 1 is a smaller rectangular cage of 5x5 m², net 2 is a rectangular cage of 15x15 m², and net 3 is a circular cage with a diameter of 15 m. The construction of net 1 was not as stable as net 2 and 3, also the diver could not maintain the proposed distance because of other nearby nets. Therefore the camera positions were not as good as they should have been.

In all three cases the resulting object coordinates were compared. The internal accuracies, object sizes, medium and maximum differences are shown in Table 2.

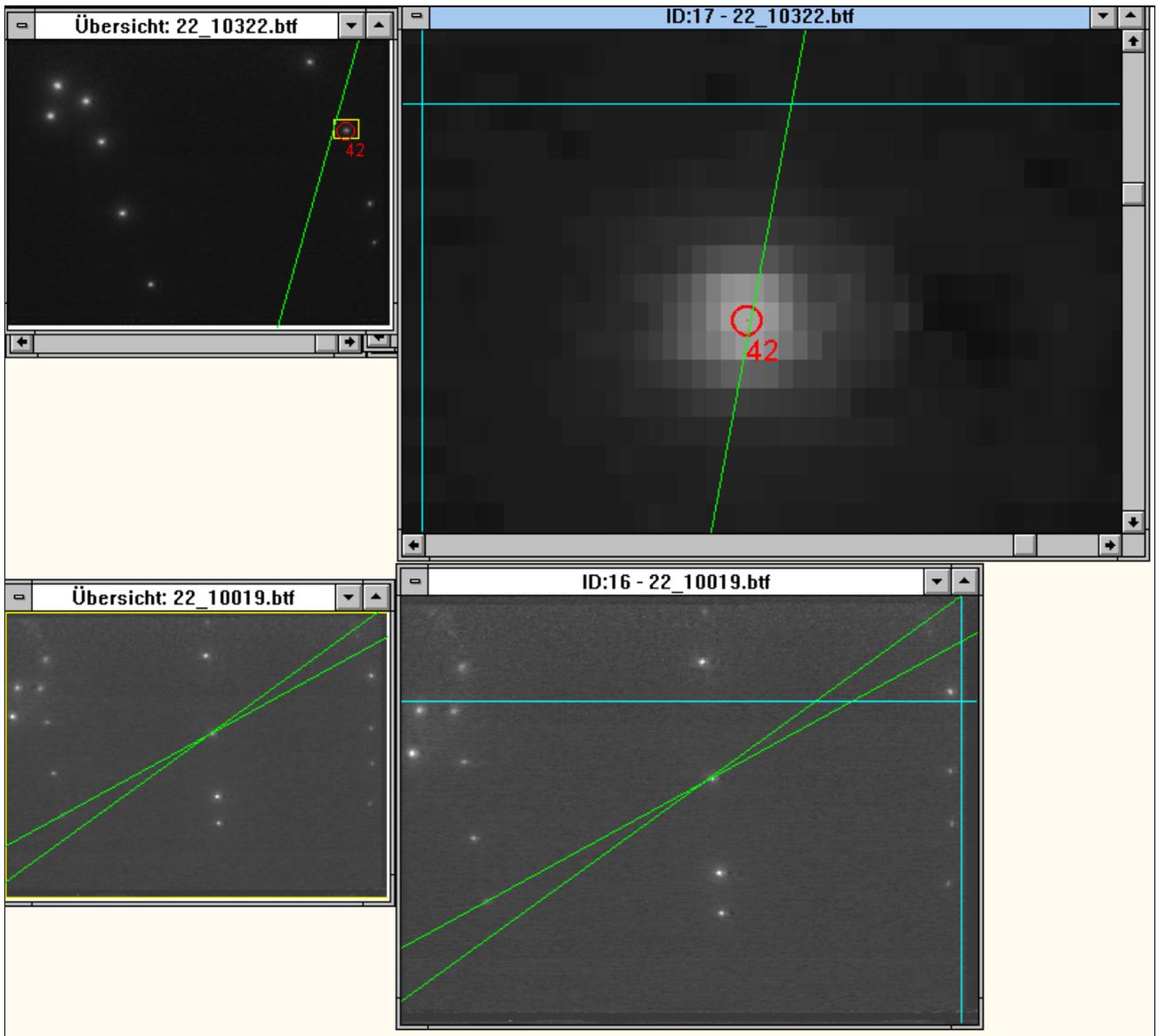


Figure 5 Example for point identification using preliminary orientation and epipolar lines.

