THE FUTURE OF THE WESTERN CAPE AGRICULTURAL SECTOR IN THE CONTEXT OF THE 4TH INDUSTRIAL REVOLUTION

LITERATURE REVIEW: Sensor Technology

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1. Technology Overview and Detailed Description

"In the broadest definition, a sensor is an electronic component, module, or subsystem with the purpose to detect events or changes in its environment and send the information to other electronics, frequently a computer processor. A sensor is always used with other electronics, whether as simple as a light or as complex as a computer." (Wikipedia).

The agricultural sector uses sensor technology mainly to collect data on soil, crops and animals through sensors that are integrated in all kinds of agricultural equipment and machines, aircraft and drones or even satellites[1]. Different sensors can provide farmers with real-time information on the environment, their crops and livestock, as well as other processes on the farm, enabling them to manage the farm more effectively. Sensor technology can be useful, the planning, crop/livestock management as well as processing/harvest phases, but also has other uses such as in transport technology, farm security, product marketing/traceability etc.

Sensors are however not only limited to soil, crops and animals, but can be seen integrated into the entire value chain in farming, supply chain or post-harvest systems – from acquiring weather data to product processing, and even up to the market or consumer in the case of possible future food tagging technology.

Sensor technology with a focus on meteorology and GPS/remote sensing

In the first section, different types of sensor technology will be discussed, including recent advances, while the second part will deal with specific applications in agriculture.

There a numerous ways to classify sensors in general, ranging from purpose, radiometric range, scale of measurement etc. For the purpose of this review, the focus will be on meteorological as well as remote/proximal sensing systems.

With regards to meteorological sensors, as with other sensors, the scale of measurement is of particular importance, and like weather/climate assessment, one suggestion could be to categorise it into nano-, micro-, meso- and macro level sensing. Nano level normally refers to sub-unit measurement as in a plant part, animal organ, with very small sensors and possibly at sub-cm scale. Micro level sensors measure around an object, i.e. within-canopy level, around an animal or plant or an organ of that animal or plant at the sub metre scale. Meso level may relate to characterisation of blocks/fields/orchards, camps, buildings at i.e. the sub 100 m scale and macro level to characterisation of climate on the farm, or for a region. Although these classifications can be found in literature, the broader scale of all these levels seem to be dependent on the purpose and scale of the topic in question. I.e. in medical technology “nano” scale can refer to sub millimetre measurements, i.e. in arteries, wounds etc., while the same scale in a fruit orchard may refer to within-fruit measurements spanning several cm.

A comprehensive scoping of different meteorological sensors and networks can be found in the work of groups such as the Semantic Sensor Network Incubator Group[2], as well as from the perspective of Environmental Sensor networks[3].

Environmental (climate), soil and water monitoring (terrestrial sensors)

Automatic weather stations (AWS) are automated versions of traditional weather stations, either to save human labour or to enable measurements from remote areas[4]. An AWS will typically consist of a weather-proof enclosure containing the data logger, rechargeable battery, telemetry (optional) and the meteorological sensors with an attached solar panel or wind turbine and mounted upon a mast. The specific configuration may vary due to the purpose of the system. Most automatic weather stations have a thermometer for measuring temperature, anemometer for measuring wind speed, wind vane for measuring wind direction, hygrometer for measuring humidity, barometer for measuring atmospheric pressure. Some stations can also have ceilometer for measuring cloud height, present weather sensor and/or visibility sensor, rain gauge for measuring liquid-equivalent precipitation and ultrasonic snow depth sensor for measuring depth of snow or a pyranometer for measuring solar radiation[5]. It is interesting to note that changes from manual observations to automatic weather stations has been shown to be a major non-climatic change in the climate record[6], but this also highlights the care that need to be taken when sensor/logging systems are upgraded/changed.

Today weather and climate (long term) data is available to farmers from weather station networks through several online sources as well as smartphone applications. In the Western Cape specifically, with its high variability in climatic conditions due to sea breeze effects and varying topography, these interpolated data sources may be inaccurate when used in prediction models at higher resolution. There is therefore a need for on-farm or collaborative weather station networks every few kilometres, but also for this data to be reliable and uploaded to a central point where it can be processed. Currently, governmental weather station networks are not of sufficient resolution, or well enough maintained to fulfil this need, hence the need for lower cost systems that can be purchased and maintained on farm level.

