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.

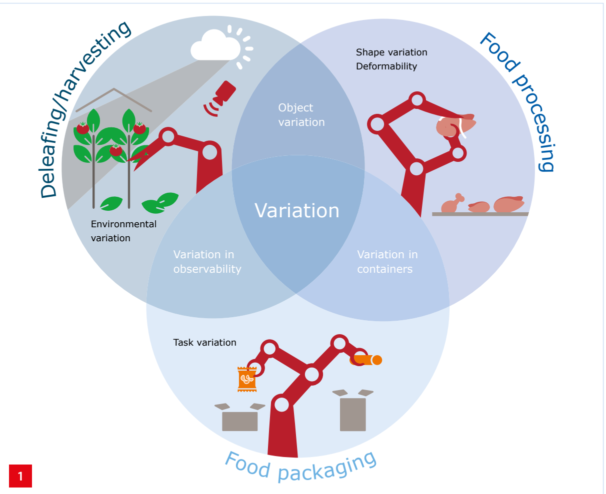
However, the robots currently used in the agri-food domain are based mainly on industrial robotic pick & place technology and still cannot meet the requirements of flexibility and the capabilities to handle complex manipulation tasks or natural environments. In terms of the above-mentioned capabilities, 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.*

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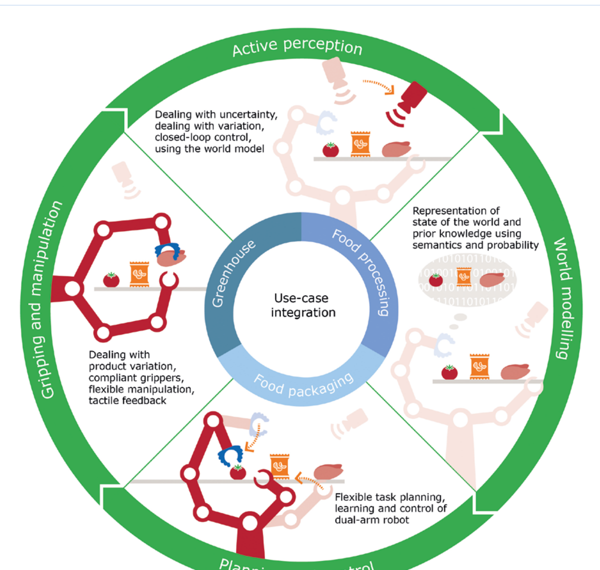
programme aims to improve flexibility in food processing and food packaging, allowing further progress in customer-specific production. Also, it will improve efficiency and effectiveness of agri-food production by implementing robotic systems that can operate tirelessly at high speeds and allow easy 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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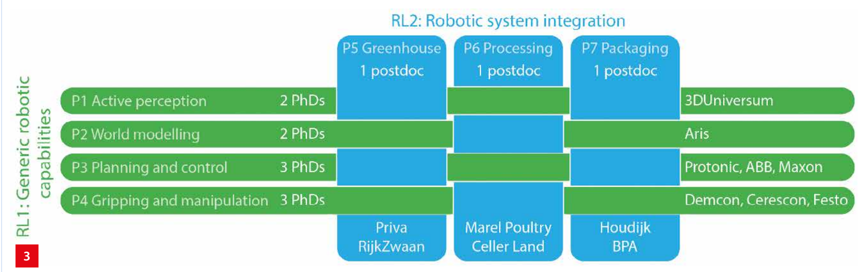
The FlexCraft paradigm for dealing with variation in objects and environment in the agri-food chain.



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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.

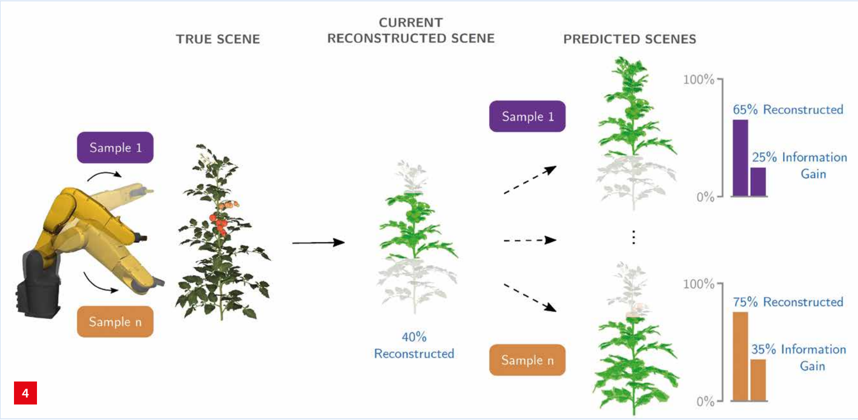
Through its sensors, the robot perceives the environment. By processing this information and combining it with prior knowledge, an internal world model is formed. The robot then reasons about that state of the world in relation to the task, in order to plan its actions, both at an abstract level, as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

