Computer vision – A versatile technology in automation of agriculture machinery

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1. Introduction

The agricultural market is evolving from being mechanised in the 20th century, with still larger machines to being automated in the 21st century. There is a growing market for more cost effective, environmentally friendly and task optimised systems, saving resources like diesel and pesticides. High accuracy in field operations is a prerequisite to optimize output and quality of the crops, as well as minimising the production cost. In order to fulfil these requirements, more and more automation is introduced. Development of automation technology for agricultural machinery has many aspects. As a high degree of automation is required, it is important that machine manufacturers consider automation in the early design stages of mechanics and electronics. It is vital that manufacturers provide the required interfaces, enabling automation and optimisation of the entire product and not just of the individual sub-components. As the degree of automation increases the complexity of the automation tasks will rise. This report focuses on the sensor sub-system and more specifically *computer vision technology*. The emergence of widely available vision technologies has enabled manufacturers to automate a wide range of tasks. However, even though computer vision technology has developed in general, special efforts are required to make such complex technology robust and mature, to meet the high demands required by modern farmers. The hardware must meet high environmental standards. The software must solve complex tasks coping with natural crop variations and the diversity of the natural scene, in respect to both soil and lightning conditions. Yet, the system must have a minimum of configuration and an intuitive user interface. Within our branch of agriculture, especially two areas have driven the development of vision technology *weed control* and *auto-guidance systems*.

2. Weed control

The awareness of the environmental impact of farming has increased the interest in organically grown land and has reinforced the need for improved mechanical weed control. Further, the restrictions and limitations in the use of herbicides have driven the need for patch weed control. This report outlines how the use of 2D colour computer vision technology has facilitated development of very accurate spot spraying systems, inter-row and inter-plant cultivation systems.

2.1 2D Computer Vision

The use of vision technology for cultivation systems took it’s beginning in the nineties, [1]. One of the first cameras on the market, especially designed for the agricultural industry, was the ECO-DAN camera (**Fig. 1**). The ECO-DAN camera is an intelligent vision sensor containing one or two CMOS colour sensor chip(s), lens(es) and image processing capabilities. The system captures 2D images of the field scenes and searches for crop row structures (**Fig. 2**). Analyzing the images is a highly complex task. The condition of the crop, *i.e.* size, height, shape, and colour changes through out the growing cycle. Initially the plants appear as rows of small dots among scattered random dots of weeds. Later they fuse to form a clear green line. For some crops the lines thicken and tend to block the laneways (**Fig. 3**). Besides the natural growth cycle soil conditions also play an important role for the condition of the crop. Availability of water and nutrients is crucial, but physical soil parameters like hardness, and dryness; chemical parameters like hypoxia and salinity; biological parameters like infection by disease organisms, also play a role for the growth, [2]. Thus, the crop conditions vary over the season, over the field, and along the individual rows. Segmentation of colour images into crop, weed and soil is complicated by the fact that the appearance of objects varies with the nature of the illumination, the texture of the surface and the shape of the object, [3]. Thus, the colour of objects in the image changes over time, from sunrise to sunset, from clear sunlight to overcast and drifting clouds (**Fig. 4**). The illumination changes also with the driving direction. When moving in one direction images are well exposed due to a perfect backlighting. In the opposite direction images are captured directly against the sun. Shadows are generated by trees in the windbreaks and by the implement and the tractor on which the camera is mounted. Even the camera itself can generate a shadow in the field of view (**Fig. 5**). The weed pressure is varying from low to high within the field, and from field to field. The structure of the weed varies from random to row-structured (**Fig. 6**).

2.2 Inter-row cultivation

For the last decade the major European cultivator manufactures have offered camera guided inter-row cultivators [4]. The basic components in a typical cultivator configuration are camera, controller module (ECU), position feedback sensor and hydraulic components (**Fig. 7**). The ECU closes a position loop based on the hydraulic actuator and the position feedback sensor. The camera is placed on the cultivator frame with an obstacle free view to the crop rows. The camera, *i.e.* the vision algorithms, provides the offset from the crop row to the centreline of the camera. The offset is sent to the controller module which side shifts the cultivator using one of the following steering concepts, parallelogram, steering disks or external side shifting frame (**Fig. 7**). A typical system provides an accuracy of ±3 cm in normal working conditions covering a driving speed of up to 10 km/h.

