

Future Trends in Precision Agriculture

A look into the future of agricultural equipment

A report for

NUFFIELD
AUSTRALIA
FARMING SCHOLARS



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Foreword

We all have a vision of what the future will look like and when it comes to technology we all have some visions of robots performing the jobs that most of us would happily pass up. The Industrial, Green and Digital Technological Revolutions have driven agricultural output to levels capable of feeding the exponential growth in human population to date. With a predicted world population increase from the 6.8 billion today to over 10 billion by 2050, growth in agricultural output will need to continue. This combined with an ever declining rural labour force and the need for greater efficiencies will inevitably lead to increasing levels of in-field automation. We've all seen video clips of modern factories, with their robots doing the intricate and repetitive tasks faster and more consistently than possible with manual labour. Is this what the farm of the future will look like?



Concept of Autonomous Agricultural Vehicles (Source. Simon Blackmore)

I've always been interested in electronics and new technology and took to Precision Agriculture with great enthusiasm. Over the past 10 years I've collaborated with Sydney University and others and had the opportunity to utilize just about every piece of commercially available Precision Agricultural equipment on the market today, but I wanted to know more. The technology we're using now started as a radical idea somewhere; it was researched, commercialised, marketed to a sceptical farming community and indeed a few of those initial ideas have become successful. I wanted to meet the people dreaming up these ideas and get a feel for the future of agriculture.

This report looks at a number of technologies that are being used on a commercial basis in agriculture today as well as the research that is being conducted by universities into the technology of tomorrow. Technological advancements, particularly in sensor and robotics design, are allowing universities and agricultural equipment manufacturers to include ever more advanced technologies in their research and development programs. It's not for me to try and predict which technologies will eventually be commercialised; that's a job for the marketing departments and entrepreneurs. My aim was to discover what is actually possible with current and evolving computer technology, to see how it could fit or be adapted for an Australian farming system and make fellow farmers aware of this research and its possibilities. My belief is that a well informed Australian farming community, which has already demonstrated its ability to think outside the square and become some of the most efficient farmers in the world, has the ability to define the future direction of agricultural research.

Acknowledgments

I would like to sincerely thank both Nuffield Australia and my sponsor, the Grains Research and Development Corporation for the opportunity to travel the world and not only meet a lot of the people responsible for the evolution of Precision Agriculture, but also broaden my understanding of global agriculture.

I would also like to thank my father, Keith and agronomist Glenn Shephard for taking on the increased workload in my absence and producing a fantastic crop in yet another difficult season.

Thanks also to the hundreds of people who took the time to share their expertise with me. While this report can never cover everything I have learnt from you all, my mind is full of new knowledge and ideas that I'll endeavour to share with the broader farming community into the future.

Finally, and most importantly, a big thank you to my wife Penny and my girls Emilie and Sophie for letting me disappear for a good part of the year to follow a passion. While it was an amazing experience, nothing can replace being with your family.

Abbreviations

CCD - Charge Coupled Device
CMOS - Complimentary Metal-Oxide-Semiconductor
CORS - Continuously Operating Reference Stations
DOD - Department of Defence
EU - European Union
GMO - Genetically Modified Organism
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
OEM - Original Equipment Manufacturer
PTO - Power Take Off

Executive Summary

The concept of Precision Agriculture (PA) has emerged over the past 15 years with the introduction of new electronic equipment which has allowed farmers to increase the efficiency of their operations and develop new farming practices. However, the investment in PA equipment represents a significant financial outlay and as with all ‘high-tech’ equipment it can become superseded relatively quickly and therefore does not tend to hold its capital value. When deciding what equipment to purchase farmers need to understand the capabilities of currently available equipment as well as the likely evolution of the technology in order to ‘future proof’ their investment. This report looks at a number of technologies that are being used on a commercial basis in agriculture today and the research that is being conducted by universities into the technology of tomorrow along with some recommendations based on my observations. They include:

- Satellite navigation and steering systems

Most PA equipment is based around the Global Navigation Satellite System (GNSS). The United States and Russia are planning updates to their systems, while the European Union and China are planning to launch their own systems. This will significantly improve the accuracy and robustness of satellite navigation but will require new receivers to be purchased, however, the timeframe of the upgrade is around 10 years so may not influence purchasing decisions in the short term.

- Standardisation of PA equipment and data

There is a major push from farmers and equipment manufacturers for standardisation between different PA equipment and the associated data. This has led to the development of the ISOBUS 11783 standard which outlines both the hardware requirements in terms of plugs and wiring as well as the communication protocols so that equipment from different manufacturers can interact. Manufacturers are well down the path of meeting the standard with a lot of commercially available equipment already compliant. It is recommended that farmers should now look to purchase only ISOBUS compatible equipment to ensure maximum functionality into the future.

