MODERN POSITIONING SYSTEM PROVIDES FOR AN INEXPENSIVE MATRESS-LAYING VESSEL AT THE VENICE SURGE BARRIER

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ABSTRACT

The Venice lagoon has to be protected against storm surges and sea level rising due to global warming. The lagoon entrances will receive dams and barrier doors. To improve the soil stability at the entrances, mattresses have to be installed. The laying of mattresses is well known from the Eastern Scheldt project, but was very expensive in construction and operation. By using the same philosophy, but adapted to modern systems, this specialized installation takes only a fraction of the costs. This makes the technology available for more lagoons and estuaries threatened by storm surges.

The mattresses are deployed from a pontoon, carrying a mattress storage cylinder 2m under water. These 4cm thick and 10m wide mattresses are made of geotextile, filled with sand and gravel. They are approximately 150m long, max 250m. Six winches position the pontoon at the required location. However, the mattress is subject to the current and waves as it is rolled down the cylinder. Therefore, the position of the pontoon is not directly related to the eventual position of the mattress. Still the mattresses have to be laid with a horizontal accuracy of ca. 20cm. Especially the adverse conditions at the entrances with strong currents (2.5m/s) and waves (2.3m); make it very challenging to develop a reliable system meeting these specifications.

The pontoon position comes from DGPS-signals and is used together in a survey system to compare this with the required position. The difference is used in a PLC to control the winches and minimize the offset. Specially developed algorithms calculate the forces on the pontoon, the pulling forces of the winches and the behaviour of the suspended mattress. The resulting signals instruct the winch controllers with the corresponding actions.

Inspection with a multi-beam echosounder reveals that the mattresses are laid down within the required accuracy.

Keywords: Automatic winch control, positioning, risk analysis, survey

INTRODUCTION

Venice is built on the Adriatic Sea, and flooding has become a severe problem in the last few decades. High water levels in the lagoon can badly damage the porous limestone buildings in the city.

A combination of atmospheric pressure and particular wind patterns can temporarily raise the local sea level. Subsidence combined with rising sea levels caused by global warming, has increased the change of water levels rising to dangerous levels over the past few decades. In 1966, many parts of the city drowned under severe floods when the water level rose by 1.8 m. In 2001 another flood raised the water level by 1.5 m.

Currently, Venice suffering some level of flooding for 200 days every year, compared with only seven at the beginning of the 20th Century. More than 50 high tides were recorded between 1993 and 2002, compared with just five in the 10 years between 1923 and 1932.

Many storm surges in History have caused great damage, 1916 St Elisabeth flood, Netherlands; 1953 Storm surge in the southwestern parts of the Netherlands and the southeastern part of the UK with large flooding as a result. Recently the hurricane Katrina also caused great damage and grieves in the southern US.

Different techniques have been used in order to create a storm surge barrier, all created in their time, with techniques available from their time and age. Examples are Thames barrier, Maeslant barrier in Rotterdam, Ems Sperrwerk and

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not to be forgotten the Netherlands master plan the Eastern Scheldt barrier. From this project it looks only a small step to the present day Mose dam project in Venice and use of modern positioning system in combination with modern automation in order to lay scour protection mattresses and create a storm surge barrier for the protection of Venice.

Figure 1. Venice lagoon inlets.

The strategic solution chosen consists of a combined system of various types of structure enabling all three inlet channels to be temporarily closed by means of mobile barriers, in combination with local raising of quaysides, compatible with the architectural and socio-economic structure of the area to combat the tides causing the most frequent flooding.

Measures affecting the physical structure of the lagoon, even when implemented together with local defence of the inhabited centres, appear not to have a significant effect on the reduction of the tide levels in the lagoon. Such measures are adopted, instead to meet the other objectives of the law that concern morphological and environmental restoration.

The inlets at Lido, Malamocco and Chioggia all have a number of oscillating buoyant floodgates, consisting of a box-shaped metal ‘flap’ attached to its housing by two hinges. Each gate is 20 m wide and varies in height from 3.5 m up to 30 m depending on the depth of the inlet. The average expecting closing time will be 4 to 5 hrs.

