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- THEME: AGROROBOTICS
- COMBINING LAPPING, FLAT POLISHING AND CMP
- WIM VAN DER HOEK'S FOCUS ON MANUFACTURABILITY
- LIS STRATEGY: NEW MODERN NATIONAL VOCATIONAL SCHOOL

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The cover image (featuring the Sparter asparagus harvesting robot) is courtesy of Cerescon. Read the article on page 10 ff.

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THEME: AGROROBOTICS

FEATURES

SWITCHING FROM HIGH-TECH TO AGRI-TECH IS A BUMPY RIDE

In the eighties, ASML started pioneering with its technology in the semiconductor industry. At the same time, I was working with ASM-Fico, which has been called BESI since the nineties; we were pioneering with our technology at the back-end of the semiconductor production process chain with our moulding and trim & form systems. Once you have pushed innovative high-tech products successfully to the market, it is difficult to stop pioneering in this way.

In 2014, after more than 25 years, I decided to leave the semiconductor industry and start pioneering all over again, this time with agricultural technology, or agri-tech. I left ASML and, as a son of a former farmer, I started Farmertronics to develop and build an unmanned, fully electric robot tractor. My father had worked the land with a horse; I planned to build an electronic horse, the eTrac. This gave me the opportunity to return to my roots.

Not knowing that much about the market and the requirements of farmers, I started searching for the right market niche in which to develop this new product. Developing a mobile machine seemed to be quite different from developing a static machine. In particular the battery pack needed to drive the robot forced me to choose applications that did not require that much energy. I ended up at the orchard, where no heavy-duty equipment is needed.

Now, we are developing and building a first prototype of the eTrac for repetitive tasks in the orchard, such as mowing, weeding and spraying. During these repetitive tasks, data will be collected by several 3D sensors mounted on the eTrac; at that moment, AI and deep learning come into play. We will hire the knowledge of companies such as VBTI and Avular in the Brainport region to turn the eTrac into an advanced mobile platform. Knowledge about mowing and weeding comes from LS Products and DvO Engineering.
In a similar way to that in which BESI or ASML work together with many technical partners, I have selected these partners, each with their specific knowledge, to make our venture into a success.

As well as pushing technology, there was also a market to find, as well as customers willing to buy our robot tractor. Due to the high-end components used to build the eTrac, such as an expensive, advanced battery pack, it seemed to me that it would be difficult to sell the first eTrac due to its relative high sales price. Marketing is always a matter of timing; you shouldn't be too early but also not too late. And you need some luck.

With the help of an incentive from the government that opened at the end of 2021, I found three tree nursery farms willing to buy a first-edition robot tractor, so production and sales can really take off next year. One day I hope that all my efforts with Farmertronics and the eTrac will pay off. After leaving the semiconductor industry and pioneering for nearly ten years in the agricultural market, things seem to be developing in the right way.

Thieu Berkers
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EMBEDDING MORE FLEXIBILITY IN ROBOTIC SYSTEMS

Robots have been extremely successful in the past decades, for instance in the car industry, and have also entered the agri-food production chain. However, current robot technology is no match to human workers when it comes to dealing with variation and flexibility. The NWO Perspective programme FlexCraft addresses the scientific challenge of how to deal with large variations in shape, size and softness of agri-food products in combination with variations in environment and tasks in a robust way. To that end, it aims to equip robot technology with generic capabilities in active perception, world modelling, planning and control, and gripping and manipulation.

ELDERT VAN HENTEN

Robot technology has been extremely successful in the past decades, for instance in the car industry. Repetitive operations on large numbers of objects that are well defined in terms of location, orientation, shape and size were instrumental to this success. Robots have also entered the agri-food production chain, where adoption continues to grow rapidly. This trend expresses the readiness of that agri-food industry to adopt more advanced technology.

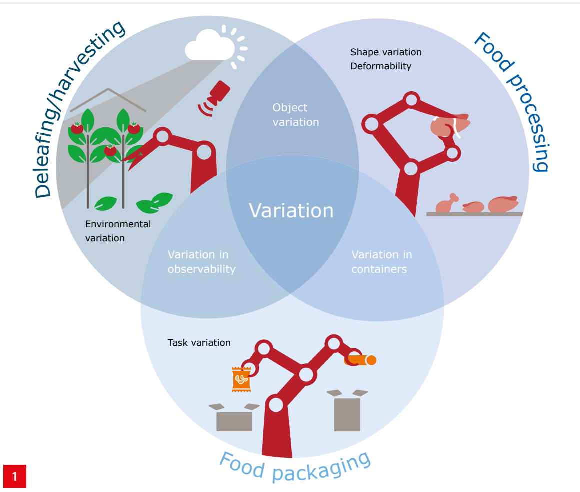
However, the robots currently used in the agri-food domain are based mainly on industrial robotic pick & place techno-logy and still cannot meet the requirements of flexibility and the capabilities to handle complex manipulation tasks or natural environments. In terms of the above-mentioned capabilities, current robot technology is no match to human workers in the agri-food industry, where dealing with variation and flexibility proves to be the biggest challenge.

What makes humans so flexible and capable in dealing with complexity and variation? Firstly, active perception allows humans to adapt their observations to the conditions at hand and effectively identify location, orientation and material properties of objects in complex environments where objects are only partially visible. Secondly, humans learn from previous experiences and build a world model, which they use to reason about the environment and to guide their active perception as well as the planning and control of arms and hands. Thirdly, humans employ very effective eye-hand coordination, i.e. planning and control of their arms and hands with respect to the object to be manipulated. Finally, humans are equipped with hands; hands are gripping and manipulation systems that are compliant and very effective in dealing with objects that have widely differing shapes and sizes as well as differing material properties, ranging from solid to soft and deformable.

The NWO Perspective programme FlexCraft addresses the scientific challenge of how to deal with large variations in shape, size and softness of agri-food products in combination with variations in environment and tasks in a robust way. The FlexCraft programme aims to equip robot technology with generic capabilities in active perception, world modelling, planning and control, and gripping and manipulation; capabilities that are needed to deal with the aforementioned conditions in a robust way.

Benefits to society

Besides building on a novel network of research institutes and agri-food industry in the Netherlands, the FlexCraft



1 *The use-case projects and the challenges they address. 'Deleafing/ harvesting' in the upper left corner refers to the Greenhouse use case.*

AUTHOR'S NOTE

Eldert van Henten is professor of Biosystems Engineering in the Farm Technology Group at Wageningen University & Research in Wageningen (NL). Input was provided by members of the FlexCraft team, including Gert Kootstra, Robbert van der Kruk, Herman Bruyninckx, Rehka Raja, Xin Wang, Akshay Burusa Kumar, David Rapado Rincon, Ad Huisjes and Rodrigo Perez Dattari. The financial and in-kind support of the FlexCraft programme by NWO and companies under Grant Nr. P17-01 is gratefully acknowledged.

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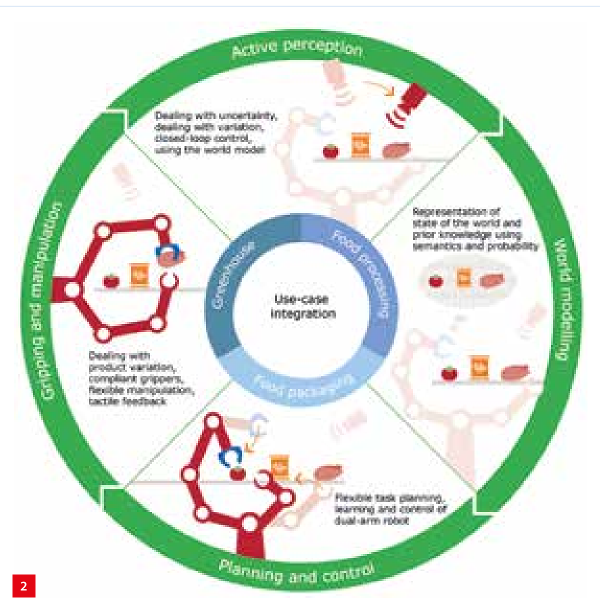
programme aims to improve flexibility in food processing and food packaging, allowing further progress in customer-specific production. Also, it will improve efficiency and effectiveness of agri-food production by implementing robotic systems that can operate tirelessly at high speeds and allow easy upscaling of the production. Using robotic systems instead of human labour in food production and food processing will improve hygiene. And last but not least, FlexCraft aims to mitigate the continuously growing labour scarcity in agri-food production.

Use cases

Central to the programme are three use cases that will demonstrate the technology developed. Addressing variation in objects and environment are the key challenges and as illustrated by Figure 1, use cases share some challenges but also differ on the challenges encountered in practice. The three use cases:

- The greenhouse use case will address the removal of leaves (deleafing) and ripe fruits (harvesting) from tomato plants, two important plant-maintenance operations. This use case addresses the challenge of how to deal with variations in the environment, such as changes in illumination and humidity, as well as variations in objects (leaves and fruits), and complexity in the environment due to a high level of clutter and partial occlusion of objects by other plant parts.
- The food-processing use case will address poultry processing. This use case addresses the challenge of how to deal with variation in shape and size of objects (chicken fillets, wings, thighs), deformability of objects, and the picking of these objects from large piles or bins.
- The food-packaging use case addresses packaging of various food products, such as packs of cookies and bags of chips.



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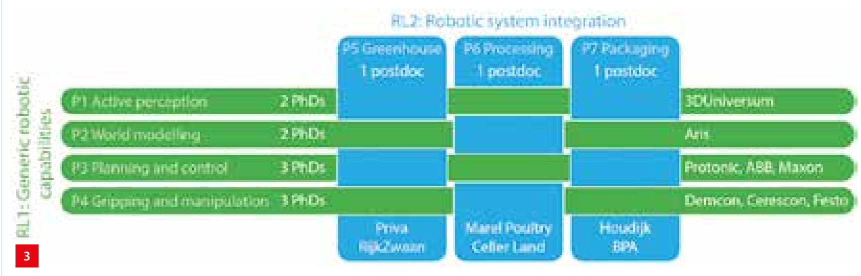
The FlexCraft paradigm for dealing with variation in objects and environment in the agri-food chain.



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The matrix structure of the FlexCraft programme, with along the horizontal axis the four generic capabilities of active perception, world modelling, planning and control, and gripping and manipulation, and along the vertical axis the three use cases on greenhouse production, food processing and food packaging, respectively. Key staff in terms of Ph.D. candidates and post-docs are indicated.

Key challenges

Robotic research is a multi-disciplinary endeavour, with perception, cognition and action aspects, and entailing both hardware and software components. A robot is a sensori-motor system, where perception and action are tightly coupled through the interaction of the robot with the environment.

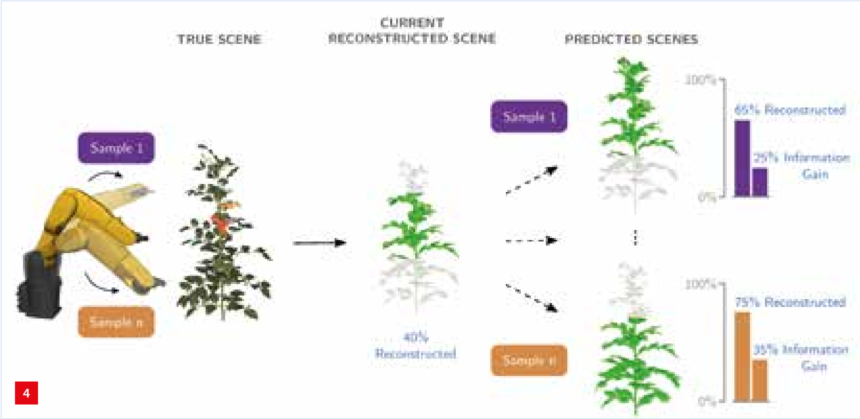
Through its sensors, the robot perceives the environment. By processing this information and combining it with prior knowledge, an internal world model is formed. The robot then reasons about that state of the world in relation to the task, in order to plan its actions, both at an abstract level, as well as in the low-level control loops. Through its actuators, the robot interacts with the environment.

From the scope of the programme, this entails the manipulation of objects. This interaction has an immediate effect on new sensory observations, completing the cycle. Figure 2 illustrates the FlexCraft paradigm for dealing with variations in objects and environments when deploying robotics in the agri-food chain.

Programme overview

The FlexCraft programme builds on a strong and multidisciplinary research community led by Wageningen University and including Delft University of Technology, Eindhoven University of Technology, University of Twente, and the University of Amsterdam. This community covers all academic disciplines needed to tackle the challenges of variation and deformability when manipulating products encountered in the agri-food domain. As shown in Figure 3, the programme is supported by industry having stakes in the agri-food chain, represented by 14 companies including Marel Poultry, Priva, Houdijk, BPA, ABB, Aris, Festo, Demcon, Celler Land, Protonic, ABB, 3D Universum, Maxon and Cerescon.

The research programme operationalises a matrix structure as shown in Figure 3. Along the horizontal axis, research Line 1 focuses on the generic methodologies and concepts



Active perception – a next-best-view planning approach.

in active perception, world modelling, planning and control, and gripping and manipulation. Along the vertical axis, the generic concepts will be integrated and evaluated in Research Line 2 in the three use cases. TRL levels to be achieved in the use-case demos are in the TRL 4-5 range. As usual in NWO Perspective programmes, key staff constitutes Ph.D. candidates and post-docs, supervised by leading principal investigators in the respective domains.

Work in progress

Active perception

It is known from previous projects in agri-food robotics that multiple views can help in identifying hidden objects or parts of a plant, but choosing these viewpoints in a goal-directed and effective way is still a challenge. Methodologies are developed to enable robots using instruments to resolve uncertainty through actively gathering new sensory input by changing perspective; an approach called active perception (Figure 4).

Currently, methods are investigated to plan the next best view by proposing camera viewpoints optimising the gain in information. Recent results show that next-best-view planning is effective in reconstructing, for instance, a tomato plant. Yet, when particular parts of a plant need to be found, prior knowledge will be needed to guide the viewpoint planning. Next steps in the research will focus on including such prior knowledge that is contained in a so-called world model. Interestingly, building the world model and active perception are tightly connected.

Observations of tomatoes, leaf nodes and fruit nodes (left) are translated into a world model (middle), including a graph-based representation (right).

World modelling

The central theme of world modelling aims to instigate a paradigm shift in the robot's level of understanding of the world in which it has to execute its task. A task-centric world model is built and maintained from uncertain and partial sensory inputs, together with available prior models. Task-centric means that only those parts of the world that are relevant to the execution of the task at hand, including the robot itself, will be represented.

In particular, the programme focuses on the development of data association and object-tracking methods that allow to incorporate subsequent sensory observations to deal with noise and occlusions and to cope with changes in the world. The world model accommodates different levels of semantic abstraction that will facilitate abstract reasoning and task planning for robust task execution.

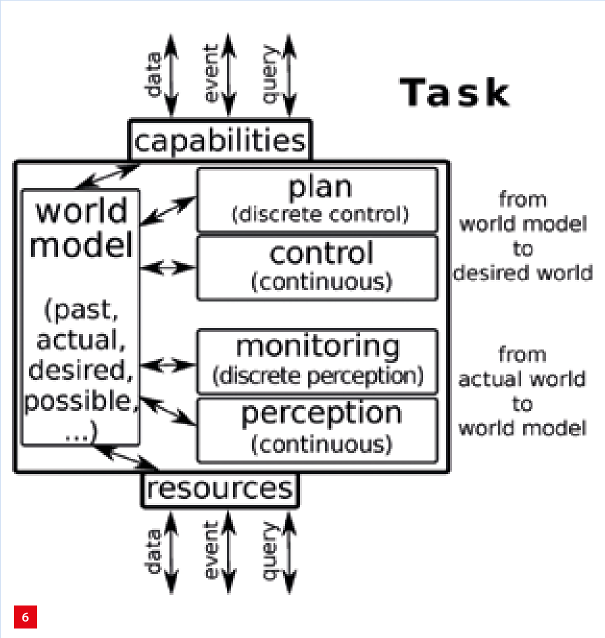
First results of this world-modelling approach in an agri-food context are shown in Figure 5. At the left, a new camera observation is depicted including the detected tomatoes, leaf nodes and fruit nodes. This observation is incorporated in the world model in the middle, which includes a graph-based representation on the right, allowing for reasoning and task planning.

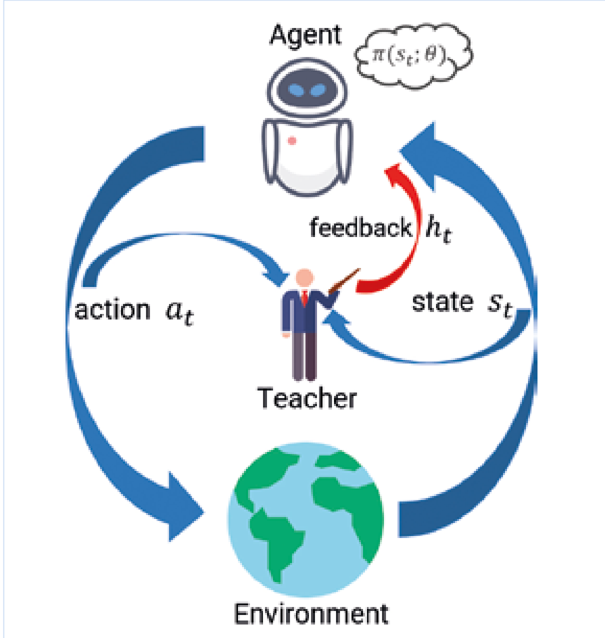
Planning and control

Traditionally, robots are programmed by hand: defining trajectories, compliance parameters, sensor-actuator coupling, etc. This approach results in very efficient, but also highly task-specific robot control. This approach is insufficient when trying to handle the large variation in natural products, or when changing the task frequently. In mainstream robotics, task plans are almost exclusively imperative – that is, they consist of recipes of motion, sensing, and decision-making actions to be realised by the robot; such recipes are created at development time.

The FlexCraft programme makes steps in the direction of declarative task plans – that is, at development time, the task requirements are formulated as a combination of one or more objective functions to optimise and one or more constraints to satisfy. Jointly encoding the objectives and constraints, as well as their connection to each other, and the robot's motion and perception capabilities is an unsolved problem.

The subsequent challenge is semantic-task planning, i.e. reasoning about how the robot will turn the declarative specification into a concrete recipe given the current local





In the FlexCraft planning and control scheme, the world model (left) is central. Learning by demonstration, specifically interactive learning, is used to generate motion plans using human input (right).

and temporary context of the task execution, which is represented in the world model. In that way, the recipe can be automatically adapted to the actual variations in the process, tasks and environments. The world model will couple the semantic primitives of planning (discrete control), continuous control, perception and monitoring (see Figure 6).

One of the major challenges in optimisation- and planning-based approaches is the precise task specification. A number of hard constraints are straightforward to specify; however, specifying trade-offs between multiple criteria is typically unintuitive and requires many iterations until the outcome of the optimisation matches the expectations of the user. This is especially crucial in tasks that have thus far not been automated. Transferring the expertise of human workers to automated systems is a major challenge, especially in the deleafing, harvesting and trimming use cases.

In this project, we will learn from human demonstrations, both in terms of concrete strategies and movements they employ (imitation learning, also called programming by demonstration) as well as higher-level objectives (inverse reinforcement learning, also called inverse optimal control, i.e. learning the optimisation criterion from demonstrations, in contrast to reinforcement learning, which optimises a behaviour according to an optimisation criterion by learning from experience). This form of prior knowledge will be integrated in the world model and, in turn, employed by the semantic task-planning. The approach followed at Delft University of Technology to investigate learning by demonstration is shown in Figure 6.

Grasping

Robotic grippers have a pivotal role in modern automation. Current robotic gripping technology can handle well-defined rigid objects; however, grippers for harvesting, food processing and packaging have to perform their tasks under demanding requirements such as product variation in size, shape and softness, and as fast as possible to reduce cycle times. The variability of the objects led gripper manufacturers to expand their catalogues to accommodate this issue; therefore, commercially available grippers come in innumerable shapes and sizes.
Recently, considerable research has been devoted to soft robotics, typically consisting of non-metal materials, allowing for increased flexibility and adaptability for accomplishing tasks. In a FlexCraft project, a novel design of a compliant gripper has been developed.

Greenhouse use case

Crop production in greenhouses is advantageous over the open field because of the ability to control the indoor climate for optimal crop growth and production, and to protect the crop against pests. Due to increasing labour costs and a growing difficulty to find sufficiently-skilled workers to perform the heavy and repetitive tasks, the interest in greenhouse robotics is growing. There are currently, however, no commercially available robots for operation in the greenhouse that can deal with the challenging environment.

The FlexCraft programme aims to use the generic robot capabilities developed to advance greenhouse robotics. In this use case, the deleafing and harvesting operations

Experiments on active perception and world modelling in the greenhouse use case.

are addressed. Figure 7 shows an ABB manipulator in the greenhouse in an experiment on active perception and world modelling, supporting the developments in this use case.