2.3 Inter-plant cultivation

Recently the concept of auto-guided inter-row cultivation has been extended to inter-plant cultivation by the Robocrop InRow system from Garford [5]. Besides the normal hoes for inter-row cultivation special weeding rotors are used to work around the individual plants (**Fig. 8**). The rotational speed of the weeding rotors is continually adjusted to take into account plant spacing variations. The system components are similar to those for inter-row cultivation however the complexity is higher as one additional degree of freedom is added**.** To be successful the vision algorithms must provide the location of the plant rows and the location of the individual plants. The performance is a nominal 2 plants per second per row and a weeding coverage of up to 98.5% surface area has been achieved, [5].

2.4 Patch weed control

In case that use of herbicides is allowed another trend in weed control is patch weed control. The goal of patch weed control is to minimize the amount of herbicides by reducing spraying to areas where the infestation level is high. There are three types of patch spraying systems, *spot*, *cell* and *micro* sprayers which differentiate in terms of resolution and accuracy [6]. A typical configuration of a patch weed control system consists of a sprayer boom with integrated cameras, a central vision and image processing module, and a spraying computer controlling the spray nozzles (**Fig. 9**). A prerequisite for the system to perform is an on-line localization of the weeds. The aim in the project [7] is to be able to distinguish weeds positioned close to or under normal cereal leaves (**Fig. 10**). The desired accuracy and the computational complexity cannot be attained at the speeds that are normal for conventional sprayers. According to [6] such high precision systems can only be attained when driving at low speed and therefore only realistic with unmanned sprayers. Patch weed control systems are a hot research topic covering plant/weed segmentation, spray nozzle technology and many aspects of mobile robotics.

2.5 Benefits

The wide acceptance of camera-guided implements, especially inter-row cultivators shows that it is possible to make camera systems that meet the demands of highly efficient modern farming. Applying 2D colour computer vision makes it possible to detect crop rows, plant and weed location with an accuracy of a few centimetres. Despite crop variations, different light and weed conditions the systems maintains their accuracy at all time. Detailed information regarding the actual position of the crop makes it possible to improve the efficiency of well known field operations like inter row cultivation. Cultivator blades and hoes can work closer to the plants increasing the efficiency of the weed control. The operator just needs to drive the tractor within the rows, thus less experienced drivers can operate the system. Still the forward speed can be increased and the driver fatigue reduced. The system operates without any physical contact with the plants or the soil thus break downs caused by, for example, mechanical feelers plugging up, is avoided. Detailed information about the actual plant and weed location provides a mean for automation of labour intensive operations like inter-plant cultivation and spot spraying. As the sensor technology and processing capabilities increases features from more and more complex scenarios can be extracted and thus a higher degree of automation can be obtained.

3. Auto-guidance of tractors and self propelled machines

For farmers, long working days with repetitive tasks are normal, as their work is seasonal and highly dependent on the weather conditions. Throughout the day, the driver is responsible for an optimal and safe navigation of the vehicle, while ensuring that the equipment is adjusted for optimal throughput. By automating the navigation tasks when the vehicle is driving along crops and other field structures, the operator stress level can be reduced. High precision steering in sensitive crops can also be maintained for longer periods of time as driver fatigue is greatly reduced. Within auto-guidance systems the use of computer vision technology complements the use of GPS systems. The GPS is a global position sensor that provides information regarding the actual position of the GPS antenna in a global frame of reference. Such information is sufficient for field operations like seeding, ploughing, and mowing. Other field operations require that an existing field structure, like a swath, is being followed. Thus, information about the position of the field structure relative to the vehicle is required. This report presents the basic concept of stereo vision (3D) and describes three use-cases where stereo vision technology is adopted. The first case allows automatic tractor guidance in the narrow rows of vineyards. The second case is automatic tractor guidance following tramlines, ridges or swaths. The third case describes automatic spout control on a self-propelled forage harvester.

3.1 Stereo Vision (3D)

The first commercial available stereo camera dedicated for agricultural applications was the ECO-DAN stereo camera. The camera has two colour CMOS sensor chips, two lenses, and a mainboard architecture with two DSP's for image processing (**Fig. 11**). The advantage of the stereo camera is it's capability to measure distance. Image pairs are captured simultaneously by the two sensor/lens systems. The sensor/lens systems are placed with a fixed distance known as the baseline. Because the images are captured with different viewpoints, features in the two images will be offset as a function of the distance to the feature. This offset or disparity can be calculated by finding the same image features in both images. Since the characteristics of the camera are found by calibration the

3D coordinates of the features can be calculated [8].