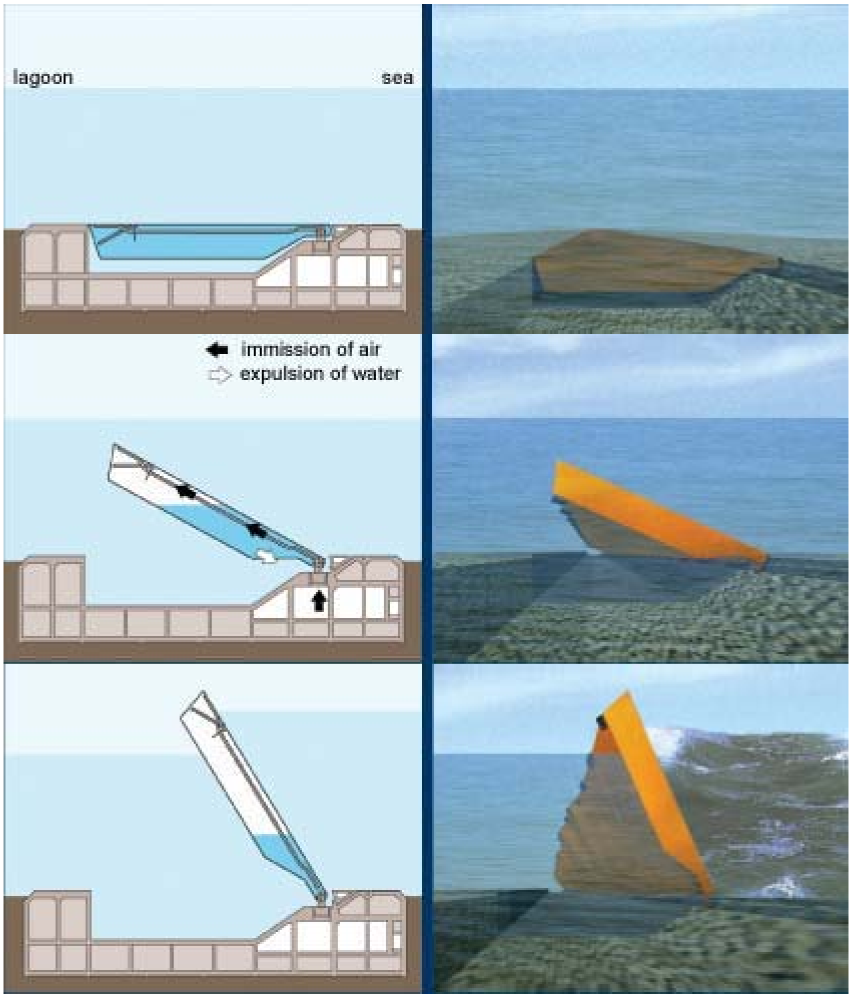

Figure 2. Venice surge barrier floodgates.

The floodgates at rest are “folded-away“ into their housings buried at the bottom of the lagoon inlets. The housing consists of prefabricated concrete caissons, which are dug into the lagoon bed. The housing also contains the service tunnels, machinery and service buildings required to the gates operation.

PROJECT APPROACH

DDE has been approached with the request to supply a positioning system for laying protective mattresses within certain tolerances. Initial discussions resulted in conclusions that a mattress-laying vessel would be required with full automation on winches and mattress roll.

Experiences with the mattress-laying vessel Cardium called for an in depth study and risk analysis for this project. Automation was not as developed in those days as it is now, but still represents a challenge to combine automation with positioning systems. The open structure of DDE’s own survey system “ NAVGUARD ” seemed ideal to combine the two systems and reach the required accuracy.

Project Risk Analysis and Contract Award

DDE is specialized in 'Total Dredging Solutions' based on standard proven designs.

In order to meet client expectations, delivery time and reducing economical and technical risks to a minimum, risk analysis is a standard tool.

- Client analysis
- Product analysis
- Technological risk analysis
- Financial analysis
- Project risk analysis and contract award

In order to reduce the risk and take advantage of the time it was decided to make a phased computer aided model, as soon as all risks where in view, the final contract for winches, control system and positioning system was given. In the mean time the sectional barges and the mattress-laying device where independently under construction. This unusual building path was completed within 6 month's in time to position the first mattress in March 2006.

Client Analysis

Sarti, the contractor, has been a loyal, open-minded and innovative client for many years but had limited experience in this kind of large projects. The open mind and innovative co-operation has created possibilities to think outside standard solutions whilst the time frame from start of design to start work was very limited (only 6 month's). Therefore design and construction had to be realized at the same time and close co-operation with Ravestein Shipyard was of utmost importance.

Product Analysis

- Project within standard range
- Minimum 75 % within standard range or experience
- Re-usability of technical details for new standards
- Order size and production capacity within DDE, Damen Shipyards or external partners

Financial Analysis

Financial risks are always difficult to judge in this kind of innovative projects, therefore a few criteria are important:

- Client needs to be prepared to jointly develop the project and is willing to share the risk
- Designer/manufacturer needs to be in an unique position on a basis of trust and reliability
- Client needs to be credible for the work and risks involved

TECHNOLOGY RISK

As experience gained at the Eastern Scheldt Barrier was not at all compatible with techniques required in this situation and modern techniques, a professional risk analysis and project approach where required to benefit both client and our selves. In order to supply a Total Dredging Solution following steps where taken:

- Project data collection
- Definition of project requirements
- Study of available systems
- Operational risk analysis
- Computer aided model studies, in stead of tank model studies (also due to lack of time)

Definition of Project Requirements

In the initial stage of the project data collection proved to be a difficult and time-consuming process.

- Data required:
- Tidal information
- Current information
- Wave history
- Availability and type of reference signals for DGPS systems
- Actual project definition and position of barriers to be constructed in relation to tidal, current and wave information.
- Definition of accuracy of pontoon position and final Mattress position

Operational Boundary Conditions

The placement of the mattresses has to be done under various weather conditions. The system had to be able to work under the following operational boundary conditions.

- Maximum track length: 250 m
- Allowable cross track error mattress: 20 cm
- Track speed: 4 m/min
- Maximum ‘crab’ angle: 0°!!!

The allowable cross track error sounds already rather forgiving. However, the accuracy of a DGPS system is only ca. 4 cm, this is already 20 % of the 20 cm range. The accuracy of the control system should therefore keep the pontoon within a working tolerance of 15 cm. During operations, the environmental conditions that could be experienced were as follows: Table 1.

Table 1. Environmental conditions.