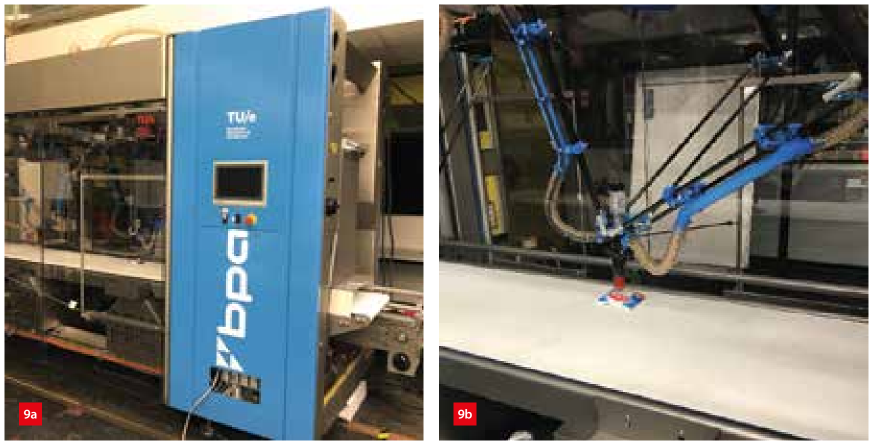
Food-processing use case

Current robotic systems in the processing of chicken, fish and red meat are capable of simple manipulations of singulated, equally-spaced products transported on a conveyor belt. Simple manipulations consist of grasping, repositioning and changing the orientation of objects for subsequent operation and positioning of single pieces of meat or fish into a well-defined package, such as thermoformed pouches.

The FlexCraft programme aims to lay the foundation for technology that is able to perform more advanced operations in food processing – operations that, due to their complexity, are still the realm of human labour. With a specific focus on chicken processing, the project aims to realise a demonstrator at TRL 4-5 of bin-picking of chicken pieces, whole-chicken shackling and trimming of chicken fillets. Figure 8 shows some preliminary results of grasp position estimation of chickens in a bin using multi-view perception.

Food-packaging use case

Key stakeholders in the food-packaging use case are the companies Blue Print Automation (BPA) and Houdijk.



A BPA spider twin delta robot installed at TU/e for research and demonstration purposes in the food-packaging use case.
(a) Overview.
(b) Close-up.

BPA has installed a spider twin delta robot (Figure 9) at Eindhoven University of Technology (TU/e) for development and demonstration of progress. It features two conveyors and a camera to represent an industrial state-of-the-practice food-packaging set-up. The two robots enable flexible packaging of mixed products with variations in dimensions, shape and colour.

The high speeds and accelerations of this robot create a challenging research environment to explore the trade-off between productivity and flexibility. Cooperative workspace sharing of the robots as well as vibration reduction of swinging products due to the high accelerations involved are topics of research. The open-control system features a real-time Beckhoff PLC Structured Text environment for actuators, sensors and safety (TwinCat3). High-level control is enabled by interfaces such as Matlab/Simulink and Python. Deploying a working system at TU/e facilitates efficient technology transfer between academia and industry.

Processing of chickens in a bin.
(a) Grasp position estimation using GraspNet.
(b) Modelling.
(c) Multi-view perception.

CUTTING-EDGE MECHANISATION

Automation of asparagus harvesting has been a long-time challenge because of the delicate nature of the crop. Cerescon has now developed the first selective harvesting solution for white asparagus, called the Sparter, which both reduces harvesting costs and significantly improves quality. What is characteristic and distinctive in the design is its underground detection of asparagus, using a box of probes that is attached to the machine through a well-thought-out suspension, while the design of the Sparter robot features an ingenious actuation concept.

AD VERMEER AND THÉRÈSE VAN VINKEN

Mechanising selective harvesting

Asparagus cultivation has been under pressure for years, partly due to the lack of manual workers for harvesting. The current manual way of working also has its limitations in terms of the quality of the harvested products. In a harvest round, asparagus spears cannot always be detected by eye, so by the next round they are protruding far above the sand bed. This causes the asparagus heads to fold open and exhibit violet discolouration, both of which result in lower sales value.

For almost all crops where the harvest is done in one go (bulk harvesting), the harvest is mechanised. Examples of these are grain, potatoes and sugar beets. Indeed, the first patent for a combine for the grain harvest dates back to 1831. Some crops, however, have to be repeatedly harvested for each part of the yield, which is called selective harvesting. This affects crops such as apples, mushrooms, strawberries and also asparagus. Still now, all selective harvesting worldwide is done manually, which makes these types of crops very labour intensive and more and more expensive. There is a clear need for the robotisation of selective harvesting.

Advantages

Cerescon has developed a selective harvesting solution for white asparagus, called the Sparter, which both reduces harvesting costs and significantly improves quality. What is characteristic and distinctive, is its underground detection of asparagus, after which the vegetable is removed from the sand bed by a robot.

The Sparter offers asparagus growers the following advantages when compared to traditional hand cutting:

- Better quality asparagus due to a patented underground detection system. This means that the asparagus is harvested before emerging from the soil, thus avoiding violet discolouration and reducing the number of open heads.
- Higher yield through improved quality, because the asparagus harvester restores the sand bed after picking, thus reducing the percentage of (discarded) bent spears caused by inhomogeneous compression of soil.
- Reduction of the harvesting frequency with subsurface detection to once every three days, thus tripling the harvesting capacity per passage compared to a (daily passage) system with detection upon surfacing.

Mode of operation

The machine has been designed as a one-row machine with an internal drive train. It is suspended by caterpillar tracks without additional castor wheels (like an army tank), which facilitates sharp turns. An operator drives the machine in the row with a remote control; see Figure 1, which also shows the handling of the plastic foil covering the asparagus beds. Once positioned in the row, both the steering and the speed control are switched to fully automatic for harvesting. The machine stops when it detects the end of the row. While harvesting, the operator's only tasks are to monitor the process and put the asparagus in crates.

For subsurface detection of the asparagus, on both sides of the machine a slider with a knife cuts into the soil at approx. 80 mm depth (Figure 2). A detection signal is injected into the soil making the asparagus detectable for sensors. The knife needs to reach wet soil, as very dry sand does not conduct the electric signal.

The detection module incorporates a number of probes with sensors that move through the soil at an adjustable depth (Figure 3). When a probe detects an asparagus spear via the sensor, the coordinate is registered and the probe is withdrawn at high speed to prevent the asparagus being damaged. In this way, the probes do not touch the asparagus spears.

AUTHORS' NOTE

Ad Vermeer and Thérèse van Vinken are the co-founders of Cerescon, a high-tech scale-up in agritech, located in Heeze (NL). Cerescon's mission is the development and marketing of advanced mechanised selective harvesting solutions.

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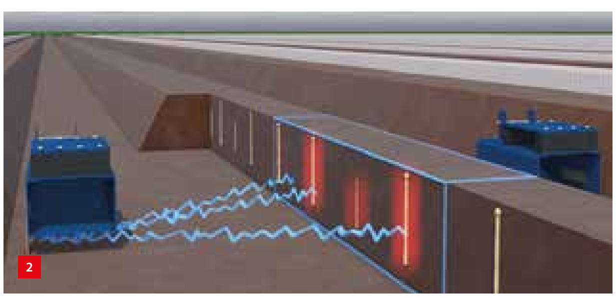
Remote control of the Sparter by an operator. The inset shows the handling of the plastic foil. At the row entrance, the operator puts the foil in the machine; then further along the row, the Sparter picks it up and places it back on the bed at its rear.

The measured coordinates are transmitted to the harvesting robot, which picks the asparagus from the top side of the bed, cutting and lifting it in one swift action (Figure 4). During this picking action, the robot moves synchronously in the opposite direction of the machine. Even during driving accelerations, the cutting knife is stationary relative to the soil while performing its picking action, so the machine does not have to slow down or even stop during harvesting. There are two robot heads to increase the capacity of the machine. While one robot head is picking, the other head is putting a harvested asparagus on an adjacent conveyor belt.

Asparagus that are placed on a conveyor belt are transported to the operator position on the rear platform of the machine (Figure 5). The asparagus are handled deliberately with some sand to avoid damaging the spears. This is a well-known trick in harvesting machines, also used for potatoes and sugar beets. Finally, the sand bed can be homogenised to ensure that the next asparagus spears will grow straight.

Steering and driving

Steering is done by adjusting the speed of both hydraulically driven tracks via proportional valves, based on measurement of the lateral position of the machine in relation to the sand bed. At the front of the machine,



Injection of the detection signal into the soil.

Detection trigger at close proximity of an asparagus spear to a probe.

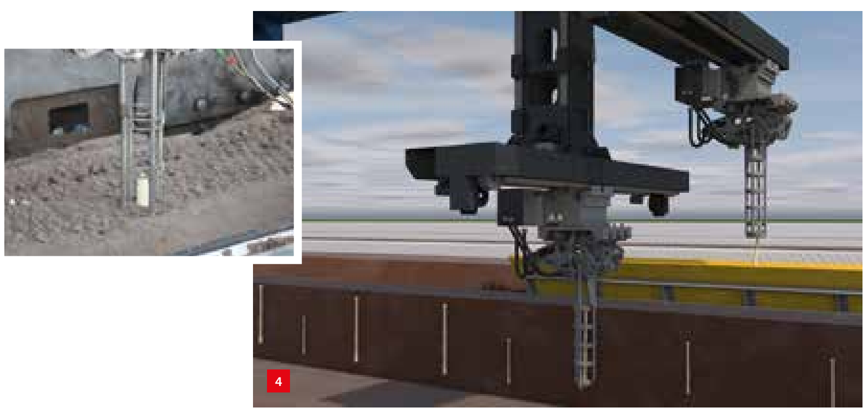
two steering wheels follow the side of the sand bed. The movement of the steering wheels is measured with analogue position sensors. The control loop of the steering has been designed to adjust the driving direction only gradually, in order to secure the position accuracy between the asparagus detection and the asparagus picking robot.

The driving speed is also adjusted automatically based upon the number of asparagus detected. The maximum speed is configured at 0.6 m/s, but this speed is not often reached because the robot cycle determines the harvesting capacity. With subsurface detection, sufficient asparagus spears are detected to keep the robots occupied at a moderate driving speed.

Detection

The detection module contains a number of probes that move through the soil at an adjustable depth (Figure 6). The depth adjustment and the sand bed tracking movement are realised by a control loop with ultrasonic sensors (the little green device at the top in Figure 6) and linear electric actuators.

In the first version of the Sparter, the box with all the probes was suspended using: three pivoting couplings that were to a large extent horizontally oriented in the X-direction, i.e. driving direction; one linear actuator oriented in



Cutting and extracting asparagus spears from the top of the sand bed. The inset shows a live close-up.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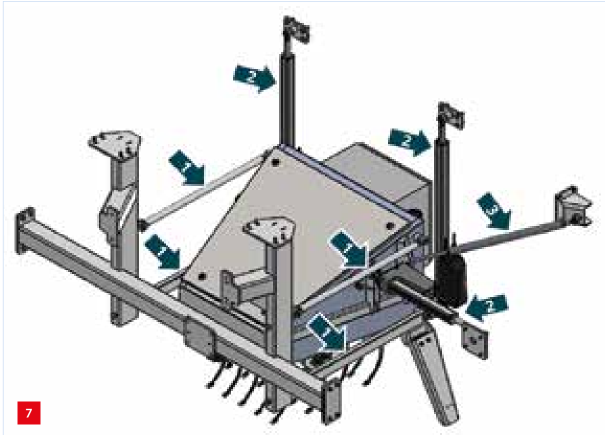
Asparagus transport.



Detection module suspension with 1) coupling rods, 2) linear actuators, and 3) a gas spring.

the transversal Y-direction; and two parallel linear actuators in the vertical Z-direction (Figure 7). The Rx rotation was thus controlled by the synchronous movement of the two Z-actuators, not by a guidance. The suspension of the detection box was perfectly statically constrained, using six rods with ball joints, which worked very well in the sandy environment.

In the next iteration of this design, it was decided to allow torsional compliance of the box and add one more horizontal coupling rod for compensation, analogous to a table having commonly four legs (while an infinitely stiff table requires only three legs for a stable placement). In addition, one gas spring was added to eliminate backlash in all the ball joints, improving the stability of the box in the moving machine.

As the tips of the probes approach an asparagus spear, the signal measured by the probes increases rapidly with decreasing distance. This is based on the fact that the electrical conductivity of the asparagus, which consists almost entirely of water, is much higher than that of the


6

Front view of the detection module. This is a prototype version, featuring four rows of five or six probes each. In the final version, the spacing between the detectors in the lateral direction has been increased, to prevent 'concerted' shoving of the soil by adjacent detectors. This resulted in seven rows of three or four probes each.

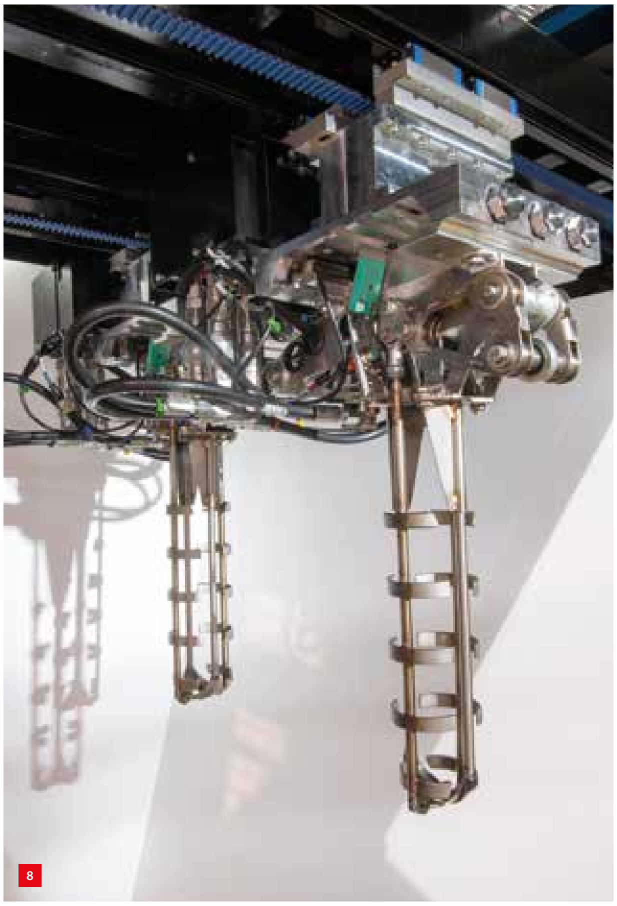
surrounding moist sand. At the same time, the sand must show some conductivity, otherwise there would only be current upon touching the asparagus. Fortunately, really dry soil does not occur in practice, otherwise nothing would grow.

Detection typically occurs at a distance of 3 to 6 mm. The threshold level of detection can be adjusted dynamically based on multiple input data, using an advanced proprietary algorithm that makes the detection process very robust. Almost no asparagus spears are missed and the number of false positives amounts to only a few per cent, so the system works very reliably in practice.

Once the asparagus has been detected, the probe is retracted immediately through backward rotation driven by a servo-controlled motor via transmission gears. The gearbox has been custom designed to fit 23 probes in the box space. The transmission is non-blocking to external forces on the probe, so if it bumps on a mechanical obstruction, the probe is pushed back. This is detected and an automatic reset procedure follows.

Robot

A detected asparagus spear is approached by the cutting robot from the top of the sand bed. The robot then takes out the asparagus in one movement and puts it on an adjacent conveyor belt. The asparagus is transferred on the conveyor belt by a Y-movement. The robot has two cutting heads (Figure 8), each one equipped with a combined Y/Z-drive. This configuration turned out to be well balanced, as cutting (Z down, hydraulically driven cutting action, Z up, and then moving to the next cutting position of the other knife) takes about the same amount of time as the Y movements to the conveyor and back. For this reason, it was decided to place both robot heads with their own Y/Z degrees of freedom on one common X-slider. The knife that is cutting determines the X-position, the offloading can be done at any X-position.



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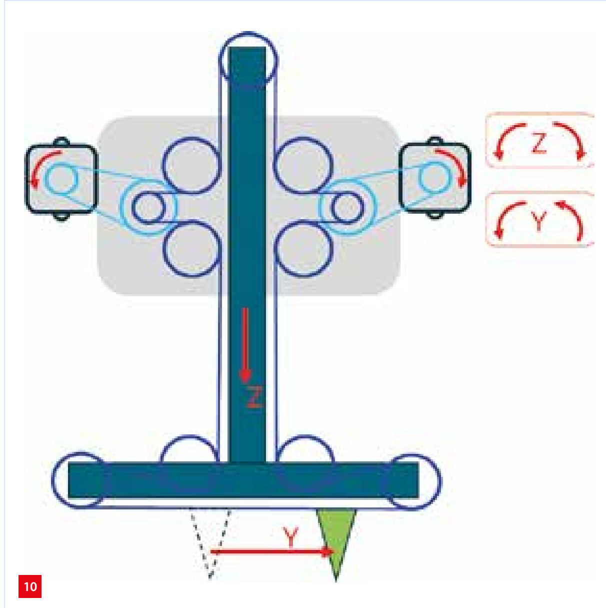
The two cutting knives.



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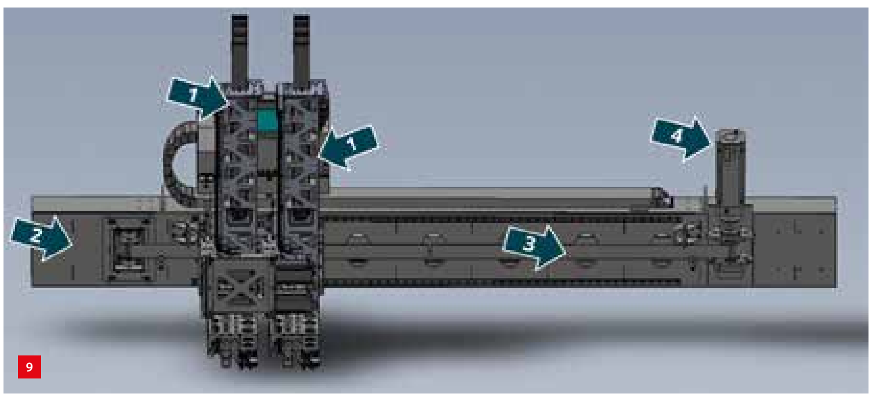
Drive train of the Y/Z-module. Y- and Z-movement are achieved by both motors turning in the same direction or in opposite directions, respectively.

The cycle time per asparagus is approximately 1 s. The length of the X-axis was designed to be long enough to cover clusters of up to four asparagus at close X-coordinates without the need to slow down. This reduces drive speed fluctuations and helps to keep the robot heads busy.

The Y-Z drive design of the cutting heads is based on one timing belt driven by two servo motors (Figures 9 and 10), which is a very suitable solution in this machine for several reasons. The crux of the actuation concept is that both Y/Z-motors do not move in either the Y- or Z-direction, which limits the moving mass. The Z-movement requires a high force of 300 to 900 N for penetrating the cutting knife into the soil. On top of that, high accelerations are needed, up to 20 m/s^2. Both servomotors contribute evenly to the Z-force. The Y-movement can only start after the upward Z-movement has (almost) finished, so again both servomotors work together, in this step to reach high accelerations up to 30 m/s^2.



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Robot with 1) Y/Z-modules, 2) X-beam, 3) X-timing belt, and 4) X-motor.

Linear guides

A specific challenge in the design was posed by the linear guides. The ones used typically in high-tech machines with recirculating balls are not the best choice. If sand penetrates the guidance carts, it limits the lifetime. That is why Cerescon selected roller guides for the X-movement.
The roller bearings can be effectively sealed, while the rails and the outer surface of the rollers can still be affected.
To prevent this, wipers are installed. If wear occurs on these surfaces, the system can still be used until the end of the season, so that maintenance can be planned later. The results over the coming years will indicate how serious the remaining problem is.

Asparagus transport

The cut asparagus is placed on a conveyor belt and transported to a collection bin (Figure 5). Due to the conveyor belt movement, almost all asparagus fall in the same direction, with the cut in the direction of transport. This is desirable in order to prevent as much damage as possible to the sensitive heads of the asparagus during further handling. At the end of the conveyor belt is a sand-asparagus separation function, which returns the sand to the sand bed. In this way, the sand bed is better maintained throughout the season than with manual harvesting.


11
Introduced by Cerescon; the first selective mechanised harvesting system in history that has made it to the market.

Conclusion

Cerescon has introduced the first selective mechanised harvesting system in history that has made it to the market (Figure 11). Many other selective machines for different types of crops will follow, as there are many projects in the research phase awaiting market introduction. This is a great opportunity for the Netherlands as a country strong in both agritechnology and mechatronics.

The user advantage of subsurface detection

The total capacity of the Sparter measured in hectares of asparagus field is determined by the capacity per day multiplied by the number of days between two consecutive harvesting cycles. An important advantage of subsurface detection is that many more asparagus spears are harvested per meter per cycle.

Some figures can illustrate this effect. A normally skilled manual worker can detect asparagus just before they surface, typically as of –1 cm with respect to the top of the sand bed, because the worker can recognise small features like sand cracks and bulbs caused by the asparagus heads. To maintain their quality, asparagus heads should not be allowed to grow higher than +3 cm above the surface. So, the range that can be harvested is 4 cm. This is, on average, close to the asparagus growth rate per day. The Sparter detects asparagus at maximum –10 cm, so the range for the Sparter is 13 cm, over three times more than with the manual process.