Tracking of field structures using 3D is typically done by detecting the height of features in the environment relative to the ground plane (**Fig. 12**) [9]. The ground plane is determined using information about how the camera is mounted in terms of height and angle or by estimation directly from the 3D data [9]. The tracking is then performed by labelling pixels in either image based on the calculated height. Shape based matching can then be used to recognize the pose of the field structure in the 2D image using known constraints such as the width and height of the structure. After localisation, the pose of the structure relative to the vehicle, can be calculated and parameterized in terms of an angular and lateral deviation relative to the vehicle. Based on the angular and lateral deviation a control signal is calculated ensuring that the vehicle keeps track of the field structure (**Fig. 13**). In case of a poor match result the angular and lateral deviation is set to zero ensuring that the vehicle is driving straight ahead.

3.2 The Clemens VineScout

The vineyard equipment manufacture Clemens GmbH & Co uses 3D tracking in their VineScout product (**Fig. 14**). The driver drives the tractor into the row and activates the auto-guidance system. The VineScout automatically guides the tractor along the narrow rows in the vineyard independently of the vegetation level, (**Fig. 15**). The tractor driver has no need to steer and can give his full attention to the attached equipment. An accuracy of ±3 cm can be obtained. The system runs also at night time using the normal working light of the tractor. An acoustic signal alerts the driver at the end of the row so that manual steering can be resumed for changing to the next row.

3.3 The CLAAS CAMPilot

The CLAAS CAMPilot uses a stereo camera to recognize the field structures in front of the tractor or the forage harvester (**Fig 16**). The CAMPilot is currently released for tracking along swath, tramlines or ridges (**Fig 17**). The CAMPilot guides the vehicle automatically along the field structure leaving the driver free to concentrate on monitoring and optimising his machine settings. This considerably eases his work load and helps to guarantee the same high level of work quality all day long. The CAMPilot can automatically guide the vehicle along the field structures with an accuracy of ±5 cm up to 10 km/h and ±10 cm up to 20 km/h.

4. CLAAS AutoFill

Forage harvesting is a demanding operation requiring full concentration from the driver to both steer the machine and to control the spout for crop overloading to a moving trailer (**Fig. 17**). Especially driving into the field, around curves and obstacles can be very difficult and stressful. In these situations the tractor driver often has difficulties maintaining a fixed position next to the forager, which makes it difficult for the forager driver to avoid losses and use the full capacity of the forager. As the CLAAS CAMPilot automates the navigation task, the CLAAS AutoFill automates the operation of the spout. AutoFill is a stereo camera based spout control system. Using a stereo camera has significant advantages, allowing 3D interpretation of the scene elements compared to the use of traditional 2D-features in intensity images, such as edges and lines. Compared to GPS-based trailer tracking and model-based fill level prediction [10], the use of a camera has the advantages of less hardware complexity, the possibility for detecting trailer height, doing online corrections of the crop jet model and doing online fill level estimation, [11].

4.1 System Operation

When a trailer approaches the side of the forage harvester, the vision system detects its position by means of 3D image analysis techniques (**Fig 18**). When a trailer is detected an overlay is drawn on the picture shown to the driver. When a green line is drawn the AutoFill system can be engaged. The system predicts where the crop jet will hit within the trailer using measurements of the spout and deflector rotations. Due to crop conditions and drift the precision of the predicted hit point isn't sufficient. Thus, the predicted jet trajectory is corrected online by measuring the distance to the jet (**Fig 19**). The fill level within the trailer is constantly measured (**Fig 20**). The basic filling strategy is to fill the trailer until a certain fill level has been reached. Once a trailer section is filled the spout turns to a new position where filling is required, always going from one end of the trailer to the other. When the trailer moves out of sight the spout moves to a default position and is ready to resume the trailer filling process.

4.2 System Components

The system consists of a 3D stereo camera mounted on the spout (**Fig 21**). The camera calculates steering commands to the spout rotation and deflector (flap) angle to ensure that the crop hits inside the trailer and that the trailer is filled in the correct way. The steering signals are sent via CAN bus to a module (ECU) performing closed loop control of the actuators for the spout and deflector rotation, respectively. Additionally a video signal is transmitted to a monitor in the cabin to show the driver the filling process. System status is shown on the monitor using colour overlays. The system is activated from the multi-function lever (MFL) and configured via the graphical user terminal (**Fig 22**).