Certain environmental measurements can be quite challenging with conventional sensors. For instance, precipitation measurements are difficult when snow is involved, as a gauge must empty itself between observations. For current weather, all phenomena that do not touch the sensor, such as fog patches, remain unobserved.

In terms of soil remote/proximal sensing, spectral imaging may be useful, but the spectral response can be difficult to discern when tillage conditions differ and crop residue are present. Several on-the-go sensors are however available to map soil organic matter, electrical conductivity, nitrate content and compaction levels[7]. Electromagnetic induction and resistivity devices, as well as gamma-radiometry have been in use in precision agriculture for several years, but the technology, especially where fusion between the technologies are concerned, will remain quite expensive to deploy by individual farmers[8]. Furthermore, while renting as well as surveying services for these instruments seem to be widely available and relatively inexpensive (i.e. around $100-150 per day for EM device rentals in Australia), these services are extremely rare in South Africa, probably due to the capital cost when importing these sensors and other related costs of ownership.

It will not be attempted here to go into the exhaustive literature available on soil moisture and temperature sensors, some good reviews can be found i.e. by Zazueta and Xin[9] and others where the different types of sensors are compared. One common issue with soil sensors is that in highly variable soil conditions, as experienced in the Western Cape for instance, deployment of research grade sensors to monitor conditions accurately can be very costly. In many applications, the data-logging equipment are also very expensive, even though sensors may be relatively cheap, and some service providers charge a premium for data uploading, handling and visualisation.

It is also problematic to accept that all sensors will be suitable in all applications and for all soils, as comparison of several commercially available electromagnetic soil moisture sensors have shown[10]. This also applies to soil water content measurement, as the different types of apparatus need calibration to soil texture and chemical differences in order to represent the correct soil water content quantification that can be used in irrigation scheduling. Further information on different sensors applied in soil water content determination can be found in many different review, such as the one by Lekshmi[11].

The deployment of wireless sensor networks at field scale, coupled with low-cost soil moisture sensors may change the landscape of agriculture irrigation management in the years to come. A further issue in farm management, is the (now enforced by law from February 2017) measurement of water resources on farms, where keeping accurate data records is a requirement. Sensors can aid in the measurement of levels of tanks and dams, as well as flow measurement in furrows, but accurate measurements in pipes and boreholes are also important. Few studies focus on methods and technologies for integrating both water flow and water quality measurements in sensor networks, but these applications are expected to become more and more important as the quality of surface and ground water resources are under severe pressure[12].

Positioning/localisation/tracking sensors

Although global positioning system (GPS) technology has been in use in precision agriculture for a long time, autonomous navigation for i.e. tractors or accurate position for implements such as laser ploughs or precision planters require more accurate localisation. Satellite based augmentation systems (SBAS) use additional messages from satellite broadcasts to support signal augmentation. SBAS makes additional satellites and signal corrections available at regional or continental level to end users therefore improving integrity, accuracy, availability, and continuity of existing global navigation systems known as “core navigation constellations” (i.e. GPS, GLONASS, Galileo, Beidou). The main application of SBAS is in aviation industries, i.e. to improve safety during approach and landing phases, and as well as in other domains that require improved accuracy and/or integrity (e.g., agriculture, maritime, land management, road etc.)[13]. Several systems have been deployed or are under deployment, including WAAS in US, Mexico and Canada, MSAS in Japan, GAGAN in India, SDCM in Russia, and EGNOS in Europe and in Northern Africa. The extension of the SBAS service to the whole African continent would make SBAS available around the world, which could result in significant social and economic benefits[13]. Recently the technology has been tested in South Africa, which successful improvement of tractor localisation in trials in Stellenbosch as well as in Heidelberg by the South African National Space Agency (SANSA)[14].