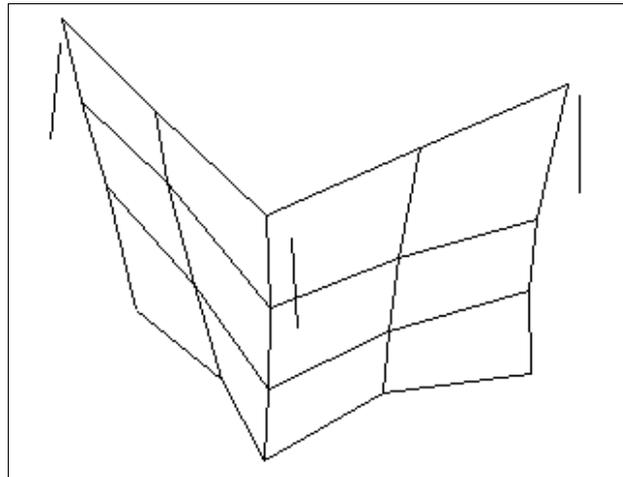


Figure 6 View of two sides of a rectangular pen structure with three control point poles.

Net	Operator	Internal point accuracy (med/max)[m]	Difference (medium/max.) [m]
1	1	0.053 / 0.081	
	2	0.057 / 0.086	0.057 / 0.169
2	1	0.037 / 0.046	
	2	0.046 / 0.064	0.043 / 0.129
3	1	0.061 / 0.092	
	2	0.068 / 0.123	0.062 / 0.207

Table 2 Internal accuracies of independent measurements and differences.

The differences between the two measurements are in the range of the internal accuracies which are given as result of the bundle adjustment. The maximum differences are still in the range of 3 sigma of the point accuracy.

The calculation of projection centres and view vectors for each of the 2D images used for the photogrammetric analysis has proven helpful. By comparing the paths taken by the divers to those planned, it is possible to improve the efficiency of the data acquisition procedure.

Other On-site Tests

Figures 7(a-c) show inverse examples of the images obtained from a test of a complete pen. Full photogrammetric analysis was performed on the data obtained for both a normally loaded and an asymmetrically overloaded configuration. Figures 8(a-b) show the reconstructed geometry of the normally loaded net in plan and side view. Figure 9 shows the same geometry in relation to the image projection centres. Figure 10 shows the reconstructed geometry of the asymmetrically overloaded net in side view.