5. Conclusion

A prerequisite for high efficiency and quality in many types of field operations is that detailed information regarding the position of the crop relative to the implement and/or tractor is available. GPS systems can provide high accuracy of the antenna position in a global frame of reference. Using multiple antennas, for example on both the tractor and the implement, improves the accuracy of the implement location relative to the tractor but it does still does not measure the actual crop position. Laser range finders and in some cases mechanical feelers makes it possible to provide information regarding the actual position of the crop. However such systems are inflexible and dedicated to a specific task. Using computer vision and especially when combining both 2D and 3D techniques it is possible to make a detailed scene interpretation of the area in front of the implement or tractor. The spatial structure can be measured and features extracted based on colour, intensity, size and shape. Computer vision systems are touch less and compact and thus flexible with respect to mounting. This makes it possible to reuse vision sensor systems across different machine types and different field operations.

Applying computer vision technology makes it possible to automate the navigation tasks when the vehicle is driving along crops and other field structures. The operator stress level can be reduced in general and high precision steering in sensitive crops can be maintained through out the day. The driver can concentrate on optimizing the machine settings and ensure a safe operation of the system. Machine settings can be optimised yielding a higher quality in the field operations. The working speed can be increased thus saving time and money.

6. Outlook

In the future the versatility of the computer vision technology will be further explored in order to find solutions to complex automation problems. Further development of advanced sensor technologies is important, but it is vital that these technologies are combined to ensure reliable position information under all conditions. The use of vision technology will be combined with other sensors like GPS's, laser scanners, radars, etc to solve the challenges inevitably connected with obtaining systems with higher degrees of autonomous behaviour. Technologies being researched within the field of mobile robotics, like *sensor fusion*, *optimal path planning*, *situation assessment* and *multi-vehicle logistics* will be the next reaching the maturity level required for use in agricultural machinery ensuring robust and reliable operation in all field conditions.

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FIGURES

Figure 1 - The ECO-DAN camera. The single camera (*left*) was introduced in 1999 and the dual camera (*right*) in 2001. The camera contains a colour CMOS sensor with a resolution of 640x480 pixels. Image processing is handled by a single Digital Signal Processor (DSP). The dual camera processes 10 images per second. The camera interfaces to external equipment via CAN bus.

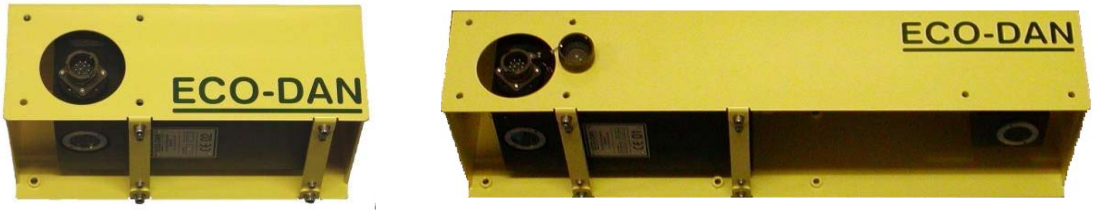

Figure 2 - The ECO-DAN camera captures 2D images of the natural scene and searches for row structures.

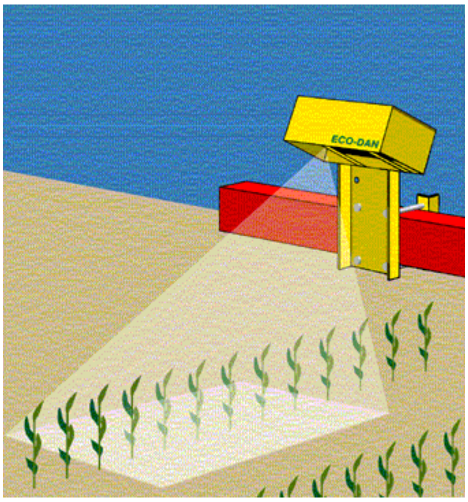

Figure 3 - Sugar beets. Over the season the plants change from a hardly visible row of small green dots over a solid green line to a dense green structure covering must of the field of view.

Figure 4 - Corn field. The pixel colour varies with the intensity of the illumination. Here drifting clouds.

Figure 5 - Corn field. Shadows cause variations in pixel values. Shadows come from trees but also from the implement, tractor and the camera itself.