The average harvesting frequency that users will choose with the Sparter is therefore expected to be three days. Compared to a machine that uses optical detection, the harvesting frequency advantage is even greater, as optical detection only works once the asparagus heads are really visible.

FARM OF THE FUTURE

European policy aims at reducing crop protection chemicals, nutrient losses and fertiliser use, and stimulating organic farming, while maintaining our current high level of food safety and security. This huge transition is addressed by the Synergia-AGROS and the Dutch Farm of the Future project, both focusing on improved, ecologically sound cropping systems based on crop diversification and controlled traffic farming in various crops. In collaboration with commercial partners, Wageningen University & Research is developing innovative field applications, such as autonomous weed control with spot spraying, using vision-based deep learning algorithms.

JOHAN BOOIJ

Introduction

Dutch agriculture is one of the most innovative sectors worldwide and the Netherlands is the second largest food and feed exporter in the world, just after the United States. High costs of land and labour have contributed to intensification, specialisation and increase in the scale of farms and machines. The downside of all this is the impact of agriculture on the ecology and society, which has led in Europe to strict conditions on production. The European Commission developed the Farm to Fork strategy to redesign the food system and make it more circular, resilient and sustainable.

Important challenges of the European strategy are reducing crop protection chemical use (herbicides, pesticides and fungicides) in agriculture by 50%, nutrient losses by at least 50%, and fertiliser use by 20%, and stimulating organic farming (25% of total farmland by 2030), while maintaining our current high level of food safety and security. This means a huge transition from the current perspective.

The Dutch Ministry of Agriculture, Nature and Food Quality and Wageningen University & Research (WUR) therefore started the Farm of the Future project, as an example to demonstrate a transition to new crop production systems that farmers are able to bridge. The guiding principle in this farm is the combined agronomic and ecological aspect, supported by (new) technology.

Farm of the Future

The WUR Field Crops business unit has several farms in the Netherlands where it conducts field experiments in crops such as potatoes, cereals, sugar beets, vegetables and fruit. Each farm represents a region with its own crop rotation, soil type and challenges. In Lelystad (clay soil), 25 hectares of a farm of about 800 hectares have been converted into a field lab for the Farm of the Future. In order to reduce crop protection chemical use, crop diversification is introduced in a system where potatoes, sugar beets, onions, carrots, grass-clover, leguminous crops, cereals and cabbages are cultivated in strips (Figure 1).

Furthermore, all mechanisation is adapted to controlled traffic farming: machines follow a predefined path at each operation on the field. Soil compaction is focused on permanent traffic lanes (30 cm wide) with uncompacted crop beds in between (3 m wide). These features are specific for the Farm of the Future in Lelystad. In Reusel (sandy soil) and Valthermond (reclaimed peat soil) there are other challenges, for which WUR is creating a system design together with local stakeholders.

As each crop has its own operation plan, intercropping increases the amount of traffic on a field. The lower efficiency of this system increases the amount of labour needed in a social environment with decreasing labour availability. It shows that there is a high demand for automation of operations, not only by introducing autonomous implement carriers, but also automating crop operations (implements) and monitoring the quality of work. Furthermore, in order to reduce the number of inputs for crop protection and fertilisation, monitoring systems are needed to monitor pests, diseases and weeds in the crop, time- and place-specific.

1

Strip intercropping is combined with controlled traffic farming (CTF) to increase biodiversity and natural predators and to reduce soil compaction. This potato harvester is adapted to the CTF system.

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WUR Field Crops is always looking for opportunities and partnerships to collaborate in developing innovative solutions for monitoring crops and fields and automating agricultural tasks. Interested parties are welcomed to explore the possibilities for their products or services.

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Hardware components of a prototype spot sprayer.

Autonomous weed control with spot spraying

One of the major challenges in farming is weed control. In the Northeast of the Netherlands, farmers have a crop rotation of potato - cereal - potato - sugar beet. Because of mild winters, tubers left over after harvest will grow as plants again in the next season. The result is a sort of monoculture, where in every season potato plants grow in that field. This increases the populations of soil-borne diseases such as nematodes and fungal diseases (such as phythopthora). A farmer spends between € 150-450 per hectare to effectively get rid of these 'volunteer' potatoes. In the Synergia project, WUR – together with commercial partners – worked on a solution to detect individual potato plants in a sugar beet crop and selectively spray these plants.

Figure 2 shows a prototype of the system to selectively spray potato plants in a sugar beet crop. The spot sprayer implement (Figure 3) is carried by an autonomous implement carrier named Robotti and manufactured in 2019 by AgroIntelli. This mobile platform has a wheelbase of 3.00-3.15 m and has a standard 3-point hitch to carry 3.0-m-wide agricultural implements. Two Kubota D902 18-kW diesel engines are used to provide power to a hydraulic drive and steering system and a power take-off drive. Its speed is 0-8 km/h. The system is equipped with

The spot sprayer implement is carried by an autonomous platform.

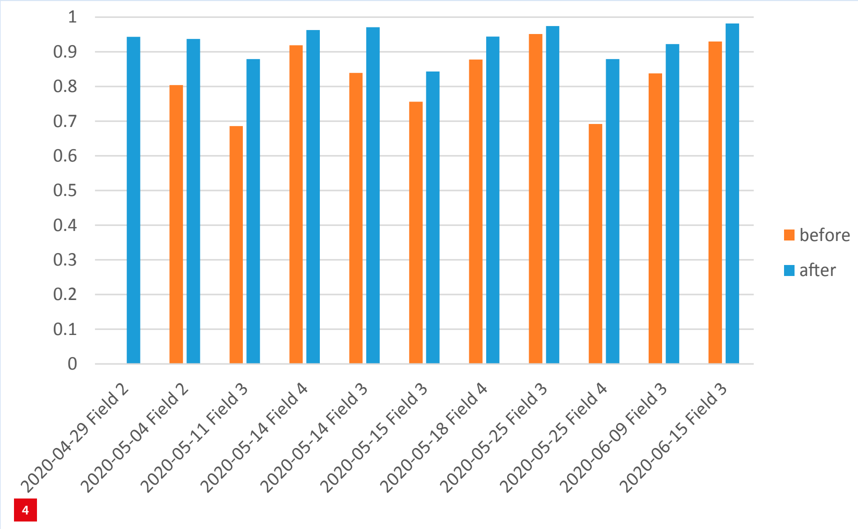
an AgLeader GPS6500 RTK-GNSS (real-time kinematic global navigation satellite system) receiver for accurate positioning and autonomous navigation.

The spot sprayer consists of:
- A tank for water and crop protection chemicals.
- An aluminium cover with diffuse LED lighting and four Chameleon 3 CM3-U3-31S4C RGB cameras. The cameras each have a resolution of 2,048 x 1,536 pixels and have a field of view of 0.53 m by 0.70 m.
- A Lenovo ThinkPad P53 laptop with a Nvidia Quadro RTX5000 Mobile GPU with 16GB memory size, Intel Core Xeon E-2276M CPU with 32GB DD4 RAM.
- Some electronic and PLC boards to control spray nozzles.
- A spraying boom with 29 spraying sections spaced 10 cm apart. The width of the spraying boom is 2.8 m, covering six rows of sugar beets.

The laptop triggers the cameras and processes the images with a vision-based deep learning algorithm. In this case, YOLOv3 is used [1]. The algorithm consists of a single neural network and applies it to the full image. It divides the image into regions for objects of interest, i.e. either potato or sugar beet plants, and predicts bounding boxes and probabilities for each region. The bounding boxes are then weighted by the probabilities. When the probability is higher than 0.5, the bounding box is stored and further processed.

The algorithm was trained using about 7,000 images with 20,000 sugar beet and 4,600 potato plants. After the bounding box is stored, the relative position of the bounding box in the image is translated to its pixel position. With a vehicle coordinate system, the pixel position is translated to a real-world position under the machine. The laptop sends the time of data acquisition, current time, vehicle speed derived from the GNSS receiver and the position and width and length of the detected object to the PLC. The PLC then turns on the nozzles at the right moment and position to spray the object.

During 2019 and 2020, the prototype was demonstrated in several fields with differences in soil type and varieties of the sugar beet and potato plants. The performance of the system differs from year to year and from field to field, due to differences in field circumstances. In 2020, the performance of the algorithm was tested for three different fields and two to four dates. For each subsequent date the most recent algorithm was used and the mean average performance was calculated by testing the algorithm on new annotated data from the field (55-843 images). Then, for each subsequent date part of the annotated images was used to retrain the algorithm and test it again. Figure 4 presents the results.



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The mean average precision of the trained Yolov3 algorithm to detect sugar beet and volunteer potato plants in several fields and at several moments in 2020, before and after retraining with new annotated images gathered in each field and at each moment.

The figure shows that the algorithm can have a real performance drop if it encounters new circumstances for which it has not yet been trained. Examples of such new circumstances are plants damaged by frost or insects, the presence of tree leaves, an untrained growth stage of sugar beets, blurry images (settings of the system), etc. By adding just a few images for each new circumstance (50-100), the performance of the algorithm is much improved [2], [3].

However, the calculated performance of the algorithm at image level does not consider the full pipeline of the system from data acquisition to spraying action. Ultimately, the performance should be evaluated at application level [4]. For the farmer it is important that his main crop is not damaged and that the volunteer potato plants (or other weeds) are removed or killed. With conventional methods a maximum damage of 10-15% of the sugar beets is allowed. With the use of non-selective herbicides this can only be achieved when the system is capable of spraying within centimeter accuracy.

To accelerate the development of this kind of applications and produce robust market-ready systems, there is a need for 1) a check on the quality of the field application and the feedback of the farmer; and 2) a digital infrastructure and methods to gather, annotate and share image data and retrain algorithms efficiently. In 2019, WUR together with telecom provider KPN already demonstrated a proof of principle. Images from the robot were sent using 5G to an off-site server and processed with the object detection algorithm, and then the locations of the bounding boxes in the images were sent back to the field robot [5]. With a digital ecosystem it would also be possible to use the same field equipment for other use cases, such as weed control in onions.

Other applications

WUR collaborates with commercial partners to develop such innovative field applications, where WUR contributes knowledge of the complex field circumstances (soil types, weather conditions, crops, cultivation methods, diseases, plagues and weeds, etc.) at a farm, as well as the experience with the implementation of complex systems in farm management (tactical, operational).

Some other examples under development by WUR within the Synergia-AGROS project (*www.agros-smartfarming.nl*) are vision-based weed detection in onions, aphid detection in several crops, disease detection (Erwinia and Y-virus) in seed potatoes, and yield monitoring in bulbs and potatoes. In the Farm of the Future project solutions developed by commercial parties are also tested, for example weeding robots for onions and carrots. WUR Field Crops supports the development of the field application, testing the application in the field, as well as demonstrating the applications to farmers to gather feedback for the developers.

Besides applications for the field, WUR also works on crop growth models and decision support systems to give farmers tactical advice. WUR has already published a few online applications for e.g. potatoes on its platform called Farmmaps. Examples are a Nitrogen Topdress App (location-specific advice for nitrogen supply based on satellite or drone images), Blight App (time-specific advice for fungicide applications to prevent phytophthora disease, based on weather data), Herbicide App (place-specific advice for soil herbicides based on soil maps) and IrrigationSignal (time- and field-specific advice for irrigation based on soil and weather data).

These are just a few examples of the projects and applications WUR is working on. There are still many challenges for the farm of the future where we need innovative solutions for monitoring crops and fields and automating agricultural tasks.

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DURABLE COOPERATIVE AGROBOTS SYSTEMS ENGINEERING

In the first phase of mobile robot control software development, high-level design and performance analysis are supported by discrete-event simulations. In a later stage, more detailed continuous-time simulations help to develop and verify the robot (cooperative) control algorithms. This is demonstrated in the DurableCASE project for adding robust cooperativity to existing agrobot solutions. Here, a framework needs to address requirements regarding safety, security and performance. Robot operating system ROS2, combined with behaviour trees, creates a good foundation to address 'safe' and 'secure'. Discrete-event simulations help in developing good logistics planning algorithms, while heuristics-based algorithms have already demonstrated cooperative robot behaviour being more 'performant' as compared to non-cooperating robots. Reinforcement learning-based planning might further improve on this.

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Introduction

The agri-food sector faces significant challenges in feeding the growing world population while reducing environmental impact, decreasing resource usage, increasing animal welfare, maintaining soil viability, and simultaneously intensifying productivity and improving human safety. The sector is confronted with a growing need for upscaling to improve efficiency, as well as to be able to cope with increasingly stringent environmental legislation. At the same time, labour is getting harder to find. This is especially true for skilled employees who can operate the complex, modern agri-food machines.

Technology can support the improvement of agri-food production processes [1] [2], especially automation, which is helping to improve productivity per employee. Hence, innovative OEMs such as Lely Industries are developing robotic barn solutions to support a highly efficient farming environment with little need for human labour. This increasing level of automation is clearly the next step in agriculture.

Many robotic solutions enter a booming market [3] [4]. Robots perform tasks autonomously, taking the work out of human hands. Autonomy requires complex technology, such as perception of the surrounding world and proper reasoning to make safe and performant decisions to get the task done in an environment filled with humans and animals. Due to this complexity, automation and autonomy evolve step-by-step, starting with human-support systems, followed by robots that can perform simple tasks autonomously.

Farmers need these solutions, for example to clean their barns and harvest their crops. These processes cannot be done by a large number of tiny machines. Bigger machines are required to transport manure and crops. However, they should not become too big, as large machines create unwanted soil compaction and are less flexible in manoeuvring. The logical solution is a team of robotic machines that can cooperate to take over tasks from humans while performing these tasks in a robust way.

Project DurableCASE

The desire for this cooperativity was the impetus behind DurableCASE, a RAAK-PRO project funded by the Dutch Taskforce for Applied Research SIA. DurableCASE aims to bring a market-viable solution that adds robust cooperativity to existing agrobot solutions. DurableCASE stands for Durable Cooperative Agrobots Systems Engineering and is a cooperation of many farmers, machine builders, technology suppliers and knowledge organisations, such as TNO, universities and universities of applied sciences.

DurableCASE focuses on two use cases:

- Adding cooperativity to Lely Discovery Collector robots (Figure 1). Currently, each Collector is responsible for cleaning a section of a barn. Cooperativity could make the solution more robust: one robot could take over from another in the case of a malfunction, or flexible sharing of resources such as charging and dumping stations could become a reality.

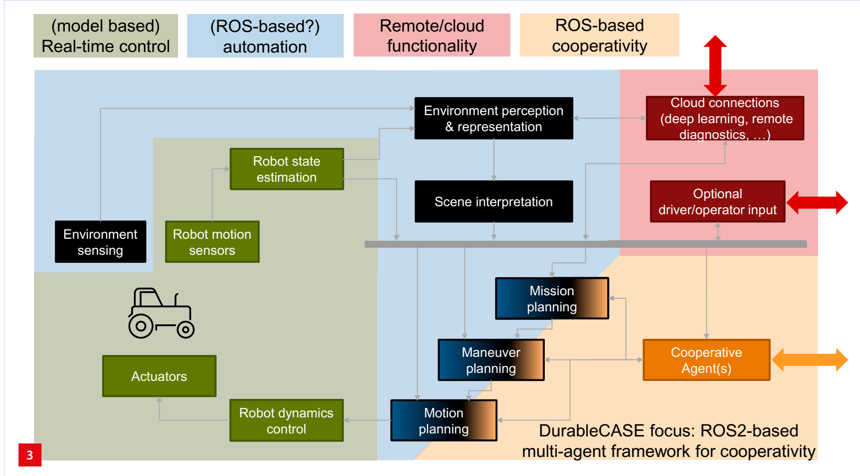
Lely Discovery Collector.

- Adding cooperativity to robotic chaser bin vehicles for the harvesting process, as foreseen by H2Trac, a developer of innovative hydrogen-/electrically powered tractors (Figure 2) that are becoming available in human-driven and robotic, cabin-less versions. Cooperating chaser bins could ensure that the harvester can continue harvesting without interruptions, as they can take over seamlessly by following each other very closely (e.g. within ~30 cm). Cooperating chaser bins can also be smaller and lighter than the current human-driven, tractor-pulled chaser bins, so they can reduce soil compaction as well.

These use cases share interesting similarities, as material needs to be transported cooperatively in a rather structured environment, which simplifies trajectory planning. Nevertheless, the aim is to come to a solution with wider applicability.

DurableCASE aims for robust cooperativity. Before starting the project, the architectural approach was defined. Figure 3 shows the assumed functions in the control of each mobile agrobot. The green elements control the machine motion. The blue elements add automation, via perception and representation of the environment, followed by scene interpretation and decisions based on the robots' goals. The red elements add external edge/cloud functionality, such as cloud-based training of AI (artificial intelligence)

EOX 175, the hydrogen-/electrically powered tractor developed by H2Trac.



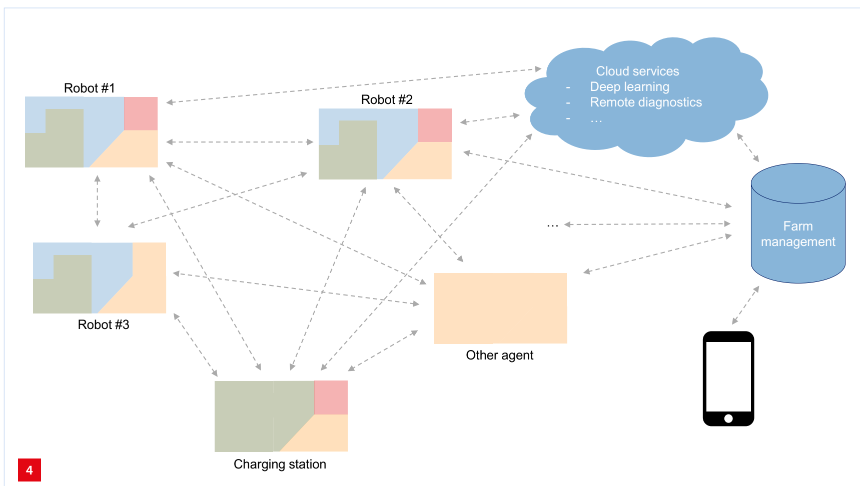
Functional robot control; see text for further explanation.

algorithms and (remote) operator connection. DurableCASE focuses on the yellow-pink part in the lower right corner of Figure 3: a ROS-based (Robot Operating System [5]) solution for cooperativity, influencing mission, manoeuvre and/or motion planning of the robot, to be developed based on multi-agent systems (MAS) technology.

Figure 4 shows a zoomed-out picture of cooperating agrobots, containing some or all of the abovementioned control functions, with in any event the yellow-pink elements that allow for cooperativity between the agrobots performing their desired function.

Steps towards a market-viable solution

In order to translate the initial project idea into valuable solutions, DurableCASE comprises a set of pragmatic steps as indicated in Figure 5. While appearing simple, the steps prove quite powerful. The consortium includes parties with relevant experience for all (sub)steps from both process and technology perspective. This results in effective requirements elicitation and a design process building on proven solutions. These steps will be further elaborated.



Cooperating robots: multi-agent environment.

Box 1 – Safe: behaviour trees

Our multi-agent system is implemented via an infrastructure using the second generation of the Robot Operating System (ROS2). The agents are implemented as nodes that communicate in a synchronous way (via ROS services), in an asynchronous way (via ROS topics), or in a combined way (via ROS actions). These primitives in ROS2 are based on the industry-standard Data Distribution Service (DDS) middleware.

We prefer to model robot behaviour explicitly instead of directly coding it in a programming language, because coding in the traditional, procedural way leads to many complex if-then-else structures in the robot code, which is hard to develop and difficult to maintain and improve. Behaviour Trees (BT) is our preferred way of modelling because it integrates important paradigms such as composition, the subsumption architecture and decision trees [6]. A BT is a tree consisting of decision nodes, i.e. sequence, fallback, parallel, and action and condition nodes. The actions and conditions are the leaves of the tree. In a BT you define when and under what conditions which action must be performed. BTs are derived from the world of video gaming and AI. We have observed a growing interest in BTs as a tool to describe and implement robot behaviour; see e.g. [7].

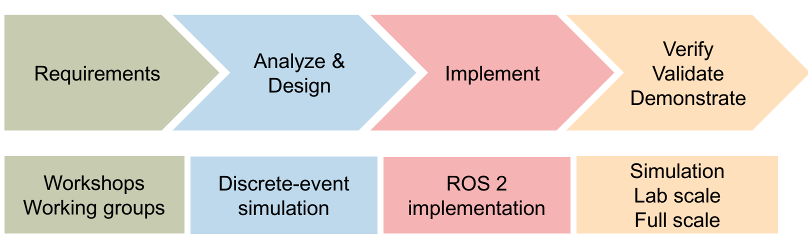
The BTs for the Vehicle Operating Agent (VOA) and the Cooperative Agent (CA) are specified in XML. The XML file can be created with an ordinary text editor or with a special graphical BT editor called Groot [8]. We have implemented a generic BT-based agent in ROS2 to read the BTs. For this, the BehaviorTree.CPP library was applied, which is also used in ROS2 in the navigation stack (Nav2). The BT.CPP library can read and execute BTs specified in an XML file. The conditions and actions defined in the BT must then be coded as plug-ins in C++.