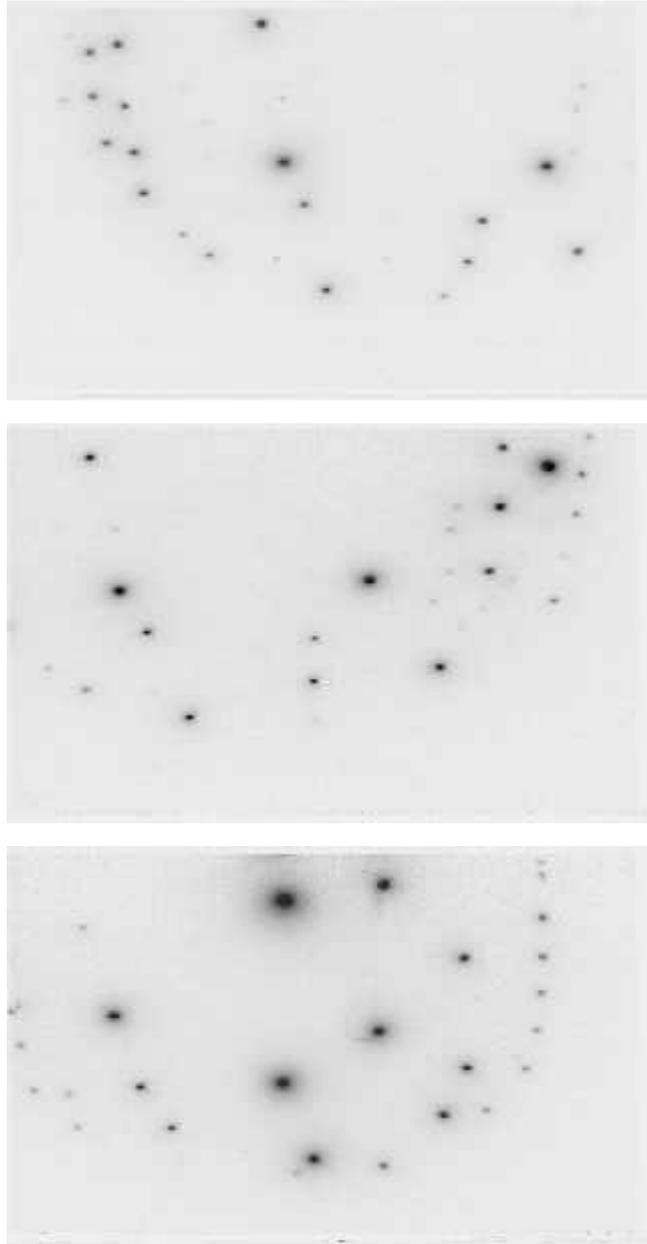


Figure 7(a-c) Typical inverse images from on-site test 3.

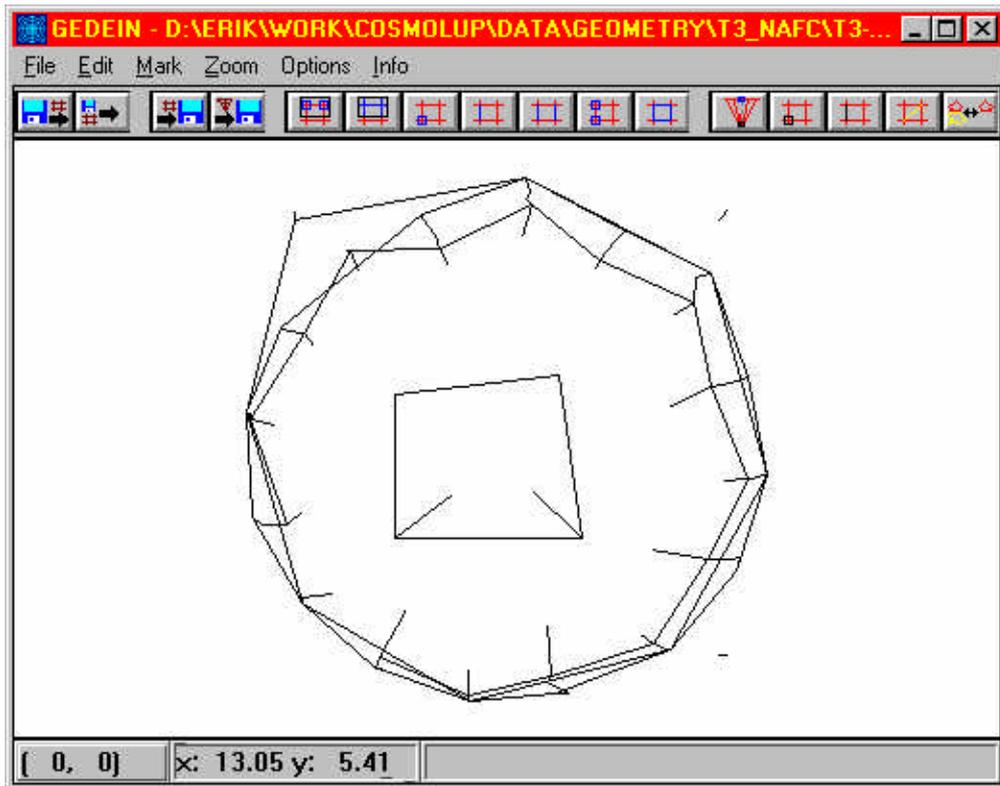


Figure 8a Plan view of reconstructed geometry of NAFC on-site test 3 normal loading conditions.