Figure 6 - Weed pressure. The weed pressure varies over the field and can have either a random structure or a row structure. In the right image the light green coloured plants are the crop.

Figure 7 - The system components of an auto-guided cultivator is camera, electronic controller unit (ECU), position feedback sensor and hydraulic valve and cylinder. Three different steering concepts are used, parallelogram (*left*), steering disks (*middle*) and external side shifting frame (*right*).

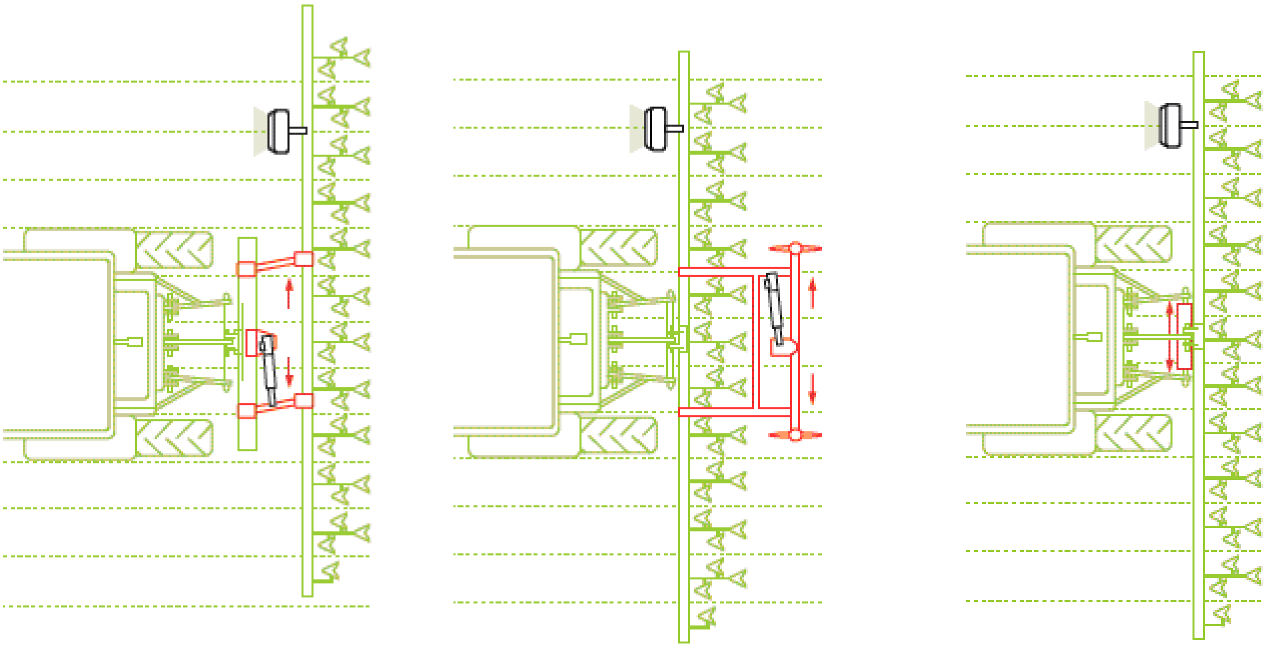

Figure 8 - RoboCrop InRow – complete inter-row and inter-plant weed control system from Garford [5].

Figure 9 - A typical configuration of a patch weed control system consists of sprayer boom with integrated cameras, a vision and image processing module, and a spraying computer controlling the spray nozzle. In the project Intelligent Sprayer Boom, *[7]* the tractor is equipped with an advanced auto-guidance system based on GPS and stereo camera technology allowing for optimal tractor implement control.