Sensor fusion in applications such as the Robot Operating System (ROS) and several other open-source solutions makes it possible to enable auto-navigation in complex environments at relative low cost, which opens the door for both autonomous robots or implementation on tractors and other vehicles in i.e. orchards or vineyards[15]. The sensors for these applications are in mainstream use in Unmanned Aerial Vehicles (UAV’s), from hobbyists and stunt flyers to commercial and military operations – leading to exponential development of these fused platforms and accelerated cost decrease of both sensors and software. For instance, the cost of inertial navigation systems (INS) has decreased significantly during recent years with the use of micro-electro-mechanical system (MEMS) technology in production of inertial measurement units (IMU’s). These units however does not provide the accuracy and stability of their mechanical counterparts, limiting its potential applications. This is especially problematic if high-accuracy GPS is not available, or unreliable. Studies have been launched to improve altitude and heading reference system (AHRS) algorithms fusing IMU and magnetometer data[16]. These are good examples of how sensors on their own cannot achieve certain objectives – the power lies in fusion and processing of the data in order to reach certain objectives.

LIDAR technology now also plays a critical role in localisation, as it can scan the environment with high accuracy[17], and now at relatively low cost. It has developed from an aerial survey tool with which high resolution digital elevation models (DEM's) can be created, to a system that can be used to navigate cars (or agricultural vehicles, robots) in an urban/rural environment using a process named simultaneous localisation and mapping (SLAM)[18].

Imaging sensors, spectrometry

Although imaging sensors and spectrometers are already available over virtually the whole electromagnetic spectrum in the form of both active and passive sensors (Figure 1)[19], the applications and cost of deployment of these sensors vary significantly. More recent developments include advances in microwave and millimetre wave sensors - i.e. millimetre wave sensors that enable contact free measurements in the core of a food product. The specific interaction between these waves and water allows manufacturers to optimise drying and freezing processes in the food industry[1].

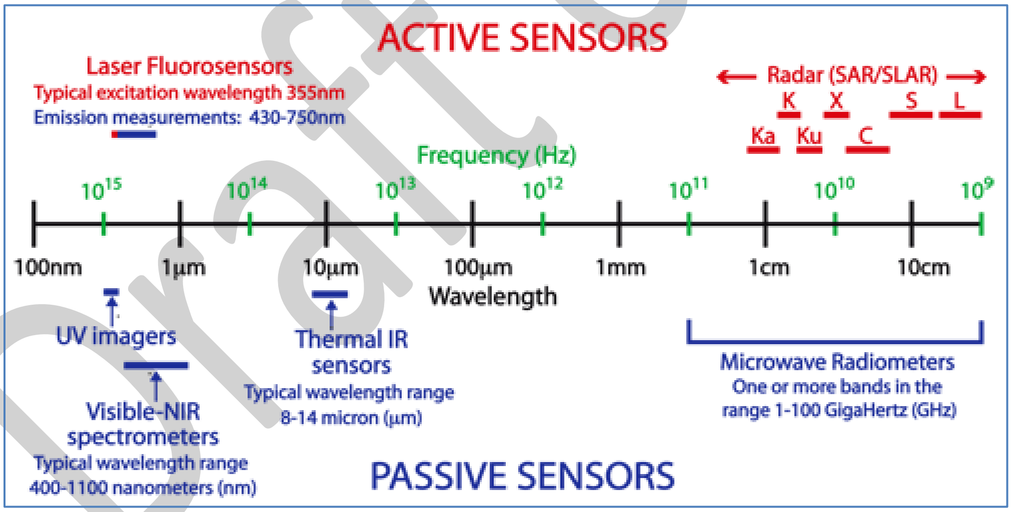

Figure 1: Wavelengths and frequencies of electromagnetic waves on logarithmic scales, and spectral range of remote sensing instruments used for marine pollution detection and analysis. Passive instruments detect signals, which are naturally available, e.g., sunlight reflected or thermal radiation emitted from a target. Active instruments provide their own source of radiation for target illumination and signal detection[19].

Radiometric sensors also enable lab-on-a-chip technology integrating laboratory functions for i.e. diagnosing sick animals, gas detection or food freshness status monitoring. Hyperspectral and thermal cameras can also be used to detect anomalies and analyse or visualise composition of products at different stages[20].

