Delft Outlook

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RESEARCH & EDUCATION AT DELFT UNIVERSITY OF TECHNOLOGY

The taste looks good!

Sharp fat contours

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Living on water

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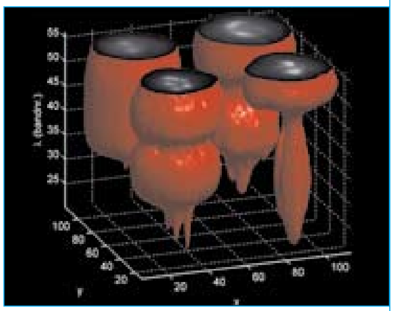
For over two decades, fruit and other agricultural products have been sorted using the 'electronic eye'. The eye selects purely by such external properties as colour, and cannot judge taste. Dr Gerrit Polder, an electrical engineer at Wageningen University, carried out his doctorate research at Delft University of Technology laying the foundations for an image processing system that can be used to determine the taste and smell of fruit as it is being sorted. Polder's 'taste viewer' could also come in very useful in the pharmaceutical industry or in waste processing.



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In search of sharp fat contours; A mathematical model to arrange ultrasound images of coronary arteries

A heart attack is usually caused by a build-up of fatty deposits in the coronary arteries. In many cases the patient will have noticed early warnings signs such as rapid exhaustion and shortness of breath. A cardiologist can now use an ultrasonic sensor to detect fatty deposits in the coronary arteries. With the heart pumping away as usual during the examination, the artery containing the sensor is constantly being stretched and compressed in concertina fashion. This results in a collection of shuffled images, which makes measuring the thickness of the deposits a tricky and inaccurate business. At the faculty of Electrical Engineering, Mathematics, and Informatics, Prof. Henk Koppelaar and his post-doc guest Dr. Xiaoqiang Liu have developed a mathematical model that rearranges the recorded images in the correct sequence to reconstruct the picture of the artery.

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Wave power

All over the world hundreds of thousands of initiatives are being developed to generate sustainable energy. The great majority of these are aimed at solar and wind energy, if only because they are available all over the world. What's more, the initial investments required are relatively low and are often helped by government support, so even private developments boast a surprising range of solar panels. Another source of sustainable energy is the motion of the sea. Technology to tap this source has also been developed in the Netherlands. In October 2004 the Archimedes Wave Swing generated its first electric power after more than a decade of research and development: power generated by a 420 tonne underwater biscuit barrel resonating up and down to the frequency of the ocean's swell off the Portuguese shore.

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Living on water

If we don't come up with something soon, the Dutch will be forced to leave the Netherlands in 100 years' time, according to hydrologist Prof. Dr. Ir. Cees van den Akker of Delft University of Technology. The climate is changing, and more rain is going to fall, in particular during winter months. The level of the sea is rising, the land is subsiding, and in the meantime the rivers flowing through our country will be called upon to carry increasing volumes of water to the sea. To keep the water at bay , the Netherlands needs to put aside an area the size of the province of Utrecht (200.00 hectares) to act as a water storage zone, according to the experts. Scientists are increasingly turning towards multiple use of space as a solution. Industrial designer engineer Ties Rijcken has developed a modular system for a floating foundation using expanded polystyrene foam, reinforced with a frame of high-strength concrete. In addition to the technical aspects, Rijcken also investigated the planning problems involved with living on water. The problem is that a house floating on water no longer counts as real estate, which complicates matters when it comes to planning permission, mortgages, and insurance.

COVER: Floating offices towed across the IJsselmeer, formerly known as the Zuyderzee. (photograph ABC ArkBouwers BV, Urk, The Netherlands)

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Spectroscopic views show flavour compounds of fruit and vegetables

The taste looks good

Until now, the only criteria for sorting fruit and vegetables were external properties such as blemishes and ripeness (insofar as they were visible).

BY ARNO SCHRAUWERS

For over two decades, fruit and other agricultural products have been sorted using the 'electronic eye'. The eye selects purely by such external properties as colour, and cannot judge taste. Dr Gerrit Polder, an electrical engineer at Wageningen University, carried out his doctorate research at Delft University of Technology laying the foundations for an image processing system that can be used to determine the taste and smell of fruit as it is being sorted. Polder's 'taste viewer' could also come in very useful in the pharmaceutical industry or in waste processing.

It used to be done by hand. A conveyor belt carrying potatoes, tomatoes, eggs, or whatever needed to be sorted, would be run past an army of sorters whose task it was to pick out, with lightning speed, any items that had gone off or were otherwise unsuitable for consumption.

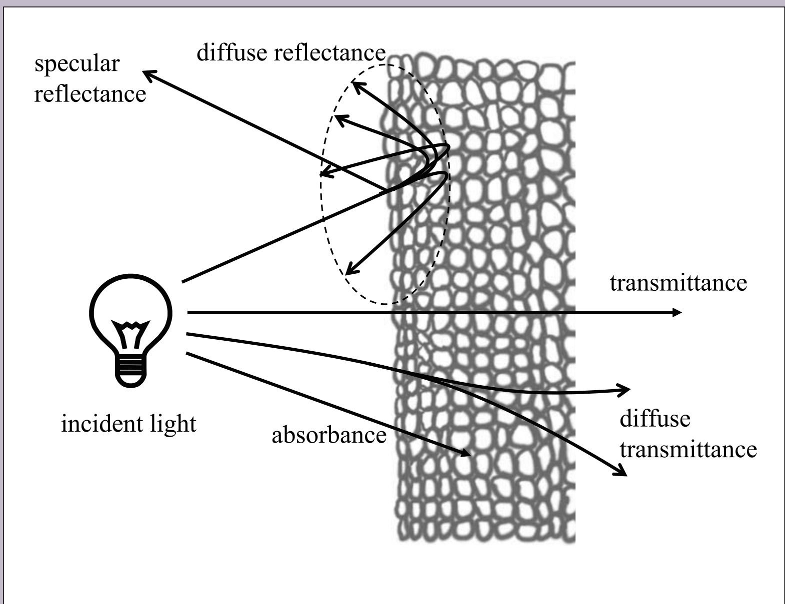
Experiments with electronic sorting systems started quite a few years back, and it was twenty years ago that the first sorting machines using cameras actually appeared on the market. All these sorting systems do is to look at the colour on the outside of the fruit (or any other produce being scanned). Although in some ways the colour can tell us something about the fruit, it cannot tell us what it tastes like.

A notorious affair, and one that the Dutch market garden industry would rather not be reminded of, is that of the water-bomb tomato. For many years, Germany had been a major consumer of Dutch tomatoes, which looked perfect on the outside, but in fact were little more than water held together by a red skin.

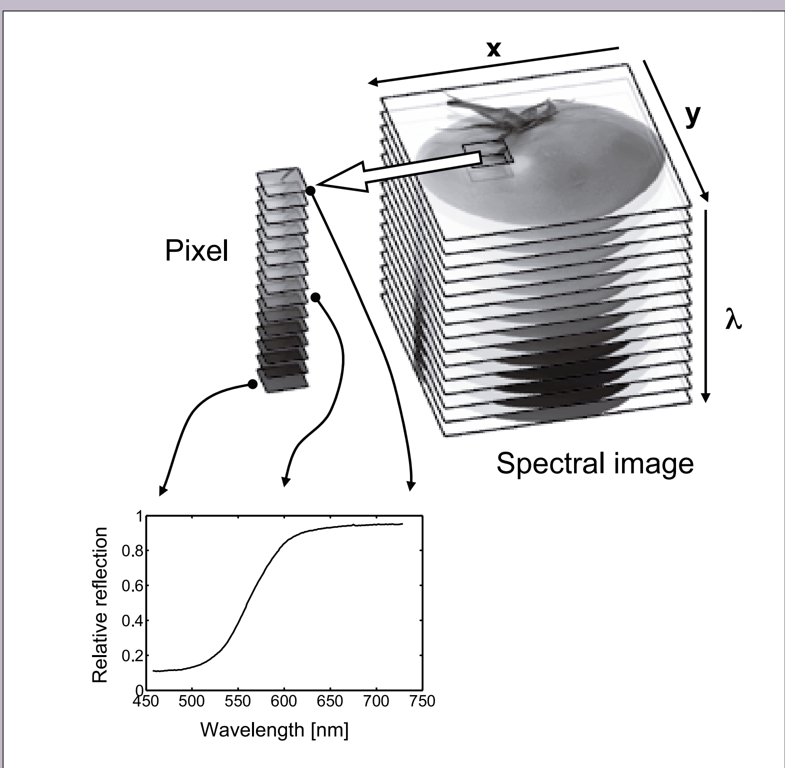
At least, that is what the Germans thought, and they switched to the much better-tasting Mediterranean tomatoes.

The best thing would be for an electronic sorter to give an indication not only of a tomato's ripeness, but also of its taste. One good method of gaining such information without cutting up the fruit uses spectroscopy. A spectroscope is a device that enables the user to analyse the light, both visible and invisible, reflected by an object (a tomato, for example). The light consists of various

Sorting machine for apples and other types of fruit, manufactured by Greefa BV, Tricht. Image processing plays a major role in the sorting process. (Photo: Greefa BV, Tricht)



Incident light striking the tissue cells of food is reflected, absorbed, and transmitted in different ways, as show above. The extent to which this occurs depends greatly on the type of tissue and the wavelength of the incident light. The constituents of the tissue produce specific reflection and absorption spectra.



A spectral image can be represented as a cube with two spatial dimensions (X and Y) as well as a spectral dimension, λ. Each image pixel contains a complete reflection or absorption spectrum.

wavelengths that reveal something about the composition of the object. This is because every chemical has its own spectroscopic fingerprint. Applying the method to fruit or vegetables in essence allows their composition to be determined, not only at the surface, but also deeper below the skin. The spectroscopic method Polder used for his research can look a few millimetres inside a tomato and can even see straight through kernels of grain, allowing them to be checked for contamination by the fusarium fungus.

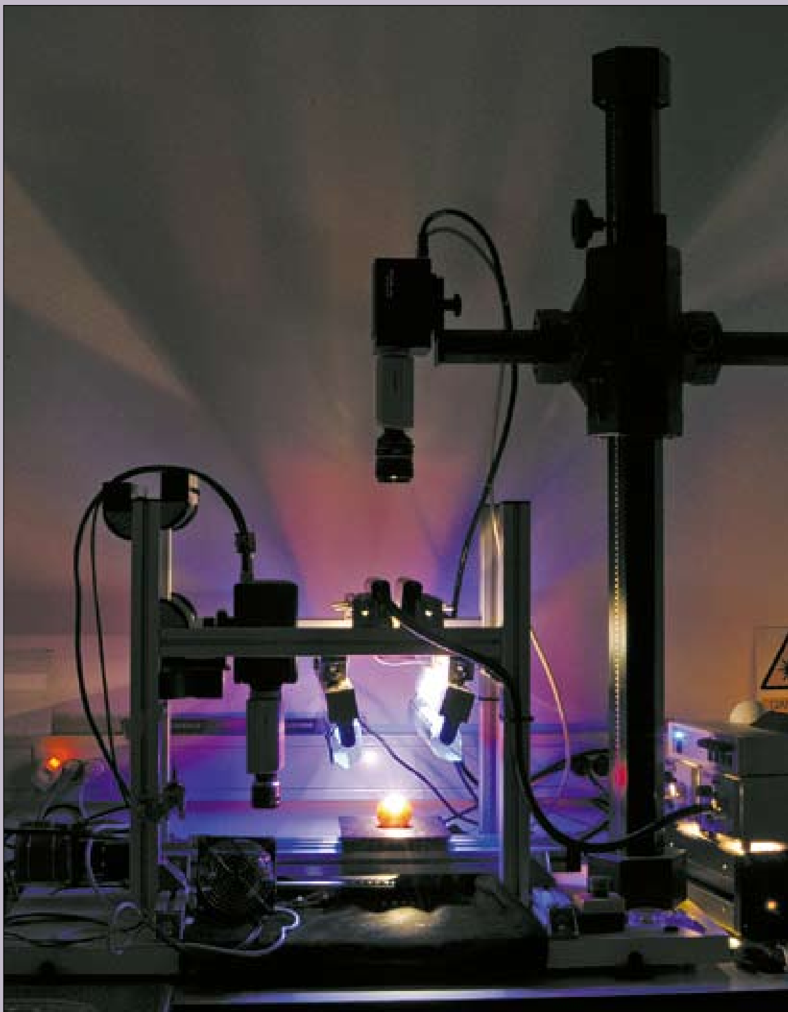
The object of the exercise is not to scrutinise every aspect of the fruit, since this would yield such a mass of data that processing it would slow down the sorting machine to the point where it would cease to be practical.
A number of commercially available systems use various sensors sensitive to certain wavelengths, enabling them to determine the presence of essential nutrients inside the fruit. This can be done for any number of precise wavelengths, depending on the information required about the fruit. Rather than 'nutrients', Polder refers to 'compounds', a wider and more accurate term.

Image processing If you're looking for information about the precise location of things within an object, its spatial layout, the traditional sensor technology mentioned above will be of little use. This is where image processing comes in. Using tomato 'shots', Polder has been trying to gather information about the fruit's compounds by means of spectral image processing. To get the required information about the distribution of the compounds, he had to collect his data pixel by pixel.

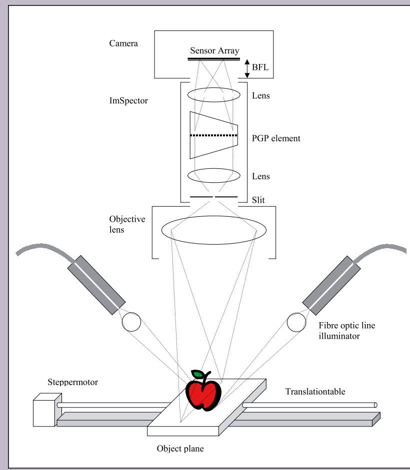
Various techniques exist to record spectral images of fruit. One is to shine light of a certain wavelength onto a tomato, take a two-dimensional picture of the reflected light, then change the wavelength, take another picture, etc. The tomato has to remain in exactly the same spot, or the experiment will fail. Polder has opted for a method in which the entire reflection spectrum (or transmission spectrum if the light were to pass through the tomato) is recorded line by line by a special camera. The lines are chopped into pixels, each of which produces a complete spectrum. This means that information is gathered pixel by pixel. To 'shoot' the whole tomato, it has to be moved in small steps. This is hardly a viable method, since shooting a single tomato takes the better part of thirty seconds. In a real sorting machine the job has to be done in a fraction of a second.