- Better Boomsprays

Electronic monitors and controllers have long been utilised with boomsprays, from simple running totals to today's automatic boom section controllers. Research is being conducted into further advancing application control across the boom, driven by increasing boom widths and wider travel speeds. A lot of this work is centred around controlling the application rate and spray pattern of individual nozzles. Another line of research is based around further advancing the concept of weed identification and automatic spot spraying. Systems are being developed that can identify and even differentiate plant species. This research is also closely tied to 'Micro Spray' research whereby several different systems are being developed to target and control weeds on a finer scale or individual basis. Given that an increasing proportion of Australia's cropping system is converting to minimum and no-till with the associated heavy reliance on bigger boomsprays, Australia should consider actively contributing to this major research effort.

- Automation of agricultural equipment

Advances in digital technology and sensor systems over the past decade has resulted in a great deal of research and development of more intelligent agricultural vehicles capable of automating tasks with minimal operator input. The ultimate aim is to remove the human operator all together and have tasks completed autonomously. While most of the hardware and control systems are already a reality, issues of machine interaction with an essentially unpredictable environment still need to be addressed. It is generally accepted that autonomous operations will need to be conducted by a number of small machines which interact to complete a task rather than one large machine. This not only improves the safety aspects but also offers greater flexibility in terms of scalability. Australia should also be a part of this research effort as there are many operations in our farming systems which could greatly benefit from this technology.

This report aims to give Australian farmers an insight into future technology and allow them to continue to innovate and evolve Australian farming systems and help them to effectively define the future direction of agricultural research.

Introduction

Over the evolution of mankind, we have been inventing tools to make our lives easier and more productive. Modern agriculture, whereby humans moved from exclusively hunting and gathering to planned systems of sowing seeds and harvesting grains, traces its beginnings to the Lavent region of the eastern Mediterranean around 10,000 years ago. It was our ability to plan tasks, then develop and utilize the tools and methodologies needed to achieve that task which allowed us to develop a more reliable food supply. The past century has seen major developments in agricultural productivity through the development of selective breeding, hybridisation and Genetically Modified Organisms (GMO), along with the development of synthetic fertilizers and chemical weed and pest control. The industrial revolution saw increasing levels of mechanisation in agriculture replacing most of the human labour previously required.

The invention of the transistor in 1947 marked another milestone in human technological achievement. It led the way to more advanced digital circuitry and the widespread adoption of all types of electronic technologies which has seen the economies of scale required for rapid development of new technologies. Digital technology has also found its way into agriculture with the development of various technologies ultimately aimed at increasing productivity. While early pieces of equipment included area counters, seeder blockage monitors and harvester grain loss monitors, it was the development of the Global Navigation Satellite Systems (GNSS) which allowed the semi-automation of various farming vehicles, and in conjunction with developments in electronic sensor technology, has seen the development of site-specific agriculture. This technological revolution in agriculture is generally referred to as 'Precision Agriculture'.

Today an exponentially increasing human population coupled with diminishing arable land means that agriculture will need to keep evolving in order to meet the challenge of continually increasing output while improving use efficiencies of inputs such as nutrients, water and labour. Research and development into the further integration of digital technology and agricultural production continues with researchers and manufacturers looking for new ways to utilise ever increasing computing power and more accurate sensors. It seems it's only a matter of time before a vast majority of agricultural tasks could be carried out by autonomous robots and all crop plants, from tree's to cereal plants, are monitored and managed on an individual basis.

1.0 Satellite Navigation and Steering Systems in Agriculture

The development of a civilian Global Positioning System (GPS) alongside the military version has seen a whole range of new positioning and navigation systems developed for a range of industries over the past decade. Agriculture is no exception and a whole new range of equipment has been developed from basic field guidance and mapping equipment through to fully automated steering and equipment control systems. While the accuracy and capabilities of this equipment has evolved and improved over the past ten years, the raw positioning data derived from the GPS satellites has remained the same.

1.1 Upgrades to Satellite Navigation Systems

Over the next ten years we are going to see several improvements to satellite navigation systems. This is a result of the upgrade of the USA's Navstar GPS and Russia's GLONASS systems, as well as the development of two other systems: Galileo by the European Union (EU) and Compass by China.