The conventional application of these imaging or scanning sensory types in remote sensing on different platforms, i.e. satellites, aeroplanes, UAV's, have evolved mostly due to the cost reduction with regards to higher resolution as well as other sensor properties. A more than thirty-year old issue in satellite remote sensing, namely image fusion from different sources and technologies (multisensory, multitemporal, multiresolution and multifrequency) have now become very relevant also on other platforms i.e. the possible fusion between satellite, aerial (i.e. UAV) and terrestrial (i.e. robotic) image data.

2. Application Examples and Case Studies

Apart from some applications mentioned in the previous section, from weather stations to proximal remote sensing platforms, many applications will be dealt with in the respective technology applications for sensors, i.e. UAV's, robotics, IOT, smart farming, etc.

Due to the extremely diverse nature of different agricultural sectors and vast number of recent sensor advances, we will only touch on a few applications/case studies that could be of value in South African agriculture. This diverse nature of topics is illustrated for instance in the recent special issue of the "Sensors" journal with 45 papers already submitted, i.e. the one on 3D imaging applications in agriculture[21]. Further keyword searches on "sensors in agriculture" revealed the extremely prolific nature of developments in the field, with the Sensors journal crucial in linking engineering applications and other fields such as agriculture.

It would be interesting to also see an update of reviews such as the very comprehensive one of wireless sensor technologies in the agriculture and food industries written more than a decade ago[22] with updated technologies (i.e. the smartphones replacing the PDA device) and adding some new advances in sensors. It is however clear that, even though technologies are advancing very fast, there are crucial issues linked to its fast uptake especially in these industries, which were also highlighted in the article.

Apart from the previously mentioned sensors, it also has to be remembered, that actually recent smartphones already are integrated "solutions" based on an array of sensors, as a recent review also emphasised[23]. The possible applications of this widely available solution and its potential integration with other sensors must not be underestimated, in fact, many UAV systems today make use of smartphone or tablet operating systems for control and navigation purposes.

Positioning/localisation/tracking sensors

While the idea of a driverless tractor is as old as 1940[24], to implement totally autonomous navigation (as opposed to supervised autonomy or "follow me" systems[25]) accurate localisation i.e. with GPS and IMU or LIDAR systems are necessary.

GPS applications in agriculture are of a diverse nature[26], but in essence, it enables the localisation and timestamping of all data collection, be it on a harvester, tractor, animal or aeroplane. It therefore also enables adaptive technologies, i.e. variable rate spraying or fertiliser spreading. An example of this is the tractor spraying application Farmtrack, developed by engineers at Stellenbosch University and now used on wine farms[27].

In terms of tracking and traceability, RFID technology has been extensively reviewed[22] [28], and it creates opportunities, in combination with sensors, for animal tracking, fruit cold chain management, irrigation technologies to name but a few. One of the reviews however also highlights an important issue regarding sensors in general in the agricultural environment, which is the harsh environments it is often subjected to.

3. Technology or Application Life Cycle: Current Status and Expected Development in 2020 and 2025

This is very difficult to develop in detail considering the diverse phases of adoption and development/maturity based on different sensor types – would need to be developed per sensor type if the level of detail is required. I.e. it cannot be developed for the collective "sensors" grouping, but rather on the applied technologies – i.e. UAV's, robots, IOT applications of sensors etc.

Table 1: Heading

Technology Area	Current application in agriculture	Expected applications in agriculture by 2020	Expected applications in agriculture by 2025
Applications need to be reviewed with the respective technologies			

4. Business Eco-System View

UAV's require sensors for operation, and provide important outputs for precision farming/smart farming systems. As an example see Figure 2 showing just some of the many sensor systems on even a very simple UAV system.