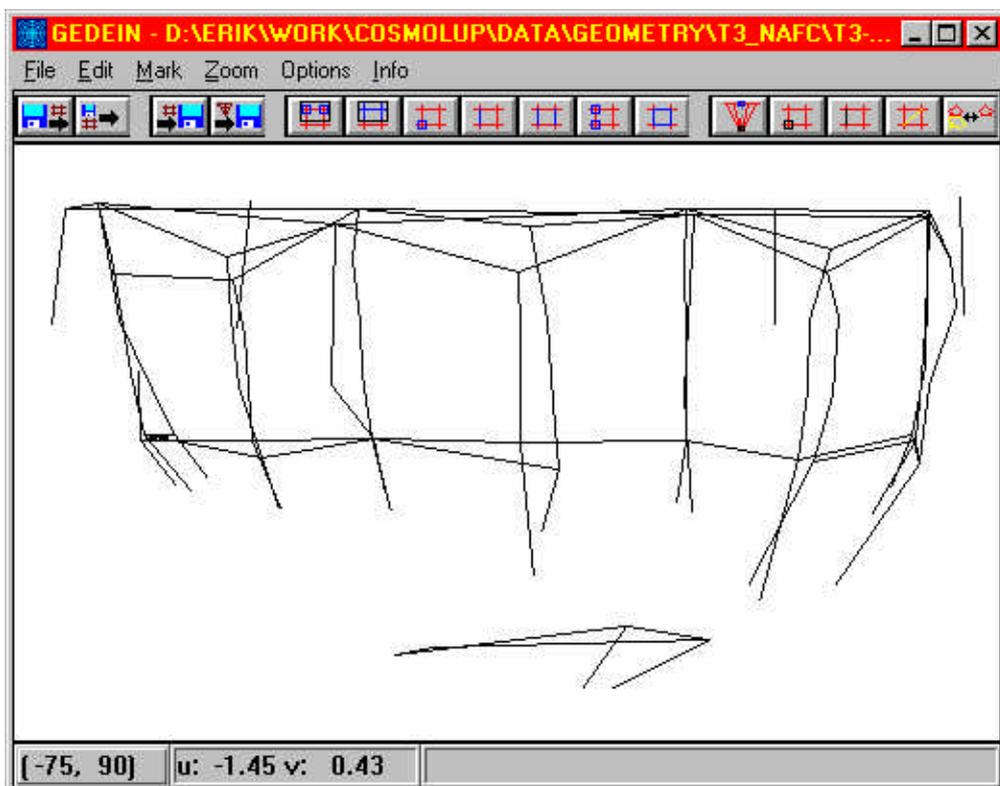


Figure 8b Side view of reconstructed geometry of NAFC on-site test 3 normal loading conditions.