Environmental conditions	Wind m/s	Waves m	Current pontoon m/s	Current Mattress m/s
Normal environmental condition	7.5	0.5 @ 0.3 Hz	0.5	0.5
High environmental condition	11.4	0.8	1.0	1.0
Survival condition	25	1.0	2.5	-

From the above requirements we already suspected, that a swell compensating system on the mattress arm might be necessary when the pontoon would be too much influenced by the waves. This would be an issue to investigate in detail.

Constructional Requirements

The mattresses have to be laid in the direction of the entrance. The dimensions are 80 to 250 m long and 10 m wide. In total, 400 mattresses have to be laid. Between each mattress a small gap of maximum 40 cm is allowed. Flaps on both sides of the mattresses cover these gaps. See Figure 3.

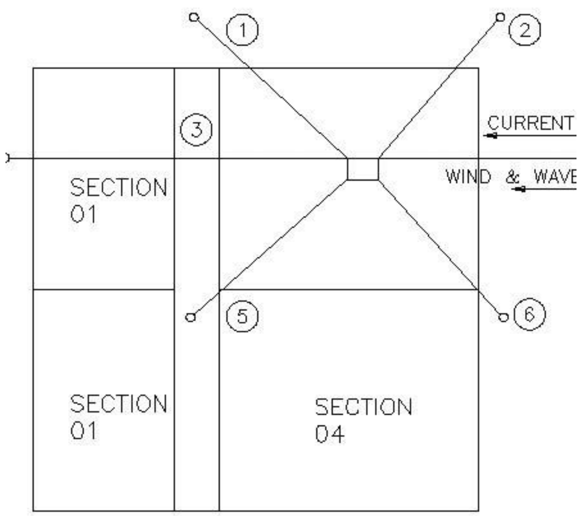

Figure 3. Mattress pattern in lagoon entrance.

The overlapping flaps allow that the mattresses fully cover the floor and prevent that gap erosion can take place and undermine the mattresses. The overlap also enables any irregularities during the positioning the mattresses. Care has to be taken, that when the directions are not carefully monitored, the mattresses can not be shifted during laying. The mattresses are not that flexible, that directional changes can be compensated. They will form ripples or tear in the bends.

Study of Available Systems

Eastern Scheldt Surge Barrier Technology

The laying of mattresses for stabilising the sea bottom, does immediately remind one to the great Eastern Scheldt Surge Barrier Project. This was such a milestone project that historical data were researched to investigate our own project.

Figure 4. Mattress laying vessel 'Cardium'.

The conditions at the Eastern Scheldt site were not favourable for an easy construction. Tides, wind, waves and currents were all competing with each other to counter the human activities. At that time the positioning systems available, were not that accurate, to place the mattresses within the required tolerances. Especially the coordination from acquiring the position and controlling the final position of the mattress took a large effort to get it right. Eventually the Minilir system was used to attain an accuracy of 10 cm horizontally (Arts, 1995).

The Minilir system was an infrared target locking system initially developed to follow missiles. At the Eastern Scheldt project a mercury light bulb of 1000 W was attached to all vessel working in the area. The Minilir was only capable of measuring angles. In order to obtain distances a Geodimeter distance sensor was mounted on the Minilir. See Figure 5. Although the accuracy of the Minilir system is quit impressive and comparable to the modern DGPS systems, the operation and maintenance of the total installation is rather cumbersome and weather dependent.

Figure 5. Positioning system of the 'Cardium'.

As the 'Cardium' was finally finished and operating, the building costs exceeded already more than 80% of the budgeted price. Although the principle of covering a soft sea floor with mattresses was a very good concept, the price for the required equipment prevented widespread use. Therefore a more cost effective system would be required for this project.

Navguard

As survey system the client looked at DDE's Navguard that through its open structure and proven track record was expected to be ideal for operational control, position indication and monitoring of the complete process starting at pre-laying data acquisition up to final position recording of the mattress.

For accuracy the client requested a DGPS system for which the main contractor should make available the reference signal from its own reference station (technical data not know until half way testing on site, client assumed the unit to be within DDE's requirements).

Figure 6. DGPS-RTK system.

NAVGUARD is a survey system acquired by DDE in 2004 after it had been successfully on the market for many years and mainly operational in The Netherlands, Middle East and South Africa (South African Navy). By integrating this system into DDE's scope of supply we now have systems operating in many parts of the world.

Navguard has four functionally integrated modules:

- Profiler (positioning and visualization on board of the vessel/excavator)
- Sextant (Hydrographic Survey data acquisition system)
- Geo-plot (Post survey processing unit)
- Model (Modulation of acquired data into 3-D plots)

The experience gained with the combination of profiler and different dredging tools (excavators, deep suction dredgers, trailing suction hopper dredgers and cutter suction dredgers) with different technical requirements made DDE and it's client feel more confident about the final outcome with regards to accuracy in the combination of mattress layer position and automatic winch and track control system.