Carotene To return to the tomato, which according to Polder is not just a nice fruit, it is also one of the most important horticultural products. What's more, the boffins at Wageningen University know a thing or two about tomatoes. Unripe tomatoes are green, the colour of the chlorophyll that also makes the leaves on trees green. As tomatoes ripen, they produce lycopene, a vitamin-like substance that belongs to the carotene family. The fingerprint spectra of lycopene and chlorophyll are known. If you look at images taken at the right wavelengths, you can see that the concentrations of chlorophyll and lycopene inside the tomato change over time. The chlorophyll content decreases, while the lycopene content increases, turning the tomato red. Of course, it could be argued that the same can be observed using a straightforward RGB (Red/Green/Blue) colour camera, but in the course of his research Polder has discovered that colour cameras are not very good at determining ripeness.
"I took pictures of a tomato on five consecutive days. It turned out that the RGB camera was unable to detect the difference in ripeness, whereas it was perfectly visible using the spectroscopic method."

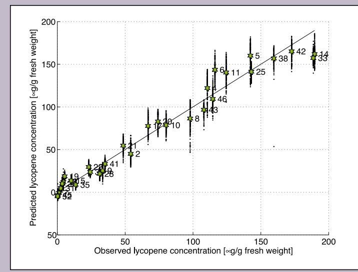
Flavours The spectroscopic method can also be used to determine the fruit's content of a certain type of flavour (as the reader probably surmised on the basis of the above). Put simply, the height of a spectral peak at a wavelength specific to the substance under scrutiny is a measure of its content. However, it takes a lot of applied mathematics to unravel the spectrum before the concentrations of the constituents can be determined – but the fact remains that it can be done.
Using a chemical analysis device called an HPLC (High Pressure Liquid Chromatograph) to determine the flavour concentration inside the tomato, a relationship can be established between the spectral readings and the



The experimental set-up used by Gerrit Polder at Wageningen University.



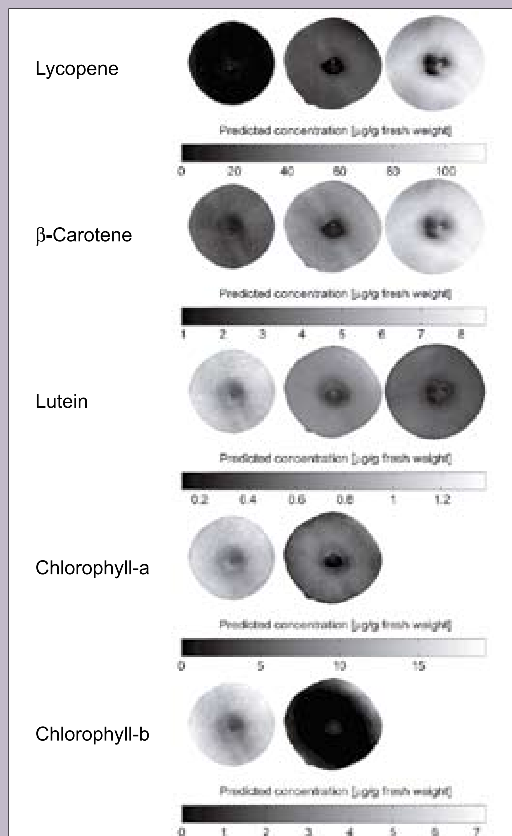
Schematic diagram of the measuring apparatus. An imaging spectrograph (Imspector) has been placed between the objective lens and the camera. The spectrum of an image line is projected onto the sensor. To scan a complete image, the item of fruit or vegetable is moved along in steps under the camera using a stepping table.



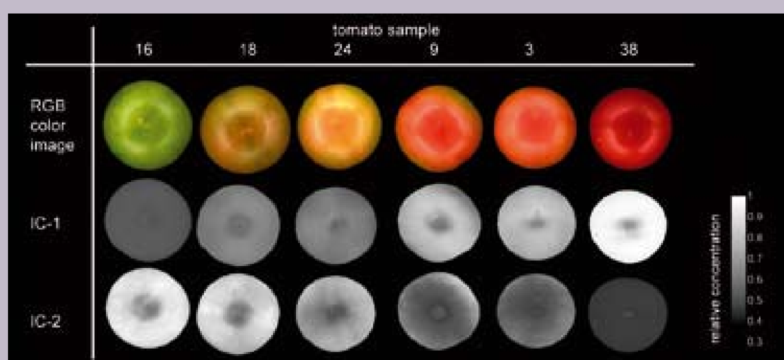
Prediction of the concentration of lycopene in tomatoes at varying stages of ripeness. The concentration of lycopene of the entire tomato, measured using analytical chemical equipment (HPLC), has been plotted along the X-axis. The concentration of lycopene predicted from the spectral image has been plotted along the Y-axis. The points represent randomly selected pixels from each tomato. The green asterisks represent the mean concentration of the entire tomato.

concentration of the flavour inside the fruit. Once this relationship has been established, there is no longer any need to drag every tomato through the chromatograph. Having obtained a pixel-based set of spectra, the concentration of the various constituents can be measured for each pixel. This helps to detect uneven ripening fruit or the first inkling of a blemish.
Polder: "This type of sorting system is much more flexible in its applications than other sorting systems that use fixed filters and sensors. You can measure any substance you like without having to modify the sorting system. The enormous amount of data the system produces does remain a slight problem, although the number of data can easily be reduced by using only the parts of the spectrum that tell us something about the substance we're looking for. One could also use the full resolution of the sensor, which would yield the best possible readings, but this would produce hundreds of megabytes per image and still would not produce any additional information, the optical system being the limiting factor. This method is eminently suitable for measuring a large number of constituents. Of course, and I have become well aware of this, it is essential to ensure that the system is accurately calibrated."

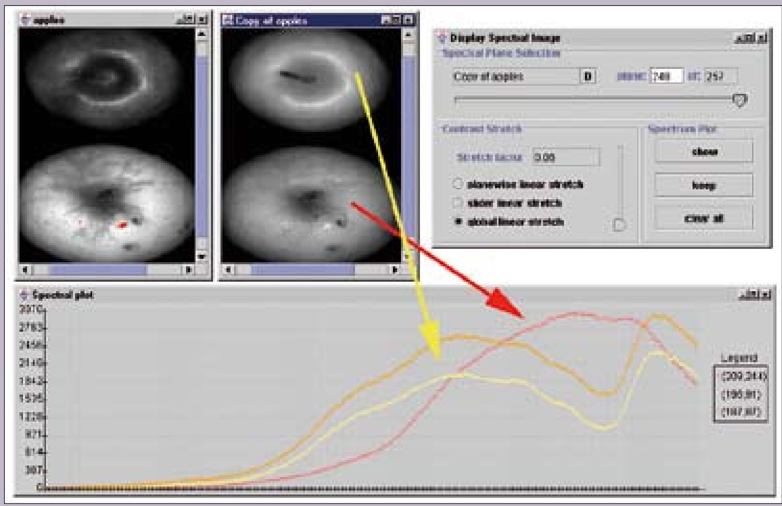
Test Polder was able to demonstrate his skill measuring the presence of fusarium in grain using a transmission light method. The grain was placed between a halogen light source and the camera, a technique known as transmission spectroscopy.
Polder: "These measurements are important for organic farmers who are not allowed to use pesticides."
Other industries also use spectroscopic systems, according to Polder, who gained his B.Sc. in electrical engineering in Arnhem.
"I know that some of my colleagues are working on systems for separating waste flows using the spectroscopic method, and a colleague in Austria is working on a way to extract various types of plastic from waste material, something for which the method is eminently suitable."



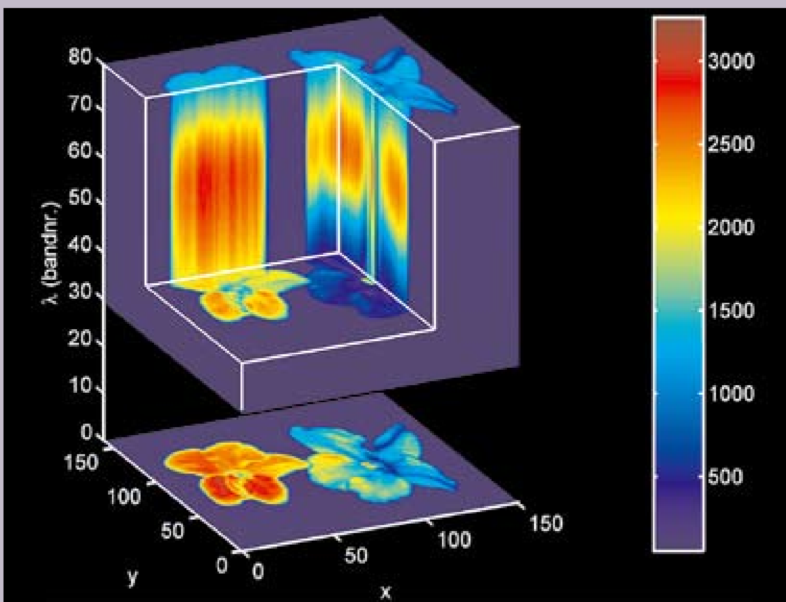
If the model is applied to all the pixels of the tomato, it produces concentration images of the various compounds. This figure shows the concentration images of five different compounds of three different tomatoes. Dark pixels indicate low concentrations, lighter pixels indicate higher concentrations. These images can show local differences in concentration that may be caused by non-uniform ripening.



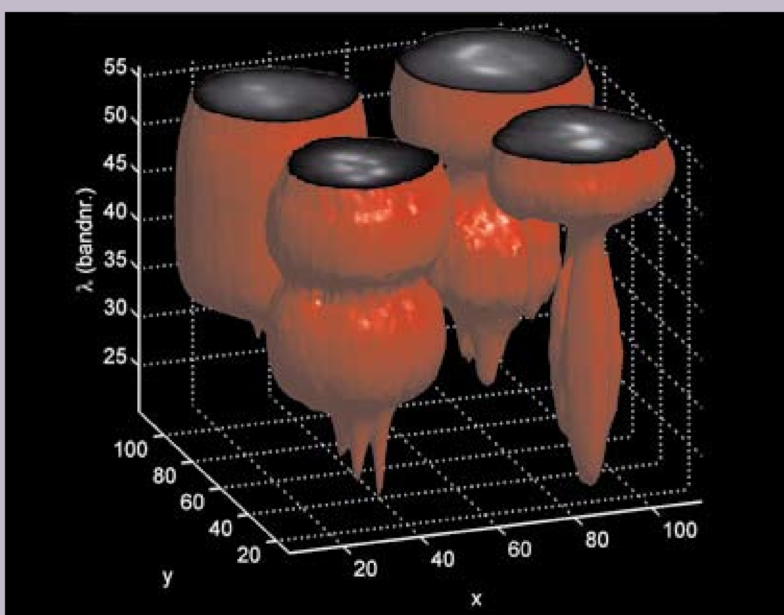
Creating a regression model as shown in the previous images requires a costly reference method, e.g. HPLC. For this figure, no reference method was used. Instead the analysis was carried out using Independent Component Analysis, a new statistical technique. In this case two components are found which more or less match chlorophyll and lycopene. This figure shows how the concentrations of these components decrease and increase as the tomato ripens.



To record the spectral images, Polder developed the ISAAC (Imaging Spectroscopy Acquisition And Control) program. This illustration shows a spectral image of two apples as seen in ISAAC. The top left part shows the image for two different wavelengths, and the bottom part shows the spectrum of three different pixels.



A spectral image is a 3-D data cube, which is difficult to visualise. This figure uses volume rendering techniques to visualise the spectral image of African violets.



An isosurface image of four tomatoes in varying stages of ripeness. By drawing a surface through points with identical reflection values, a combination of spectral and spatial information is obtained. The indentation seen for three of the tomatoes is caused by the chlorophyll absorption maximum at 670 nm.

Testing having been successful, the time has come to market the method. After all, Polder's doctorate research formed part of the Innovative Research Programme for image processing funded by the Ministry of Economic Affairs. A requirement of the programme is that the industry participates in the research project. Did they?

Polder: "Yes, they did, in the form of Greefa BV, one of the world's major manufacturers of sorting equipment for fruit and vegetables. I just hope the industry takes it from here."

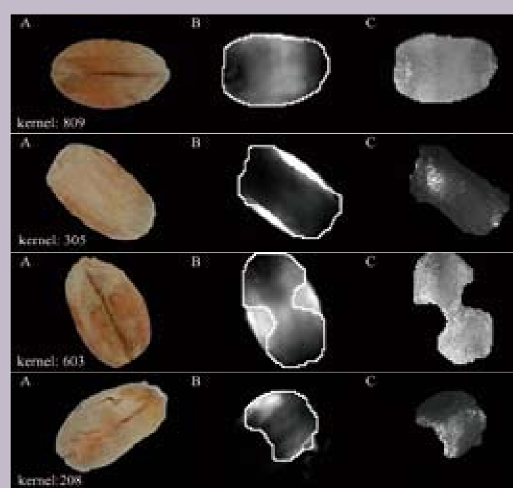
Of course, although Polder has demonstrated that the spectroscopic method is perfectly suitable for determining the content of flavours and aromas and for classifying fruit and other produce, the system is still a bit on the slow side.