The communication between VOAs and the CA is recorded in terms of ROS communication primitives and ROS messages, which is used to communicate with the Lely robot that applies DDS as a communication protocol. The specification by Lely of their interface to their robot enabled us to implement a specific VOA agent based on the generic BT agent software. The required C++ BT plug-ins were kept as small as possible by delegating tasks to specific server processes that are implemented in Python.

BTs have advantages such as their understandability and maintainability. We have also observed a positive impact on safety [9], by which we mean the capability of avoiding undesired outcomes. The BT describes and provides a plan and ensures that the robot will do its task. Because of this description of the BT, the desired outcomes are obvious. The next steps of the project are to find patterns to construct the BT, which also should provide more insights in system safety.

Requirements

At an early project stage, top-level requirements were defined by further analysis of the foreseen use cases. For robust cooperativity, the word 'robust' was concretised as: safe, secure and performant. Robots, also when cooperating, need to perform their tasks in a safe way. That is why the software agents in the DurableCASE cooperativity framework are implemented using behaviour trees (see Box 1). As we assume cooperative robots will communicate with each other and the cloud wirelessly, a security-by-design approach was used to design and develop the framework (see Box 2). A team of cooperating robots should show an improved performance compared to non-cooperating robots. A specifically challenging aspect in this respect was the logistics planning of all robots in the cooperating team, see Box 3.



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Main steps for bringing value to the market.

Design

Following a pragmatic approach, in DurableCASE some important design choices were made at an early design stage. Dynamic instantiation of working groups and frequent thematic workshops were key to these choices.

Robot operating system

A first choice was the use of ROS vs ROS2 for the cooperative framework. In an early design stage, the original ROS was by far the most mature and supported solution, allowing for a relatively quick set-up of a software development environment that allowed for a scenario-driven DevOps-style solution. However, ROS lacks determinism and integrated security support. ROS-Industrial (ROS-I, [10]) exists, focusing on software quality to bring ROS to an industrial level. On the other hand, ROS2 gains more determinism and security by design. Hence, the choice was made to implement as much as possible in ROS2 and use bridging with ROS when a ROS2 implementation (of algorithms as well as development tools) appears too challenging. The choice for ROS2 supports the key requirements 'safe' and 'secure'.

Cyber security
A second choice was how to integrate security-by-design. For this purpose, the EBIOS approach was used [11]. The EBIOS (*Expression des Besoins et Identification des Objectifs de Sécurité* – Expression of Needs and Identification of Security Objectives) Risk Manager methodology, developed by the French National Cybersecurity Agency (ANSSI), is a 'design thinking'-like approach for identifying and mitigating cyber risks. During five interactive and iterative workshops, DurableCASE project participants were taken through the identification of high-level objectives and guidelines, and then all the way down to the low-level choices that can be made about the concrete design of the desired cyber security.

During the workshops, a lot of attention was given to privacy; while the robot's internal software and processes can provide competitors with an insight into the precise operation of the robot, the behaviour of the robots actually tells a lot about the robot's user. In the field of information security, however, all users are also potential abusers, and during the workshops discussions were held on the scenarios in which users could take fraudulent actions.

As a result of the security workshops, a list of requirements, to be fulfilled during the development process, was drawn up. In addition to the necessary guidelines regarding operational safety and monitoring of the robots, a clear focus has been placed on defining roles and rights. An important point of attention in these roles and rights is the correctness of authentication processes and encrypted communication.

In order to achieve good cyber security, it is necessary to look at how matters such as authentication and monitoring are implemented during every step in the development process. Alongside discussions about which computer operating systems are considered secure and about version control of network protocols, good cyber security also means that choices about security must be made at the abstract level of models about multi-agent systems.

Discrete-event simulation
To evaluate the impact of design choices on operational processes in an early stage of development, DurableCASE also relies on the development of a discrete-event simulation environment. In comparison with simulation tools focused on mechatronics and vehicle control, our discrete-event simulation environment focuses on a higher 'logistics' point of view and serves as a decision-support system.

Discrete-event simulation is highly efficient as it ignores detailed physics-related behaviour and related control algorithms, and instead focuses only on simulating relevant aspects such as vehicle speed, acceleration and turning radius. This allows for a much faster simulation of an abundance of multivariable scenarios, providing quick answers to 'what if?'-style questions. For example, it supports algorithmic development (strategies for dispatching, routing, battery management...) and optimises farm operations for both use cases under various (growth) scenarios. Such a simulation environment is commonly used in logistics and manufacturing to optimise processes, perform bottleneck and scenario analyses, and to test algorithms and interventions. On the visualisation side, it can scale from simple 2D up to realistic 3D visualisation.

Within DurableCASE, we introduce such a simulation tool in the agri-food sector and build it in a generic way, allowing for easy modelling and adjustment of different (specifications of) robots. For example, in the Lely use case we allow for various farm lay-outs, different herd characteristics, and multiple cleaning and routing strategies. In this use case, we are interested in the impact of cooperativity on barn cleanliness, animal welfare, human safety, farm productivity and environmental emissions; see Figure 6 for an impression of the current model.


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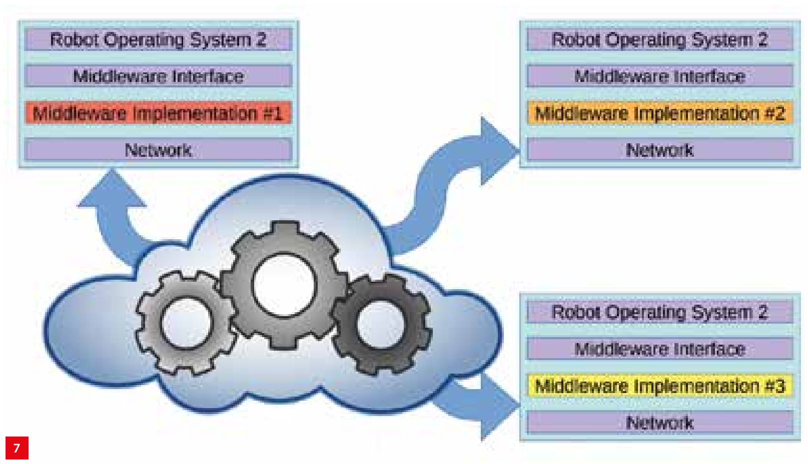
Current farm model for testing robot cooperativity in the Lely use case; see text for further explanation.

Box 2 – Secure: comparing DDS implementations

ROS2 uses DDS (Data Distribution Service) for communication between nodes. A number of different implementations of ROS2 middleware (RMW) exist, and as part of a cyber-security semester project, a group of students from The Hague University of Applied Sciences compared three RMW implementations (Figure 7). The focus was mainly on the usability, interoperability and security aspects of the middleware.

The three RMW implementations chosen for the research project were: Fast DDS and Cyclone DDS, both open-source RMW implementations available with the latest ROS2 distributions, and RTI Connext, a proprietary RMW implementation for which a university research license was obtained. These RMWs are the only ones currently supported by ROS2. Each RMW supports all three mandatory security features: Authentication, Access Control and Cryptography. RTI Connext also supports the optional Logging security feature, whereas Fast DDS supports both Logging and Data tagging, on top of the mandatory features.

The most recent ROS2 distributions are Foxy Fitzroy and Galactic Geochelone, released in June 2020 and May 2021, respectively. By default, all RMW implementations have the security features disabled. Installing Fast DDS and RTI



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Three ROS2 middleware (RMW) implementations were compared.

Connext with security features enabled was relatively simple with both distributions, but for Cyclone DDS, some dependencies were missing in Foxy Fitzroy and installing the dependencies was also tricky, so for Cyclone DDS the Galactic Geochelone distribution is recommended.

The RMWs support two communication patterns: publish-subscribe and client-server. In our interoperability tests (Table 1), with security disabled, all RMWs could communicate with each other in the publish-subscribe

Table 1
Interoperability tests for publish-subscribe and client-server communication patterns, with security either disabled or enabled, for three RMW implementations; Fast DDS, Cyclone DDS and RTI Connext.
Green: working;
Red: errors;
Orange: only working in a specific compatibility mode.

Publish-subscribe interoperability without security.

	FastDDS	Cyclone DDS	RTI Connext
FastDDS	Working	Working	Working
Cyclone DDS	Working	Working	Working
RTI Connext	Working	Working	Working

Client-server interoperability without security.

	FastDDS	Cyclone DDS	RTI Connext
FastDDS	Working	No client response	Working
Cyclone DDS	No client response	Working	No client response
RTI Connext	Working	Compatibility mode	Working

Publish-subscribe interoperability with security.

	FastDDS	Cyclone DDS	RTI Connext
FastDDS	Working	Working	Working
Cyclone DDS	ASN.1 error	Working	Participant key error
RTI Connext	No messages received	Participant key error	Working

Client-server interoperability with security.

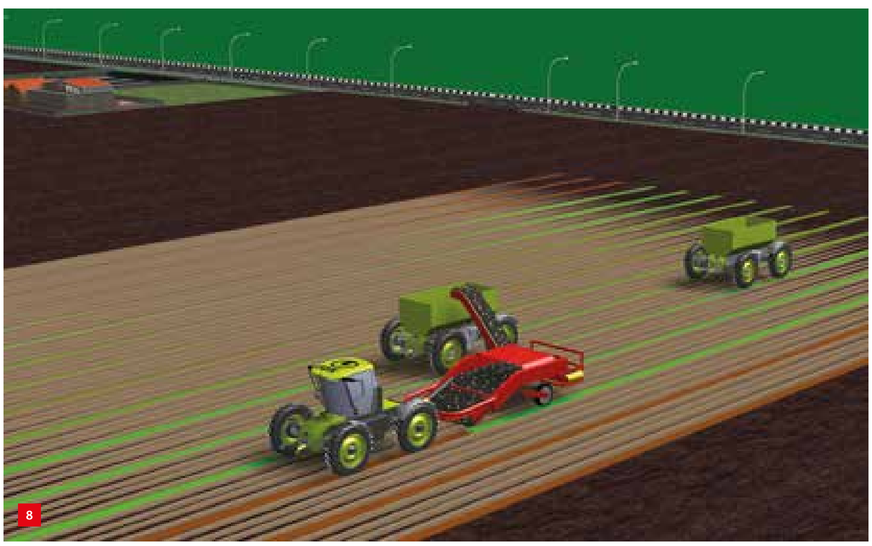
	FastDDS	Cyclone DDS	RTI Connext
FastDDS	Working	No client response	Working
Cyclone DDS	ASN.1 error	Working	Participant key error
RTI Connext	No client response	Participant key error	Working

mode. For the client-server mode, some RMW combinations did not work, and one only worked with a specific compatibility mode turned on. After enabling security, the number of supported publish-subscribe configurations were further reduced, with only two RMW combinations working with different publisher and subscriber implementations, whereas with client-server mode, only one combination of different client and server implementations worked.

Most of the interoperability issues seem to be the result of (too much) flexibility in the specification, rather than programming errors, although the latter cannot be ruled out. Some combinations are mentioned as non-working interoperability-wise on the official ROS2 website, whereas for other combinations, the issues were only discovered as part of our testing.

In the H2Trac use case, we allow for different fields, different crops, various technical specifications of chaser bins (speed, turning radius, capacity, availability of IoT (Internet of Things) sensors, etc.), and various dispatching and routing algorithms (e.g. when and where to switch from an (almost) full chaser bin to a new empty one). In this use case, we are interested in the utilisation of the harvester, total harvesting time and soil compaction; see Figure 8 for an impression of the current model.

Moreover, the simulation environment is useful for:
1. evaluating different (swarm-based) cooperative algorithms and AI techniques for planning and forecasting in terms of important farm KPIs (key performance indicators);
2. establishing insight into the added value of cooperative and advanced planning to build a business case;
3. engaging and inspiring stakeholders such as robot manufacturers, farmers, researchers and students to facilitate the development and uptake of cooperative robotics and digitalisation in the agri-food sector.



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Current field model for testing robot cooperativity in the H2Trac use case; see text for further explanation.

This simulation environment is thus mainly focused on selecting the right courses of action from a business point of view, but can also support technical development (e.g. what would happen to important KPIs if we increase battery capacity or robot speed?).

It goes without saying that the logistic and technical views are intertwined, as for example technical specifications may limit operational performance. A specific example is WiFi-coverage. When a robot is not able to communicate with other robots, cooperative behaviour may fail. In our simulation we can model various degrees of WiFi coverage and stability to assess the impact on operational performance under various design choices (e.g. central, hybrid or decentral control hierarchies).

Implementation
Based on the initial design resulting from discrete-event simulation, a detailed implementation step is done, taking robot kinematics and dynamics into account. While the discrete-event solution is mainly concerned with the functional architecture, the implementation needs to conform to the technical architecture. For example, the algorithms are being implemented as ROS2 nodes in Python, using a behaviour-tree approach (see Box 1). As ROS2 and its underlying middleware DDS (Data Distribution Service [12]) implementations are still evolving, an evaluation of the different solutions makes sense, especially when the security features are a must (see Box 2).

DurableCASE applies a scenario-based, continuous-time simulation environment that includes robot physics behaviour and the related real-time control algorithms. One of the powerful aspects of ROS/ROS2 is that the resulting implementation can be used both for verification on simulation level as well as validation in a practical environment, as ROS2 nodes can be deployed easily on the real hardware. In addition, this enables efficient iteration steps between practical tests and simulation activities.

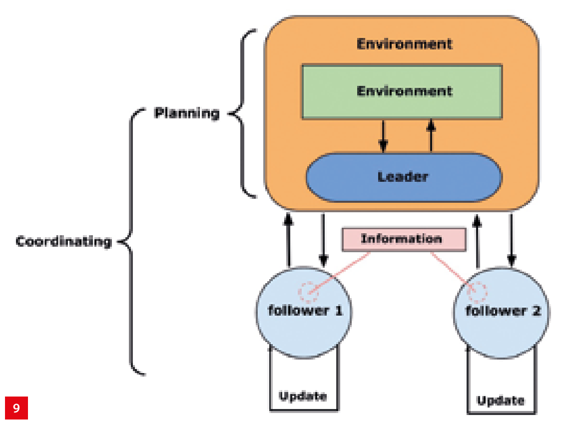
Box 3 – Performant: reinforcement learning-based leader-follower logistics

Up until now, most of the approaches for logistics planning of agricultural machines use heuristic algorithms. Moreover, most of the research focuses on one single machine. Since 2015, researchers have started to consider multiple machines, but are still limited to machines with the same functions; for example, using the multiple agrobots with the same function for sowing.

Instead of using traditional heuristic methods to solve a travelling salesman problem, as used in the initial design phase of DurableCASE, researchers from the Farm Technology Group of Wageningen University & Research propose a learning-based approach using leader-follower reinforcement learning. The proposed approach aims to explore the power of reinforcement learning (RL) in planning and coordinating generically, using a leader learner (harvester) and the joint follower learners (trucks or chaser bins).

In DurableCASE, we would like to explore what RL can bring to the logistics planning. The motivation is that the multi-agent harvesting system is not only complex with many factors, but also has high variability and uncertainties in geometry and application environment, so building a physical model is not easy. Besides, relying on one generalised model for different use cases is not realistic. Moreover, future harvesting systems need to become more automated with minimal human involvement, so the logistics principles need to be adaptive and able to handle uncertain incidents during the application. All these challenges require the application of a learning-based approach, which is adaptive and can keep improving during running.

For logistics planning, we will use the leader-follower RL architecture as shown in Figure 9. First, we will build, in this architecture, an RL agent for leader machine planning.



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The leader-follower RL architecture: centralised training, decentralised execution.

Through trial & error we can then obtain an optimal planning. In this task, the arable farm is considered the environment. Afterwards, we will define joint RL agents for the follower machine, in this case the chaser bin, to obtain optimal manoeuvres of the chaser bins in order to coordinate with the harvester motion; this coordination can also include the ability to handle an unexpected malfunction of chaser bins. In the coordination step, both the arable farm and master agent will be considered the environment.

In this architecture, the coordination mechanism we use can be called 'centralised training, decentralised execution', where at each time step the leader can receive local information from followers and share its internal state in return. The follower agents can share information with each other as well. In DurableCASE, we use the Siemens Plant Simulation software for the virtual-reality description of the environment. The KPIs we consider are soil compaction, harvester utilisation, energy usage and operation time.

Verification and validation

In DurableCASE, a first verification of whether the implemented design fulfils the set requirements is performed at simulation level. For this purpose, the DurableCASE SDE (Software Development Environment) working group defined workflows for MiL (Model-in-the-Loop) testing and HiL (Hardware-in-the-Loop) testing using a scenario-driven approach. The idea is to come to a DevOps-style environment in which the evolving algorithms are automatically tested in a simulation environment executing a growing database of scenarios. Practically, the simulation environment is used as a development tool as well as a quality assurance tool. This approach is taken from the automotive SOTIF standard (ISO 21448), which describes how to ensure safety of the intended functionality in a complex practical environment.

The MiL workflow is a simulation-only workflow, used as a supporting tool for the first implementation and verification. The HiL workflow combines simulation with real-world hardware and can be used for initial validation: checking whether the solution is proving the desired functionality in practice. DurableCASE foresees two validation steps for having maximal flexibility with minimal cost: initial validation in a scaled laboratory environment, followed by full-scale validation in the real application environment.

The scaled lab environment requires integration of the algorithms in physical hardware, so it uncovers many integration challenges and unforeseen practicalities. At the same time, it is easily available, relatively cheap and flexible to adapt.

The more the lab environment replicates the real world, the more the integration and validation represents that of the final product. Therefore, scaled robots are used with realistic kinematics and control interfaces. For the barn cleaning use case, Lely provided scaled development robots that have the same controller hardware, with the same software interface as the normal robots. For the harvest-unloading use case, HAN University of Applied Sciences student teams developed scaled H2Trac robots with the same fully flexible 4-wheel drive and steering capabilities as H2Trac's real EOX 175 tractor. The robots also include the proposed EOX 175 ROS2 automation interface on top of the vehicle control software to emulate the real vehicle as closely as possible.

The lab is instrumented with an OptiTrack system to emulate GNSS (global navigation satellite system) positioning equipment. In DurableCASE, the cooperative algorithms (see Box 1, describing the related software agents) are partly integrated into the scaled robots and partly into a PC, simulating aspects that cannot be physically emulated at scale. This allows for emulating and testing cooperative scenarios in a safe, scaled way.

Demonstration

Full-scale validation and demonstration are the only real 'proof of the pudding'. Being a research project with limited funds for real-life testing, DurableCASE places a strong focus on simulation-based verification and lab-scale validation. Nevertheless, a full-scale demonstration will occur, especially with the barn-cleaning use case. By preparing as well as possible with simulation and integrated laboratory tests, we hope to minimise the remaining work required at full scale. Thus, the full-scale robots as well as the lab-scale versions use the same ROS2 interface.

Conclusion

Developing mobile robot control software is supported by using the right processes for the right purpose. In an early phase, discrete-event simulation helps in high-level design and performance analysis supporting the product's business case. In a later development stage, more detailed continuous-time simulations help to develop and verify the robot (cooperative) control algorithms. When implementing using ROS/ROS2, algorithms can be re-used for simulation as well as on the robot. An experienced partner network helps in making the right choices in this respect.

A framework for agrobot cooperativity needs to address requirements regarding safety, security and performance. ROS2 creates a good foundation to address 'safe' and 'secure'. Implementing the software agents in the framework using behaviour trees further supports this, as they modularise robustness and safety in robot control software [9]. Cooperative mobile robot solutions require good logistics planning. Discrete-event simulations help in developing good planning algorithms. Heuristics-based algorithms have already demonstrated that cooperative robot behaviour is more 'performant' than that of non-cooperating robots. Reinforcement learning-based planning might further improve this.

When DurableCASE is in the implementation phase, more specifics can be shown of the expected solution. The consortium seeks interaction with market parties, either developers or end-clients, to discuss the current approach and adapt it when necessary.

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REDUCING TIME-TO-FIELD

Dutch start-up AgXeed developed the AgBot, a fully autonomous tractor for sustainable agriculture. The company selected Nobleo Technology to develop the AgBot's autonomy software and make sure the AgBots are able to successfully complete the tasks that they receive from a cloud portal. Nobleo Technology created a digital twin of the AgBot to facilitate testing. It was demonstrated that virtual testing saves development time and costs.

FERRY SCHOENMAKERS, TIM CLEPHAS, CÉSAR LOPÈZ AND FRANK SPERLING

Introduction

Nowadays, farmers face multiple challenges. One of these is to feed an ever-growing population by producing food and fibre. To do this, a lot of fieldwork has to be performed within short time frames. The lack of capacity, labour and time has resulted in farmers using bigger and heavier tractors to get the work done in the limited time they have. Nevertheless, the lack of capacity and labour keeps on growing. Another problem is that these heavy machines compact the soil and make it hard for new crops to grow. The yield per hectare of the farm field is reduced, which makes the challenge of producing enough food even harder.

AgXeed [1], a Dutch company founded in 2018, believes the solution to these challenges lies in the introduction of fully autonomous tractors. With today's technologies it builds and sells AgBots (Figure 1), fully autonomous robots, made for doing all kinds of fieldwork. Together with these machines, it also offers a cloud portal to plan the tasks for these AgBots, as well as gather data during the process, and provides the user with more insights than ever about the status of their farm fields and crops.