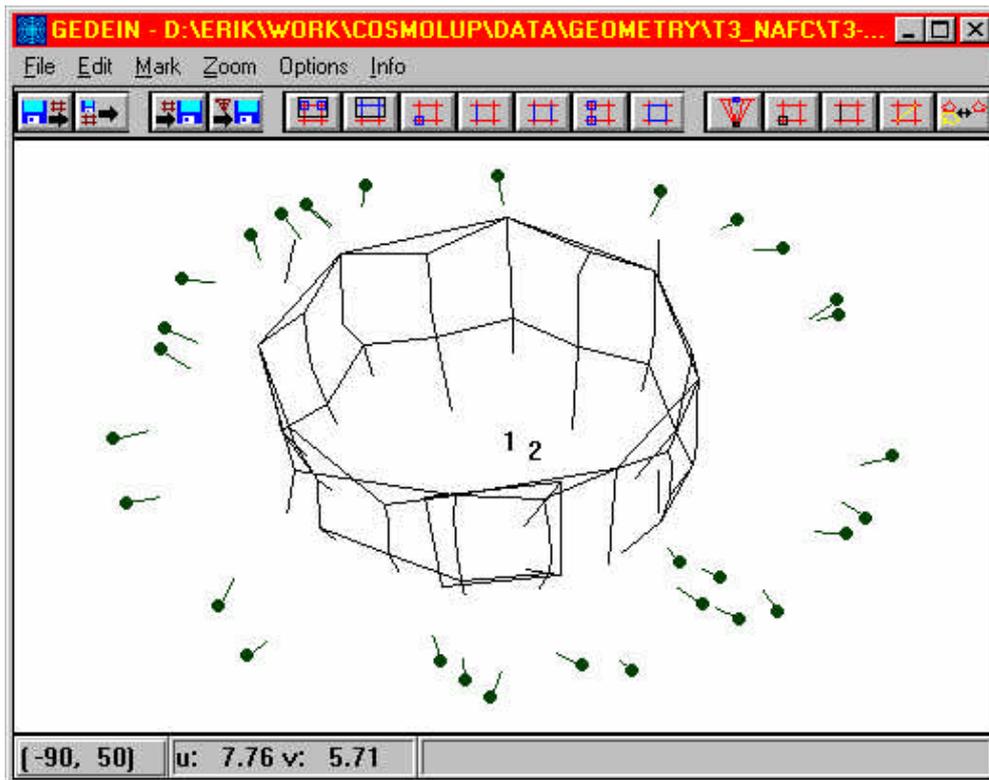


Figure 9 Orthographic view of reconstructed geometry of NAFC on-site test 3 normal loading conditions showing camera positions.

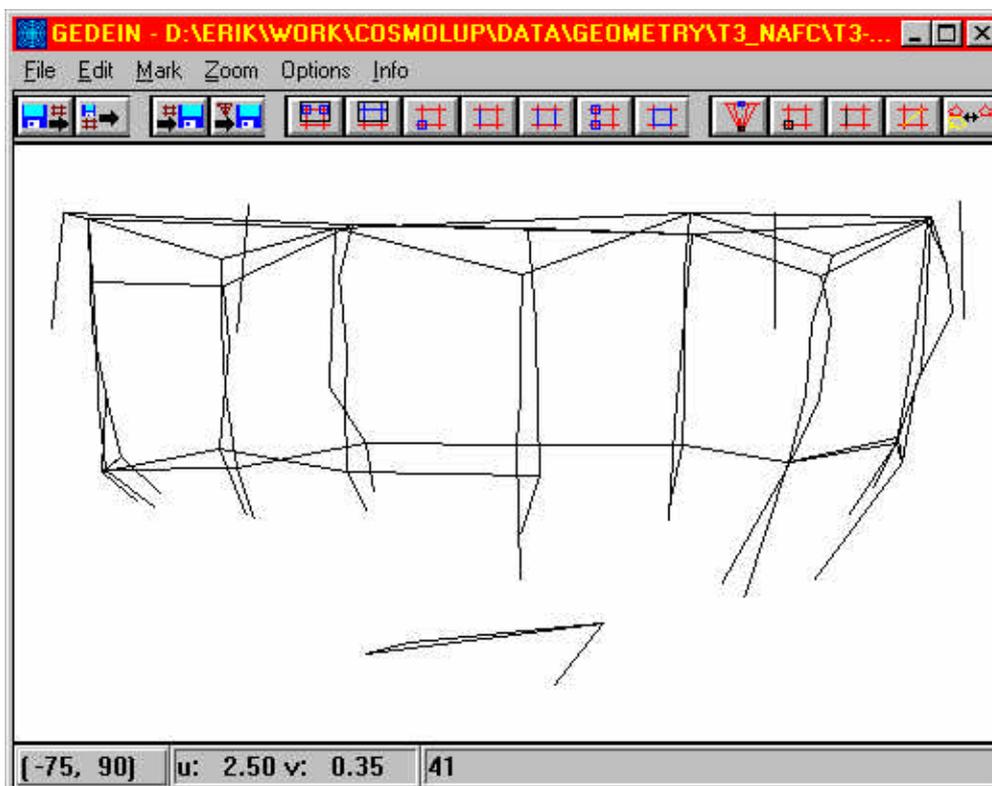


Figure 10 Side view of reconstructed geometry of NAFC on-site test 3 asymmetric overloaded condition.