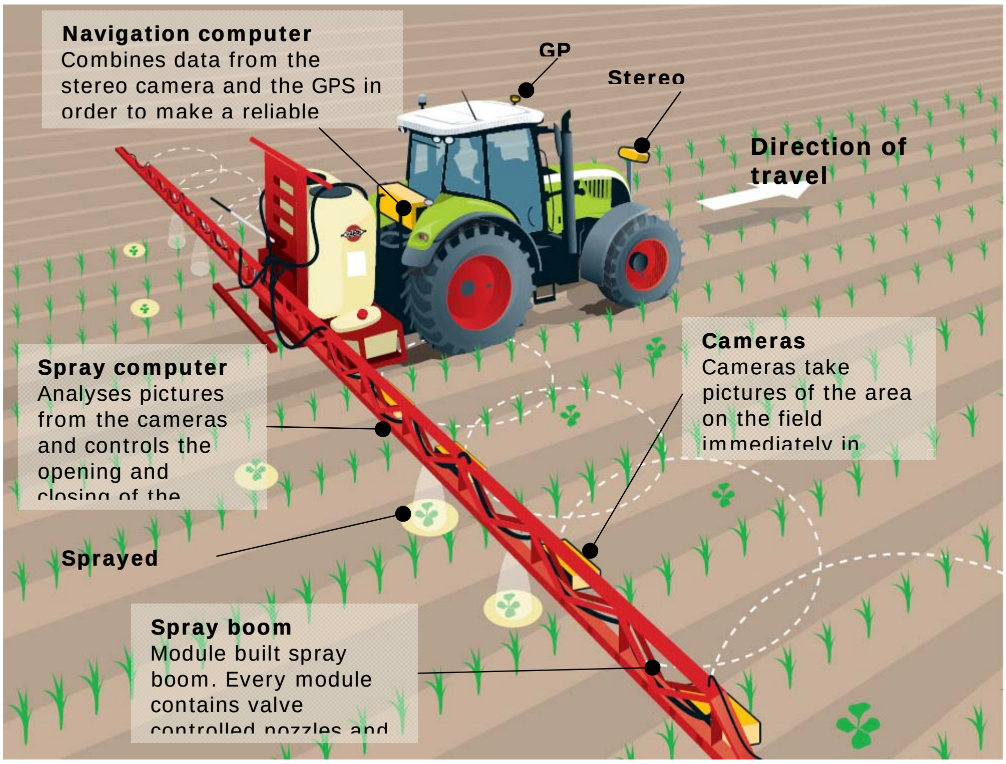

Figure 10 - The aim for spot spraying systems is that the vision algorithms must detects every single piece of weed. In the project [7] the aim is to distinguish weeds positioned close to or under normal crop leaves. An ambitious goal when taking into account that reliable operation is required under many different conditions.

Figure 11 - ECO-DAN stereo camera, 2005. The camera contains 2 CMOS sensor chips with a resolution of 752x480 pixels located with a distance of 12 cm (base line). The camera holds a processing board with 2 DSP's for image processing. It is a multi purpose camera with algorithms for detecting of ridges, tramlines and swaths. The frame rate is in the range 10-15 frames per second depending on the application. The interface includes USB and CAN bus.

Figure 12 - 3D tracking. (a) Left image from stereo camera. (b) Disparity image with warmer colors indicating shorter range. (c) Pixels in the left image labeled with height above the ground lane. (d) 3D tracking showing borders of detected field structure [9].