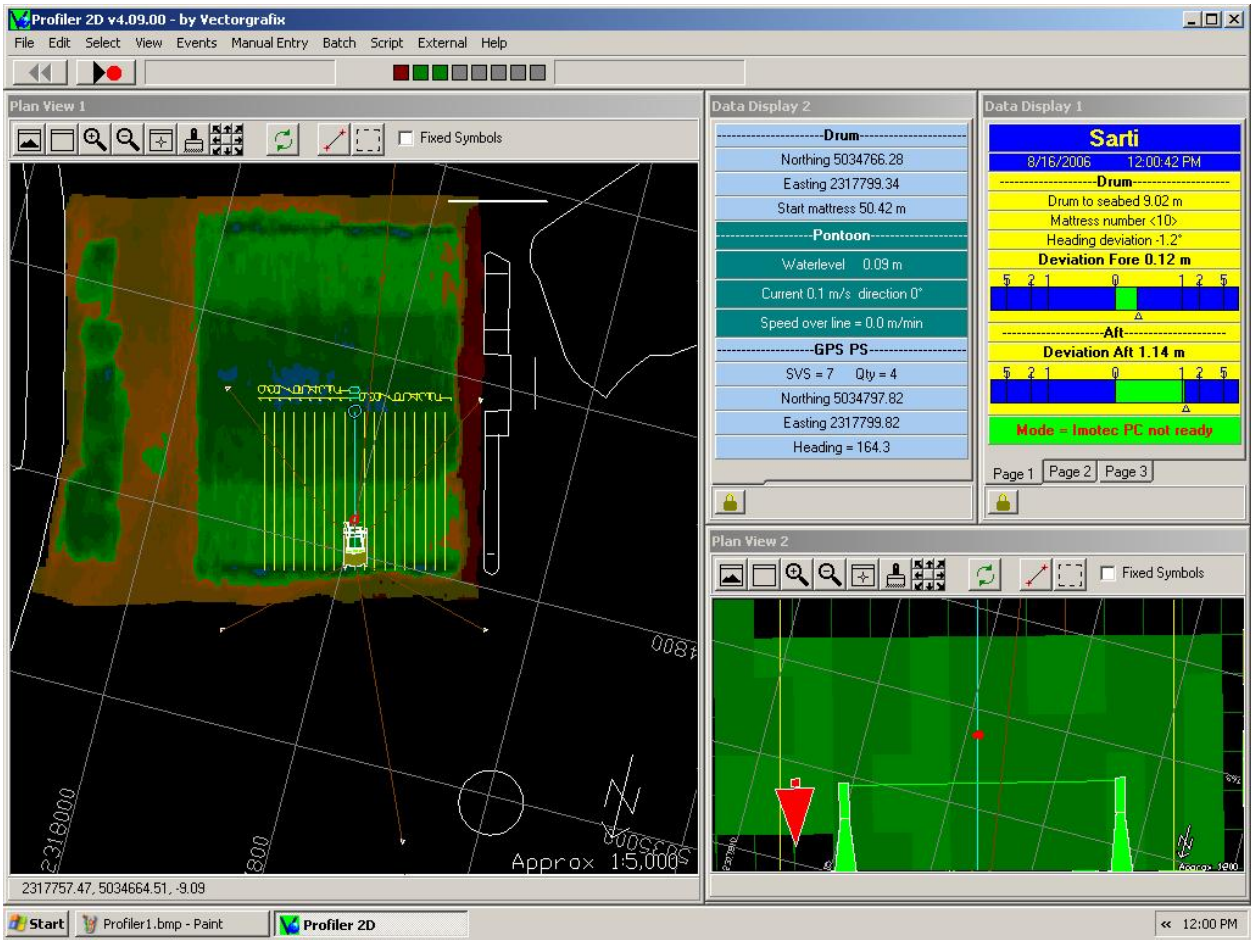

Figure 7. Profiler window.

Operational Risk Analysis

Operational risks can be divided in man-made errors, system errors and environmental / conditional influences. All of these subjects needed to be reviewed in order to make the control system predictable up to a certain level of external influences that where clearly marked in the technical specifications finally agreed upon with the client after the model studies.

Every imaginable problem that could occur was investigated and listed. Some examples are mentioned in Table 2.

Table 2. Example risk analysis.

ID	Problem	Field	Cause	Effect	Chance	Remediation
1	Storm	External	Weather	Flooding lagoon	Nil	Ride out the storm, wait
2	Reference signal down	External	Several	Position error	Low	Alarm, stop system
3	No DGPS position	Equipment	Receiver failure	Position error possible	Nil	Alarm, stop system
4	Mattress drum askew	Operation	Crew attention	Mattress breaks	Medium	Recover mattress
5	Anchor dragging	Wires	No anchor holding	Wrong position	Medium	Contractor buys bigger anchors or anchor poles
6	Winch control stalls	Wires	Anchor configuration not optimal	Unable to keep position	Nil	Require better configuration
7	Winch load zero	Wires	Wire breaks	Wrong position	Medium	Alarm, stop system
8	Winch load zero	Electrical	Contact broken	Wrong position	Nil	Alarm, stop system
9	Control model needs adjustment	Design	Model not correct	Delay in delivery	Nil	Programmer on board for commissioning
	etc.					
	etc.					
	etc.					
83	No electricity	Equipment	Out of fuel	Unable to operate	Nil	Install fuel gauge

COMPUTER AIDED MODEL STUDIES, INSTEAD OF TANK MODEL STUDIES

Selection and construction of the mattress laying vessel should be on its way in order to start the project in time, whilst design of some of the critical components where not completed by the client. Therefore tank model test where not possible in time. As this is seen as a complex process, assistance has been requested from Twente University of Technology and jointly it was decided to initiate a computer aided behaviour model in order to be able to estimate technical risks and determine the capacity of the PLC and other components required. This model study was delegated to Imotec, an office specialised in designing intelligent machines and working under the care of the Twente University of Technology.