As the AgBot has been designed from a blank sheet of paper, it does not carry legacy from existing traditional tractors. It does not have a cabin, seat, steering wheel, suspension system, transmission or air-conditioning, and hence is a lot less complex without these systems. Furthermore, this saves weight, while AgBots can even be fitted with tracks to distribute ground pressure and further reduce soil compression. Since the robots are able to cultivate, plough, drill and perform many other field operations without user intervention, farmers or workers save valuable time which otherwise would be spent sitting in the tractor.

The current team behind AgXeed has over 70 years of combined knowledge and experience in the development of agricultural equipment. Moreover, they recently joined forces with Claas [2], a well-known German agricultural machinery manufacturer. AgXeed partners up with best-in-class companies to develop their solutions and has selected Nobleo Technology for their broad knowledge and experience in the development of autonomous machines. Nobleo Technology has been involved in the project since 2019, to develop the AgBot's autonomy software and make sure the AgBots are able to successfully complete the tasks that they receive from the cloud portal.

AgBot design

The AgBots are fully electrified, although a diesel engine is the main power source of the machine. The diesel engine directly drives a generator to generate 700 V_{DC}. Battery packs or hydrogen fuel cells are too big and heavy for the machine's power demand at the moment, but might be a future replacement for the diesel engine.

Traction inverters in turn create 700 V_{AC} to drive the electric motors in the tracks. The electrification allows for precise control of the speed and direction of the vehicle and thus accurate path tracking. In addition, it also enables more control of the implements connected to the tractor. The 700 V_{DC} can be shared with attached implements that are also electrified and may be regarded as 'smart'.

A communication bus between tractor and implement allows for accurate actuation of the equipment, while variables such as actual speed can be communicated to facilitate a good quality of work every time. A worldwide standard known as ISOBUS (ISO 11783) is commonly used and hence is implemented in an AgBot, which allows

1 AgBot cultivating fodder radish, an annual green manure.

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An electrified Imants spading machine attached to an AgBot.

AgXeed's tricycle for fully autonomous spraying in orchards.

for quick integration with existing agricultural machinery. ISOBUS is delivered over a Controller Area Network (CAN) bus. CAN, a popular, robust communication bus used in the automotive and other industries, is also the main communication bus in the AgBot itself.

Another option available on the AgBot is an electrified power take-off (PTO). A PTO on a conventional tractor allows for a mechanical coupling between the tractor's gearbox and the implement to actuate it. With an electrified PTO, the speed of rotation can be set precisely, independent of the diesel engine's rotation speed, while still providing the conventional mechanical coupling for existing implements.

The AgBot is also equipped with standard 3-point hitch systems on the front and back. This allows a farmer to use the equipment he already has in his shed, for example a spading machine (Figure 2), avoiding the need to invest in new implements.

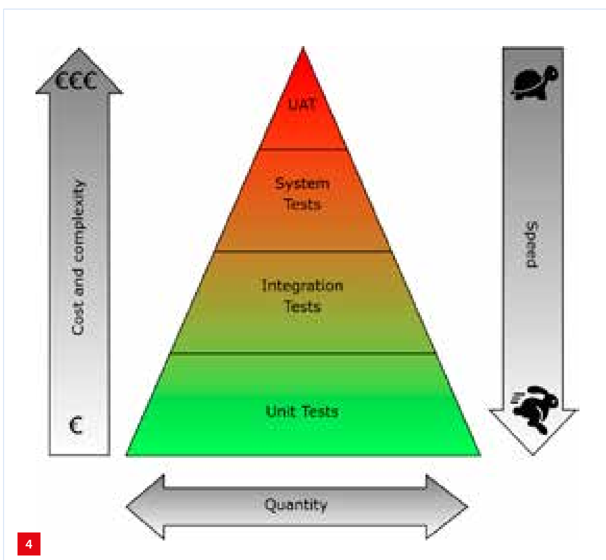
For localisation, one of the main sensors is an RTK GNSS system. Where a traditional GNSS (global navigation satellite system) at best can achieve sub-meter precision, an RTK GNSS system allows for centimeter-level precision. RTK here stands for real-time kinematic positioning and uses several correction techniques to correct for common errors in a GNSS. US-owned GPS is one of the best known GNSS systems. Glonass (Russian), BeiDou (Chinese) and Galileo (EU) are similar GNSS systems. Modern receivers are able to utilise all these systems simultaneously. In addition, using multiple receivers enables even greater accuracy, fail safety and improved orientation estimation. In addition to localisation sensors, sensors for collision avoidance are also installed to make sure collisions with trespassers or unplanned obstacles are prevented.

As well as the tracked version of the AgBot, a 3-wheeled, front-steered version (a tricycle) has also been built for full autonomous spraying in fruit orchards (Figure 3). While the application might seem completely different to performing fieldwork, the purpose of autonomously following a pre-planned path very accurately is also key here.

Digital twin

While solving some challenges of the farmer, developing complete autonomous machines poses a lot of challenges on its own. Testing is of vital importance during this development but also thereafter. And testing is a very broad concept. Consideration can, of course, be given to the testing of an assembled AgBot as a system: does it work, is it able to fully autonomously cultivate a field? But testing modules should also be considered. Efficient running of the diesel engine, maximum torques in a gearbox, and lifetime of a track are a few of the hardware-related tests. Communication with the cloud portal, correct start-up of all electronic control units (ECUs), processing GNSS and encoder and inertial sensors for precise localisation in the field are a few of the tests involving software.

Here, the focus is on the development of a 'digital twin' by Nobleo Technology to assist with testing. All the testing mentioned above consumes a lot of valuable time and hardware. In software development, automated tests are



Typical testing pyramid.

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Snippet of a task planned in the cloud portal.

a well-known concept. When a programmer creates even the smallest changes to the source code, typically a lot of tests will automatically evaluate this ‘delta’ and notify the programmer of errors. These tests can evaluate small pieces of the source code in so-called ‘unit tests’, but also multiple blocks of source together in so-called integration tests.

Even further down the road, a system test could be defined when a test engineer puts an AgBot on the field and tests the complete set of hardware and software systems together. The final user acceptance test (UAT) could then be considered a final test when a customer accepts the delivered system. This ‘testing pyramid’ is depicted in Figure 4.

Figure 4 also shows the relationships between cost, speed, quantity and the level of testing. Unit tests are small and can be executed rapidly in multiples with little cost since a unit test can run on a cloud computer automatically. While a final test with the complete system takes a lot of time and money, because it requires a test engineer, a field and time to complete work on this field.

One way of saving resources can be to use a virtual version of this system for testing. This is where the digital twin comes into play. A digital twin is a virtual copy of an AgBot, in this case consisting entirely of software. Such a digital twin allows for testing at the level of a system test with the cost and speed of unit tests.

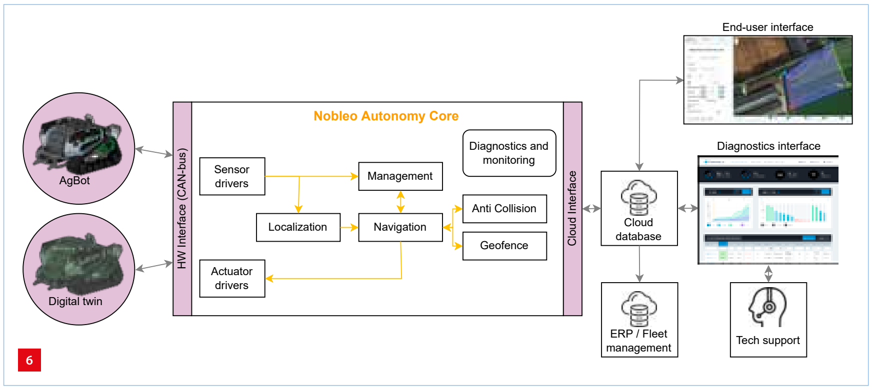
When an engineer wants to test the latest software release on a digital twin, he can do so while sitting at his desk. The engineer will start to plan a complete task in the cloud portal (Figure 5). This cloud portal was developed by another partner of AgXeed, i.e. Phact [3].

This is exactly the same tool as used for planning tasks of real AgBots. When the task is now sent to the machine, the digital twin will receive it and start executing the task in a simulation. Doing so, it will run an exact copy of a real AgBot’s software, thereby testing every software component, as well as communication between cloud and (virtual) AgBot. The simulation will also simulate sensor input for GPS sensors, inertial sensors, encoders and anti-collision sensors.

To the extreme, Nobleo’s digital twin of the AgBots even runs a complete virtual CAN bus. Small digital copies of the ECUs send and receive data on this virtual CAN-bus. This means that for the largest part of the software stack, there is no notion of whether it is running on a real AgBot or in a simulation environment. All low-level component drivers are thus also included in a digital twin test. While executing its task, the digital twin will send progress and sensor data back to the cloud, exactly in the same way that a real AgBot does so. A test engineer can thus monitor progress while still sitting at his desk. If desired, this engineer can even analyse CAN-bus traces from a digital twin as if it was from a real AgBot.

Since digital twins are software copies of AgBots, they scale easily; multiple digital twins, running in the cloud, can easily be created. This allows for simultaneous testing of several scenarios, for example a Phact engineer testing a new feature in the cloud portal, one AgXeed engineer testing a task on a tracked version of the AgBot and another testing task execution of a tricycle AgBot in an orchard.

A schematic overview of the software architecture is depicted in Figure 6. It clearly shows the identical software stack ‘Nobleo Autonomy Core’ being used on both a real AgBot and a digital twin. Sensor data comes into the software stack that is used for precise localisation. A task comes in via the cloud interface, which is processed by the management module that orchestrates correct navigation.



Schematic of the AgBot software architecture.

Finally, output is given to the actuators to make the AgBot move. Several signals and states are continuously monitored and sent to the cloud for remote monitoring, while they are also processed locally, for example in an anti-collision and geofence module.

Connecting a real AgBot or a digital twin occurs at the level of the hardware interface, which is the CAN-bus here. On the other hand, cloud software is connected to the Nobleo Autonomy Core in either a real or a virtual AgBot identically. Task planning, monitoring of the task's progress, all is available in the cloud without a distinction being made between a real AgBot and a digital twin. Figure 7 gives an impression of a digital twin in action.

Currently, such a digital twin is in use by Wageningen University & Research for academic explorations in path planning. This digital AgBot facilitates quick evaluation of planning algorithms with the full cloud portal integration but without the need for real hardware on the field. At the same time, however, testing on a real AgBot is just the click of a button away.

Digital twin in action, processing the task created in Figure 5.

In the near future, it will also be easy to test collaborative tasks between multiple digital twins. This could be a feasible scenario when very large fields need to be cultivated within a short time for example, or when AgBots need to work together with harvesters.

Conclusion

It can be concluded that testing with digital twins has a lot of advantages. Many tests can be performed quickly, saving time and requiring no engineers on site. Tests are run virtually, so there is no need for expensive hardware or the availability of fields, thus saving costs as well. And it is even possible to test tasks globally, without the need to actually transport an AgBot globally.

Obviously, real-life system tests are still needed in the end to test for things that are not easily tested digitally, such as mechanical load, electrical wiring and lifetime. But using digital twins can save a tremendous amount of time and money and identify issues early on before experiencing them in the field.

At the moment, some of the digital twins are actually performing virtual fieldwork. During development of the AgBot, the digital twin has proven to be extraordinarily useful. Roughly nine months before the first AgBot started its engine, the digital twin was already driving in the cloud, testing the complete software stack and cloud integration. In these nine months it already performed approximately 400 hectares of virtual fieldwork. The result was a first real-world test with a real AgBot within two weeks of the engine being initially started. At the moment, the first series of AgBots is being built. They are scheduled for their first autonomous jobs at the customer this summer.

Without all the digital testing beforehand, this would not have been possible in this amount of time. Continuously testing every bit of software up to the level of a virtual CAN bus, ensured that a lot of bugs were solved long before the first field test took place. And today, the digital twin gives confidence in rolling out software changes to real AgBots when these have been successfully tested virtually.

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NANOMETER PRECISION IN PRACTICE

In 2020, Nobby Assmann won a Zeiss #measuringhero Award for the smallest measured object on a coordinate measuring machine: 0.4 mm x 0.4 mm x 0.03 mm. The next year, he won another award, this time for the smoothest surface, with a surface roughness of R_a 540 pm and R_z 3.1 nm. The surface was finished by lapping, flat polishing and chemical mechanical planarisation; three extremely precise processes. What exactly are these processes and what is it that drives this technician?

Profile of a precision winner

Nobby Assmann (1978) runs a precision toolroom in Zevenbergen (NL); Assmann Verspaningstechniek. The company provides manufacturing processes that go beyond the usual CNC turning and milling. Nobby (Figure 1) is supported by his parents, while the company does not have any employees. Since 1998, he works in the family business that his parents founded in 1985 in the small garage behind their home. Currently, the company covers a 500 m^2 facility for wire-EDM, die-sinking EDM, lapping, honing, cylindrical grinding and surface grinding. The company also has a measuring lab for contract measuring jobs. Nobby holds a bachelor's degree in mechanical engineering.

1

Nobby in front of his largest lapping machine, with a lapping disk of 1 m.

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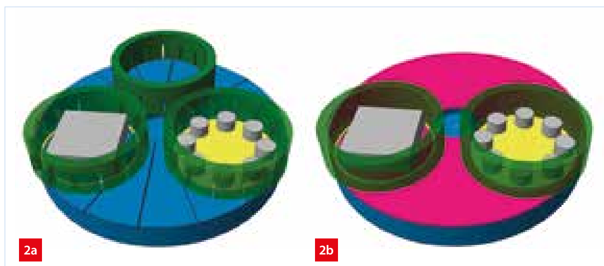
Of all the finishing processes, lapping – rubbing two surfaces together with an abrasive between them – is the most precise, explains Nobby Assmann. "I remember a table about expected tolerances for different techniques from coarse to fine. It began with milling and turning – which was IT (International Tolerance) grade 7 to 10. Then came grinding: IT grade 3 to 7. Lapping was at the very bottom with IT grade 1 to 3. That really drew my attention." A few years later, he bought his first lapping machine.

Back then, the company already performed wire-EDM (electrical discharge machining), die-sinking EDM, grinding and honing. It seemed to be a small step towards lapping. But it wasn't: lapping really is something else. It takes more patience and a whole lot of experience, according to Nobby. "Lapping is a true craft. It might be hard, but it is very rewarding in the end." See Table 1 and Figure 2 for the various finishing processes.

Applications for lapping

Only few people are familiar with lapping and its benefits. What is it for and why? The most common example of lapped surfaces can be found in mechanical seals. Two ring-shaped surfaces are pressed together; one stationary and one rotating. The surfaces must have a superior flatness and surface, or the seal will leak.



2a 2b

Schematic comparison of lapping versus polishing and CMP.
In gray, the workpieces (one large and multiple small);
in yellow, the workpiece holders.
(a) Lapping.
Blue: lapping disk.
Green: lapping rings.
(b) Polishing and CMP.
Pink: polishing pad.
Note that the green rings are not serrated.

EDITORIAL NOTE

This article was contributed by Assmann Verspaningstechniek.

Table 1
Properties of various finishing processes.

Process	Abrasive	Liquid	Disk
Conventional lapping	1-20 µm corundum	Oil	Cast iron (hardened)
Diamond lapping	1-20 µm diamond	Oil or water	Epoxy mixed with metal particles
Polishing	1-8 µm diamond	Oil or water	Flat carrier disk with adhesive polishing pad
Chemical mechanical planarisation (CMP)	10-100 nm silica	Etchant	Flat carrier disk with adhesive CMP pad

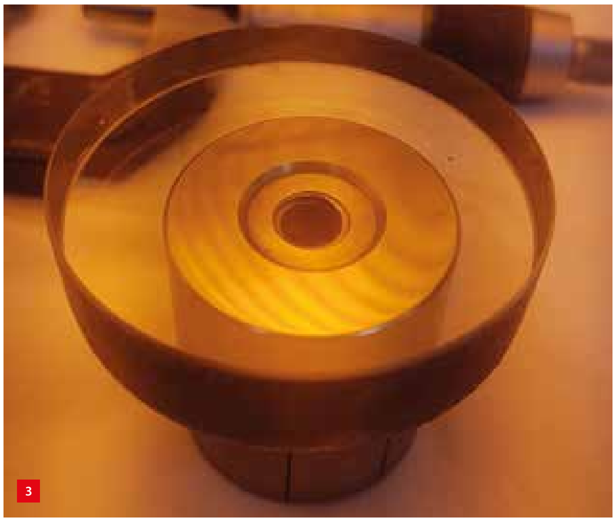

4
Polishing pads come in a large variety: wool, polyurethane, artificial silk and many more. The hardness and thickness of the pad are important parameters. Different types have their own colour for easy recognition.

Also, many precision components are lapped. The increasing precision of turning and milling machines cannot keep up with the industry's current hunger for precision. Sometimes grinding and EDM might be a solution. But true precision is only obtained by lapping. Flatness values under 1 µm are common. Surfaces roughness is often below R_a 100 nm.

Measuring extreme flatness

Even the most accurate coordinate measuring machines can not measure the flatness of a lapped plane. Their measuring uncertainty is simply too high. Flatness values under one micron are measured optically – using an interferometer. That compares the flatness of a workpiece to a reference with a known flatness. This reference usually is an optical flat: a glass disc with a flatness under 50 nm. The measurement is taken without contact between optical flat and workpiece.

With lapping, the optical flat is often placed directly on top of the lapped surface. Under monochromatic light, fringes appear (Figure 3): a pattern of lines, alternatingly dark and bright. This is the most basic form of an interferometer. The flatness of the workpiece reads from the straightness of the fringes. The straighter they are, the flatter the workpiece. In order to see the fringes, the surface must reflect light. This occurs below a surface roughness of about R_a 100 nm.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Flatness measurement with an optical flat laying on top of a lapped workpiece. The fringes indicate a flatness of 500 nm. The orange colour derives from the 589-nm monochromatic light used in the measurement.

Another application for lapping is improving the flatness of precision parts that are non-magnetic. Surface grinding machines usually have a large magnet to hold the parts – which is ideal for steel parts. Nobby: "Often clients ask me to improve the flatness of parts of aluminium, titanium or austenitic stainless steels. They expect me to grind their parts. When I tell them lapping is easier, faster and therefore cheaper, the client is happily surprised." Lapping has a unique way of holding the parts: they lie freely on top of the lapping disk. Only roughly held in place by a work holding plate. This way, there are no clamping forces on the workpiece – in contrast with the use of a machine vice or a three-jaw chuck. No clamping forces means no deformation and that is the basis for extreme precision.

Conventional lapping and diamond lapping

When grinding, the abrasive is held by the grinding wheel. With lapping, the abrasive is free, suspended in a liquid. Rubbing two items together with some abrasive lapping fluid in between them, will cut both items. The same happens with a workpiece and the lapping disk. This constantly jeopardises the flatness of the lapping disk.

This flatness is crucial since the workpieces are a 'reflection' of the lapping disk's flatness. If the disk is convex, the workpieces will turn out concave and vice versa. To keep the lapping disk flat during lapping, three or four lapping rings continuously rotate on top of the lapping disk, slowly cutting the lapping disk flat in a controlled manner. In case the lapping disk would turn convex, the operator moves the rings' centres of gravity a few millimeters towards the centre of the disc. In that way the disk turns flat again. Nobby summarises: "The most important thing during lapping is the flatness of the lapping disk. The better it is, the flatter the workpieces will turn out."

The abrasive is usually corundum or silicon carbide. Lapping disks used to be made of metal – often hardened cast iron. A revolution came about 40 years ago: diamond lapping. The ceramic abrasive was replaced by diamond, while the metal lapping disks were now made of epoxy containing metal particles. The epoxy disks are available with different metal particles, such as iron, copper or tin, which results in a different hardness. A lapping disk with high hardness is more wear-resistant and is therefore used for coarse lapping. Softer lapping disks, giving a better workpiece finish, are used for finishing operations.


6
Nobby Assmann placing the winning workpiece on the Zeiss LSM 900.

Both conventional and diamond lapping will give a perfect flatness. Additionally, diamond lapping will give a bright finish. That is because the epoxy disks will hold some diamond grains that will polish the surface. With conventional lapping all the abrasive grains will roll between the lapping disk and the workpieces – just like rolling meat balls. This results in a dull surface. Nobby: "Both have advantages; I use conventional lapping for roughing and diamond lapping for finishing." Cleaning the parts between operations is highly important. Coarse grains from roughing might cause unwanted scratches during finishing.

Flat polishing

Diamond lapping easily gives a surface roughness of R_a 25 nm or better. Further improvement by diamond lapping is often time-consuming and costly. An easier way is flat polishing. The lapping disk is then replaced by a flat carrier disk covered by a self-adhesive polishing pad (Figure 4). This process resembles lapping – apart from the abrasive, which is held by the polishing pad. It is just like polishing a car's paint or your grandmother's silver cutlery.

Flat polishing is a quick and easy way to improve the surface finish. The flatness, however, will not improve and, in fact, can get worse. Since the workpiece is pushed into the soft polishing pad, the edges of the workpiece will round off. It is up to the operator to try and limit the rounding of the edges. Just like with lapping, flat polishing is performed in multiple stages: from coarse to fine. Grain sizes are usually between 10 and 1 μm. After polishing, the surfaces are bright and shiny, but under a microscope cutting marks can still be seen.