COMPUTATIONAL MODELLING

Due to the geometric non-linearity of pen structures, it is necessary to use high quality statical analysis software. The *EASY* lightweight structure design system was used to model the pens under applied load. Pen structures were represented by a finite element mesh of pin-jointed bar elements, with the rigid floating collar assumed fully fixed. The net was modelled using a rectilinear finite element mesh corresponding to the spacing of the reinforcing ropes. Mesh link stiffness was assigned on the basis of the rope stiffness together with contribution from the net itself. Self weight loading was calculated using the fundamental member sizes together with material density values. Applied current loading was represented by lumped nodal point loads. Predator loading was also similarly modelled using point loads.

DESIGN IMPROVEMENT

Having developed an applicable computational model, it could be used to predict the behaviour of existing systems, as well as the behaviour of novel systems. A series of experiments using the model were performed to assess the effect of varying the net systems various tensioning and geometric parameters.

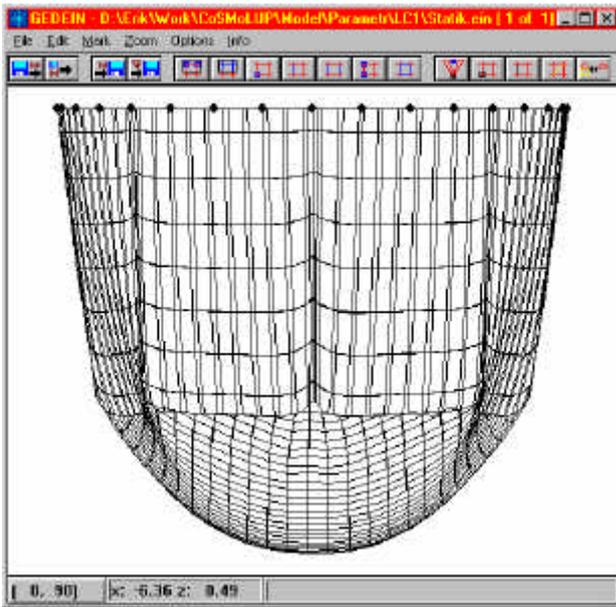
A series of parametric studies were performed looking at the effect of varying horizontal current loading; net aspect ratio; and directly suspended tensioning weight mass; on deformation and volume loss. See Figures 11(a-c) for some results from these computational tests.

With respect to the completely novel design proposals, two specific areas which looked particularly promising were the use of curvilinear net cutting patterns, and stiffening from pneumatic pressure. The former does indeed lead to better behaviour. Whether the benefit is worth the extra expense involved in assembling the more complex nets is not clear.

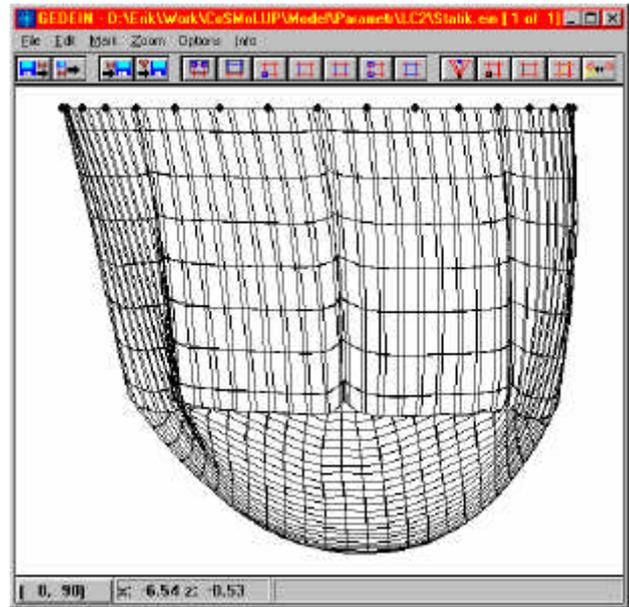
The use of pneumatic stiffening is very good from an engineering viewpoint, but it became clear that operationally it is not a good solution. Pneumatics also suffer from the problem that if they fail during bad weather, which is the most likely time, the result is catastrophic. It must be expected that holes will appear after a period of use, so this is not a practically good proposal. It would seem reasonable to predict that when much larger oceanic industrial farms are developed pneumatic structural systems will become feasible.