Polder: "The problem is that large quantities of data must be manipulated in a short space of time. The test system still uses 80 megabyte images that have to be processed in some way. A practical system would have to be able to process several images every second. This could be done by using filters specific to a certain substance as well as other types of cameras, such as CMOS cameras, which can address specific pixels, and so reduce processing times."

Anyway, that's all practical stuff. At least the foundations have been laid.

For more information please contact Dr. Gerrit Polder, phone +31 (0) 317 476842, e-mail polder@ph.tn.tudelft.nl, or Prof. Dr. Ted Young, phone +31 (0) 15 2785390, e-mail i.t.young@tnw.tudelft.nl.

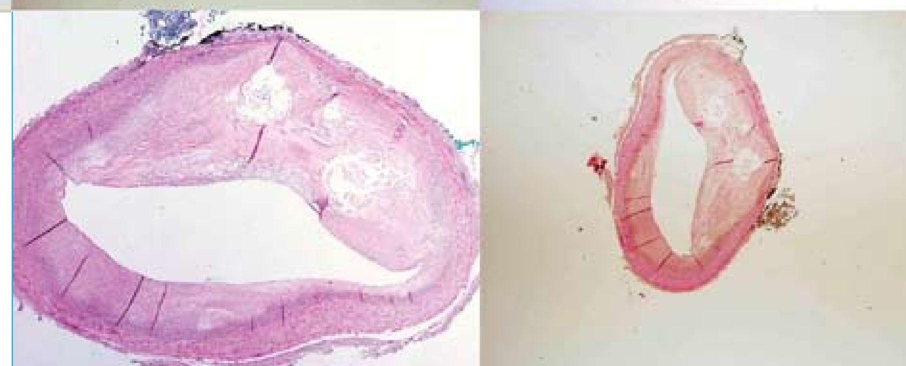
Transmission light image of wheat grains infected with the fusarium fungus, which can produce the poisonous substance DON.



The spectral images allow the spatial distribution of a fusarium infection to be predicted. On the left, a colour image of four wheat grains in the centre, a NIR (near infrared) transmission image taken at a wavelength of 1050 nm. On the right, the fusarium infection concentration image.

In search of sharp fat contours

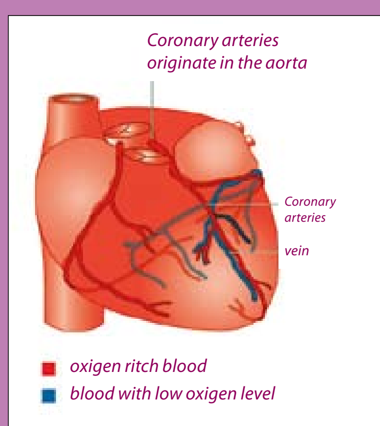
A trick that uses a mathematical model to arrange ultrasound images of diseased coronary arteries in the correct sequence



Composition of sections through coronary arteries

A heart attack is usually caused by a build-up of fatty deposits in the coronary arteries. In many cases the patient will have noticed early warnings signs such as rapid exhaustion and shortness of breath. A cardiologist can now use an ultrasonic sensor to detect fatty deposits in the coronary arteries. With the heart pumping away as usual during the examination, the artery containing the sensor is constantly being stretched and compressed in concertina fashion. This results in a collection of shuffled images, which makes measuring the thickness of the deposits a tricky and inaccurate business. At the faculty of Electrical Engineering, Mathematics, and Informatics, Prof. Henk Koppelaar and his post-doc guest Dr. Xiaoqiang Liu have developed a mathematical model that rearranges the recorded images in the correct sequence to reconstruct the picture of the artery.

BY ASTRID VAN DE GRAAF

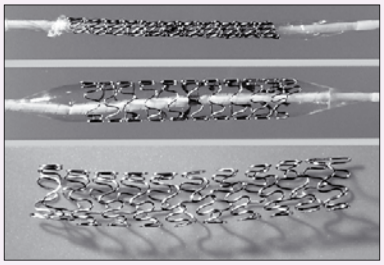


SOURCE: WWW.NATUURINFORMATIE.NL

The heart, with its large blood vessels, including the aorta, at the top. The coronary arteries can be seen encircling the heart.

Sectional view of a coronary artery under the microscope. The material has been dyed to make the differences in cell types visible. This blood vessel has minor deposits on the vascular walls that still leave enough room for the blood to pass through (the area in the centre).

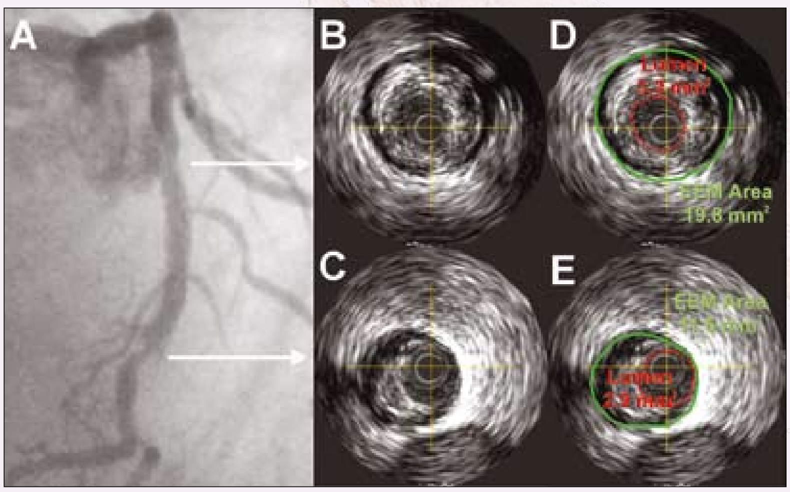
Another sectional view of a coronary artery. In this case most of the blood flow is blocked by the massive deposits on the vascular wall, which has been severely affected by arteriosclerosis.



A stent is a metal structure that can be expanded by means of a balloon in order to stretch a constricted artery. The stent is introduced into the coronary artery using a catheter. Once expanded (bottom picture), the stent remains behind in the blood vessel to make sure the artery does not return to its former, constricted condition.

(Foto: AV-Thorax, Paula Delfos).

View of the cardiac catheterisation laboratory at the Erasmus Medical Centre, where a catheter is being introduced into the coronary arteries. (Photo: Paula Delfos, AV-Thorax, Erasmus Medical Centre, Rotterdam)



To make the apertures available to the blood (lumen) in the coronary arteries, the cardiologist uses a contrast fluid that shows up on X-ray images. The disadvantage of this type of X-ray technique is that, although the lumen becomes visible, it does not show the amount of plaque adhering to the vascular walls, which is a measure of the severity of the arteriosclerosis. The intravascular ultrasound (IVUS) technique was developed to make the plaque visible by making ultrasound images of the coronary arteries from the inside. A miniature sensor is introduced through a catheter into the blood flow of the coronary arteries. Images B–E were generated using the IVUS method. As it turns out, the X-ray images appear to indicate constrictions of the same severity, indicated by the arrows. However, the images B-D and C-E clearly show (as has been measured in D and E) that the plaque at point B is worse than at point C. The red circle indicates the available aperture (lumen). The area between the green and red circle indicates plaque.

"Suppose you' re driving along a road in the centre of town and your job is to photograph every house in the street. The road is very bumpy, so you are constantly being thrown backwards and forwards in your seat, as if you were riding the surf. In the meantime, you're taking pictures of all the houses. Unfortunately, the houses are not numbered, and you do not have a GPS to tell you exactly where you are. In spite of all this, you have to somehow get the pictures of the houses laid out in the right order to see what the street looks like."

Using this analogy, Henk Koppelaar, professor of knowledge-based systems at the department of Mediamatics at TU Delft, tries to explain the complex task facing him and his colleague, Dr. Xiaoqiang Liu of the Chinese Donghua University.

Fatty deposits In this case, the bumpy road is a coronary artery. There are three of these surrounding the human heart. Their task is to supply a constant flow of oxygen to the heart's muscles. The heartbeat takes on the role of the surf, with the coronary arteries following each and every motion of the heart as it expands and contracts, a cycle that gets repeated 60 times a minute on average. Riding this roller-coaster is our camera – actually an ultrasonic sensor – looking for fatty deposits in the artery. Arteriosclerosis, as it is officially known, is still the number one cause of death in our society.

The growth of plaques starts at the age of sixteen, as Dr. Nico Bruining, a Cardiology department researcher at the Thorax Centre of the Erasmus University in Rotterdam, explains.

"The exact cause remains unclear," Bruining says. "The interior wall of our arteries is lined with a very smooth layer to prevent damage to the thrombocytes as they flow along it, as this would cause them to clot together. Even so fatty deposits, or plaques, manage to stick to the walls. The build-up can be very smooth, but there can also be volcano-shaped mounds, like pimples.

"Strangely enough, everyone tends to look at the most complex solution first. As is so often the case, the solution lies in restriction."

These are inflammations of the artery's inner wall. When the pimple erupts, its scab is released to flow with the blood into the artery, where it can cause a blockage, resulting in a coronary.

In addition, the fatty substance (pus) released in the process is immediately detected by the thrombocytes, which then clot together to form a thick wad that can block the artery (thrombosis). If this occurs at the beginning of the coronary arteries, close to the aorta, the result is a massive heart attack. Severe arterial strictures are often presaged by symptoms such as shortness of breath and lack of stamina."

Ultrasonic vision When a patient's coronary arteries are being examined for strictures, a contrast fluid is first injected, and then an X-ray picture is taken of the blood vessels around the heart (angiography). However, the contrast fluid only shows the shape of the flowing blood. Any sudden strictures will be clearly visible, but a gradual build-up in an artery will simply show up as a narrow blood vessel.

Bruining: "Once inflammations occur in a blood vessel, or when plaque is formed, the body at first attempts to maintain the required aperture for the blood flow, so the vascular wall is pushed outwards, plaques and all. Only when the wall can stretch no further, will the plaques start to build up inwards. This can be observed very well using IVUS, intravascular ultrasound."

Ultrasonic waves with a frequency of 20-40 MHz can penetrate sufficiently deeply into the tissue to produce a clear image of both the interior and exterior walls of the blood vessels.

Sawteeth The ultrasonic sensor is inserted into the coronary artery using a catheter. Entering through the patient's groin, the physician first inserts a guide tube up to the entry point of the coronary artery. Through the tube, he then pushes a guide wire some 10 to 14 cm into the artery. The ultrasonic sensor

then slides over the wire and into the artery. An electric motor then gradually retracts the sensor at a rate of 0.5 mm per second. Each second, the sensor produces 25 images, the final result being a 4500 frame movie picture.
Bruining: “When you piece all these images together, what you get is not an uninterrupted view of the vascular interior, but something rather more like a sawtooth pattern. A contour detector, a piece of software that visualises the vascular wall, is useless in these circumstances, since there is no way of telling where the boundaries between the vascular wall and the plaques lie; they could be at the tops of the sawteeth, at their base, or anywhere in the middle.”
For the treatment of a patient this makes it very difficult to accurately measure the thickness of the plaques, which is necessary in order to assess the effect of a possible intervention, such as the insertion of a stent, which is a metal brace that forces the blood vessel open, or the prescription of medication to reduce the plaque thickness. But for medical research into new methods of treatment, too, the inaccuracy of the plaque measurement means that the number of subjects tested for each study has to be much higher.
“There is quite a difference between having to test 100 patients for a research project rather than 1000,” Bruining says.
To find out where the constrictions due to the plaques are located in the coronary arteries, the data have to be reprocessed, a time-consuming job that, still produced anything but perfect results even though it was carried out by experienced staff.

Subset Before Bruining went to see Koppelaar in Delft, he had been working on the synchronisation of ultrasound images using an electrocardiogram (ECG), a recording of the patient’s heartbeat. The highest peak in the ECG (known as the R top) occurs when the heart’s ventricle has just filled with blood (the end-diastolic situation). The R top represents the electric pulse that makes the left ventricle ejects its blood content. Based on an average heart rate of 60 beats per minute, the top occurs once every second.
At the R top moment, the catheter will always be at the same distance from the beginning of the coronary artery, though its location since the last top will have shifted by 0.5 mm as a result of the automatic retraction. Between the R top moments the sensor is being swept all over the place by the pumping action of the heart. By placing just the R top images in sequence (i.e. 1 in every 25 images), a subset of images can be constructed that provides a reasonably accurate image of the plaques inside the blood vessel, sufficient for a contour detector to do some additional calculations on the intermediate positions.

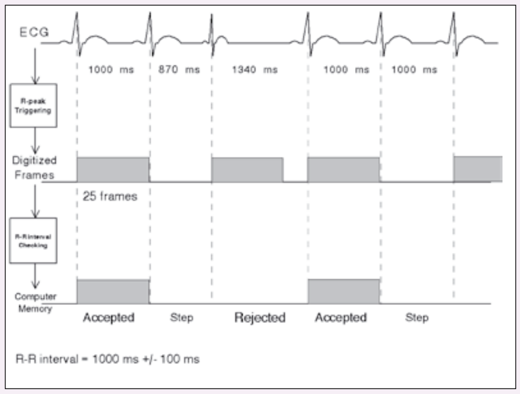
Multitasking The solution sounds simple, but it did require a heavy-duty multitasking system to complete the calculations.
Bruining: “You have to be able to find the R top moment in the images. The problem is that a heartbeat is far from regular; each one differs slightly from the next. One may span 1000 milliseconds, the next 975, another 1125, and so on. In addition, you need all sorts of filters to weed out noise, artefacts, and signal delays, and then link the results to the IVUS readings.”
The synchronisation method is not very widespread, because it is very complicated and extends the length of the examination, which adversely affects the patient. In addition, large quantities of data from a great many patients were recorded without any synchronisation, but still have to be analysed. Therefore the group went in search of a method that could be used to post-process the data in order to correct any catheter motion artefacts.
The Intelligate model software for the multitasking system was developed by a student of Koppelaar, Sebastiaan de Winter, under the supervision of Dr. Ronald Hamers of Curad B.V., a company developing software for the analysis of cardiovascular images. For some years now, Hamers has been spending one day each week on Bruining’s research project.
Bruining: “It was primarily a pragmatic solution. We dearly wanted to use the full set of ultrasound images, and so we had to be able to tell where the catheter was all through the heartbeat. To do so, we first of all had to convert the motion process into a mathematical model.”