CMP for optical surfaces

Improving the surface roughness of a shiny polished surface requires chemical mechanical planarisation (CMP). This is similar to flat polishing, on a polishing pad. The abrasive is suspended in an aggressive fluid that etches the surface while polishing. Grain sizes typically are 10 to 100 nm – often silica or corundum.

The part that Nobby won his second award with [V1], was ultimately polished using CMP – after surface grinding, conventional lapping, diamond lapping and two stages of flat polishing; see Figure 5 for a comparison of the results of the various processes. The surface roughness of R_a 540 pm is extremely low. For optical surfaces, though, this is a fairly common roughness. It is the material that made Nobby's effort extra special, since the complicated structure of hardened tool steel is far from ideal. Homogeneous and single-crystal materials give the best roughness, while glass has an amorphous structure, which makes it ideal for polishing – that is why glass is often used for lenses.

A typical CMP application is polishing wafers for the semiconductor industry. Materials such as silicon, silicon carbide and sapphire have a very high hardness and a homogeneous composition. Surface roughness values below 2 nm are very common.

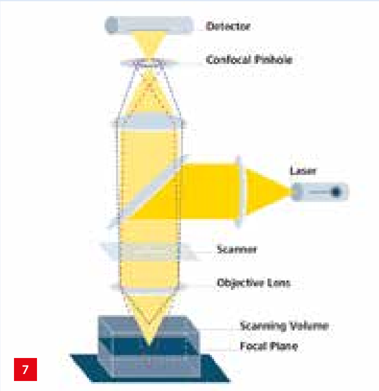

5a

5b

5c

5d

A comparison the results of the various processes.
(a) Conventional lapping. (b) Diamond lapping. (c) Polishing. (d) Chemical mechanical planarisation.



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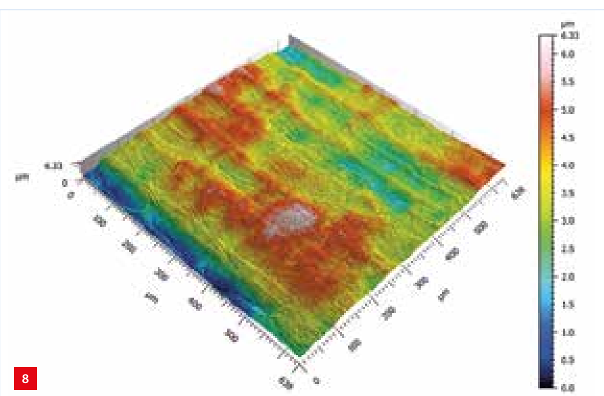
Working principle of the laser scanning confocal microscope Zeiss LSM 900 for materials. (Image courtesy of Zeiss)

Measuring extremely low surface roughness

Many machine shops measure roughness with a surface roughness tester. Such a device scans the surface using a 60° diamond cone with a tip radius of 2 μm or more. It measures milled, turned and most ground parts just fine. For nanometer surface roughness, however, the tip is just too blunt and the resolution of the device is just not good enough.

Atomic force microscopy and confocal microscopy are more appropriate to measure polished surfaces. "The roughness had to be measured on a Zeiss device, for the competition," Nobby says. "And by the way, glass was not allowed as workpiece material." He had the surface roughness measured on a laser scanning confocal microscope, the Zeiss LSM 900 (Figure 6). It scans the surface using a laser (Figure 7), taking pictures at several heights with a very small depth of field. Software uses this stack of pictures to reveal the 3D topography (Figure 8).
The Zeiss ConfoMap software easily calculates the roughness of the surface. Since it is an area that is inspected, these are all *S*-type surface roughnesses: S_a and S_z, for instance. Part of the Zeiss competition for the smoothest surface was that R_a and R_z should be calculated along a line of at least 1.25 mm. ConfoMap can also calculate *R*-type roughnesses after a line has been drawn manually on the inspected area. In Nobby's case a zig-zag line of 3.4 mm length was used to calculate the winning R_a and R_z values.



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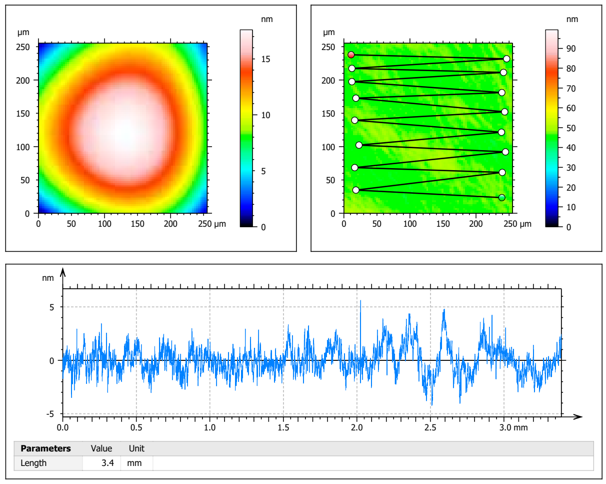
3D topography scanned with the Zeiss LSM 900. ConfoMap software can calculate surface roughness from this image. (Image courtesy of Zeiss)



Parameters	Value	Unit
Length	3.4	mm

ISO 4287 - Roughness (S-L)				
F: None				
S-filter (λs): Gaussian, 2.5 μm				
L-filter (λc): Gaussian, 0.08 mm				
Evaluation length: All λc (42)				
Amplitude parameters				
Rp	1.5	nm		Maximum peak height of the roughness profile
Rv	1.6	nm		Maximum valley depth of the roughness profile
Rz	3.1	nm		Maximum height of roughness profile
Rc	1.7	nm	No averaging (single value)	Mean height of the roughness profile elements
Rt	5.4	nm		Total height of roughness profile
Ra	0.54	nm		Arithmetic mean deviation of the roughness profile
Rq	0.67	nm		Root-mean-square (RMS) deviation of the roughness profile
Rsk	-0.059			Skewness of the roughness profile
Rku	2.7			Kurtosis of the roughness profile
Material ratio parameters				
Rmr	100	%	c = 1000 nm below highest peak	Relative material ratio of the roughness profile
Rdc	1.1	nm	p = 20%, q = 80%	Roughness profile section height difference

9

Measuring report of the winning workpiece. Top left: the scanned surface. Top right: waviness filtered out, and a manually drawn zig-zag line included. Middle: roughness profile along the zig-zag line. Bottom: measured surface roughness.

"I am really impressed by the microscope's resolution," Assmann comments on the LSM 900. "With an optional accessory it is even possible to extend the resolution far below one nanometer. This option uses total interference contrast to measure R_a roughness of only tens of picometers. Figure 9 shows the final measuring report.

Lapping: future or history?

Lapping is a very old technique – it looks rather old-fashioned. Is there room for such a labour-intensive classical production method in our digital future? Manufacturing seems to be limited to CNC turning and CNC milling these days. Cylindrical grinding is occasionally replaced by hard turning. Jig grinding seems to be forgotten – precision CNC milling is said to reach the same level of accuracy.

Still, there is not a single finishing method that achieves the form accuracy of lapping. And no other process can achieve the roughness of polishing. Our industry's future will depend on lapping, polishing and CMP. Besides the modern CNC machines with their flashy controls, there will always be demand for craftsmen (male or female) who know the art of lapping and polishing. "The lapper/polisher is a rare species in the metalworking habitat," Nobby concludes. "You might recognise one by the dirty hands and a satisfied smile when the work is done."

VIDEO

[V1] "2021 measuringhero awards", *youtu.be/6YsMfFBQmJM*

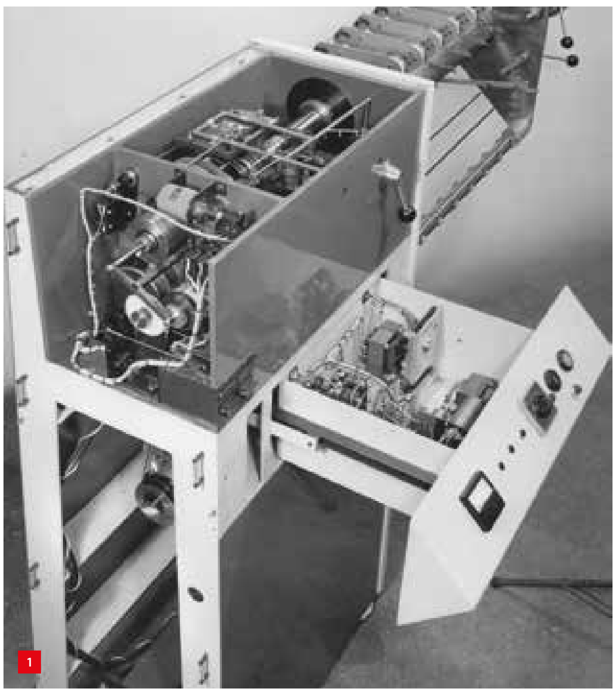
MECHANISATION AND MANUFACTURABILITY

Wim van der Hoek's concept of light, stiff and statically determined mechanical design originated from his work in Production Mechanisation at Philips. The manufacturability of Philips's mass products required machines that were realised according to his design principles. Until a very advanced age, Van der Hoek continued to study production and manufacturability issues. This second in a series of articles covers his views on mechanisation and manufacturability, as described in DSPE's Dutch-language book "Wim van der Hoek (1924-2019) – A constructive life".

Production Mechanisation...

When Van der Hoek joined Philips in Eindhoven (NL), in 1949, he started working in the department of *Bedrijfsmechanisatie* (Production Mechanisation, or PM) of the *Apparatenfabriek* (Appliances Factory), later the *Hoofdindustriegroep* (Main Industrial Group, or MIG) RGT (Radio, Gramophone and Television). Each MIG had its own PM, tasked with supplying the factories with means of production, specific to the Philips products.

In the case of incandescent lamps, fluorescent tubes and electronic components (carbon resistors, capacitors, electron tubes, imaging tubes, transistors), the numbers per type were very large (up to many millions) and their lifecycle was up to several years, so mechanised production was definitely worthwhile. In addition, high demands were placed on electronic components concerning the reproducibility of their physical characteristics and external dimensions.



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One of the many designs by Van der Hoek and his colleagues from Production Mechanisation at Philips: a winding machine for choke coils.

These kinds of specifications and the large numbers of products produced per hour were only achievable by using advanced machines. Philips had to design and manufacture its means of production itself (Figure 1). A PM department would create production machine designs and build prototypes, while the serial production of the machines and the manufacturing of the tools took place in Philips Machinefabriek M in Eindhoven.

...or Automatisation?

Around 1955, the name 'Production Mechanisation' came under discussion. Wasn't 'Automatisation' a better name? Van der Hoek listed the pros and cons in a note, beginning with a description of Greek words such as 'automatos' and 'mèchanè'; here, the scholar in him emerged for a moment. In his opinion, the concept of 'mechanisation' remained too restricted, especially for outsiders and foreigners, to 'arms and legs machines', while it lacked the glamour of the fashionable concept of 'automatisation'.

However, automatisation only comprised part of the tasks of PM, Van der Hoek argued. After all, consultation with product designers or production departments could lead to improvements in product design or production process without the need for investments in automatisation. "Automatisation must be seen as an evil (i.e. an investment), which is necessary for the time being due to the inadequacy of the required state of the art, the imperfection of the product design or the scarcity of common sense." Later, he even stated that the fact that designers and PM engineers only managed to achieve efficient production with expensive machines was to be considered as "a proof of our limitations". "The best mechanisation is doing nothing! – omitting work is an art that must be practised more and more."

2

The CVT (left) and a pushbelt, made up of loops and steel elements. (Images courtesy of Bosch Transmission Technology)

Manual dexterity

At the end of 1961, Van der Hoek was appointed part-time professor in the chair of Design and Construction at Eindhoven University of Technology. The following year, he gave his inaugural address, entitled "Constructing as a confrontation between critique and creation", in which he paid a lot of attention to the desired qualities of a mechanical designer. "You have to *be* a designer first, then you have to try to *become* one, and then comes the hardest part: trying to *stay* a designer."

According to Van der Hoek, being a designer was a matter of innate talent with a receptiveness to the beauty of technology. Becoming a designer required a good education in the practical and scientific foundations. He attached great importance to that practicality: the knowledge of manufacturability, the understanding of production technologies and "the simple manual dexterity to select and use the right tools in the drafting room, laboratory and workshop". This practical skill should connect the young engineer in a business and personal sense with the people with whom they would be working. Moreover, *penser avec les mains* could stimulate sometimes too-sterile thinking.

Pushing production

Thinking about mechanisation and manufacturability continued to be a theme in Van der Hoek's career, even after his retirement in 1984. As a 'pensionado', he was a part-time consultant with Van Doorne's Transmissie (VDT) in Tilburg (NL) for twelve years. VDT was in dire straits at that time, as the production of the pushbelt for its continuously variable transmission (CVT) was causing constant headaches. The heart of the CVT was a so-called variator, consisting of two pulleys over which ran a pushbelt (Figure 2). The pulleys had an infinitely variable radius for regulating the transmission ratio. The pushbelt was made up of hundreds of steel elements, strung together along two steel loop packs. A brilliant design, but nigh impossible to produce in large numbers with reproducible high quality.

Van der Hoek helped VDT to fathom the functioning of the pushbelt and scale up production. He did this in his characteristic style, as one R&D employee recalled. "Of course, we came up with many theories and discussed them with Wim regarding the operation of the pushbelt. We thought in terms of forces, speeds, displacements and deformations, and in doing so, completely in accordance with Wim's doctrine, managed to 'empathise' completely with the pushbelt, wondering how an element or a loop felt as it made its rounds through the variator."

In 1995, just before he retired as a consultant, the company passed into the hands of the large German automotive supplier Bosch and became Bosch Transmission Technology. At that time, they were producing about 250,000 pushbelts per year – in 2019 the company passed the milestone of 75 million in total. Wim van der Hoek had helped to 'produce' this success.

"Wim van der Hoek (1924-2019) – A constructive life"

After the passing away of Wim van der Hoek, in early 2019, DSPE took the initiative to publish a book (in Dutch) about the Dutch doyen of design principles (Figure 3). It covers his formative years, including World War II 'adventures', his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion. It concludes with his busy retirement years in which he continued to tackle design challenges, technical as well as social, believing that technology should support people.

His specialism, dynamic behaviour and positioning accuracy, was the main subject of his part-time professorship at Eindhoven University of Technology, from 1961 to 1984. There, he endeavoured to enthuse first-years in the mechanical engineering profession and to teach fourth-year students (some 600, over the years) mechanical design. In his lecture notes, he built on his research at Philips. He collected examples of designs that were lightweight, sufficiently stiff and play-free with regard to dynamics in his famous "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP), which he presented as a source of inspiration for upcoming and experienced designers. Now, this book about Wim van der Hoek conveys the same enthusiasm.

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Lambert van Beukering & Hans van Eerden (eds.), "Wim van der Hoek (1924-2019), Een constructief leven – Ontwerpprincipes en praktijklessen tussen critiek en creatie", ISBN 978-90-829-6583-4, 272 pages, €49.50 (€39.50 for DSPE members) plus €6.50 postage, published by DSPE in 2020.

NEW MODERN NATIONAL VOCATIONAL SCHOOL

Last year, Stef Vink was appointed director-administrator of the Leidse instrumentmakers School (LiS). Since then, he has been working on a new strategy for the LiS, under the denominator of 'New Modern National Vocational School'. The objective is to modernise the curriculum by offering more challenging projects and paying more attention to digital design and manufacturing. This strategy should help the LiS to strengthen its position as an independent, unique and relatively small vocational school in the Dutch scale-driven educational system. For this, support from the professional field is indispensable.

The Leidse instrumentmakers School (LiS) is one of the oldest Dutch vocational educational institutions. The school was founded in 1901 by the Leiden professor and later Nobel Prize-winner Heike Kamerlingh Onnes because he needed professionals who could develop and make tools for his research into the liquefaction of helium and the phenomenon of superconductivity at ultra-low temperatures. Over the years, the LiS has retained its status as an independent vocational school, dedicated to the training of (research) instrument makers, despite the trend in the Dutch educational system towards scaling-up that has led to the establishment of large, multi-disciplinary regional training centres (RTCs, or ROCs in Dutch).

EDITORIAL NOTE

This article was based on an interview with Stef Vink, director-administrator of the Leidse instrumentmakers School (LiS).

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Vocational school

Stef Vink worked in both education and industry; before joining LiS he was domain leader Metal and Process Technology at ROC Da Vinci College in Dordrecht (NL). He enjoyed training both adolescents and senior professionals and appreciated the traditional concept of a vocational school. At the LiS, he can combine his passions in the further development and modernisation of the education at the 'vocational school' of the Dutch research community and high-tech industry. "I was attracted by the LiS history, its focus on craftsmanship, the highly motivated and passionate students and staff, and the extensive facilities, partly sponsored by 'friends' of the LiS", explains Vink.

The latest extension of the housing of the Leidse instrumentmakers School at the Leiden Bio Science Park. (Photo: BryanR1, Wikipedia)

The LiS is by far the smallest vocational school in the Netherlands, counting 360 students at the moment. The latest extension of the facility (Figure 1) in 2016 doubled its capacity from 200 to 400 students. Against the demographic trend, year-on-year growth is achieved. Vink: "In my opinion, secondary vocational schools have distanced themselves too much from industry. At Da Vinci, I managed to restore and intensify contacts with companies and their vocational schools. That's also what I like about the LiS; the close contacts with research institutions and companies. It is a regular school but it looks a lot like a 'company vocational school' (*bedrijfsvakschool*, in Dutch)." It was, however, the right time for reviewing LiS's strategy and curriculum. "We have established an excellent track record of over 100 years and we will continue this performance in the coming years."

USPs and action points

Vink was put on the trail of the New Modern National Vocational School by the feedback in a report from the Dutch Ministry of Education, Culture and Science. He instigated workshops and interviews with staff, students, the professional field and network partners, which resulted in a summary of the LiS branding, in terms of unique selling points, as perceived by internal and external stakeholders:

- cultural foundation: involvement in the school, passion for the profession, master-apprentice principle;
- broad and professional practical training – (quality) standardisation;

2

LiS director Stef Vink: "We want to modernise our education, both didactically speaking, by offering more projects and integrated assignments, and in terms of content, by paying more attention to digitalisation of design and manufacturing."

- students who are disciplined and immediately employable;
- students who are able to work together in broad teams – problem-solving by nature;
- connection with the business community (coordination of programmes, facilities and competences);
- enterprising, flexible and independent students.

This served as input for a redefinition of the LiS strategy, culminating in five points of action for the coming three to five years:

- Authentic and specialist craftsmanship.
- Being together and being yourself.
- Practically skilled with the most modern techniques.
- Preparing yourself for your future while working on the most beautiful projects.
- Network of partners at home and abroad.

Vink (Figure 2), in conclusion: "We want to modernise our education, both didactically speaking, by offering more projects and integrated assignments, and in terms of content, by paying more attention to digitalisation of design and manufacturing."

Digitalisation

Currently, the vast majority of practical training at the LiS is still focused on conventional technology (Figure 3), Vink acknowledges. "In consultation with the professional field, we want to devote at least 25% of the practical training to digital technology, with for example 3D design, CNC machining and 3D printing. We are reaching out to the professional field for support. In their opinion, what should remain conventional technology in our training and where is room for digitalisation? And can they make hybrid teachers available, for example for training digital manufacturing techniques?"

Appropriate learning

The LiS must therefore to some extent let go of its focus on conventional technologies. Flexibility is also required for a modern vocational school in other respects, explains Vink. "We traditionally believe in a fixed four-year curriculum with students attending school 32 hours a week – much more than the average of 25 hours at other RTCs – with a tremendous discipline and drive to be trained in the LiS culture, solution-oriented and always looking for improvements in design or production. But students who are ill or are doing an internship abroad should be able to follow lessons online, for example."

At the same time, Vink continues, "our master-apprentice principle is already fully focused on flexibility in student supervision and progress testing, not on the basis of formal tests but of what can be observed in the student's learning development. Our teachers and technical teaching assistants have been praised for this by the Education Inspectorate. Our practical education is therefore already very modern."

Improving student intake

Vink has no further plans for expansion of the LiS at the moment. "We do, however, want to improve our student support. Currently, we have a relatively high drop-out rate. On the one hand, this is because we set the bar very high for our students, because 'our' companies and research institutes demand highly qualified students and employees. For example, in Covid-19 times, we have not made any concessions to the qualification requirements for students. We only recently had to decide in consultation with our

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Currently, the vast majority of practical training at the LiS is focused on conventional technology, but a shift to digital technology, such as CNC machining and 3D-printing, is ongoing. (Photo second left: Monique Shaw) professional field committee that some students who have not yet passed their practical exam completely may already do an internship, albeit with an assignment based on an analysis of their points for improvement."

On the other hand, Vink continues, "too many freshman students still enter with misconceptions about our education and the profession of research instrument maker. We must therefore provide even better information and advice to interested students and their parents. That is more important than unlimited growth. In addition, we pass up opportunities with students who have a different motivation than our standard target group. For example, consider diversity; we are overlooking the potential of girls and young people with a migration background who are not familiar with the profession of research instrument maker and our school."

Future-proof?