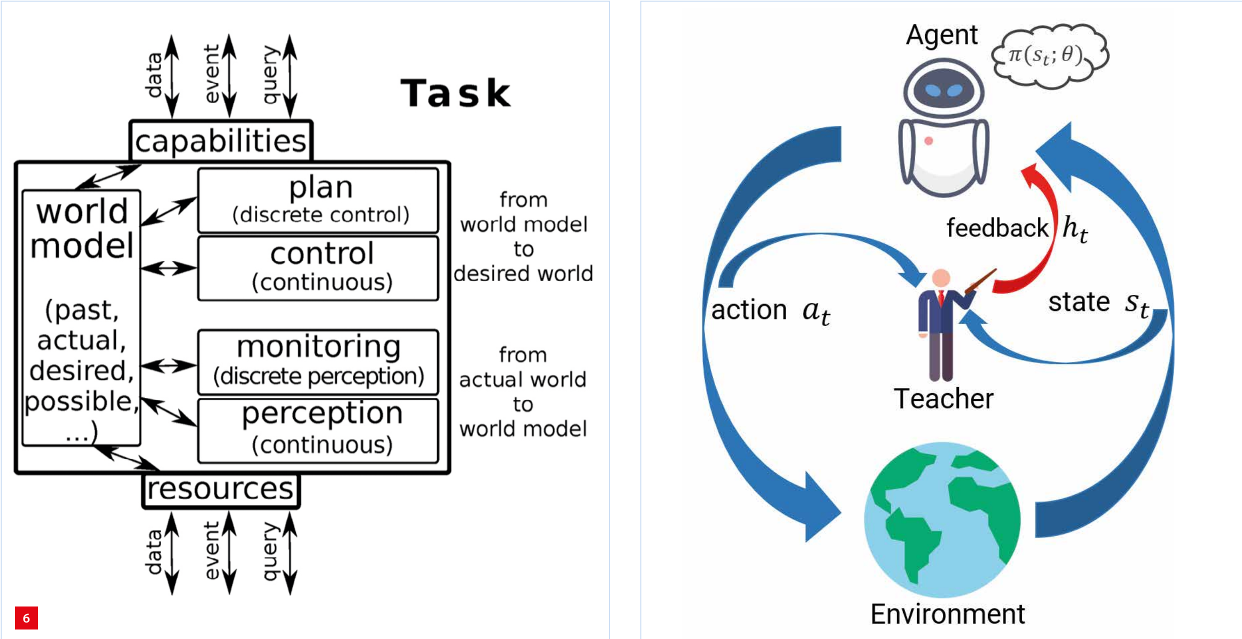
First results of this world-modelling approach in an agri-food context are shown in Figure 5. At the left, a new camera observation is depicted including the detected tomatoes, leaf nodes and fruit nodes. This observation is incorporated in the world model in the middle, which includes a graph-based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

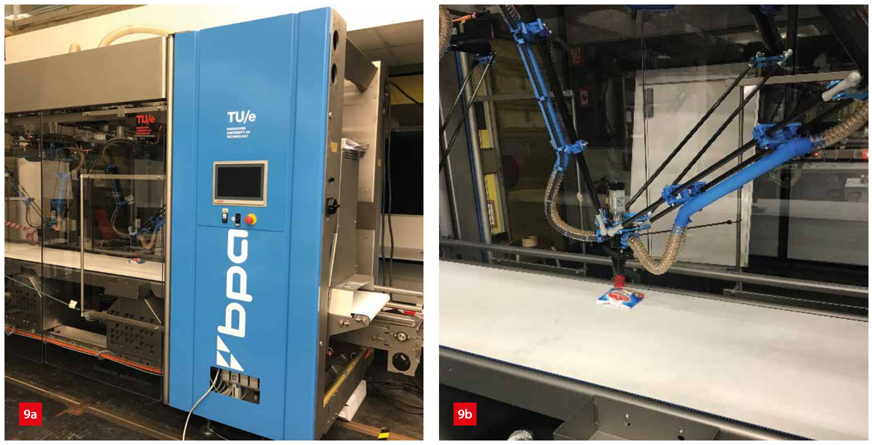
Robotic grippers have a pivotal role in modern automation. Current robotic gripping technology can handle well-defined rigid objects; however, grippers for harvesting, food processing and packaging have to perform their tasks under demanding requirements such as product variation in size, shape and softness, 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.



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.

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

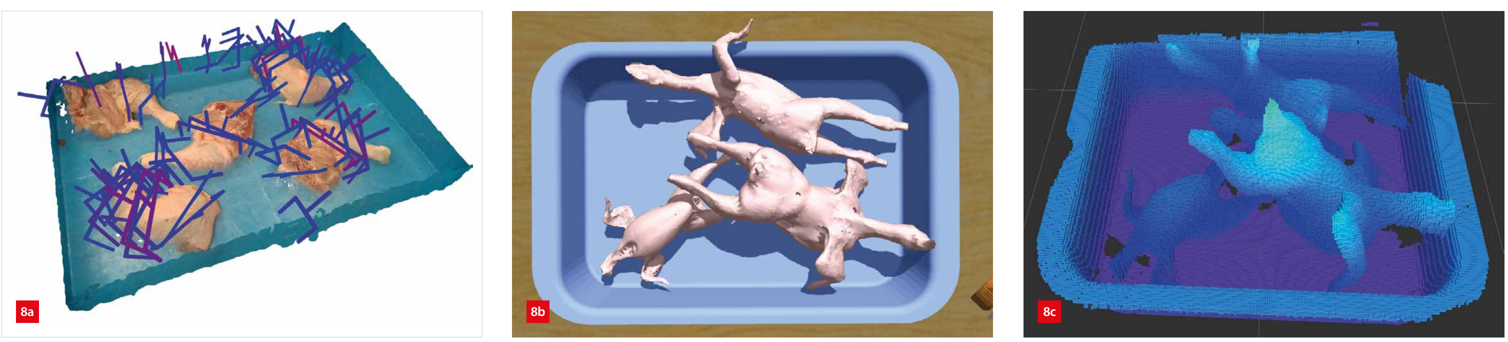
Current robotic systems in the processing of chicken, fish and red meat are capable of simple manipulations of singulated, equally-spaced products transported on a conveyor belt. Simple manipulations consist of grasping, repositioning and changing the orientation of objects for subsequent operation and 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. 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.