Coronary artery Hamers had provided Dr. Liu with a motion picture of a beating coronary artery produced by means of bi-plane angiography. This uses X-ray images taken from two different directions to produce a 3-D reconstruction of the blood vessel.

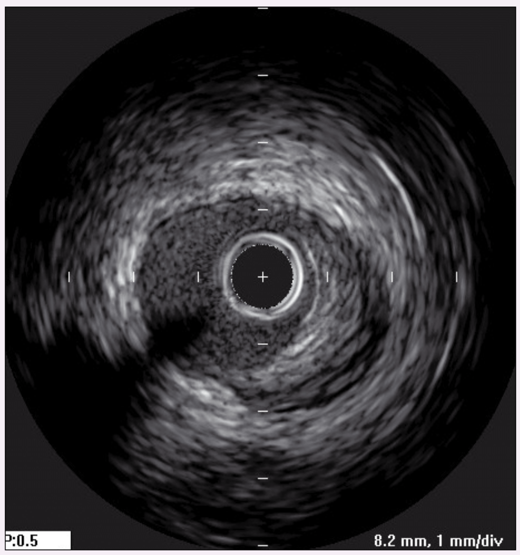
Detailed view of the miniature ultrasound sensor.

Console of the IVUS which controls the ultrasound sensor and converts the ultrasound waves into images. The system is a typical example of extremes, with the sensor being a fraction of a millimetre wide, whereas the console is almost the size of a fridge.

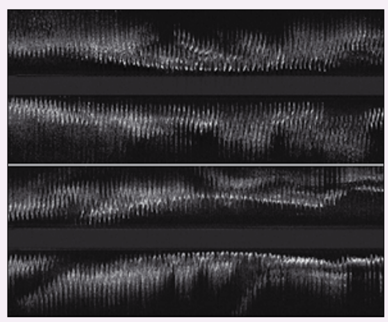
An example of the kind of equipment used to retract the ultrasound catheter from the coronary artery at a constant rate of 0.5 mm/s. This is necessary in order to subsequently calculate the amount of plaque present in the examined section of artery and to assess whether treatment will offer a lasting effect.



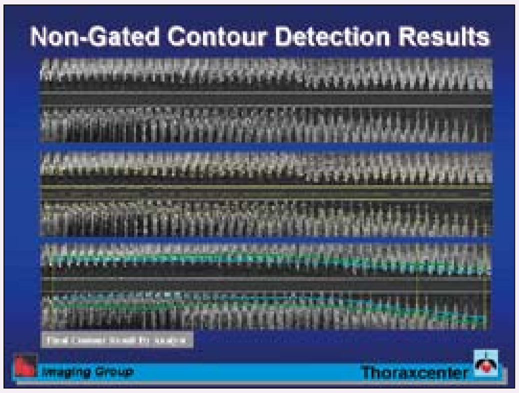
The ECG printout clearly shows the varying lengths of the heartbeats.



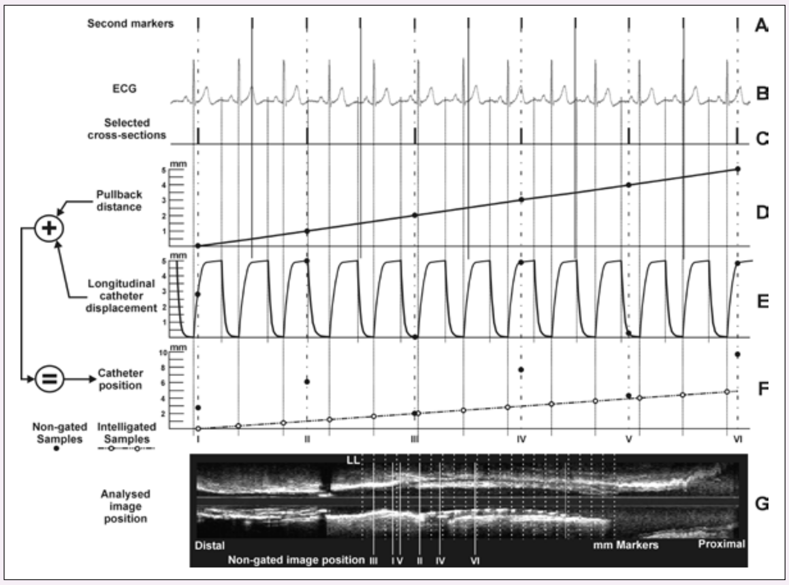
Detailed view of an IVUS image, also known as cross-sectioning. The catheter can be seen at the centre. Surrounding it (dark grey/black) is the blood flow. The catheter rests against the vascular wall in the 2 o’clock position, and a plaque is visible between the 2 and 6 o’clock positions.



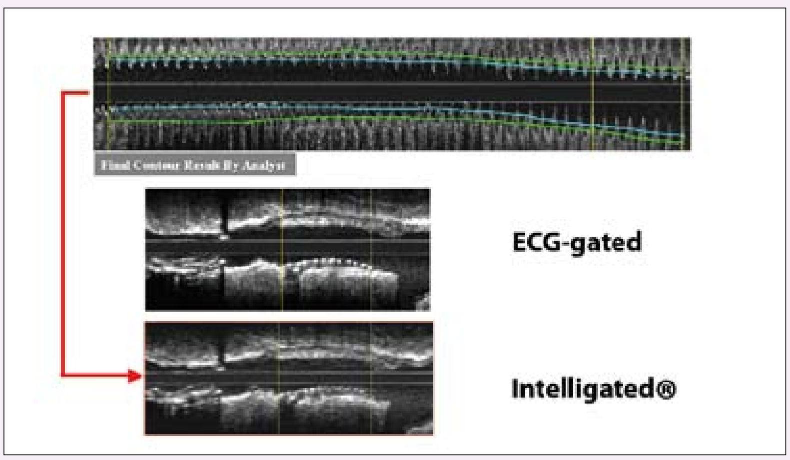
Reconstruction of a large number of IVUS images (cross-sections) that were made using the retraction method, then mounted in sequence and cut lengthwise, the way a banana is split in half. This is also known as longitudinal reconstruction. The sawtooth nature of the way in which the vascular wall is represented is caused by, among other factors, the movements of the ultrasound sensor relative to the coronary artery.



(Top) A reconstruction like the one in the previous figure.
(Centre) This figure shows the result of an automatic contour detector. The sawtooth effect makes it almost impossible to use an automatic detection method, necessitating manual intervention.
(Bottom) The result of the contour detection as performed by an analyst.



This complex figure is a representation of the selection process: the retraction of the ultrasound sensor (D); the heartbeat (B); the movements of the catheter during the heartbeat (E); and the result (F), which indicates where and at which point in time an image is being recorded inside the coronary artery (e.g. geometrical location). To subsequently be able to accurately quantify the amount of plaque covering the vascular wall, it is important to know the relative positions of the successive cross-section images and the absolute distances between them. If this information is ignored, the resulting calculations will be based on an anatomically incorrect set (G).
The correct sequence of the images in this case is III, I, V, II, IV, VI. The figure also shows that the distances between consecutive images vary. The amount of plaque on the vascular wall is expressed as a volume.



To avoid the problem visualised in the previous figure, a method was developed to select only those images made at a certain point during the heartbeat cycle, i.e. the moment just before the heart ejects the blood from its ventricles, known as the end-diastolic phase. Once the end-diastolic images have been identified and selected, a new reconstruction can be made, the result of which is shown in the lower panel. The algorithm was developed at the Erasmus Medical Centre in collaboration with the group of Prof. Koppelaar and has been named Intelligate®. The vascular walls have now been aligned, giving automatic contour detection a better chance of success, and even more importantly, requiring fewer manual operations, much improving the reliability of the readings.

Hamers: “A 25 frames per second movie gives us some idea of how the shape of the blood vessel changes in time. We gave this to Liu and asked her whether she would be able to quantify it.”
Liu started by delving into a stack of medical textbooks and attending a number of heart inspections in hospital to understand what actually goes on. Her result was a 3-D simulation of the way the coronary artery moved. It looked like a fat string of spaghetti spiralling back and forth in space every second, which is a fine mathematical description of what takes place, but did not help much to get the pictures in the right position.
Koppelaar: “Strangely enough, everyone tended to look at the most complex solution first, i.e. a three-dimensional heart. So did we, since it is the most tangible image and appears to provide the best insight. Many groups all around the world are currently working on complete mechanistic models of the heart, but as is so often the case, the solution lies in simplicity.”

Inner tube Liu and Koppelaar still had to make the conversion from an artery encircling a pumping heart to a mathematical model that arranges the images in the correct order.
Koppelaar: “In fact, it takes a non-medical person to come up with a solution. A coronary artery is nothing more than a bicycle inner tube that expands and contracts, lengthens and shortens. This was to be our second attempt to produce a virtual two-dimensional simulation model that would describe the way the coronary artery works. All we had to do was apply a suitable relative coordinates system that would enable us to string the ultrasound image together.”
For this purpose, Koppelaar wrote a computer program that reconstructs the expanding and contracting motion of the coronary artery. To visualise the process, he used marker lines that move to and fro from the centre, where the elastic deformation caused by the heart is at its greatest, like a longitudinal sound wave.
“The difference between the expanded and contracted states can be up to 5 mm, so if we did not apply the correction to the image position, we could be out by as much as ten times,” Koppelaar says.

Reference point “And then came the day when we noticed how the doctors applied a small rubber ring to guide the sensor. That was the turning point for us. The ring provides the reference point for all our ultrasound images, reducing the problem to a one-dimensional relative translation,” Liu recalls with relief.
The trick required to arrange the ultrasound images in the correct order had now become relatively simple: just add the periodical longitudinal motion of the blood vessel, which consists of sinus functions, to those of the uniformly receding sensor. Using this reconstruction, an automatic contour detector can easily map the thickness and position of the plaques.
Koppelaar: “Our third model worked perfectly. Of course, it is not as if our model will suddenly stop people dying, but it will affect the quality of life as a whole. Since the Thorax Centre looks at IVUS image information from all over the world, its impact on research into new therapies and treatment is huge.
In the Netherlands alone, every year, thousands of people are examined using IVUS. According to Bruining, the Netherlands are ahead of the pack in this respect.
“This is because we do many of the IVUS measurements ourselves. These measurements are very expensive and are not covered by insurance. A sensor can cost up to 1200 euro and for reasons of safety it is discarded straight after use. Hence about 80% of the inspections are funded through manufacturer’s studies into newly-developed intervention techniques or medication. The remainder is paid by the hospital itself.”

Real time The first step has been done. What remains is for the model to be validated through long-term monitoring studies using information from the database.
Hamers: “Liu’s current model is still too narrowly defined. It fits our patient data set too well. We now want to take a small step back in order to extract a basic validity from it that will enable us to gain even more insight into the artery motions. Given a robust model we will later be able to analyse the remaining data as well, and arrange the images in the correct order.”

In addition to this method for distilling the information from the images off-line and in retrospect, Bruining already dreams of the next model that will no longer require the multitasking processor, but instead can be implemented on a single microchip. The new measuring equipment will present the images in real time, with instantaneous and fully automatic contour detection. "It will enable us to examine patients and apply treatment at the same time. You will actually be able to oversee the positioning of a stent. Modern stents are more than just a piece of wire gauze. They include a coating of medication that prevents the forming of connective tissue. Since stents are not made to measure, you sometimes need two in a row. It is pretty difficult to position them exactly next to each other. They will often overlap a little, or leave a small gap. The overlap will cause overdosing of the underlying tissue, causing it to mortify (necrosis), while a gap may become the start of a new blockage."

Computer tomography

However, instant treatment methods are still a long way in the future. Bruining is continuing his collaboration with TU Delft through the group of Professor Dr. Ir. Michiel Verhaegen of the Delft Centre for Systems & Control at the Faculty of Mechanical Engineering & Marine Technology. The group will also look at non-invasive methods for inspecting blood vessels by means of computer tomography, which uses a rotating X-ray source to produce sectional views (called CT scans) of the body. One of Verhaegen's doctorate students will be investigating the possibility of validating the images using images obtained through angiography.

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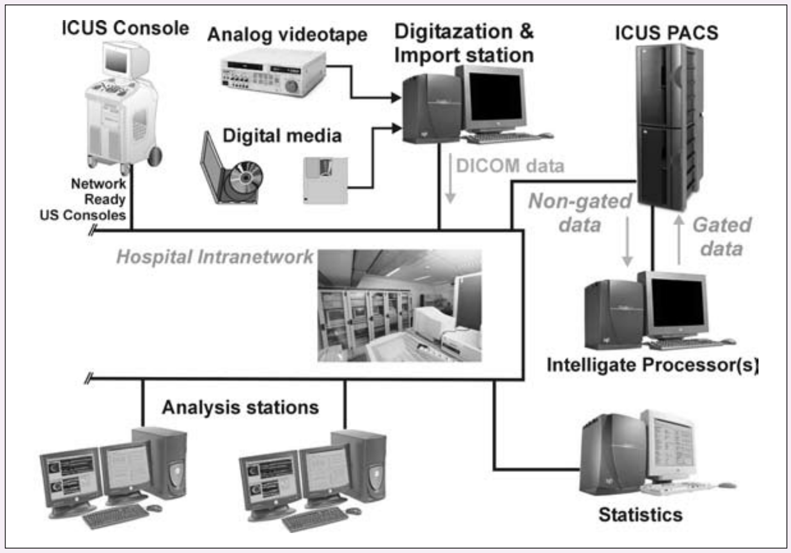
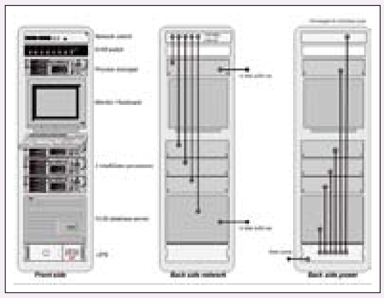
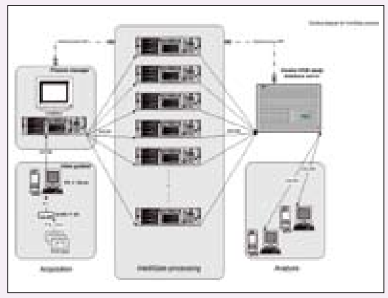


General diagram of the IVUS image processing structure used at the Erasmus Medical Centre. The IVUS images are stored in a picture archive system (PACS) using the standard DICOM medical information format. A special multitasking environment has been devised to run the Intelligate® algorithm. Once the images have been processed, they are returned for storage to the PACS, where they will be available for further analysis through the hospital network. All measuring results are stored in a database from which they can be retrieved by means of SQL for statistical analysis.