With the new strategy and curriculum modernisation, the LiS is once again future-proof. However, there is still a major threat, as posed by national education policy, i.e. the revision of the qualification structure in the secondary vocational education system. "The qualification dossiers for the metalworking-related courses in particular are under scrutiny. The government wants to go back from 14 dossiers to three; then the question is whether Research Instrument Maker will survive as an independent outflow profile in the Precision Technology qualification dossier. If we are placed under a broad metalworking dossier, what does the LiS still stand for and what will still make us distinctive? Will we lose our focus on craftsmanship, with more than 50% practical education, to which we and our 'customers' attach great value?"

Every reason for Vink to appeal to the professional field – DSPE members and Mikroniek readers included – to make themselves heard and argue for a stable, independent and recognisable position for the LiS in the future educational landscape.

LiS in space

One of the elective modules in the LiS curriculum is 'Instrumentation for Space'. The aim is to train students to specialise in the design and construction of instrumentation for satellites, rockets and astronomical observatories. The special programme was set up with support from the Regional Investment Fund, local government, (research) institutes (such as NLR, NOVA, SRON and TNO) and companies (including Airbus, AJB/Madern, ISIS, Lens R&D, Microtechniek, SSI and WestEnd).

In addition, Peter Paul Kooiman, engineer at SRON Netherlands Institute for Space Research, was appointed practor ('practical professor') of Instrumentation for Space. He will contribute to the LiS curriculum and act as a liaison between the worlds of space research and vocational training.

The practorate was established as part of the recently formalised collaboration between LiS and SRON (Figure 4), which covers:

- training students in space research instrumentation;
- obtaining new practical knowledge about manufacturing and integration methods in space research;
- raising external funding for the development of instrumentation skills and knowledge;
- identifying and promoting applications outside space research.

"Development and realisation of ground-breaking instruments requires the LiS type of craftsmen," Kooijman comments. "Here at SRON, most of our instrument makers are LiS alumni. Now that SRON and the LiS have become direct neighbours at the Leiden Bio Science Park (following the recent move from Utrecht to Leiden by part of SRON, ed.), we can further intensify the knowledge exchange between SRON and the LiS."

A next candidate for a practorate at the LiS is in the field of quantum technology. The LiS was invited to participate in the Leiden-Delft hub of Quantum Delta Nederland because of its expertise in cryogenics, photonics and optics. LiS students have already carried out projects at QuTech, the internationally renowned, Delft-based research institute for quantum computing and quantum internet.

4

From left to right, SRON engineer and LiS practor Peter Paul Kooijman, SRON scientific director and general director Michael Wise, manager of the LiS TOP centre for innovative craftsmanship Frank Molster, and LiS director Stef Vink. (Photo: SRON)

WWW.SRON.NL
WWW.QUTECH.NL

UPCOMING **EVENTS**

Please check for any rescheduling, online reformatting or cancellation of events due to the coronavirus crisis.

17 May 2022, Veldhoven (NL)

CLEAN 2022

This theme day, organised by Mikrocentrum, provides an expert's view on cleanliness, focusing on design, production, assembly and packaging.

WWW.MIKROCENTRUM.NL/CLEAN

30 May - 3 June 2022, Geneva (CH)

Euspen's 22th International Conference & Exhibition

The event features latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, topics will be addressed covering robotics and automation, precision design in large-scale applications, and applications of precision engineering in biomedical science.

The conference keynotes are presented by Dr. Rhodri Jones, head of Beams Department, CERN, on present and future CERN projects and their associated engineering challenges; Dr. Begoña Vila of NASA about on-orbit commissioning of the James Webb Space Telescope; Dr. Thomas Sesselmann of Heidenhain, on Geneva's special contribution to precision manufacturing and metrology; and Prof. Darwin Caldwell of the Italian Institute of Technology, on robotics, AI and assistive technologies for precision medicine.

WWW.EUSPEN.EU

8-9 June 2022, Den Bosch (NL)

Vision, Robotics & Motion

This trade fair & congress presents the future of human-robot collaboration within the manufacturing industry.

WWW.VISION-ROBOTICS.NL

15 June 2022, Enschede (NL)

TValley Tech Conference

Event devoted to unmanned robotics systems: recent developments, future possibilities and TValley partner projects.

WWW.TVALLEY.NL

22 June 2022, Den Bosch (NL)

Bits&Chips System Architecting Conference

The fifth edition of this conference will be a live event, preceded by a series of online sessions that started early this year.

WWW.SYSARCH.NL

22-23 June 2022, Eindhoven (NL)

3D Production Days

New event organised by Mikrocentrum, as the merger of four events: RapidPro (22-23 June), Smart Maintenance Congress (22 June), Virtual (R)evolution (22 June), and MBD Solutions Event (23 June). Together they cover all aspects of 3D production: the 3D drawing with product and manufacturing information (PMI), 3D scanning, prototyping, 3D simulation, 3D printing / additive manufacturing, postprocessing, and 3D visualisation.

WWW.3DPRODUCTIONDAYS.NL

11-15 July 2022, Knoxville, TN (USA)

ASPE Summer Topical Meeting

Event of the American Society for Precision Engineering devoted to advancing precision in additive manufacturing

WWW.ASPE.NET

30 August - 2 September 2022, Utrecht (NL)

ESEF 2022

The largest and most important exhibition in the Benelux area in the field of supply, subcontracting, product development and engineering, showcasing the latest innovations.

WWW.MAAKINDUSTRIE.NL/ESEF

27-30 september 2022, Utrecht (NL)

World Of Technology & Science 2022

Four 'worlds' (Automation, Laboratory, Motion & Drives, and Electronics) and Industrial Processing will be exhibiting in the Jaarbeurs Utrecht.

WWW.WOTS.NL

28-30 September 2022, Huddersfield (UK)

SIG Meeting Structured & Freeform Surfaces

Special Interest Group Meeting, hosted by euspen and dedicated to replication techniques, structured surfaces to affect function, precision freeform surfaces, large-scale surface structuring, surfaces for nanomanufacturing, and metrology.

WWW.EUSPEN.EU

12-14 October 2022, Eindhoven (NL)

Optomechanical System Design course

The course focuses on the mechanical and mechatronic design of optical systems, and is intended for mechanical, mechatronic and optical engineers involved in opto-mechanical system design. It will also be a very valuable course for any engineer interested in opto-mechanical design approaches and solutions.

WWW.DSPE.NL/EDUCATION

16-17 November 2022, Den Bosch (NL)

Precision Fair 2022

The 21th edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	4 July 2022
Mechatronics System Design - part 2 (MA)	5	HTI	10 October 2022
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	28 September 2022
System Architecting (S&SA)	5	HTI	13 June 2022
Design Principles for Precision Engineering (MA)	5	HTI	7 November 2022
Motion Control Tuning (MA)	5	HTI	20 June 2022
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	21 March 2023
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	14 June 2022
Thermal Effects in Mechatronic Systems (MA)	3	HTI	14 June 2022
Dynamics and Modelling (MA)	3	HTI	22 November 2022
Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	26 September 2022
RF1 Life Data Analysis and Reliability Testing	3	HI	to be planned
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	31 October 2022
Advanced Optics	6.5	MC	to be planned
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	16 September 2022
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	to be planned (Q1 2023)
Tribology	4	MC	18 October 2022
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	20 June 2022
Experimental Techniques in Mechatronics (MA)	3	HTI	8 June 2022
Advanced Motion Control (MA)	5	HTI	17 October 2022
Advanced Feedforward & Learning Control (MA)	3	HTI	18 May 2022
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (2023)
Passive Damping for High Tech Systems (MA)	3	HTI	29 November 2022
Finite Element Method	2	MC	3 November 2022
Design for Manufacturing (Schout DfM)	3	HTI	4 October 2022

ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

WWW.ECP2.EU

Course providers

- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LIS.NL/LISACADEMY
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Schout DfM
  WWW.SCHOUT.EU
- Systems & Software Academy (S&SA)

A glove that restores grip strength

People usually wear gloves for warmth or protection. There are gloves with other purposes, however, such as restoring mobility to the wearer's fingers. This is the idea behind a mechatronic orthosis called the exomotion® hand one.

This orthosis is worn like a glove and consists of custom-fitted exo-finger mechanics, a supporting forearm splint, a sensor, a control unit, and four miniature drives that provide the power to open or close the wearer's fingers. Six types of grip are available, to restore to the wearer the freedom of movement he or she may have lost as a result of a stroke, accident, or degenerative disease.
The hand orthosis was developed by two medical engineers, Dominik Hepp and Tobias Knobloch. They first met in university, where they both focused on this issue, and finally, in 2017, founded a start-up, HKK Bionics, located in Ulm, Germany. They hope to offer patients with fully or partially paralysed hands an aid than helps them to perform everyday tasks on their own again.

The designers had a number of challenges to overcome before arriving at the latest version of their bionic orthosis. The product is intended to be worn all day long, so it needs to be robust, high-performing, and lightweight. After developing the initial prototype, the main focus therefore was on making the orthosis smaller, which involved finding suitable new components.

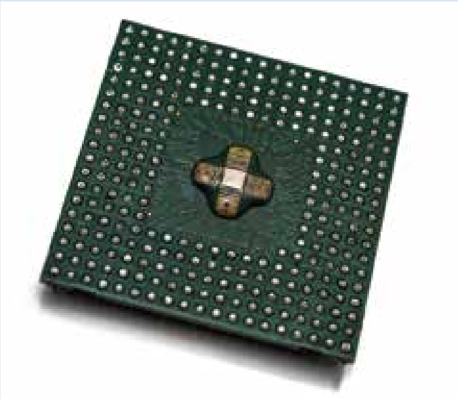
Four customized EC motors from maxon are at the core of the hand orthosis. These motors need to be small but powerful, and they must guarantee years of service with hundreds of thousands of operating cycles. The brushless micromotors supply the necessary grip strength and are controlled via sensors that respond to still-intact muscles, a principle that is also used in prosthetic arms.

WWW.HKK-BIONICS.DE
WWW.MAXONGROUP.COM

Energy-efficient AI chip for robots

Researchers from imec and KU Leuven, both located in Belgium, have designed the very first chip that combines a digital and an analog co-processor to accelerate computations for artificial intelligence (AI). The Digital and ANalog Accelerator, DIANA for short, performs various types of calculations automatically in the most energy-efficient way. DIANA can be used, among other things, to allow robots to efficiently calculate which object is in their field of view and how they can grab that object.

To enable meaningful AI applications, these devices need to be able to interact with their environment even faster and better. For privacy reasons, it is best to process the environmental images, sounds or other data on the device itself, but it this requires a lot of computing power, which threatens to drain the battery quickly. Today, some vehicles and smartphones are already equipped with a digital processor specifically designed to speed up calculations for AI. However, to enable high-performance augmented reality glasses, an autonomous drone or a smart robot, a new generation of AI chips is needed.



The DIANA chip on a printed circuit board. (Image: imec)

Two years ago, researchers at imec developed a new chip architecture in which the calculations are performed directly in the computer memory by means of analog technology. This analog accelerator makes it possible to perform most of the operations 10 to 100 times more energy-efficiently than in a digital accelerator. For another part of the operations, the computational precision and programmability of a digital accelerator is better suited. To combine the best of both worlds, the researchers, with the support of the Flemish government, have developed a processor that combines the analog and a digital co-processor. This led to DIANA, a new AI chip manufactured by chip manufacturer GlobalFoundries.

It is the rapidly increasing heterogeneity in AI algorithms that requires new hardware for performing the different types of calculations efficiently and energy-efficiently. For some applications, such as pattern recognition, an analog co-processor is most suitable. Other applications, such as reasoning about those observations, also require a digital co-processor. The hybrid chip automatically performs the operations on the co-processor best suited for each specific task.

DIANA thus combines the advantages of an analog co-processor (processing speed and energy efficiency) with the broad usability of a digital co-processor. This opens up a wide range of new applications that will be further investigated within the Flemish AI research programme. For example, a robot arm is being developed that can automatically recognise and grasp objects. The various calculations required for image recognition and robot control can be performed energy-efficiently on one and the same chip.

WWW.IMEC.BE
WWW.KULEUVEN.BE

Melexis gives robots a sense of touch

Belgian micro-electronics company Melexis has unveiled Tactaxis, a fully integrated tactile sensor that is compact, soft and provides the 3D force vector acting on its surface. This improves the capabilities of robot hands and grippers, making delicate operations such as fruit picking possible. The technology has been successfully implemented in a functioning prototype.

The ground-breaking prototype features multiple 3D magnetometer pixels, using Melexis' industry-proven Triaxis® technology. The sensor is accompanied by a magnet embedded in an elastomer material. This presents a soft contact interface, emulating the attributes of human skin. The arrangement offers a high sensitivity, so that detection of even small amounts of force will generate a response. The achieved force resolution is 2.7 mN, which is enough to distinguish the weight change of a fraction of a gram (~ 0.3 g).

The Tactaxis prototype is highly compact (with dimensions of just 5 mm x 5 mm x 5 mm) and therefore suitable for tight spaces. The gradiometric approach taken by Melexis makes the sensor immune to magnetic stray fields, which prevents potential measurement errors. It is also robust enough to cope with harsh conditions (temperature variations, etc.). Unlike competing optically-based tactile sensors, Tactaxis is completely integrated. It will be possible to produce high volumes of factory-calibrated sensors in a semiconductor process, resulting in major cost and reliability benefits.

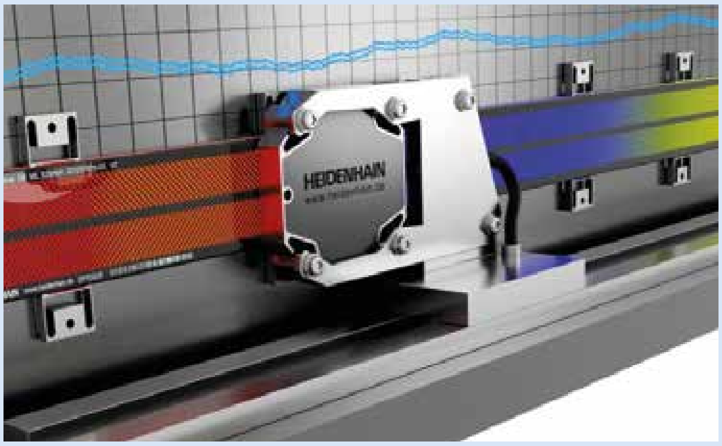
One finger of this robot hand is fitted with the Tactaxis tactile sensor.

WWW.MELEXIS.COM

Multi-dimensional measurement technology

Linear encoders measure the position of linear axes without intervening mechanical elements, thereby eliminating multiple potential sources of error, such as positioning errors due to thermal changes in the recirculating ball screw; reversal errors; and kinematic errors due to the ball-screw pitch error. As a result, linear encoders are essential components on machines requiring high positioning accuracy and machining speed. Exposed linear encoders are deployed on machines and automated systems requiring high measurement accuracy. They feature touchless measurement with a scale or scale tape and measuring head. As a result, ensuring high encoder accuracy requires a particularly flat mounting surface for the scale.

Conventional encoders can measure only one degree of freedom, rendering them blind to unavoidable errors in other directions. In multi-axis systems, these errors can have an effect on downstream axes. Errors in the first axis can change the position of the entire second axis, and so on. These errors are not normally measured. The Dplus encoders from Heidenhain can measure multiple degrees of freedom on a single axis. As a result, errors can be measured for one axis and compensated for in the next. Dplus encoders provide exceptional possibilities for optimising motion systems, particularly when high dynamic performance and accuracy are called for.
The accuracy of a motion system depends on multiple factors: non-linear guideway errors; vertical flatness, horizontal straightness; pitch, yaw, and roll; squareness error; kinematics error; thermal expansion and other thermal effects; and hysteresis. The challenge of perfecting position measurement in the primary axis is significant. Simply optimising the scale and scanning head is not sufficient for maximising a motion system's precision and dynamic performance. Machine design factors and thermal changes play a greater role as accuracy and dynamic-performance requirements increase. Using multi-dimensional encoders such as the LIP 6000 Dplus, these factors can be directly measured and compensated for.



WWW.HEIDENHAIN.COM

NTS installs cutting-edge 3D printer

NTS-Group, a leading high-tech systems supplier, has installed a cutting-edge MetalFABG2 3D printer at its Hengelo (Ov, NL) location to better serve high-tech OEMs in semiconductor, analytical and health markets. This new industrial printer from Additive Industries is equipped with three large build chambers and four lasers, which enables high productivity and repeatable quality. NTS considers as the main advantages of 3D printing for high-tech OEMs: part consolidation, decreased mass of components, part performance improvement, shorter manufacturing lead times, and reduced inventory costs.

NTS has been experimenting with additive manufacturing since 2013 and has developed its competency through various collaborative efforts. NTS was one of the founders of AddLab and AddFab, a 3D printing factory with the ambition to develop world-class 3D-printed metal parts for a broad range of high-tech and high-end manufacturing applications. Its Drachten (NL) location was home to the 3D printer of another consortium actively working with the technology. The expertise and experience gained through these initiatives by NTS' 3D printing competence team was central to its decision to purchase a MetalFABG2 and offer significant manufacturing capacity, in-house, to its customers.

"Starting with the more efficient and faster production of conventional parts, we guide our customers through the world of 3D printing," said René Vlaskamp, fellow at NTS-Group. "Our next step will be to change the engineering mindset and redesign key parts together with additive manufacturing in mind to unlock additional value. That will allow us to manufacture consolidated parts and improve part performance significantly. Lighter parts with improved performance will, for example, allow OEMs to further improve the efficiency of their applications." With the new 3D printer, NTS has the capability to print titanium, stainless steel, aluminium and (under development) other exotic materials.

WWW.NTS-GROUP.NL

The MetalFABG2 Continuous Production industrial 3D printer that NTS has installed.

ZYGO in NIF

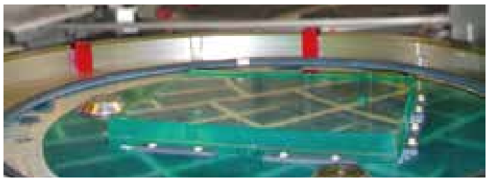
Zygo Corporation, so it claims, holds a prominent position in a recent success in the area of laser fusion, which opens up the possibility of virtually unlimited supplies of low-carbon, low-radiation energy. ZYGO's ongoing partnership with Lawrence Livermore National Laboratory's (LLNL's) National Ignition Facility (NIF) in the US is helping to bring safe, virtually unlimited carbon-free energy one step closer to reality.

NIF scientists are using laser fusion to harness the energy that powers the stars, with the goal of producing more energy than it consumes in a sustainable reaction called 'ignition'. Existing nuclear reactors used across the world split atoms to produce energy (and as a by-product produce radioactive waste). NIF fuses together atoms from easily obtainable materials commonly found across the globe. NIF's scientific breakthrough generated more than $10 \cdot 10^{15}$ W of fusion power for a fraction of a second. NIF is continuing its work to achieve ignition and create a viable source of power.

ZYGO manufactured nearly all the flat specialty optics used in the NIF laser. Getting the reactions going is not the problem; the trick is getting more energy out of the fusion process than is put in. To this end, NIF houses more than 7,000 ZYGO custom optics, including 3,072 amplifiers (described by NIF as "the heart of the system") that amplify a pulse of photons into 192 laser beams – focusing them on a target smaller than a pencil eraser.

When the beams hit the small target, it compresses the fuel to 100 times the density of lead and heats it to 100 million °C, hotter than the centre of the Sun. Heating the target in this way generates an electrically charged gas (plasma), and in the plasma, electron particles are stripped out of atoms, leaving the atomic nuclei that can fuse together, generating energy.

ZYGO worked closely with LLNL to develop optical manufacturing processes which support high-volume production of meter class, laser-grade optics for the NIF laser, including amplifier slabs, turning mirrors, vacuum windows, continuous phase plates, gratings and main debris shields. The optics used in NIF's 192 beamlines must have extremely low surface defects in order to achieve higher fluences.



ZYGO manufactures nearly all the flat specialty optics used in the NIF laser.

WWW.ZYGO.COM
LASERS.LLNL.GOV

More communication, signal processing and autonomous driving

Last month, MathWorks introduced the 2022a release of Matlab and Simulink. Beside over ten major updates and lots of new features, it also includes five new products:

- The Wireless Testbench provides reference applications for running on off-the-shelf software-defined radio hardware.
- The Bluetooth Toolbox provides standard-based tools to design, simulate, and verify Bluetooth communications systems.
- The Industrial Communication Toolbox supports handling of OPC UA data from control devices.
- The DSP HDL Toolbox supports the development of signal processing applications such as wireless, radar, audio, and sensor processing.
- The RoadRunner Scenario editor facilitates designing scenarios for simulating and testing automated driving systems.

WWW.MATHWORKS.COM

Quantum Application Lab now open

Organisations that want to investigate how quantum computing can benefit their business are invited to connect to the knowledge and technical infrastructure offered by the Quantum Application Lab (QAL) now. QAL is a newly formed public-private R&D partnership that offers a unique team of scientists, researchers, engineers, application developers, software and hardware specialists in a leading platform to explore and bring to market the benefits of quantum computing. QAL will support companies to navigate this complex and variable environment, in order to make the best possible choices for their development roadmap and their envisioned applications.