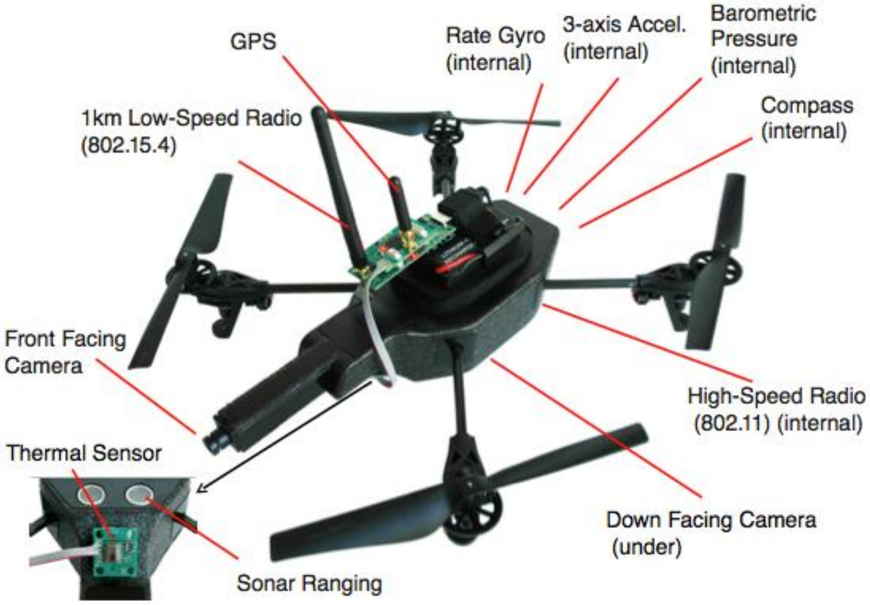

Figure 2: Just some of the sensors deployed on a simple UAV platform
Source: http://wise.ece.cmu.edu/redmine/projects/drone-rk/wiki).

Sensors are crucial base elements that form and mould several further applications. Without sensors, weather stations, remote sensing on different platforms, robotics, iOT applications as well as further data applications i.e. smart farming and precision agriculture are virtually impossible.

5. Benefits and Risks

Although several benefits and risks may be linked to sensors in itself, the real benefits and risks are also intricately linked to the application of these sensors. The same sensor may even have significant benefits in one application, and more risks in another.

Benefits

- Sensors enable several other technologies and devices, and may lead to informed decisions, compared to subjective observations (i.e. “to measure is to know”).
- Sensors may lead to increased efficiency through the more accurate depiction of efficiency in labour or of machinery, as well as resource use (water, electricity, fuel).
- Sensors can advance safety in material handling, increased food safety, reduce occupational hazards/risks by monitoring processes and conditions.
- Long-term sensor records enable comparison and planning of future remedial actions based on past data (i.e. climate change mitigation, irrigation adaptation etc).
- Sensors can help optimise resources by limiting wastage (i.e. dam level measurements or detection leaks or energy loss).

Risks

- Inaccurate or uncalibrated sensors can actually lead to erratic decisions, and in some cases may even cause accidents, crop loss or other more severe issues.
- Sensors may be calibrated and tested in environments less demanding than farms, and then fail in these conditions.
- The cost of measurement may not be warranted in certain situations, and may actually lead to unsustainable production.

6. Potential Economic, Social, Ecological and Political Developments and Impacts

Cost implications of sensors

Although many sensor systems have seen costs exponentially reduced in the recent past (i.e. RGB cameras with high-resolution CCD's), some technologies, i.e. gamma radiation, microwave sensing technologies, GPR as well as hyperspectral cameras are still seen as cost-restrictive in some mainstream applications.

Servicing/related expertise and patenting of sensors, calibration

Many sensor types require specialist service or calibration, which in an African context, makes it even more expensive where these systems cannot be serviced locally. This also mean that they will be out of operation for the time it is sent overseas for servicing. The local supply chain and servicing agents are therefore crucial where these technologies are used in i.e. third world countries.

Practical considerations (i.e. theft/vandalism, data ownership)

Who will own the data of sensors collected on a farm? The farmer or the technology supplier – therefore linked to intellectual property issues[1].

GPS technology can be "turned off" by the countries owning the satellites in time of political turmoil (reference needed).

7. Evaluation Matrices

Synthesis, Conclusions and Key Trends from the Literature

Write up the key trends and overall conclusions.

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