The novel configuration which appears to be of most merit is the use of a hybrid structure incorporating flexible splines running through sleeves sewn into the net. Computational modelling of such systems was performed and the results were very promising. The resulting system exhibits great resilience and progressive resistance to load through efficient redistribution. Operationally the system is well suited to the difficult working environment.

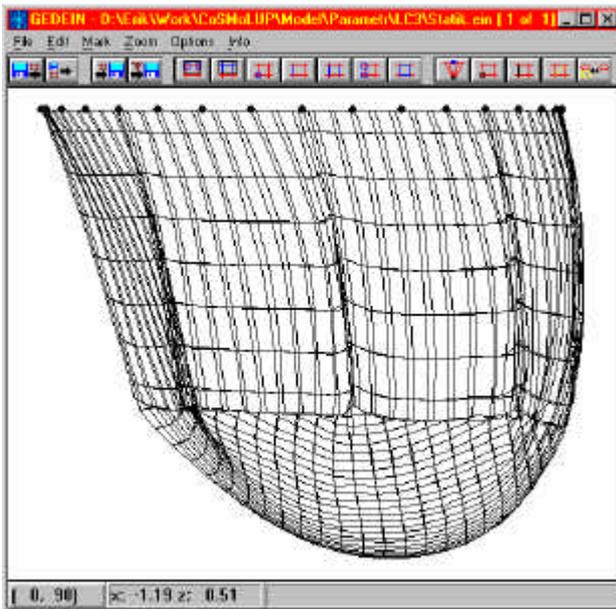
Figure 12 shows in side view, such a spline system subject to current loading.



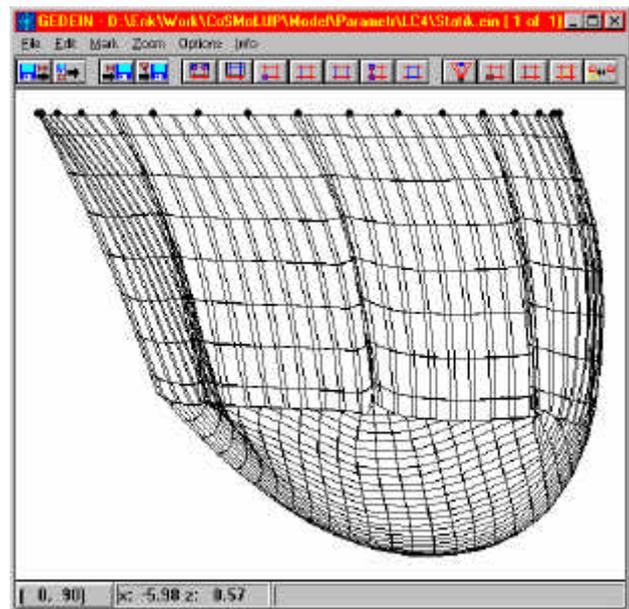
(a)



(b)



(c)



(d)

Figure 11(a-c) Example side views from parametric studies using computational model.