Quantum computing technology has attracted lots of attention in the last couple of years, because of its promise to deliver faster and better solutions to certain types of problems, compared to conventional binary (super) computers. This is because quantum bits are used, whose state can be a superposition of 1 and 0. This, along with other quantum mechanical effects such as interference and entanglement, will result in a fundamentally novel way of information processing. The enormous potential in computation power that quantum computers will offer is going to solve problems that are currently extremely difficult or unsolvable for conventional computers.

Right now, technology development of quantum hardware is accelerating strongly, spreading from the academic realm to the high-tech industry supply chains that will produce the first prototypes, for the benefit of pioneering end-users. Companies and other organisations are starting to look at useful applications for quantum computing, but the availability of deep technical expertise and suitable hardware platforms can be a bottleneck. QAL will offer access to these services, and will collaborate closely with future end-users of quantum computers to develop solutions that will benefit people and societies.

QAL will focus on optimisation, simulation, and machine learning applications initially. As such it is fully aligned with the roadmap of the Quantum Delta NL foundation. QAL will evaluate and support its partners on their journeys towards 'quantum value' and 'quantum advantage' and help them to develop R&D strategies and make investment decisions.

QAL's founding consortium partners are University of Amsterdam, CWI, TNO, SURF, TU Delft and the Netherlands eScience Center. IBM Quantum will serve as a technology provider.

WWW.QUANTUMDELTA.NL

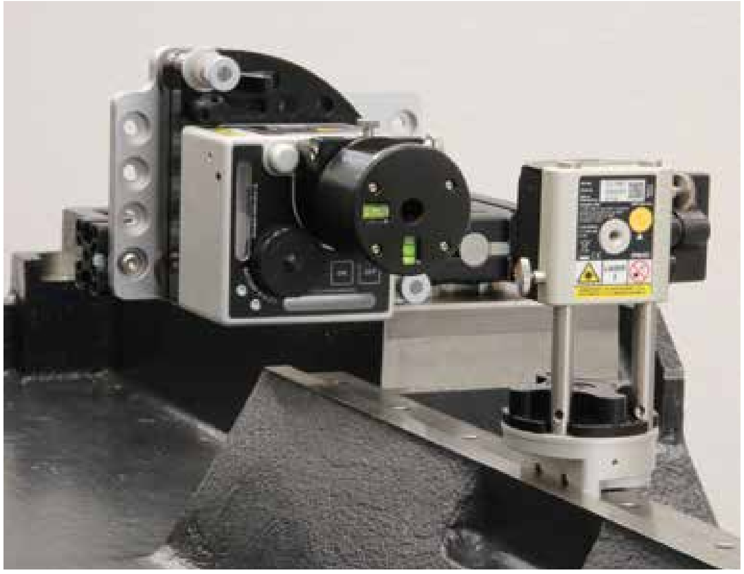
ACTUATOR 22

The 18th ACTUATOR-International Conference and the 12th International Exhibition on New Actuator Systems and Applications will take place in Mannheim, Germany, on 28-30 June 2022. The joint event is organised by VDE Association for Electrical, Electronic and Information Technologies. ACTUATOR is a major biennial event, providing a platform for leading experts, suppliers and users in the field of new actuators and low-power electromagnetic drives from all over the world. Attracting nearly 300 participants from more than 20 countries, the conference has quickly become the most important forum in the field of new actuator technologies. Among the success stories are established applications of new actuators, in particular their well-known use in fuel injection, adaptive shock absorbers, nanopositioning and precision engineering, as well as other applications of miniaturised drives.

WWW.ACTUATOR.DE

New alignment laser system

Metrology firm Renishaw has developed the XK10 alignment laser system for measurement of geometric and rotational errors of machine tools. Used with the XK10 machine tool fixturing kit, it enables faster and easier measurements over traditional methods, such as dial gauges, autocollimators and metrology artefacts. It can be used on linear rails to ensure that they are straight, square, flat, parallel and level, as well as to assess spindle direction and coaxiality of rotary machines.
Measuring geometric and rotational errors during machine build, maintenance and service, enables accurate alignment and adjustment of machine axes to achieve optimum performance. This reduces time during machine assembly processes and on-site service, including regular maintenance or following a collision. The XK10 can be used to measure and record a range of geometric error types using a single system. Live error readings allow adjustments to be made to the machine during the alignment process. Configured to provide flexible measurement solutions for machine tools, the kit allows for variations in machine sizes and configurations.



The XK10 used for alignment on a cast machine part.

WWW.RENISHAW.COM

Aerotech subsidiary Peak Metrology partners with IDC MicroInspection

Surface metrology solutions provider Peak Metrology, Aerotech's newest subsidiary, has engaged in a partnership with IDC MicroInspection. The partnership combines Peak Metrology's instrument and hardware capabilities with IDC MicroInspection's process knowledge and application software. Digital microscope users will benefit from new capabilities such as larger measurement volumes and increased automation in image acquisition. In addition, reliable positioning machines with scan automation software are now available for seamless integration with Keyence VHX digital microscopes.

Peak Metrology draws on Aerotech's extensive positioning systems expertise, while focusing exclusively on supporting industrial customers with surface metrology solutions through to complete integration.

"The market for digital microscopes is booming. However, in areas such as semiconductor manufacturing, precision manufacturing, electronics, aerospace or medical technology, they quickly reach their limits," emphasises R.J. Hardt, president at Peak Metrology.
"We want to support our customers in measuring larger parts in the best possible way. By partnering with IDC MicroInspection, we are able to deliver a fully integrated product. The bundled know-how and the operator software of our partner finally bring our solution over the finish line."

Peak Metrology develops and manufactures standard and special equipment for surface and precision measurement processes. For surface metrology applications, Peak Metrology offers a wide range of products up to turnkey machines.

IDC MicroInspection specialises in the fields of automated microscopy, optical inspection, software development and precision mechanical engineering. The Swiss company has 25 years of experience in the semiconductor and microelectronics industry, as well as medical technology. "Through our proven software interface, on the one hand we can replicate functions of digital microscopes, but on the other hand we can also add useful functions that did not exist before," says managing director Thorleif Brandsberg. "By combining our products with a well-known equipment manufacturer, we will help even more users solve their precision inspection challenges in the future."

WWW.PEAKMETROLOGY.COM
WWW.IDC-GMBH.CH
WWW.AEROTECH.COM

New, high-accuracy image dimension measurement system

Keyence has further extended its portfolio of precision measurement technologies with a new, high-accuracy image dimension measurement system. Boasting accuracy to ±0.7 μm, the LM Series combines ease of use with the breakthrough precision demanded across an ever-broader range of applications. Consistent sub-micron accuracy and repeatability is guaranteed through automated focusing and part positioning, making it ideal for applications with very tight tolerances in sectors from medical and electronics to high-precision metal manufacturing.

As with other Keyence systems, the LM Series is easy and rapid to program with intuitive on-screen help always available, and it can be operated with just one button. Items do not need to be precisely positioned, while rapid stage movement and a large field of view for a precision measurement system deliver optimum speed as fewer images are needed compared with alternative systems. The auto-focus function ensures accurate focus irrespective of operator experience.

Up to 300 dimensions can be measured at a time, while the LM Series can measure up to 100 individual parts simultaneously. A convenient integral coaxial light offers a broad variety of lighting options to provide optimised stable edge detection, whatever the material of the item being measured. While more typically used in laboratory environments, the system is sufficiently robust to withstand the rigours of the shopfloor environment with its low-vibration stage.

An integral high-magnification lens with Z-focus positioning allows for highly accurate non-contact height and depth measurement for areas as small as 20 μm x 20 μm. Additionally, plane elements can be created which are independent from the stage and overall part slope, with flatness and interplane angle measurements easily added to programs.

Suitable applications range from prototype and first-off part inspection, to in-process sample and part inspection, as well as pre-shipping and incoming goods inspections.

WWW.KEYENCE.CO.UK/LM2022

European quantum innovation

Last December, Fraunhofer and QuTech signed a memorandum of understanding for their collaboration to strengthen European innovation in quantum communication and quantum information networks. The German Fraunhofer-Gesellschaft is Europe's largest organisation for applied research, while QuTech, a joint venture of Delft University of Technology and applied research organisation TNO, is a Dutch research centre and global leader in the fields of quantum computing and quantum internet.

In a new, long-term, strategic partnership, Fraunhofer and QuTech will work together structurally on the development, and knowledge transfer, of the quantum internet. The partners aim to initiate and promote a wider scientific collaboration, to roll out new prototypes and testbeds. The resulting multinational quantum network will establish technology and interface standards in the areas of quantum communication and quantum information networks. For example, the two partners have agreed to collaborate on the deployment of complex quantum key distribution (QKD) networks across borders or around hubs in Germany and the Netherlands. They will also collaborate to develop integrated photonics solutions for such networks.

Since 2019, the Fraunhofer Institute for Laser Technology ILT and QuTech have been working closely together as part of an ICON project, a Fraunhofer programme for cooperation with excellent international partners, to develop optical components for quantum communication and information. The benefits of the fruitful collaboration are already reflected in a quantum frequency converter (QFC) architecture recently demonstrated by Fraunhofer ILT with record performance in terms of low noise and improved signal-to-noise ratio.

Both parties plan to install the first German quantum node of a transnational quantum network at Fraunhofer ILT as an extension and testbed, and as a stepping stone for a European approach to an entanglement-based quantum internet. The basis for this will be the QuTech technology as well as the Fraunhofer ILT QFC technology.

Laboratory prototype for a low-noise quantum frequency converter. (Photo credit: Fraunhofer ILT)

WWW.FRAUNHOFER.DE
WWW.QUTECH.NL

New ANTs from Aerotech

Precision motion control and automation specialist Aerotech has launched the second generation of its popular ANT nanopositioning stages. Building on the proven previous model, the high-precision ANT95 and ANT130 nanopositioners are designed to perform even better in terms of dynamics and precision. They provide positional stability and minimal incremental motion in the sub-nanometer range. This is ensured by non-contact direct-drive technology, extremely precise guides and incremental movements in the sub-nanometer range.

The new ANTs are particularly suitable for single- and multi-axis applications that require high-precision movement with high throughput. These include photonics assembly and inspection, fibre alignment and optimisation, optics manufacturing, testing and inspection, sensor testing and qualification, semiconductor manufacturing and inspection, and research and laboratory applications. The new ANT95 and ANT130 nanopositioners are available as single-axis, dual-axis, Z-axis or low-profile Z nanopositioning stages.

Dual-axis solution with ultra-precise 2D error mapping: in the ANT130XY nanopositioning stage, the integrated XY design ensures optimum stiffness and dynamics and enables efficient machine and system design.

WWW.AEROTECH.COM

PhotonDelta lands €1.1 billion investment

PhotonDelta, a cross-border ecosystem of photonic chip technology organisations, has landed €1.1 billion in public and private investments to transform the Netherlands into the leader of next-generation semiconductors. The investment includes €470 million funding obtained through the National Growth Fund (*Nationaal Groeifonds*), while the rest is co-invested by various partners and stake-holders. It is part of the Dutch government's national plan to cement and expand the country's position as a world leader in integrated photonics.

The programme will run for six years and will enable PhotonDelta and its partners to further invest in photonic start-ups and scale-ups, expand production and research facilities, attract and train talent, drive adoption, and develop a world-class design library. By 2030, PhotonDelta aims to have created an ecosystem with hundreds of companies, serving customers worldwide, and a wafer production capacity of 100,000+ per year.

Photonics uses photons (light) to transfer information. Photonic chips, also called photonic integrated circuits (PICs), integrate photonic functions into microchips to create smaller, faster and more energy-efficient devices. PICs can process and transmit data much more effectively than their electronic counterparts. Just like with traditional chips, the production process is carried out using automatic wafer-scale technology. This allows the chips to be mass-produced, reducing costs.

Crucially, PICs can overcome the expected limit to Moore's Law and will also help tackle energy sustainability issues. PICs are currently used in the data and telecom industry to reduce the energy consumption per bit and increase speeds. With data and internet use expected to be around 10% of global electricity consumption by 2027, PICs provide a powerful way to limit the impact on the climate. Photonic circuits will also soon play an important role for innovative sensors that can be mass-produced, leading to earlier diagnostics of diseases, safe autonomous vehicles and infrastructure, and more efficient food production.

The PhotonDelta proposal has been submitted by the Dutch Ministry of Economic Affairs & Climate Policy in close collaboration with Eindhoven University of Technology, University of Twente, Delft University of Technology, Holst Centre, TNO, IMEC, PITC, CITC, OnePlanet, Smart Photonics, LioniX International, Effect Photonics, MantiSpectra, PhotonFirst, PHIX, and Bright Photonics.
It is subject to three conditions: strategic partnership with a foundry agreed; research activity connected with applications of technology; ongoing evaluation of PhotonDelta's ecosystem.

The PhotonDelta ecosystem currently consists of 26 companies, 11 technology partners and 12 R&D partners. The organisation is part of a consortium that has jointly invested € 171 million in promising photonics companies, including Smart Photonics, PhotonFirst, Surfix, MicroAlign, Solmates and Effect Photonics.

WWW.PHOTONDELTA.COM

New master's programme "Applications of materials in high-tech engineering"

Last February, the new master's programme "Applications of materials in high-tech engineering" started at the Faculty of Mechanical, Maritime and Materials Engineering at Delft University of Technology (TU Delft). Pieter Kappelhof, technology director at Hittech Group, gave the first lecture, in which he explained the importance of knowledge about production and materials in the design process.

This unique course combines 13 cases presented by industry (ASML, Ceratec, BKB, Eurotechniek, Hittech Group, Huisman, Ramlab, Thermo Fischer and VDL) with lectures on the theoretical background by TU Delft lecturers. The initiative to strengthen the training of academic designers with knowledge about production and materials science is a joint effort of ASML, Thermo Fischer, VDL and Hittech, and was started by Cor Heijwegen, chairman of the supervisory board of the Hittech Group.

WWW.TUDELFT.NL/3ME
WWW.HITTECH.COM

ECP2 BRONZE FOR DOUBLE DUTY ON MECHATRONIC SYSTEM DESIGN

Maurice Lemmens, system architect at VDL ETG Technology & Development in Eindhoven (NL), has been awarded the Bronze certificate from the ECP2 programme. ECP2 is a European certified precision engineering course programme, a collaboration between euspen and DSPE. He is the eighth person to receive this certificate since the first one was presented in 2015.

Euspen's ECP2 programme grew out of DSPE's Certified Precision Engineer programme, which was developed in the Netherlands in 2008 as a commercially available series of training courses. In 2015, euspen, DSPE's European counterpart, decided to take certification to a European level. The resulting ECP2 programme reflects industry demand for multidisciplinary system thinking and in-depth knowledge of the relevant disciplines. To promote participation, a certificate scheme was instigated. The Bronze certificate requires 25 points (one point equals roughly one course day), Silver requires 35 points and Gold 45 points, which qualify a participant for the title 'Certified Precision Engineer'.

Beyond the borders

Maurice Lemmens obtained a bachelor's degree in mechanical engineering at Fontys University of Applied Sciences in Eindhoven and a master's degree in engineering product design at HU University of Applied Sciences Utrecht (NL). Subsequently, he worked for 23 years at Océ (now Canon Production Printing) in Venlo (NL), where he was hired as a mechanical designer. Soon after this, however, he started looking beyond the borders of the mechanical domain, switching over to a lead designer/system architect role for various Océ media-handling systems (copiers and printers). In 2019, after a short intermezzo at ASML, he joined VDL ETG Technology & Development, where he is now working as a system architect for wafer-handler platform development.

While at Océ, he followed the ECP2-certified Mechatronics System Design part 1 and part 2 courses, but his post-academic training career really took off at VDL ETG. In just over two years he has taken four courses. The first one was Basics & Design Principles for Ultra-clean Vacuum. "Vacuum became very important in my work, but I had as yet little knowledge of it, so I signed up for that course on my own initiative." Then followed System Architecting. "It's true that I was kind of self-taught in this area and have worked in that role for a long time. Still, I learned a lot; it was a very pleasant course." When the courses Mechatronics System Design part 1 and part 2 were offered in-company at VDL ETG, Lemmens was given the opportunity to take them again – eight years later.

Founding father of the precursor DSPE certification programme, Jan Willem Martens, handing over the ECP2 Bronze certificate to Maurice Lemmens.

Knowledge upgrade

"It was definitely time to upgrade my knowledge in this area. The subjects were the same, but the content had changed considerably in parts, such as software and amplifiers. The way in which the soft skills were treated was also different from last time. In short, there were enough deltas to pick up from these courses."

Another reason was that on Lemmens' TO DO list there is an action called 'Knowledge retainer and knowledge application'. "The aim is to keep the knowledge of this subject alive in the minds of people who have followed the courses, but also to make it accessible to people who have not followed them. It should become a kind of quick reference book, with golden tips, rules of thumb and points of interest for mechatronic design. It is at the bottom of my list because of the busyness of the projects, but the aim is to create a kind of mechatronical version of *Des Duivels Prentenboek* (The Devil's Picture Book, Wim van der Hoek's legendary design principles lecture notes, ed.), geared to the type of projects we are working on at VDL ETG, especially for the semiconductor industry."

Silver?

Lemmens was aware of the existence of the ECP2 certification scheme with Bronze, Silver and Gold, but wasn't focused on it. "During the courses, Adrian Rankers (from Mechatronics Academy, one of the course providers, ed.) did talk about it, but I had never counted my points, so it was a surprise when Jan Willem Martens came by with the certificate and the flowers." Lemmens is not going for Silver right now, but he certainly has courses on his wish list. "I can benefit from Dynamics & Modelling, while Thermal Effects in Mechatronic Systems is also fairly close to my area of work. And there are more interesting ECP2 courses. If I could win a silver medal there, that would be a nice bonus," he concludes with a wink.

WWW.ECP2.EU
WWW.VDLETG.COM

DSPE AND MIKROCENTRUM INTENSIFY THEIR **COLLABORATION**

DSPE, the Dutch trade association for precision engineering, and Mikrocentrum, an independent knowledge and network organisation for the high-tech and manufacturing industries, have decided to collaborate more closely. Their relationship goes back more than fifty years and they have always maintained close contact, with Mikrocentrum's Precision Fair as their annual highlight. Now they have decided to intensify their collaboration. As partners, they will organise more joint events and strengthen the exchange of knowledge among their members and participants.

In the Mikrocentrum building in Veldhoven (NL), DSPE chairman Hans Krikhaar (left) and Mikrocentrum director Bert-Jan Woertman seal their intensified collaboration.

DSPE and Mikrocentrum share a long history, dating from the founding of Mikrocentrum in 1968 in which DSPE, then still the *Nederlandse Vereniging voor Precisie Technologie* (NVPT), was involved. Over the years, the two organisations have often worked together. For example, in 1998 Mikrocentrum and DSPE were involved in the start of the Innovation-oriented Precision Technology Research Programme (IOP). Partly due to this programme and the numerous initiatives around precision engineering at the time, including those by NVPT, the idea for a Precision Fair was born in 2000. Mikrocentrum organised the first edition, in which DSPE was also closely involved, at the end of 2001. Over the years, this event has grown into the largest trade fair in the Benelux region for the entire precision engineering value chain.

Clubhouse

Now both parties want to give their collaboration a new impulse by intensifying and broadening it, each from its own angle. As a trade association for precision engineers, DSPE is focused mainly on the exchange of professional knowledge. Thanks to its modern location and years of experience in sharing knowledge and organising events, Mikrocentrum can support DSPE and its members even more in realising its ambitions, given that their target audiences in the precision community for high-tech and manufacturing overlap.

The two parties especially can complement and strengthen each other, according to DSPE president Hans Krikhaar and Mikrocentrum director Bert-Jan Woertman. DSPE can advise Mikrocentrum even more substantively, for example on the content of events. "We are happy to facilitate DSPE, with Mikrocentrum offering a kind of 'clubhouse' for DSPE," Woertman says. "We are prepared to invest in this and don't see it as a commercial relationship, but want to work together as partners." Krikhaar adds that DSPE organises knowledge days, among other things. "The field-specific knowledge that our members present there can be disseminated more widely by Mikrocentrum. A good example is our knowledge days on vacuum and contamination. We can link the subject of contamination to Mikrocentrum's annual Clean Event."

Central role Precision Fair

Naturally, the Precision Fair continues to play a central role in the relationship between DSPE and Mikrocentrum. "DSPE can make even more substantive contributions to our activities," says Woertman, "such as for the lecture programme at the Precision Fair. We will be paying more attention to this, in the preparation and implementation, and in the publicity surrounding it. Our collaboration fits in perfectly with that ambition." Krikhaar adds, "We also thought along with Mikrocentrum about the fair's move to the Brabanthallen in Den Bosch because of the pandemic. As far as we are concerned, it went very well and we have therefore advised them to continue holding the fair there."

Informal meetings

Periodic consultations are held to give even more substance to mutual coordination and collaboration. This can also lead to new initiatives, such as low-threshold meetings that DSPE and Mikrocentrum will organise together, for example in the run-up to a major event. "Innovation leads to innovation," Krikhaar concludes, "but collaboration is required. This applies to the high-tech ecosystem in the Brainport region in a broad sense, and to DSPE and Mikrocentrum in particular. We also want to try organising informal joint meetings, where precision engineering is featured in a casual atmosphere."

WWW.DSPE.NL
WWW.MIKROCENTRUM.NL

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