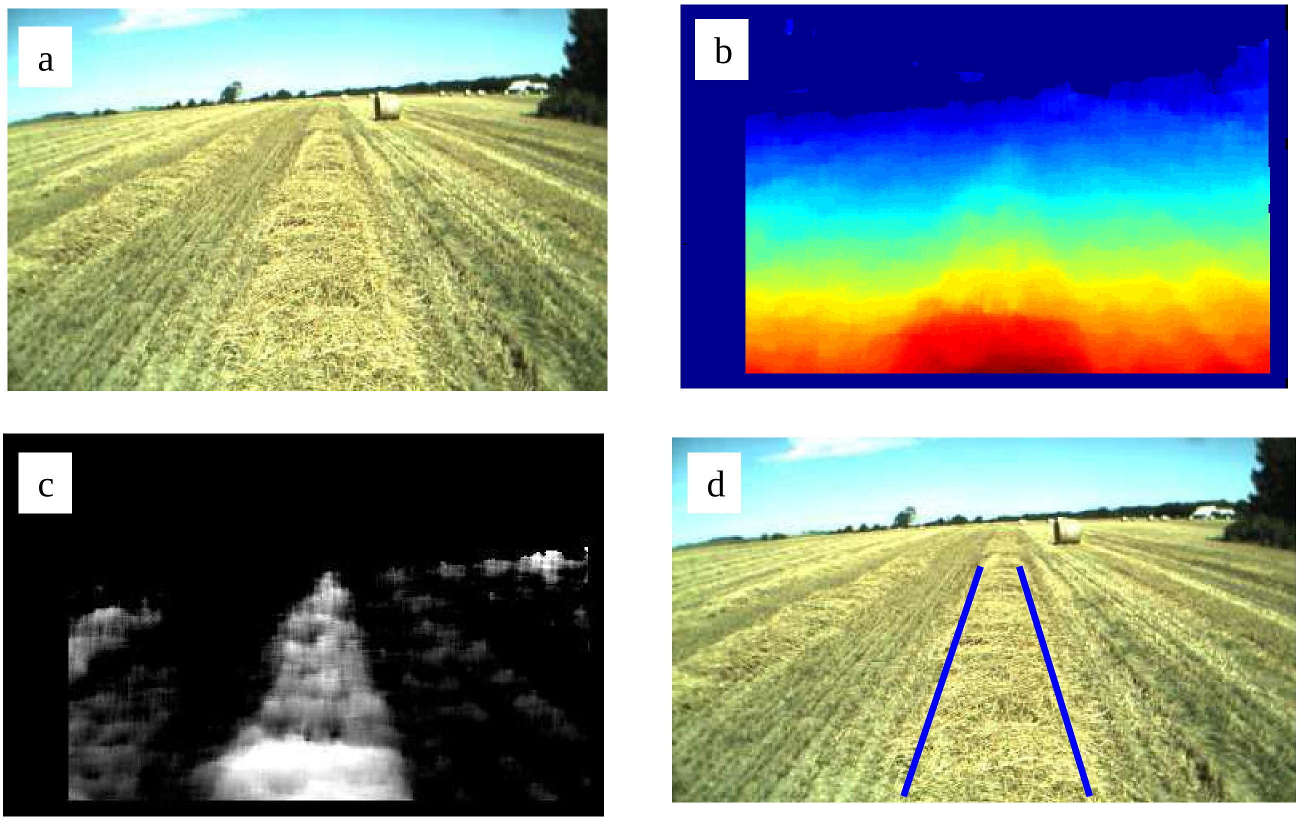

Figure 13 - Tractor auto-guidance system. The lateral and angular deviation between the field structure and the tractor is provided by the camera. A control signal is generated for the hydraulic steering system. The main components of an auto-guidance system are shown below. The system controls the front wheels while the driver controls the throttle and brakes and implement settings.

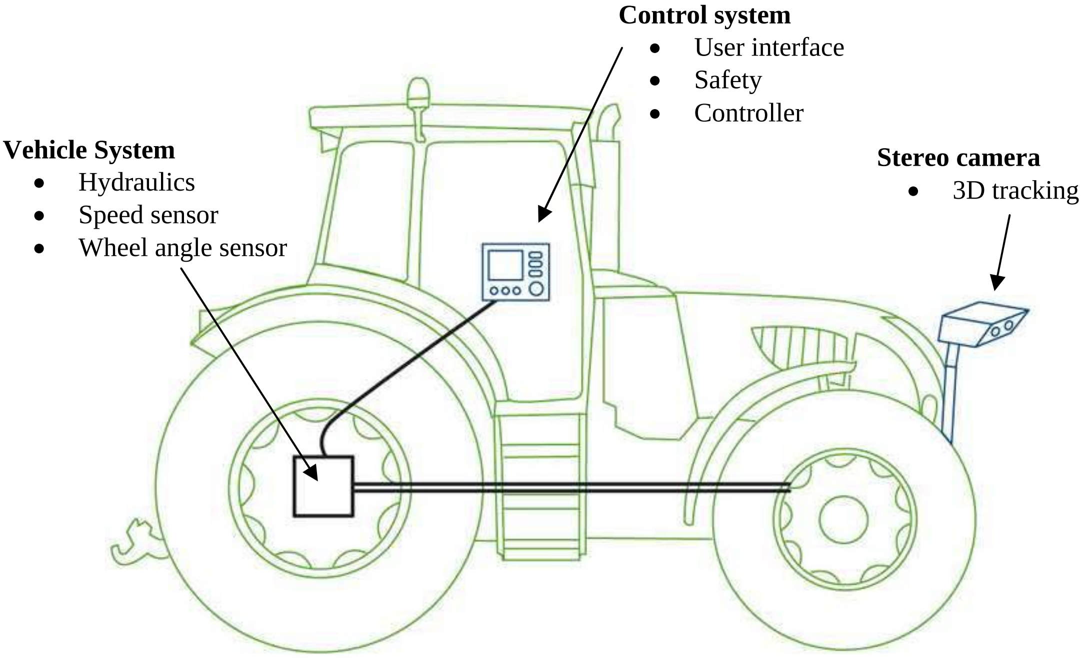

Figure 14 - The VineScout from company Clemens, [12]. The Vinescout guides vineyard tractors along the narrow tracks of vineyards.