At present, the USA's GPS system transmits two different ranging codes over two different radio channels called L1 and L2. The civilian code is transmitted on the L1 frequency, while an encrypted, more accurate code is transmitted on both L1 and L2. The cost of a GPS receiver is generally based on its level of accuracy. Most of the position error is caused by the ranging codes being degraded as they pass through the atmosphere and GPS receivers use slightly different strategies to correct this error. The highest accuracy systems use a fixed GPS base station located within 10km of the vehicle's GPS to generate an error correction value which is transmitted via a radio link to the vehicle's receiver; this is referred to RTK GPS. Dual Frequency GPS is the next level of accuracy and uses both the civilian signal on L1 as well as the part of the code on L2. It also uses correction signals generated by a global network of base stations, with the correction signal relayed to the GPS receivers via a satellite link. RTK GPS systems are also based on Dual Frequency receivers however it uses its own dedicated base station rather than the global network. Next is Single Frequency GPS which only uses the L1 civilian code and a correction signal, while the lowest accuracy receivers simply use the L1 signal on its own. Some lower accuracy systems use software, such as the E-Diff software used with Lightbars, which predicts the likely change in error based on the path of the satellites across the sky.

Currently Russia is rebuilding their GLONASS system, originally developed about the same time as USA's GPS during the Soviet era. While not globally operational in its own right at present, it's ranging codes are used in conjunction with GPS codes by some receivers in order to improve position reliability in difficult terrain where a clear view of the sky is restricted. Currently the GLONASS and GPS coding systems are not compatible, requiring two separate receivers in the GPS unit, increasing their complexity and cost. The Russian Government, however, has committed to making GLONASS compatible with GPS and this transition will start as new GLONASS third generation, class-K satellites are launched from 2010.

The proposed EU system called GALILEO and the Chinese COMPASS system will also be compatible with GPS. Both are due to be operational within the next 10 years. This will effectively quadruple the number of satellites available to the GPS receiver making satellite navigation systems much more reliable and robust, especially in difficult terrain.

The US is also upgrading their GPS with new civilian frequencies and more robust ranging codes. Currently the civilian signal is only transmitted on L1, but a new civilian ranging code on L2, called L2C, is currently being developed and will be fully implemented by 2016. A completely new frequency called L5 is also planned for completion by 2018.

Triple or Quad frequency receivers that use GPS ranging codes on L1, L2C and L5, along with ranging codes from any of the other systems will be far superior to today's dual-frequency receivers both in terms of position accuracy and robustness without the need for a third party correction signal. The highest accuracy RTK systems will still require a local base station providing real time correction data, but start up times and signal robustness will be greatly improved while the maximum range between the base and the vehicle will increase dramatically.

Once the US has fully commissioned the L2C and L5 signals, from 2010 they will no longer support the current L2 signal currently used by RTK and Dual Frequency receivers. While it won't be shut down altogether, it will no longer maintain the signal if it fails or becomes inaccurate.

As new GPS receivers come to market, farmers need to be aware of these changes and purchase a system that will meet their needs into the future, particularly when purchasing high accuracy systems. As new receivers with the ability to utilise the new frequencies and ranging codes become available, farmers need to select a system with the capability to work effectively in their environment without paying for excess capacity or functionality if not

required. A Quad-Band receiver may sound better, but if you're operating in open terrain then the ability to use 48 satellites at once won't significantly improve receiver performance.

Given the importance of, and interest in, Satellite Navigation Systems, Appendix A gives an overview of the development of the USA's Navstar GPS and more details on its upgrade.

1.2 Standardisation of GPS and Autosteer System Performance Data

Currently GPS receiver manufacturers report their performance based on their own testing without always clarifying the conditions the testing was actually done under. In an attempt to better standardise accuracy claims under real world conditions, the University of Kentucky has built a GPS test track where receivers can be tested under a variety of different scenarios. The test track simulates pass-to-pass runs, headland and sweeping turns at various speeds. The test carts can also simulate vehicle roll to determine how effectively each system's terrain compensation mechanisms react. The ultimate goal is to provide a framework whereby GPS manufacturers can voluntarily test their systems and report standardised performance data, similar to the program at the Nebraska Tractor Test Laboratory. Farmers and farm lobby groups need to encourage GPS manufacturers to use this facility.