Behavior Model

As a first exploration a simple model was set up. This model contains all elements such as the vessel itself, wires and disturbances. However, for all elements a very basic behavior was implemented. As an example, the wires were modeled as ideal spring elements instead of real wire-like behavior.

A basic control algorithm was implemented that uses all six wires to position the vessel. The controller was built in such a way that it directly and instantaneously sets the tension of each wire, ignoring the fact that this is not possible in reality due to the limited velocity of the winches. However, this algorithm demonstrated that it is indeed possible to control all three degrees of freedom (x- and y- direction and rotation) by using six wires. Figure 8 gives an indication of the resulting output.

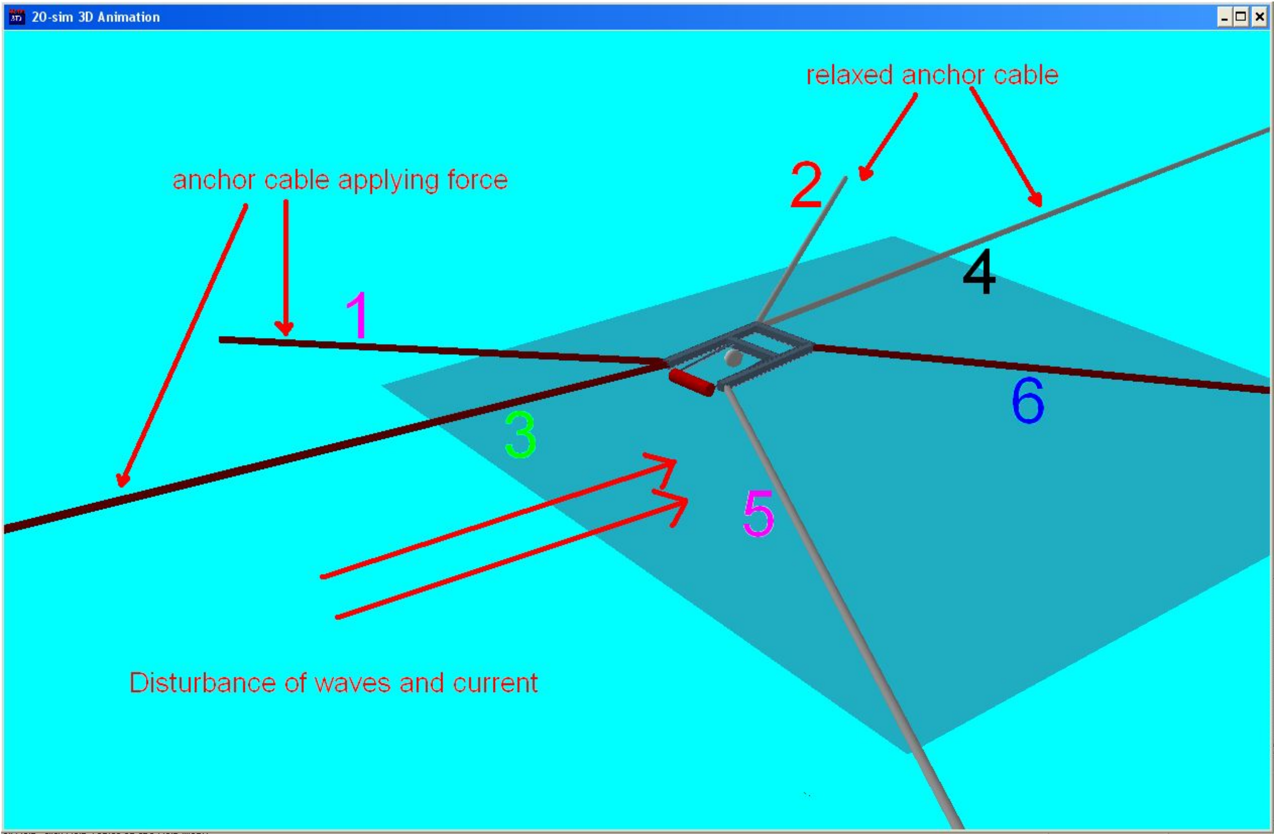

Figure 8. Simulation results.

Wire Model

An accurate simulation result needs an accurate simulation model. It was found that especially the model of the wires is of vital importance. The behaviour of wires is non-linear and just this non-linearity gives us the possibility to design a controller that functions accurately in a wide range of varying conditions. Therefore, the model should reflect the non-linearity of the wire accurately. Based on the mathematical formulas of hanging wires, a Matlab program was written that gives a good approximation of the (analytically unsolvable) tension forces in the wire. Given a wire length, diameter and water depth, it calculates the coefficients of the function:

$$F_{wire} = f(\Delta L) \tag{1}$$

Where $\Delta L = L - L_{wire}$ is the difference between the distance between the anchor and the vessel. The Matlab program also gives an approximation of the position at which the wire leaves the seabed. This is important information, because it reveals when vertical forces are exerted on the anchors. As a wire behaves non-linear, its stiffness coefficient k is not constant (as opposed to ideal springs) Formula (2). A relation was found with Matlab.