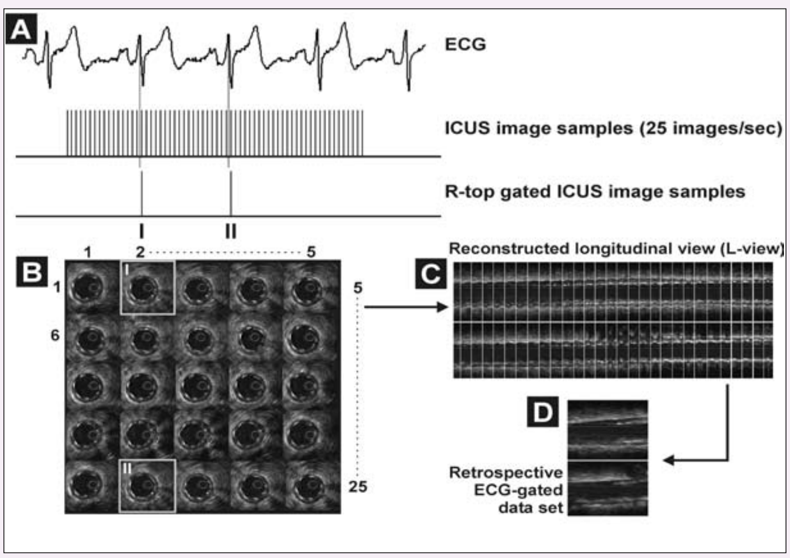
View of an analysis station for the longitudinal IVUS images in which the contours are being traced semi-automatically by an analyst. A single IVUS image cross section is visible in the top left corner of the computer display. The two horizontal panels represent the reconstructed longitudinal images produced by the retraction procedure (the banana split along its length).



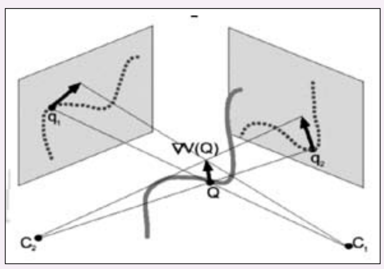
This figure shows the multitasking Intelligate rack system, which uses three processors for parallel processing of the image sets obtained through the retraction procedures. The average duration of a process is between 20 and 40 minutes, depending on the length of the coronary artery being examined.



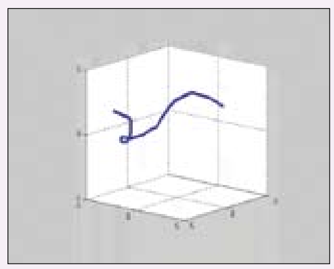
Once the IVUS images have been converted to the DICOM standard format, they are sent to a process manager who distributes them among the available processors. In theory the system can accommodate any number of processors. After processing, the processors send the data to the quantitative measuring archive, where they will be made available to physicians.



This figure shows the available images in the full image set of the retraction procedure that have to be identified and selected (B). The end-diastolic images (of the filled ventricle) are the images corresponding to a peak in the ECG, known as the R top (A). Panel C shows the end-diastolic images as lines in the set before processing by the Intelligate. Panel D finally shows the extracted set used for the subsequent quantitative analysis.



A 3-D vascular motion reconstructed from 2-D projections.



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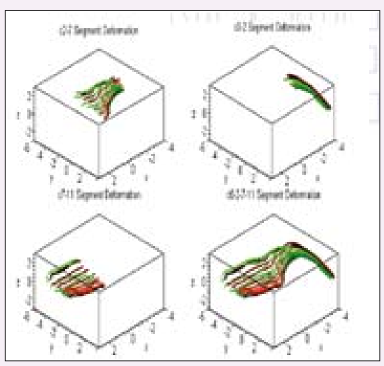
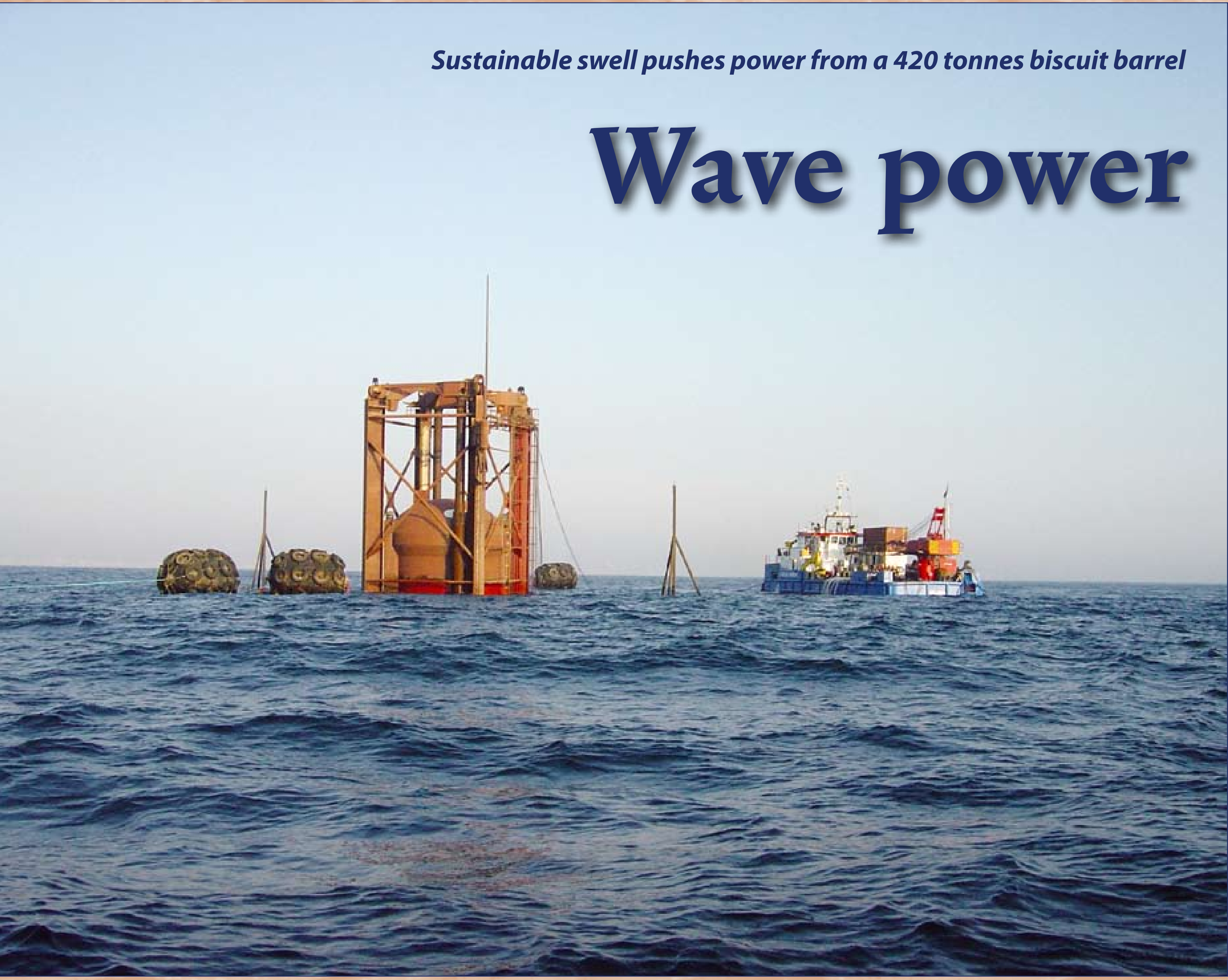


Views in 3-D of bundled momentary reconstructions of a coronary artery in motion.

Sustainable swell pushes power from a 420 tonnes biscuit barrel

Wave power



The Archimedes Wave Swing, a wave energy converter, being submerged in the Atlantic ocean off the northern Portuguese shore on 19 May 2004.

All over the world hundreds of thousands of initiatives are being developed to generate sustainable energy. The great majority of these are aimed at solar and wind energy, if only because they are available all over the world. What's more, the initial investments required are relatively low and are often helped by government support, so even private developments boast a surprising range of solar panels. Another source of sustainable energy is the motion of the sea. Technology to tap this source has also been developed in the Netherlands. In October 2004 the Archimedes Wave Swing generated its first electric power after more than a decade of research and development: power generated by a 420 tonne underwater biscuit barrel resonating up and down to the frequency of the ocean's swell off the Portuguese shore.

By Bennie Mols

The team led by inventor Fred Gardner has succeeded against all odds, with scepticism as well as technical and financial setbacks threatening to scupper the project more than once. TU Delft researchers have provided a major contribution to the linear generator providing the electric power and to the modelling of the wave patterns and the energy they contain.

Counteracting global warming and the threat of fossil fuel depletion are the main incentives behind research into sustainable energy sources. Wind and solar energy may be the best known alternatives, but the largest and most regular source of sustainable energy on earth lies beneath the waves of the oceans.

The gravitational pull of the moon induces tidal motions in our seas and oceans, and the wind creates waves on their surface, moving enormous masses of water across the surface of the earth.

Swell is one type of wave motion that covers vast distances across the oceans. Originating in heavy storm regions, its waves can reach initial speeds of up to one hundred kilometres per hour. As the waves move along, their amplitude decreases, while the interval between them increases. A typical swell wave as it approaches the shore will have a height of between two to four metres, and a length of over a hundred metres. Its slope will be so slight as to make the wave practically impossible to recognise for what it is. These are exactly the type of waves the Archimedes Wave Swing (AWS) uses to generate electricity. The AWS was installed on the sea bed for the first time in May 2004, and in October it produced its first electricity. At last, success after more than a decade of pioneering work.

Resonant air spring

The inventor of the wave swing is Fred Gardner, entrepreneur in sustainable energy. In 1993, together with his partner Hans van Breugel, he started a company, Teamwork Technology, to bring his idea to fruition. Halfway through the nineteen nineties he was granted a patent for his invention.

"My own knowledge is limited, but limited knowledge gives you ideas," Gardner explains rather cryptically. "To come up with really new innovations, you have to be clever, but not too clever," he elucidates. "You need some know-how, but not too much. According to a Rotterdam researcher, Hans van de Braak, too much learning is a dangerous thing, convincing you that things are impossible."

Although Gardner remained convinced that his AWS design was capable of generating electric power, not everyone agreed.

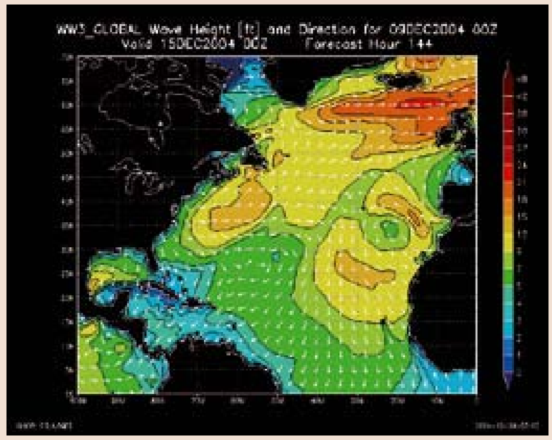
"The biggest obstacle during the realisation of the AWS remained other people's lack of faith. It made it very difficult to gather knowledge. You need to build up creditability first before those in the know at universities will condescend to talk to you. We only managed to bridge that gap halfway through the nineteen nineties, when we tested our first 1:20 scale working model at the Hydraulics Laboratory."

Biscuit barrels

The AWS principle is as simple as it is elegant. The central component consists of a pair of enormous biscuit barrels, one of which stands on the bottom of the ocean, while the other, also known as the floater, slightly wider than the first and inverted over it, is free to move up and down. The inside of the AWS is filled with air, which takes on the important role of the air spring in the system. As a wave moves across the device, the water mass pressing down on the top cylinder increases, pushing it downwards over its stationary counterpart. As the cylinder moves down, the air pressure inside the AWS increases. At some point the pressure will have risen so much that it counteracts the downward force, moving the outer cylinder back up again, and decreasing the air pressure inside. By tuning the quantity of trapped air to the mass of the floater, the system can be trimmed exactly to obtain an air spring that resonates with a certain wave frequency, just like a classic resonating mass/spring system.

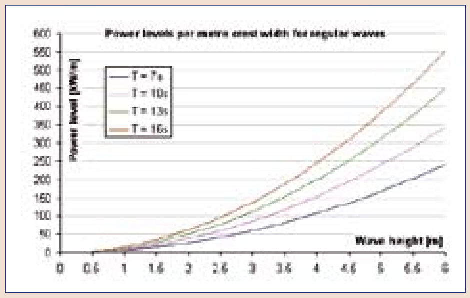
"You could also compare the resonant air spring system with a wireless aerial," Gardner explains. "From the entire spectrum of electromagnetic waves striking the aerial, a radio picks exactly the one frequency that coincides with its own modulation frequency. In the same way, the AWS is tuned exactly to the frequency of the swell."