GPS Test track at the University of Kentucky. Test cart (inset)

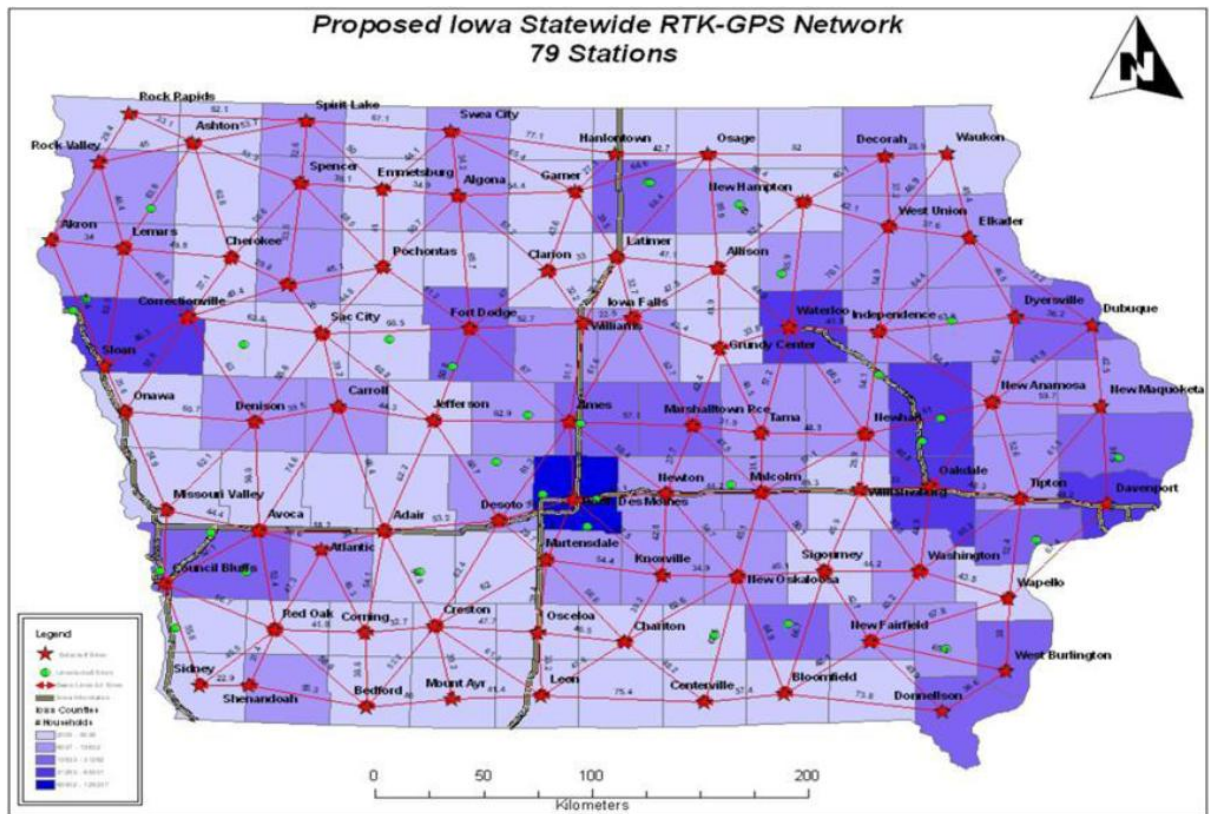
An increasing proportion of agricultural equipment is fitted with either Original Equipment Manufacturer (OEM) or third-party automatic steering systems. Auto-steering systems consist of a number of sub-systems including:

- Terrain compensation systems which account for the difference between the GPS receivers position and it's relative position on the ground on uneven terrain
- Steering software which takes the raw position data from the GPS and terrain compensation system and determines a new heading and steering wheel position
- Steering system which is usually either direct hydraulic control of the steering cylinder or electric control of the vehicle's steering wheel.

While the accuracy of the GPS receiver accounts for most of the performance of the vehicle and/or implement, the design of the rest of this system, and the dynamics of vehicle/implement itself, also has a significant influence. The University of Nebraska is looking at ways to test and report the overall auto-steering system performance on different vehicles and in the case of tractors, using different implements under different conditions.

1.3 Wireless GPS Correction Data Networks

Given that the maximum range an RTK base station can operate at will increase, how can we best establish base stations in the future? Does each farm need one or can they be shared? If shared, who is responsible for the maintenance? The other problem is that the radio transmitters sending the correction data have a maximum transmission power limit imposed by Federal legislation so transmitting over a longer range, particularly over difficult terrain, will require a network of radio repeaters. All the mobile phone companies operating in Australia now have systems, such as Telstra's NextG, for transmitting data wirelessly. Many European countries and states in the USA have established networks of Continuously Operating Reference Stations (CORS). A third party establishes the network of GPS Base Stations throughout a geographic area and the processed correction data is uploaded to the internet. Users within that area can use a wireless internet modem, either connected to, or built into the GPS receiver, to stream that correction signal from the web. This provides RTK level accuracy without the need for individual base stations.