Frequency Analysis

Vessel Dynamics

When we look at the vessel and wires as being a mass attached to springs, it is obvious that this system has a resonance frequency. This frequency is a measure for the fastest disturbances that can be actively compensated for. Because the stiffness coefficient of the wires is dependent on the tension forces, so is the resonance frequency. The highest frequency is obtained for a high wire tension. Let us have a look at the thick wires that will pull the vessel forward and backward. These wires will be attached to winches that have a pulling force of 150 kN. Under normal conditions the wires will not experience a tension more than this. From the results of the Matlab calculations we found that the corresponding maximum stiffness is equal to 200 kN/m. With a vessel weight of around 400 ton, this will give us a resonance frequency of:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{2\cdot 10^5}{4\cdot 10^5}} \approx 0.1[Hz] \tag{2}$$

Note that this frequency can only be met when the winches are working at their maximum power, which is often not desired. Hence, during normal operation the frequency will be lower.

The waves around Venice have a frequency of about 0.3 Hz, higher than the resonance frequency. Hence, it will not be possible to actively compensate for them. Fortunately, simulations show that even waves of maximum height only displace the vessel about 0.1 m in lateral direction, which is well within the specification of 0.2 m.

These characteristic frequencies are only the rigid body characteristic frequencies. As the vessel was composed of several loosely combined components such as pontoon, arms and drum, there were also characteristic frequencies of the articulated multi-body system. These were also investigated, but no problematic modes were found. Regular control system sufficed to keep the movements and forces within limits.

Winch-wire Dynamics

Once the dynamics of the vessel are modelled and the requirements for a possible controller follow thus, the limitations of the controller are set by the actuators. In this case the characteristic frequency of the (varying) stiffness of the anchoring wires and the inertia of the winches. For controller design, the winch-wire dynamics are worst

- if the wire stiffness is minimum; as the stiffness of the wires depends on the force in the wire, the minimum stiffness of the wires depends on the minimum force that may occur in the wires; assuming the minimum wire force to be about 10 kN, the minimum wire stiffness is about 10 kN/m
- if the winch inertia is maximum, i.e. if most of the wire is rolled up; based on preliminary calculations, the equivalent maximum mass of the winches has been determined to be about 2000 kg.

Under these circumstances, the characteristic frequency of the winch-wire system is minimum:

$$f_{e,winch-wire} = \frac{1}{2\pi}\sqrt{\frac{k_{wire}}{m_{eq-winch}}} = \frac{1}{2\pi}\sqrt{\frac{10\cdot 10^3}{2\cdot 10^3}} = \frac{\sqrt{5}}{2\pi} \approx 0.35[Hz] \tag{3}$$

Positioning

One of the goals of this first phase was to determine the movements that can be exerted by the actuators, and to use these movements in a simple control loop to show that it can be used for correctly positioning the vessel. The positioning task was split up into three different sub-tasks. See Figure 9

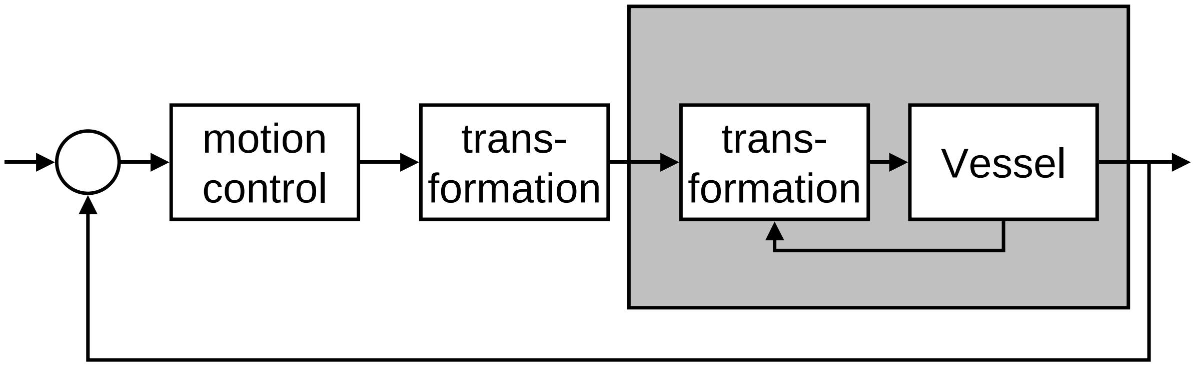

Figure 9. Controller structure overview.

Motion Control

Given a position error (and velocity error), the controller calculates a resultant force $F_{desired}$ that should be exerted onto the vessel somehow. In this sub-task no assumptions are made nor needed on what or how the resultant force will be exerted. This sub-task can be performed by a simple such as a P(I)D-controller, or by a more sophisticated one if it is found that the simple controller does not suffice.

The first sub-task calculates a desired resultant force $F_{resultant,des}$ that should lead the vessel to the desired place. Such a problem can usually be solved with a linear controller. A PD-controller was implemented for this task, giving:

$$F_{resultant,des} = -k_p x_{err} - k_d \dot{x}_{err} \tag{4}$$

where the control parameters were chosen to be k_p=50; k_d=30, which gives a gentle convergence to the set point. When extending to three degrees of freedom, a (large) stationary error in y-direction and ω direction is not allowed. In order to eliminate any stationary error, it just suffices to add an I-action to the controller.

Transformation

Given a desired resultant force, calculate a good configuration for the wires: which wire should exert how much onto the vessel? In theory, if tugboats are involved, they could also be regarded as an effort source, and they could be ‘implemented’ in this sub-task too. The output of this sub-task is a desired pulling force (tension) for each wire.