The wind also creates waves, and swell waves arrive from different directions, but the wave swing is not directional. The waves simply add up. In most cases



(Fleet Numerical Meteorology and Oceanography Center https://www.fnmoc.navy.mil/PUBLIC/)

Oceans contain huge amounts of energy, partly due to the gravitational pull of the moon which causes tidal motions, and partly due to the wind transferring part of its energy to the surface of the water. The waves can be measured using satellite radar images. By linking the wind predictions to these observations, the wave patterns can be forecast up to eight days in advance. The wave height is measured in feet. The data is made available by the United States Navy through the Internet. The information is also used by the AWS team. (image: Fleet Numerical Meteorology and Oceanography Center https://www.fnmoc.navy.mil/PUBLIC/)



This figure shows the available power per linear metre as a function of the height of a periodical wave and its period.

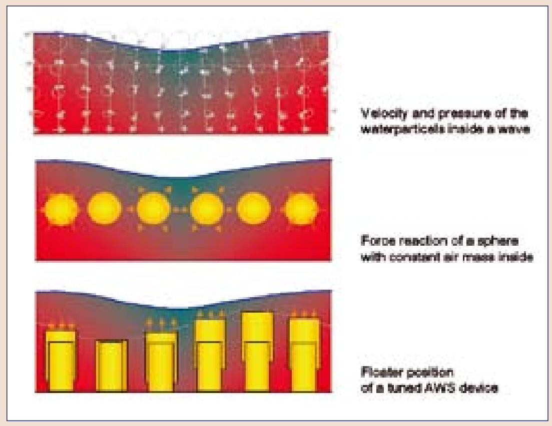
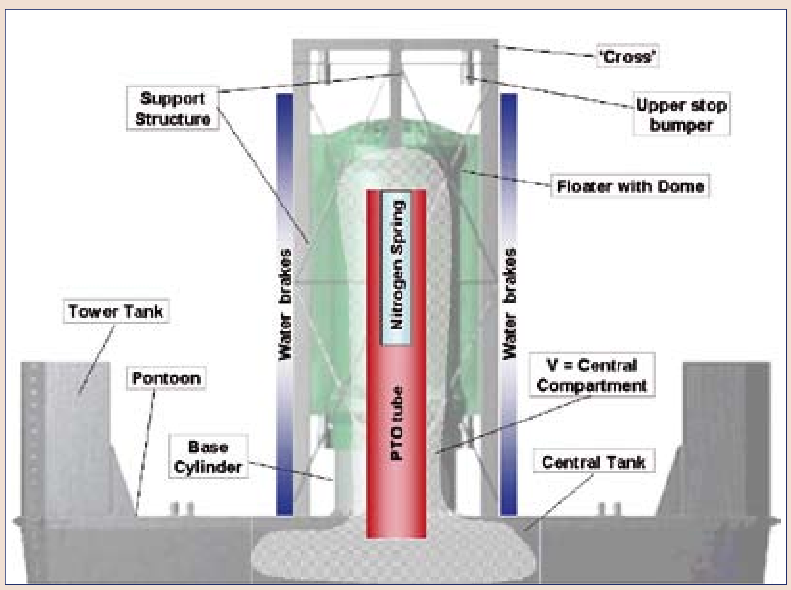
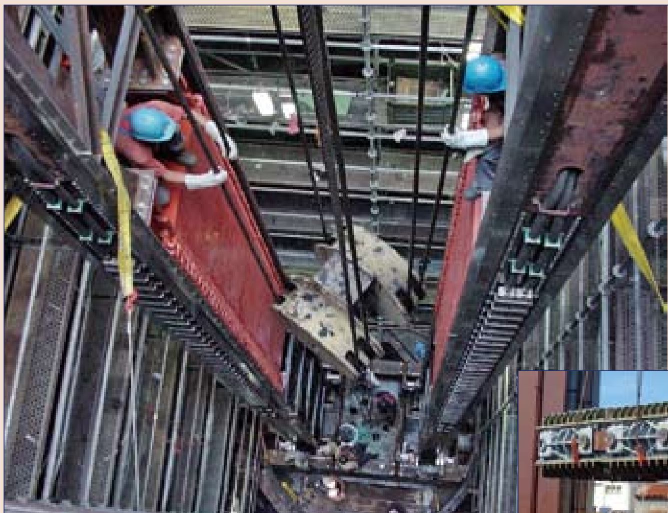


Diagram showing the principle of the AWS converter. The internal pressure within the void acts as the driving force that makes the generator's floater move up and down. The floater is pushed down below the wave tops, and as a trough passes, it moves back up again. The air pumped into the system acts like a spring. Provided the mass and the spring are in tune, the system will experience an amplified motion. The result is that the length of the floater stroke can be as much as seven times the wave height.

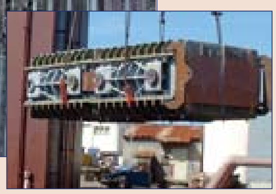


Section through the Archimedes Wave Swing. The PTO tube in the centre contains the 25-metre high generator. Only the central tank contains air. The sole purpose of the rest of the pontoon, to the left and right of the white lines, is to provide a supporting structure for the prototype wave converter.

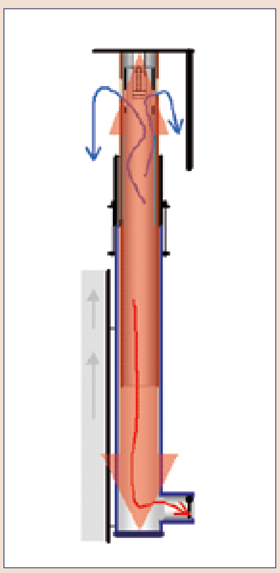
The shell of the AWS was built in Galatz (Roumania) at a shipyard of the Dutch company, Damen Shipyards Group.



The generator was designed at TU Delft and installed by Hollandia-Kloos in the port of the Portuguese town of Viana do Castelo. The 25-metre high support columns of the generator hold a pair of 5.5-metre high stators.



Each of the translators (rotor equivalents) that slide over the stators are made up of two of these blocks. They consist of a cast frame into which the permanent magnets are fitted.



The generator floater can be slowed down by four water brakes, each of which consists of two pipes sliding one inside the other, with one of the pipes moving up and down with the floater. The braking power can be adjusted by means of a hydraulically controlled valve through which the water is expelled.

the waves come in groups lasting one or two minutes, and containing waves that come from different directions with different frequencies. A typical swell has a period of about ten seconds.

Gardner: “With waves one metre high, the amplitude of the floater motion can be as much as seven metres. Just imagine, the floater weighs 420 tons. In other words 420 tons can be moved up and down seven metres by a wave only one metre high, because it contains so much energy.”

The first attempt to install the AWS on the sea bed was in 2002. As the sea water entered through the open valves, the flow was controlled by the back pressure inside the ballast space. However, the first attempt failed due to a calculation error that underestimated the compressibility of the air. As a result the AWS ended up lopsided. The researchers decided to redesign the submerging process and use shipboard cranes. This strategy proved to be highly sensitive to the wave forces that are normal for the Portuguese coast. Rigid connections between the ships would simply snap. So, it was back to the original submerging method again, but this time the flow in the ballast tanks would be regulated by means of frequency-controlled pumps. Using this method, the very first AWS was successfully submerged on May 2004 at a location 5.4 kilometres off the northern shore of Portugal, where the swell arrives with the right height and frequency.

“The floater can move nine metres up and down, but in the interests of safety we intend to use only seven metres,” Gardner says, “After all, it is a resonant system, and if we do not damp it sufficiently, the effect could be amplified and become destructive. So we have included all sorts of subsystems to handle the damping. They almost took more time to design than the actual power generating part did.”

The floater measures ten metres in diameter. The inner barrel is fixed to a pontoon resting on the ocean bed. The full height of the structure is 37.5 metres.

The sole function of the pontoon is to lower the AWS to the sea bed and recover it when needed. The top of the floater lies four metres below the surface at low tide, and almost eight metres at high tide.

Near the centre of the floater two suspended carriages support an array of permanent magnets made of neodymium-iron-boron (NdFeB). As the floater moves up and down, these magnets move along a set of coils carried by a pair of flat structures fixed to the pontoon. The moving magnetic field induces an electric potential in the coils, generating power. The distance between the floater carrying the magnets and the stator carrying the coils needs to be exactly right, down to the last millimetre. The generator is fully contained by the dry, air-filled section of the AWS.

Linear generator The linear generator was designed by Dr. Ir. Henk Polinder, who lectures at the Electrical Power Processing section of TU Delft. His design formed a major contribution to the power-generating capability of the AWS system.

During the early stages of designing the AWS the development team still favoured the idea of converting the linear motion of the floater into a rotating action, but in the end this proved to be unfeasible. Bauke Vriesema of the Energy Research Centre (ECN), who had also become involved in the AWS project, then wondered whether it would not be better after all to build a linear generator. He approached Henk Polinder and asked him to find out whether it was possible, and if so, how.

“I immediately said, yes, of course it can be done,” Polinder says, “but it will be a large and therefore costly linear generator. On top of that, Fred Gardner and his team wanted a short development time and a high level of reliability. So we went looking for a type of generator that has proved its worth. A linear generator the size of the one in the AWS had never been made before. It had to be built to order, making it much more expensive than a standard generator in combination with a gearbox. In the latter case, more or less standard components can be used, but the disadvantage of a gearbox solution is that it requires more maintenance.

An even greater problem is the irregularity of the waves. Every now and then the floater will rise and fall so far that it will run into its end stops, a set of rubber blocks whose purpose is to rapidly slow down the motion of the floater. If this happens, slowing down the generator, in which lots of rotational energy is stored, will lead to massive stresses in the gearbox. Designing a gearbox that would not break proved so difficult that we opted for a linear generator instead.”

Gearboxes “The same choice between two different systems has to be made in wind turbines,” Polinder says. “You have wind turbines with gearboxes, and the direct-drive systems without them. The ones with gearboxes are cheaper to buy, but they require more maintenance. A gearbox inside the AWS would need lubrication, and topping up the oil would not be easy with the system standing on the sea bed.

We had to weigh the pros and cons of both systems. It is not a case of one system simply being better than the other.”

For cost reasons, it was decided to construct the first-generation AWS with straight generator plates.

“Even so, with a smart design, a circular linear generator might be better in the future,” Polinder surmises. After all, the cylindrical symmetry of the AWS tends to point in the direction of a cylindrical linear generator.

Quite a few commercial parties were involved in the construction of the linear generator. The mechanical design of Polinder’s generator came from Wolters Engineering. The stator part carrying the coils was built by Alstom in Nancy, France, and the part carrying the magnets was supplied by Bakker Magnetics of Eindhoven. The construction of the pontoon and the final assembly of the AWS were carried out at a shipyard in Roumania, through a Dutch company, Damen Shipyards. Once the pontoon had been towed to Portugal, the generator was installed by Hollandia-Kloos, who also supplied the water brakes and the bearings. The final assembly of the wave swing took six months.

Water brakes If the waves are high and strong, the forces acting on the AWS may be as much as five meganewton. The generator of the AWS installed in May 2004 would not be able to withstand the accompanying stresses, and building a generator of five times the size, which would be able to cope, would not be a feasible option. This is why the system has been fitted with water brakes, which act as a safety device.

If the waves threaten to become too high, the brakes are activated, but as long as the waves are normal, the brakes can remain switched off. The current generator inside the AWS can handle about one meganewton of wave force acting on it. If the force exceeds that value, the brakes are there to handle it.

A major question facing Polinder was how the size of the linear generator had to be determined.

The operation to submerge the AWS started in 16 May 2004 and took three days.

18 May 2004, 10.15 a.m.

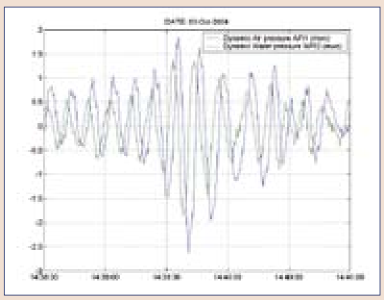
18 May 2004, 3.30 p.m.

12. 45 p.m. Ir. Michel Damen and Jan-Willem Vroege fix a last-minute connection with a level sensor that will measure the level of the water in the central compartment.

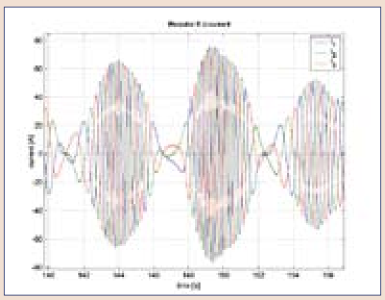
19 May 2004, 5.00 p.m. A diver having opened a valve, water flows into the AWS interior, forcing out the air to add weight to the pontoon in order to obtain the correct air spring characteristics.

The AWS team shore station is located immediately behind the dunes. This is also where the cable supplying the electricity to the national grid comes ashore.

Since the electric shore controls for the valves and pumps did not work, divers established a link that would enable them to be operated from on board the ship.

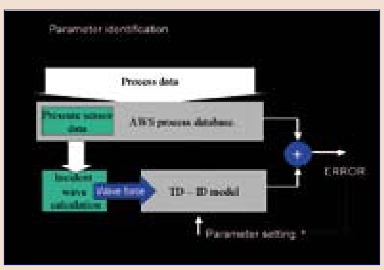


The driving force can be calculated by measuring the pressure above and inside the floater. The internal air pressure is determined by the position of the floater. As the floater moves down, the air is compressed and the pressure increases. The diagram shows that the floater remains constantly in phase with the driving wave.



During each stroke of the floater, its velocity goes from zero to maximum, and back to zero. This is reflected by the electrical current readings, in which the amplitude and frequency of the signal also change from zero to maximum and back.

The 3000 volts coming from the thyristors is fed to a transformer to step up the voltage to 15 kV.



The information written to hard disc during power generation is compared with the value calculated by the time domain model. The time domain model receives the actual measured wave pressure as input. The theoretical hypotheses can be optimised by adjusting the model parameters.