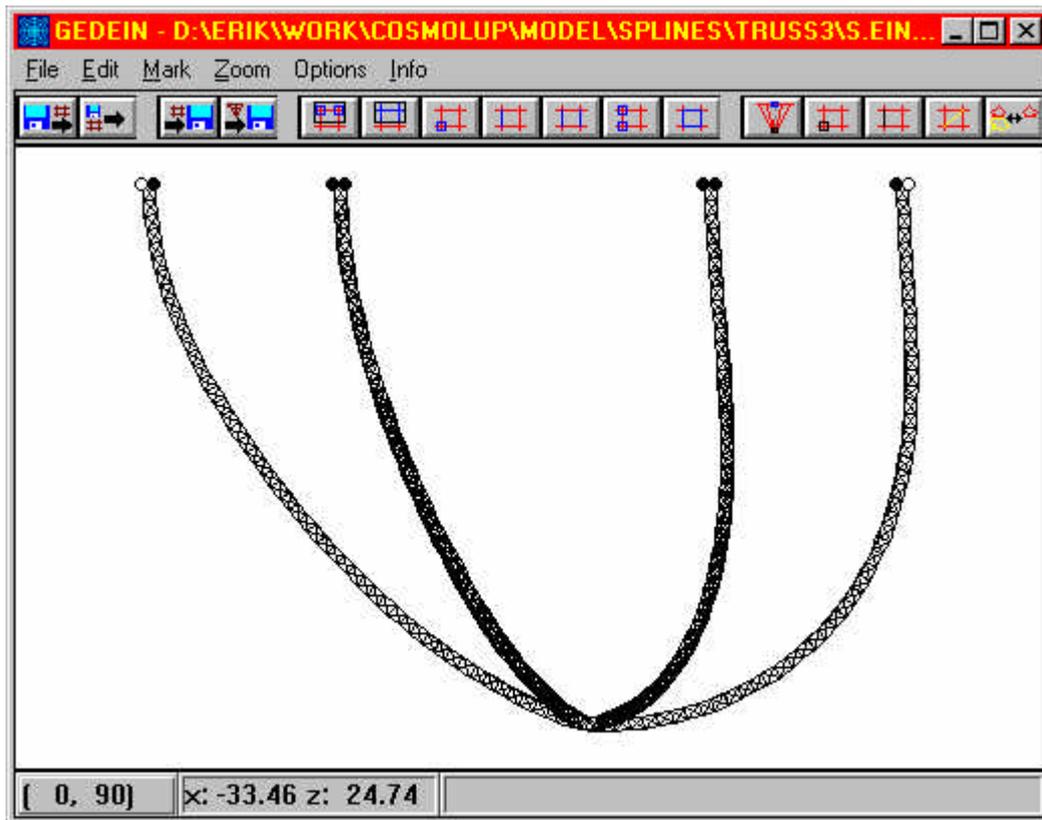


Figure 12 Side view of current loaded proposed spline reinforced novel system.

CONCLUSIONS

The results from the on-site tests of the underwater imaging, and geometry measurement systems have been extremely good. Indeed, the results have in general proven to be of higher quality than originally anticipated. The resulting system is a full featured and state-of-the-art tool for a wide range of non-contact three-dimensional measurement tasks.

Similarly, the computational model has proven to be an extremely effective tool for predicting the behaviour of fishfarm pen systems. It is also a state-of-the-art system within the field of geometrically non-linear structural modelling.

The use of lights as photogrammetric targets was effective from a technical point of view. As their deployment and retrieval proved to be the most time consuming and unreliable part of the geometry data acquisition process, replacement with a simpler target would be a priority for commercially viable measurement projects.

The use of computational modelling, together with underwater geometry measurement has been shown to be an effective tool for the development and better understanding of fishfarm pen behaviour.

It is proposed that the use of hybrid pen systems with sleeved flexible splines is the most promising novel approach to pen design improvement. Both the resilience of the resulting structural system and the simple operational requirements suggest that much improved performance can be expected over existing systems. Pneumatic approaches, while having many technical advantages do not appear to be suited to current operational conditions and suffer from a lack of redundancy. Shaping individual net panels appears to be feasible, though the economics are not clear.

The results obtained clearly demonstrate the feasibility of and power of the *CoSMoLUP/PICTRAN* system for the measurement of large underwater objects backing up earlier synthetic proof of concept studies.

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