This block divides the desired resultant force over the six wires. This is an over actuated system, so there is some choice in which wire should get what force. This redundancy can for example be used for regulating the stiffness. On a calm sea with only few disturbances it is probably easier to keep the vessel in place than on a rough sea. By adjusting the stiffness of the system accordingly one can save energy and reduce wear of the equipment.

For the one-dimensional case it was chosen to keep a constant average force of $F_{w,avg}$=10kN on the wires, so that both wires are always a little tightened:

$$\begin{aligned} F_{w3,des} &= F_{w,avg} + \frac{F_{resulatnt,des}}{2} \\ F_{w4,des} &= F_{w,avg} + \frac{F_{resulatnt,des}}{2} \end{aligned} \tag{5}$$

Force Control

Given a desired tension for a wire, adjust the velocity of the corresponding winch such that the tension is achieved. This sub-task is executed for each wire individually.

This block is actually a simple linear controller in it self. The input is a desired wire force; the output is a winch velocity. Operating the winch will in its turn influence the actual tension in the wire. This can be measured and fed back into the controller. If the winch dynamics are neglected, a simple P-controller suffices for this task. Because the winch is relatively fast compared to the slow dynamics of the vessel, we can easily construct a controller that has a first-order transfer function of 1 for all relevant frequencies. A controller was constructed, having a cross-over point of around 10 Hz. Indeed the forces in the wires were smoothly made equal to the desired force. This block is very useful for controlling the vessel, as it gives a possibility to steer with a force (which is often very convenient) instead of a velocity.

The control strategy with the three sub-tasks, as described above, was implemented and tested by specifying a set point to which the vessel should sail. Simulation shows that indeed the vessel converges to the desired set point. Other disturbances than the initial offset were turned off during this test. See Figure 10. This simulation proves that it is indeed possible to control the vessel using the cascaded set of controllers in this section.

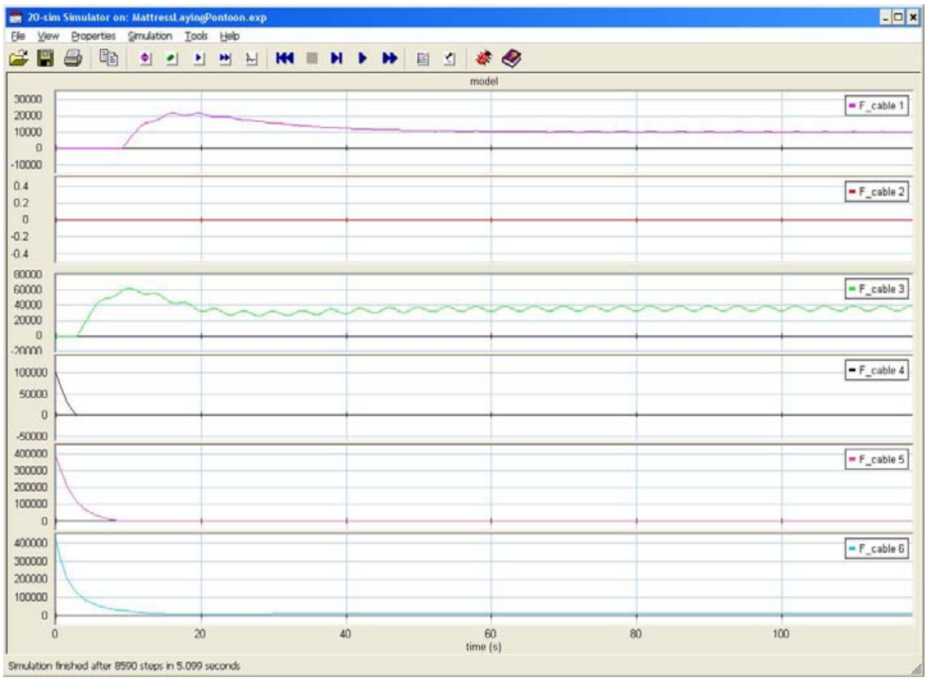

Figure 10. Simulation results offset disturbance.

Swell Compensator

Once the characteristic frequencies of the pontoon and the systems were determined, the rotations of the pontoon could be found. From these calculations, the necessity of a swell compensator on the mattress holder could be evaluated. The expected rolling and pitching was such that the holder would be moving too much. A swell compensator had to be fitted and the parameters were subsequently calculated with the same model.

COMMISSIONING AND DELIVERY

Commissioning

Manufacturing and supply of the components was like any common project. Good intentions, but there are always the various minor concerns. The biggest challenge met, was the communication and quality interpretation of the various suppliers from different countries. Due to the competence and experience of our engineers, the system was delivered and presented to the customer. Dry dock tests on the winches and DGPS equipment passed without any problem and satisfied the customer. In the mean time also the system control monitors were discussed with the client and adapted to their specific requirements.

Once everything set and tested (Figure 11.), the vessel was brought to the work area immediately instead of testing in a controlled environment, due to time constraints set to the client. The first mattresses were laid by manual control and the results were very acceptable. However, the results from the automatic positioning were not quite as expected. This was not only because of technical discrepancies but also due to severe differences in natural conditions in the field.

Figure 11. Venice matrress laying pontoon.