"Basically, the AWS can supply more energy with a bigger linear generator, but it would also drive up the cost," says the electrical engineer. "I had to weigh both the cost and the energy yield in the optimisation balance. The current generator surface is about twenty square metres."

Oscillating current The linear generator inside the AWS converts the motion energy of the floater into electric energy. The generated current then flows through six kilometres of cable along the sea bed to the shore, where a converter takes the oscillating current generated by the AWS and turns it into a rather more presentable kind of power of constant voltage and frequency, which is then fed into the national grid system.

The great day was on 2 October 2004, when the AWS supplied electricity for the first time.

"The longest floater stroke was 3.6 metres, producing a power of one megawatt," says the inventor of the wave swing. "It supplied power for a couple of days. I was really glad we managed to demonstrate the validity of the principle. Actually, I never for a moment doubted that it would work. And the behaviour of the air spring was exactly as we had predicted."

Of course, the power output depends on the waves that come past. The peak power output of the current AWS design is about 2 MW. In really high waves it could manage as much as 20 MW.

The AWS has already been removed from the sea bed. The principle has been validated, the device has generated power, the readings had been obtained, and so there was no longer any reason to leave the device standing in the sea any longer.

"The AWS pilot plant has become the property of a Portuguese power company, Enersis," Gardner explains. "They took out a licence from us and obtained permission to install the AWS off the Portuguese shore. Enersis have a long-term outlook. They are Portugal's largest wind energy construction developer and they own quite a few mini hydropower plants. Enersis were convinced that we had proved our point and they did not want to run the risk of damage from autumn or winter gales, even though the design should be able to cope. What they really want is for us to come up with the next generation AWS as soon as possible."

Future power-generating AWS plants will certainly be expected to remain submerged for extended periods of say, fifteen years.

Hydrodynamics Besides the major contribution by Henk Polinder, the AWS contains even more work from Delft. An electrical engineering student did calculations on a sensorless position measuring system for the linear generator, and two graduate students, supervised by Professor of Fluid mechanics Jurjen Battjes and Professor of Marine Hydrodynamics Jo Pinkster did calculations on the system's hydrodynamics.

"The students developed software that builds on the software we use for calculations on ships," says Prof. Pinkster. "They investigated the vertical wave forces that act on the system as well as the way the system responds. The AWS itself also creates waves, and the total wave energy after passing the AWS is less than it was before. It can be considered as a coupled system, in which waves are needed to excite the AWS, while the AWS itself also generates waves. From the hydrodynamic data and the mechanical properties of the AWS follow the natural frequency and the bandwidth of the system, as well as the amount of energy the system can extract from the waves. The TU Delft students took the results of previous model experiments at the Hydraulics Laboratory and extrapolated them to find the energy production for various locations elsewhere in the world. The AWS itself had already been built at the time."

Wave swing farm Following the success of the pilot plant, a new Scottish company, AWS Ocean Energy has been established to commercialise the technology.
Gardner and his company, Teamwork Technology, have now started work on the design of the next generation of AWS.
"We already have a basic design for the next system. It is going to be slightly bigger, will have a bigger stroke, and will no longer be on a pontoon. I have learnt a lot about do's and don'ts regarding the control system. The new device will have a much simpler control system with very few peripheral systems."
As part of the EU's Marie Curie program, Portuguese doctorate student Miguel Goden de Sousa Prado is currently working for Teamwork. Henk Polinder also wants to find a trainee researcher for further research on the AWS II.
AWS Ocean Energy expect to install the 'Mark II' device in 2006. Much interest has been generated abroad, but according to Gardner it is very difficult to raise government funding in the Netherlands.
"We can only get a Dutch government grant if we can also generate the power in the Netherlands, but our shores simply do not provide the required wave energy. In the Netherlands you would get about eight kilowatts per metre as an annual average. In Scotland it would be forty to fifty kilowatts per metre, and in Portugal the figure is about forty kilowatts per metre. Dutch waves just don't make the grade. In spite of that, Dutch investors have shown an interest."
To contribute significantly to the sustainable supply of power, an underwater farm of some fifty to one hundred AWS devices will be needed. The typical distance between two devices would have to be about one hundred metres, so one hundred devices would cover a stretch of ten kilometres.
"You would not notice them at all," Gardner says, "as they would all be under water."
One hundred devices could generate about two hundred megawatts. The electric power generated by a single AWS varies from zero to maximum and back to zero every five seconds or so. This is not very kind to the electricity network, as it can result in voltage variations that would show as fluctuations in lighting intensity. A whole series of AWS devices, with their power peaks shifted in time, would ensure a constant supply of electricity.
The European countries with the right offshore waves for the AWS are Portugal, France, Ireland, Great Britain, and Norway. The only way to widen the application area would be to install the devices further out, where the waves are always higher.
"The main advantage of wave energy," Gardner says, "is that they provide a very constant and predictable source of power, unlike wind power. Large waves can be predicted very accurately up to eight days in advance."
According to Gardner the price of wave power lies somewhere between those of wind power and solar power, i.e. more expensive than the former, but less expensive than the latter.
"The price of wave power will be about twelve or thirteen eurocent per kilowatt hour, a price we are already getting in Portugal."
"As far as quality goes, I think our system is the best of all the sustainable sources of energy," Gardner says. "The power generated by the AWS is more stable and has the least impact on the environment. In fact, any damage to the environment doesn't really occur until the moment we lift the device from the ocean. In next to no time at all the submerged AWS becomes a wonderful miniature ecosystem providing shelter to all sorts of plants and fish. Remove an AWS and you lose all that."

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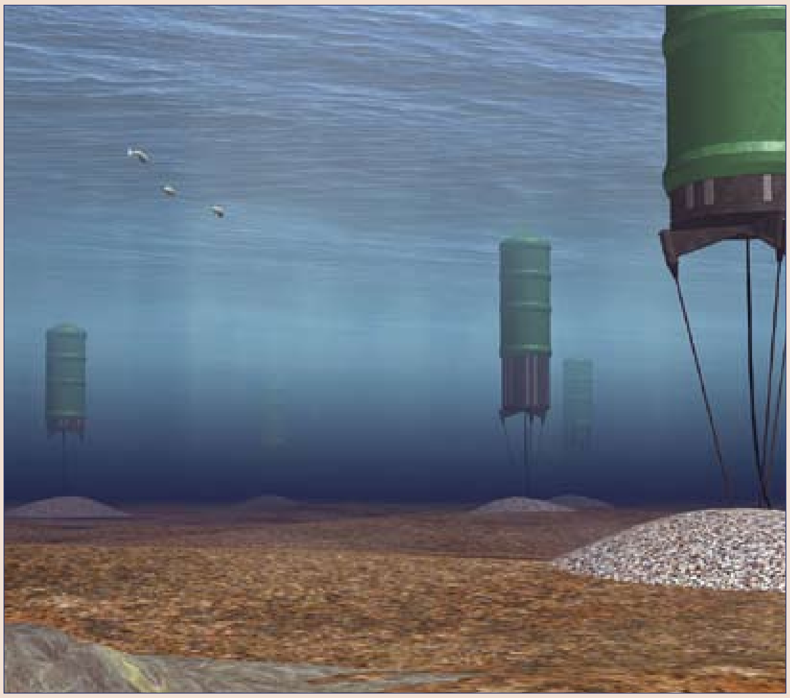


The prototype still rests on a pontoon, but future generations will float below the surface of the sea, anchored to the sea bed. Such structures will be much simpler to build and consequently much more cost-efficient.

Wave energy worldwide

Worldwide, four major types of wave energy generators are in development and partly in use. In addition to the AWS they are the Oscillating Water Column, the Wave Dragon, and the Pelamis.
The Oscillating Water Column generates electricity in two steps. When a wave rolls into the column, the air inside the column is pushed upwards through a turbine, and the pressure inside column increases. As the wave recedes, the air flows back down, again passing through the turbine. A system like that needs to be built into the shoreline and can only work efficiently if the entire shore structure is suitable.
"If lots of engineering work were to be done on the shoreline to make it fit, the system would become prohibitively expensive," Gardner explains. "The problem is that the shorelines that are naturally suitable tend to be attractive areas of natural beauty which you wouldn't want to spoil by starting a major construction project. In Oporto, Portugal, an Oscillating Water Column is being constructed on a breakwater that was going to be built anyway which is one way round the problem."
The Wave Dragon resembles a beach which the water runs over dropping over an edge into a basin. As the water falls two to three metres, it drives turbines that generate electricity.
"The great advantage of the concept," Gardner explains, "is that any one can understand it. If you have ever been to a beach you can see that the waves that come rolling in contain energy, which you can put to good use. The system can extract power even from low waves. I just wonder whether it offers a sufficiently high yield and whether it is robust enough. The Wave Dragon could be just the thing for the Netherlands, since it can extract power from low waves."
The Pelamis (sea snake) is a Scottish design and floats on the water like a giant snake consisting of a long (about one hundred metres) chain of linked floats that ride the waves. As the links move up and down, the motion of the waves is converted into electricity, generating up to 750 kilowatt for each Pelamis.
Gardner: "The Pelamis and our system are leading the wave energy field. The power to cost ratio of the two systems is roughly the same. Even so, I think our system offers some additional advantages. The problem with the Pelamis is that is has to be submerged whenever a storm threatens, since it cannot ride high waves safely. The AWS sits on the sea bed right from the start. Also, a long snake takes up lots of space and forms a shipping hazard over a large area. I think the AWS is much more robust and more capable of managing high waves."

A different outlook on housing, but innovation has not yet convinced the authorities, insurers, and backers.

Living on water:

A floating town on an unsinkable foundation – complete with gardens, streets, and squares.

Photographs by Ties Rijcken

If we don't come up with something soon, the Dutch will be forced to leave the Netherlands in 100 years' time, according to hydrologist Prof. Dr. Ir. Cees van den Akker of Delft University of Technology. The climate is changing, and more rain is going to fall, in particular during winter months. The level of the sea is rising, the land is subsiding, and in the meantime the rivers flowing through our country will be called upon to carry increasing volumes of water to the sea. To keep the water at bay , the Netherlands needs to put aside an area the size of the province of Utrecht (200.00 hectares) to act as a water storage zone, according to the experts. Scientists are increasingly turning towards multiple use of space as a solution. Industrial designer engineer Ties Rijcken has developed a modular system for a floating foundation using expanded polystyrene foam, reinforced with a frame of high-strength concrete. In addition to the technical aspects, Rijcken also investigated the planning problems involved with living on water. The problem is that a house floating on water no longer counts as real estate, which complicates matters when it comes to planning permission, mortgages, and insurance.

Houses floating in a bay near San Sausolito, north of San Francisco, California. Whereas in the United States people are relatively free to build what they like, houseboat anchorages in the Netherlands are few and come with all sorts of restrictions. At the same time, there is much confusion over the rules as a result of which local authorities still tend to steer away from living on water.

By Marion de Boo

Water storage and housing can go together perfectly well. Ir. Ties Rijcken has developed a concept for a floating foundation based on polystyrene foam and concrete that moves up and down with the water level.
"This unsinkable foundation can carry a whole town, complete with gardens, streets, and squares," says Rijcken, "You can even plant trees and drive there in your car across a flexible shore connection. It enables us to make full use of the available space. Anyway, who wouldn't want to live right on the water?"
He shows a series of inviting sketches depicting a network of peninsulas carrying floating houses in the middle of a lake. The houses each have their own jetties and a perfect view of the waves all around them.
"If the island is large enough, you wouldn't even be aware that was floating," Rijcken says, "And it's best to make the banks as long as possible. People like that."
During the wet seasons, and in particular during the autumn and winter when rain can come pouring down for weeks on end, the water authorities will run the pumps at full power to keep the surrounding polders dry. The excess water will be stored in the lake for the time being. The water level in the lake will rise, and the floating town will simply rise with it. In dryer times, the water from the lake will be released back into the polders to prevent drought. As the water drops, the floating houses go down with it. The plan was aptly named 'H_2Ope' of Holland.

'It's not a question of keeping the water out OR *getting on top of it. It's about keeping it out* AND *getting on top of it."*

The time is ripe According to the committee set up to look at water management for the 21st century, the Netherlands should be putting aside at least 200,000 hectares over the next 50 years for buffering water if they are to survive the climate changes ahead. In the meantime, land for agriculture will become scarcer and more expensive. Hence the idea to combine water storage and residential areas. In his graduation design, Ties Rijcken (whose got full marks with distinction) builds on the growing interest in floating houses. Both the government Department of Water Management and the Habiforum Foundation recently announced a design competition on the subject, and cities like Amsterdam, Rotterdam as well as the northern cities of Groningen, and Leeuwarden are ambitious on this front.
"But when push comes to shove, enthusiasm dwindles," Rijcken says. "We've seen so many designs being made, so many expensive conferences being organised, so many competitions being run. The time has now come for the next step. A number of parties will have to demonstrate their willingness to invest, or the project will never get off the ground. Water storage facilities simply have to be included in all urban development plans. According to what is known as the water test, designers of new residential areas will soon be forced to reserve a substantial percentage of space for water. In addition, floating houses could be built in deep gravel pits. It would be a perfect place for weekend houses."

Patent In the meantime, Ties Rijcken has taken up a PhD position on innovative housing constructions at the faculty of Architecture and he works as an innovation consultant for ABC Ark Builders. This company, based on the former Zuyderzee island of Urk, has become a big name in houseboat building. They have committed themselves to innovative design and have applied for a patent. A special production facility has been built, with construction taking place in dry dock and finishing work being done in a floating assembly line, so ABC can supply the floating building blocks from a mass production process as soon as a property developer or any other interested party calls.

(Photograph Ties Rijcken)

If the Dutch had no dykes, almost half of the Netherlands would be under water. These greenhouses close to the dyke are built on a level that is visibly lower than the water in the drainage canal. In view of the lack of space in the Randstad agglomeration in the west of the Netherlands, a practical use has to be found for every available square metre. A number of parties are advocating multiple use of space, for example by combining water management with floating greenhouses or houses.