Figure 15 - Crop variation. The VineScout must cope with vegetation variations over the seasons.

Figure 16 - The CLAAS CAMPilot is available for CLAAS tractors (*left*) and the CLAAS forage harvester (*right*).

Figure 17 – The CLAAS CAMPilot can guide vehicles along tramlines, ridges or swath. The accuracy is ±5 cm up to 10 km/h and ±10 cm up to 20 km/h.

Figure 18 – Trailer localisation. The trailer top boundary is detected using the disparity image created by the stereo image processing.

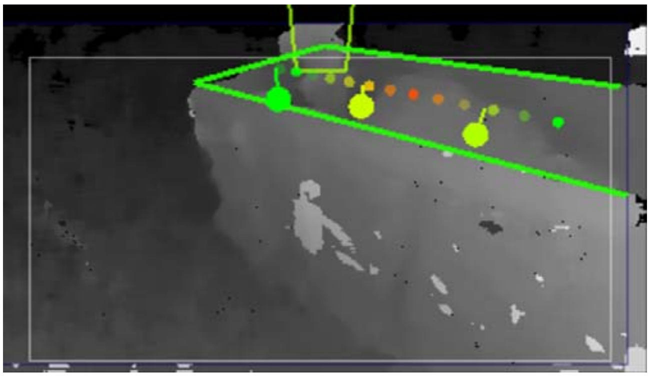

Figure 19 – Tracking of crop jet and hit point. The predicted crop trajectory is corrected online using measurements of the distance to the real crop jet. The green dotted line is the trailer seen from the rear end. White dots are measurements of crop jet. Blue lines indicate camera field of view. Solid light green line is predicted crop jet. Red lines indicate maximum bias estimates.

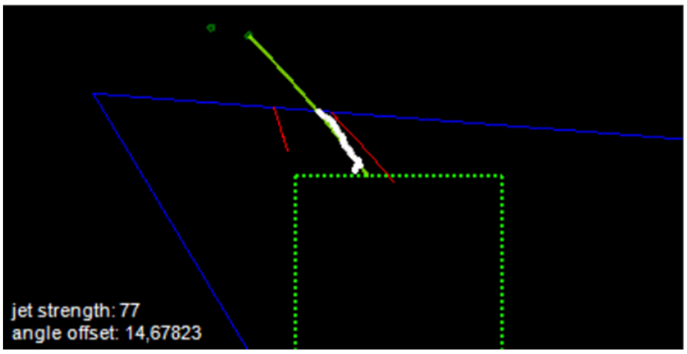

Figure 20 – Determination of fill level in the trailer. The fill potential is shown using coloured dots. A red dot indicates that trailer section is full. The system fills the trailer from one end to the other.

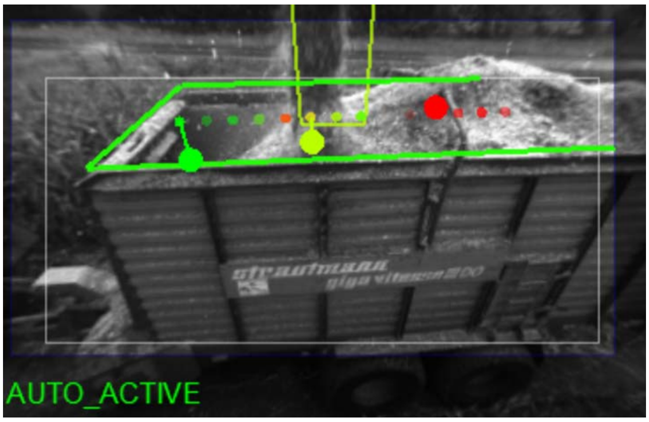

Figure 21 - The CLAAS three sensor camera mounted on the spout of a forage harvester. The camera has three image sensors, 2 CMOS gray scale sensors with a resolution of 752x480 pixels and 1 high resolution colour sensor, The processing unit has an architecture with multiple DSP's and a FPGA. The interfaces include analogue video out, Ethernet and CAN bus.

Figure 22 – AutoFill system overview. The VBM module handles the closed loop control of the spout and flap rotations. The CEBIS, the video monitor and the Multi-Function Level are located in the cabin. The CEBIS handles all user interaction concerning machine settings. The video monitor displays live image from the camera using a coloured overlay to display status information.