Remediation

DDE is always determined to deliver a good quality, working product. So we started to investigate the situation again including our fresh experiences of the full-scale model. Several problems were identified:

- The anchor positions and system was not as agreed upon with the customer. We demanded piles or other fixed structures and eventually still normal anchors were supplied. This resulted sometimes in dragging of the anchors. The controller noticed this correctly and shut down the system.
- The anchor handling was rather cumbersome and the anchor positions were not really updated regularly. This led to a sometimes very unfavorable anchoring configuration, where the tension in the wires was rose enormous, resulting in dragging of the anchors as described above.
- When the pontoon was placed in the inlet, the circumstances were much worse than as described by the client. Where only a wave height of 0.5 m was specified, the pontoon encountered waves up to 2 m in the inlet when the current and waves were from opposing directions. At least these waves, as high as they were, did behave as they should and the frequencies and wavelength were within the possibilities of the equipment. However, the control system was most disturbed by the wake of small boats zooming by at high speed. Apart that these waves could reach heights to 1 m, the short wavelength was detrimental to the control mechanism. The equipment has already demonstrated its robust design, as under manual control the mattress were laid, even with a wave height of 1 m and still within requirements. Please note that 1 m wavelength was considered survival condition!
- One major problem was not easily identified and was not investigated beforehand. At very unexpected moments the automatic control stalled and let the pontoon make a rotation what resulted in the dreaded ‘crab angle’ this was absolutely not acceptable. A geometrical study revealed that these occurrences could be explained when all the wires crossed the same node. At that moment rotation is possible under the controller as programmed. Instead now we have the bow wire setting the speed, the aft wires setting the tension and the fore wires setting the position. Computer tests show that this could be a viable operating sequence. And is probably the way the operator intuitively already feels the control.

Job Completed

March 2007 mattress no. 100 has been laid successfully within time and tolerance, we wish contractors and operators best of luck with the other 300 to go under much more severe conditions.

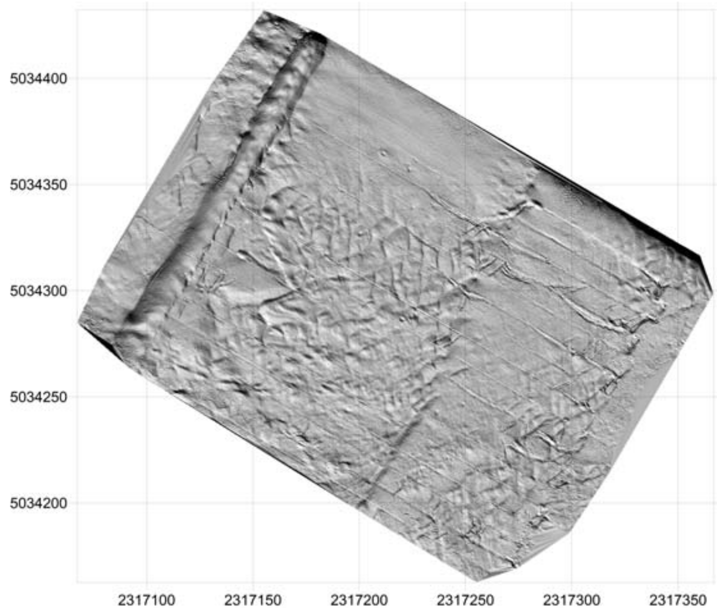

Figure 12. Multi beam recording out survey.

CONCLUSION

As always disclaimed by designers and users the phrase " Keep it sweet & simple" again also applied to this complicated pieces of technique fighting the elements. Thinking patterns in these kind of complex mathematic problems have been too complicated and have been simplified during the life tests, therefore tank test are more reliable and, if time is available should always have preference.

Influence of nature is always differ from expectations or historical reviews as they are not sufficiently specific for the working area, it is therefore advisable for this kind of complex and nature depending contracts, to arrange pre-contract measurements. These would also reveal the influence of maritime traffic on the natural conditions.

The analytical project approach, high level of technical background and experience in construction of complex vessels (mostly based on standard proven designs) make's the quality of the partner in the Marine Construction Industry. The Quality approach also results in a higher residual value of the Equipment.

Damen Dredging Equipment is dedicated to be your partner for Total Dredging Solutions and reduction in cost of Ownership.

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- Imotec for their dedicated support

NOMENCATURE

Symbol	**(Unit)**	**Definition**
F_{wire}	(N)	Wire force
$F_{desired}$	(N)	Desired force to move the pontoon
$F_{resultant,des}$	(N)	Resultant force of the wires to move the pontoon
$F_{w,avg}$	(N)	Average wire force in a particular wire
$F_{w3,des}$	(N)	Wire force in a wire number 3
$F_{w4,des}$	(N)	Wire force in a wire number 4
f	(Hz)	Resonance frequency
$f_{e,winch\text{-}wire}$	(Hz)	Resonance frequency of winch wire system
k	(N/m)	Coefficient of elasticity
k_d	(N/m/s)	Differential control coefficient
k_p	(N/m)	Proportional control coefficient
k_{wire}	(N/m)	Coefficient of elasticity of a wire
L	*(m)*	Actual wire length
L_{wire}	*(m)*	Original wire length
m	(kg)	Mass
$m_{eq\text{-}winch}$	(kg)	Equivalent mass of winch drum
ΔL	(m)	Length difference of anchor wire