(Photo ABC Ark Builders BV, Urk)

The floating office of ocean yachtsman Roy Heiner was built on several concrete hulls linked together. The timber platform frame structure on it was built in Urk harbour, after which the complete building was towed across the IJsselmeer to its destination in Lelystad. According to Rijcken this complex is currently one of the larger floating objects on Dutch inland waters in terms of surface area, though it is still relatively small compared with the floating towns he considers feasible with his modules.

Where more water needs to be stored, houses can also be built on piles raised above the water level. One disadvantage of this concept is that in due course mud can easily accumulate between the piles, reducing the water buffering capacity.

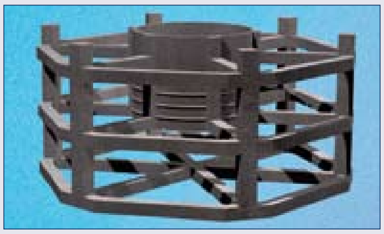
Water is a hot item, as shown by this billboard. The government, scientists, and water management authorities all emphasise the importance of water storage capacity. The current trend in housing is to live on the water's edge, which has become a recurrent theme for architects and property developers.

This is living in the water instead of on it. It does nothing to meet the government's wish to create additional water buffering capacity. Although technically speaking these houses could be made to float, the traditional brick construction makes them very heavy, so they would go down very deep in the water. This is why floating houses are usually constructed using the timber platform frame method.

The Floating Module has a modular construction. Using only five different types of discs made of EPS, a large variety of different modules can be constructed. The carrying capacity can be increased by adding more discs, the number of cross-connections can be varied (for increased strength), and the centre area can be left empty. The top disc contains cutouts for pipes.

The polyfoam structure is assembled, and self-compacting B200 concrete is then poured into the mould. The concrete is reinforced with steel fibres and liquid enough to fill even the smallest nooks and crannies.

This is what the concrete skeleton would look like without the polyfoam.



The carrying capacity can be increased by adding more foam at the bottom of the structure.

"The strengths of this product include easy handling, high durability, and low price for its carrying capacity," Rijcken says.
The Urk factory can supply the modules ready for use, complete with ducts for sewage, rainwater, etc. Rijcken's idea is to build elements that are about three metres wide.
"You have to be able to transport them by road, or float them through locks to get them to their destination. Once they get there, they can be linked together to create any shape you want, from a floating car park to a complete town."
An alternative approach might be to pour the material in situ. It would mean that fewer (expensive) corner links would have to be included, and it would make the final assembly more rigid.

Not too heavy, please Rijcken based his design on the requirement that the foundation had to be capable of supporting houses, streets, and plants. It would be ideal if the architect of a floating house would not have to worry about anything, apart from the fact that the house cannot become too heavy. This is why timber frame constructions are preferable to brick buildings, but apart from that the architect can do anything he likes on the floating foundation.
"A practical bottleneck is that most Dutch lakes are quite shallow, and if you're not careful, you might soon hit bottom with your floating house," says Rijcken. "It your structure weighs one ton per square metre, according to Archimedes' Principle its draught will be one metre. The heavier the house, the deeper it rests in the water."
Near the Amsterdam suburb of IJburg on the IJsselmeer (the new name of what was formerly known as the Zuyderzee) the water is no more than 1.5 metres deep. Suppose the water on one side of the floating platform failed to flow properly and the lake on that side started to silt up. If the water level were subsequently to drop, the platform would start to crack. So, the water management authorities will have to guarantee a certain depth of water.

Prefab elements The designer himself would prefer to construct the foundation elements in a hexagonal honeycomb shape, which lends itself well to creative solutions for harmonious designs which are also fun.
"A rectangular building block would work equally well, of course," Rijcken says. The foundation element consists of a foam core, around which a concrete space-frame is poured. Once the concrete has set, the external steel shuttering

Traditional concrete hulls are poured in the three dry-docks at ABC Ark Builders at Urk. The hulls, which weigh 20 to 80 tonnes, can only be moved by water. Rijcken designed the Floating Module to enhance the design freedom for larger floating surfaces.. This concrete and polyfoam structure is much lighter and consequently much easier to handle than the traditional hulls. What's more, the polyfoam is unsinkable, insulates, contains ducts for piping, and doubles as permanent shuttering for the concrete.

can be removed. The choice of materials took a lot of thought. The design uses mould-formed expanded polystyrene (EPS) discs, which are stacked in layers with different cutouts, depending on the application. As the EPS is used in layers, the height and with it the carrying capacity of the elements is variable. In addition various polystyrene elements can be stacked in different combinations to create certain desired mechanical properties. All together, the foam provides the buoyancy and the concrete imparts the necessary rigidity to the platform as a whole.

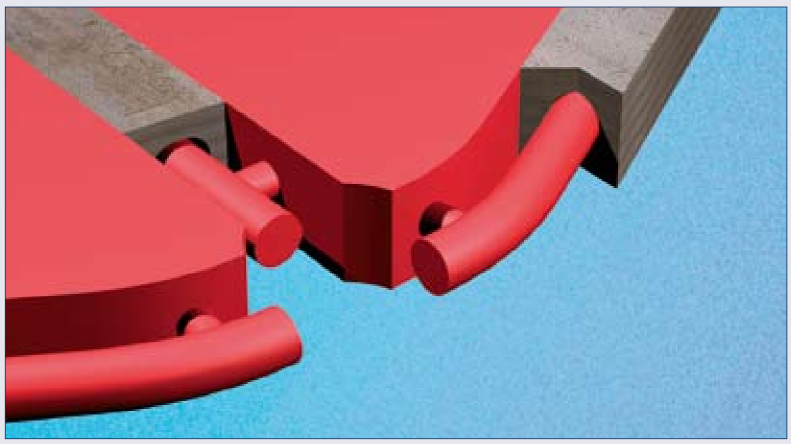
Self-compacting concrete At the advice of Prof. Dr. Ir. Joost Walraven of the faculty of Civil Engineering a new type of ultra high-strength concrete will be used that requires no additional reinforcing.

"It is a self-compacting type of concrete, which readily flows into every nook and cranny, which makes it ideal for making all kinds of complex structures," says Rijcken. "It is a new type of concrete, reinforced with steel fibres, so it needs no additional reinforcing bars, allowing you to create much more complex shapes. For example, it is much easier to round off the corners to make the structure extra strong, and you can even make hollow tubes out of concrete. Thanks to the perfect combination with mould-formed polyfoam, we can create the same carrying capacity with much less concrete, producing lighter, stronger, and cheaper structures."

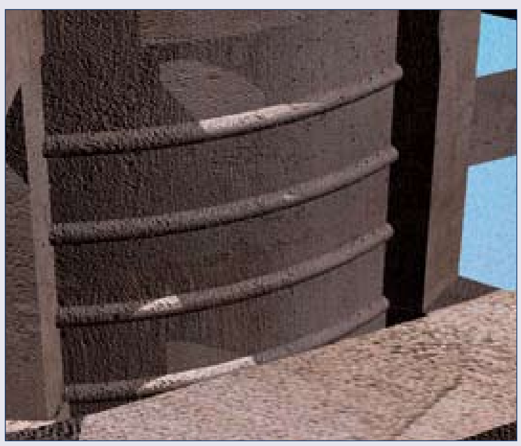
The trick is to obtain the best possible balance between the rigidity and weight of the floating platform. An element with a surface area of almost 8 square metres weighs 1–2 tons, depending on its height. By adding extra layers of EPS, the carrying capacity can be varied from 7 to 20 tons per floating module (approximately 1-2.5 ton per m²). The lightweight structure not only offers benefits in use, but also makes transport and temporary storage at the production plant much easier. If necessary the platform can be reinforced by adding extra cross-connections. And last but not least, the entire platform can also be taken apart again. As long as no one-piece floors are poured across them, all the elements can be uncoupled and moved elsewhere.

As the design is still in its initial stages, some major research questions still remain, which Rijcken would like to submit for further calculations to a team of engineering consultants.

"To begin with, their task would be to make in-depth calculations of the external forces that will act on such a floating platform, what the wind load will be, what kind of asymmetrically distributed loads can be expected, and what

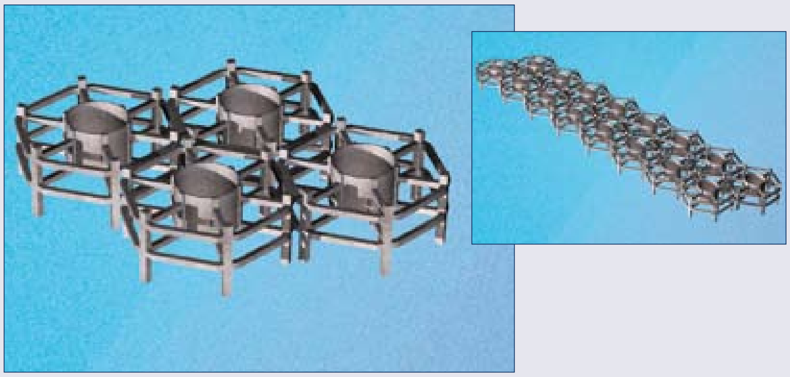


Using the design freedom offered by the mould-formed EPS and the special concrete, Rijcken intends to achieve high strength at the lowest possible weight. In other words, lightweight engineering. It is even possible to reduce the weight further by adding polyfoam cores to the concrete space frame. This would lower the cost even more and make the modules even easier to handle.

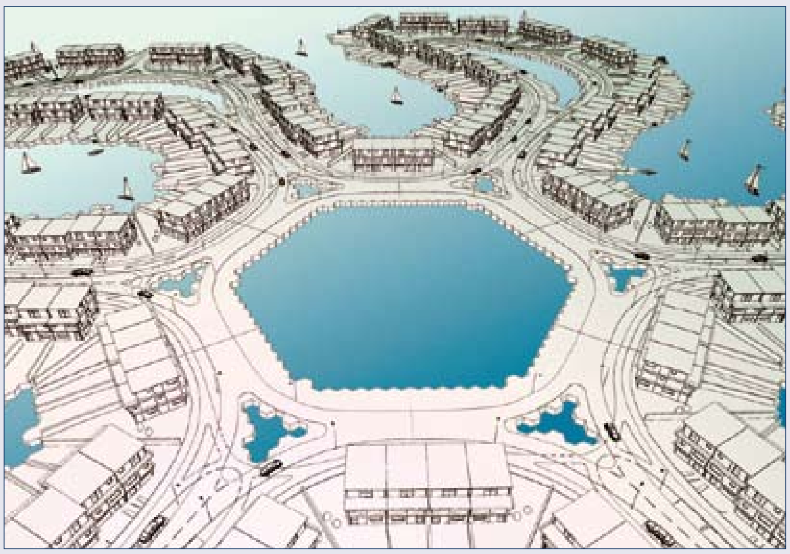


The combination of B200 concrete and EPS enables design principles from plastics technology to be applied in the shape of rounded corners, reinforcing ribs, etc.

The connections between the Floating Modules can be made in two ways. One is a mechanical connection that uses screw sleeves cast into the concrete, steel rings, and bolts. The other option is to concrete the modules together in one go. Whether this is possible for large numbers of modules is still being researched.



Rijcken developed the Floating Module concept to be able to construct a complete floating town. Although according to Rijcken the floating town concept shown here is technically feasible, it still remains out of reach for reasons of planning permission. The next step in the innovation process will be to perform the necessary calculations on the current module design and then to test a prototype. Rijcken then hopes to be able to break the ice with a small pilot project of a floating public area surrounded by a number of traditional houseboats. ▾
(Drawing by Ties Rijcken)



waves will do," the designer explains. "In addition to these external loads you also have to calculate the connection stresses, and find out what the best shape will be for the connecting hardware. Finally, we will have to take a look at our design to see if it is capable of withstanding those forces."

From utopia to practice Besides concentrating on the innovation involved in the floating construction module, Rijcken is also investigating the social context: the problems involved in water management, public housing, and what some people consider the hopelessly 'waterlogged' state of public planning in the Netherlands. According to Rijcken, misconceptions are rife about living in floating houses or building in water buffer zones.
"One often heard comment is that it would be better to build dykes than to have floating houses. This is oversimplifying the matter. The solution is to have a water management system in which the best solution can be found for each separate location. This might mean building higher dykes, but it could also mean buffering water in combination with floating houses. The problems are new and complex, and so we must take them one step at the time. A floating island carrying three houses with gardens around them would be a breakthrough. I'd be the first to apply!" Rijcken says. "The race has not been run yet. The authorities as well as insurance and mortgage companies are still hesitant, since living on water requires a fresh look at complex problems, which take time and energy. For example, a house floating on water does not count as real estate, since it is a movable object. I've been told that the land register people don't know how to deal with a semi-detached houseboat. They simply lack the administrative options."
In addition to these problems, the innovation project also faces a number of uncertainties in the technical, legal, financial, and commercial sense.
Rijcken: "I sometimes feel like a juggler trying to keep several balls in the air at the same time. If you spend too much energy on one aspect of the project, you run the risk of running aground at some other point."
In any case, ABC Ark Builders have demonstrated their willingness to take risks. When the investments in the new production facilities were not followed by large orders for houseboats, the company went bankrupt, only to resurface under a new owner, who has high hopes for living on water.

Covering the risks Rijcken: "Legally speaking, all the risks must be covered, and the arrangements between the various research partners must be mapped out very clearly. At least as important is the question of what the market is like and who your competitors are. Moreover funding has to be found to continue the research, either from ABC Ark Builders company capital, various types of government grants, loans, or business partnerships. Finally, future research results must be protected by patents to prevent competitors making off with them as soon as they are published."
Ties Rijcken is currently working with a team of students from Rotterdam Polytechnic on a design for a floating offshore stadium near Scheveningen. His earlier designs included a floating harbour extension at Urk. Experiments are being carried out in Greece with houses floating in a small pool so they can be rotated at will. And floating houses are safer in earthquake prone areas. Ideas abound.

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