Iowa CORS network (source. www.precisionag.com)

Above is an example of such a system set-up by the IOWA Department of Transport and correction data is provided free of charge to the community. The only cost is a wireless internet connection plan. The Victorian State Government is also setting up a CORS network called GPSnet. It will be interesting to see how this system develops and if it is embraced by farmers.

2.0 Standardisation of Precision Agriculture Data and Equipment

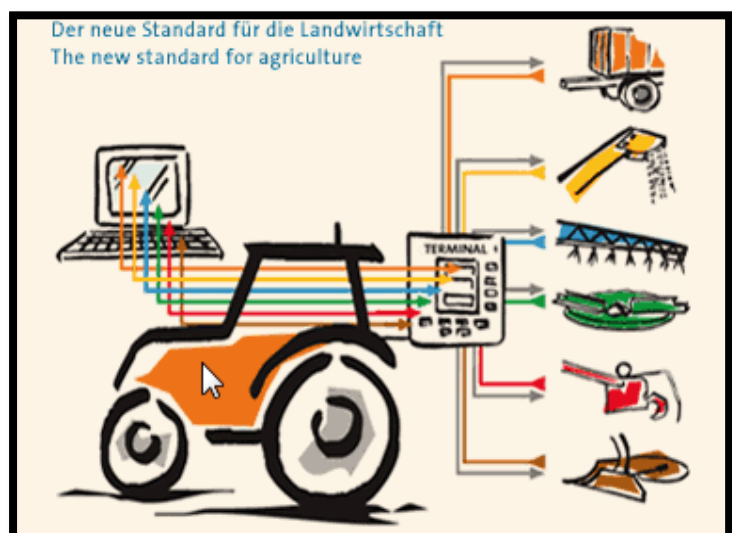
The development of Precision Agricultural equipment has progressed quite quickly with equipment manufacturers aiming to secure a reasonable market share. Overall they have tried to develop systems that are reliable, easy to install and use. The problem with this approach is that very little thought was given to making equipment that could be easily integrated with other manufacturers systems. As the number of different systems increases and each become more complex, the task of getting some standardisation in communication and data protocols becomes more difficult.

2.1 ISOBUS 11783

Over the past 20 years or so the amount of electronic equipment on machinery has gradually increased as manufacturers build more functionality, productivity and performance into their equipment. To date the majority of implements have had an individual user interface mounted in the tractor which would typically only control one specific piece of equipment. Just as the equipment manufacturers standardised items such as hydraulic fittings, power take off (PTO) drives and hitches, it was soon realised that in order to provide inter-operability between the electronic systems on different tractors, implements and user interfaces, standardisation of the electronics was required as well. This led to the development of the ISO 11783 standard by a number of working groups representing engineers from across Europe and North America.

A more detailed history on the development of the ISOBUS protocol can be found in Appendix B.

The modern ISOBUS system is based around one central communication cable called a BUS to which all the equipment is attached. The screen mounted in the cab is attached to the BUS in the same manner as all other equipment and is called a 'Virtual Terminal', as opposed to the dedicated terminals



used in the past to control a single implement's electronics. When a piece of equipment is attached to the BUS for the first time it will automatically install the software required for the user to control it onto the Virtual Terminal Screen.

A piece of equipment is said to be ISOBUS compliant when it has been tested by an approved laboratory and meets the requirements of the "ISOBUS Compliance Test Protocol" document. A piece of equipment can also have "Self Declared Compliance". In this case the equipment has not been tested by an independent laboratory however the manufacturer is confident that the equipment would meet the ISOBUS standard.

Most modern tractors come with ISOBUS compliant BUS wiring and plugs already installed and many recently released pieces of equipment are also ISOBUS compatible. I would suggest that when buying Precision Agriculture equipment in the future, it would be well worth considering purchasing equipment that is ISOBUS Compliant. As an example, a proper ISOBUS system would allow you to plug a John Deere Greenstar 2 display into the ISOBUS plug on your Case Magnum tractor and control the autosteer system utilising the GPS signal from any ISOBUS compatible receiver also connected to the tractor's BUS. An ISOBUS compatible Simplicity Air Seeder cart can also be attached to the tractor's BUS via the standardised ISOBUS plug on the back of the tractor. It will load the appropriate software into the Greenstar Display allowing the user to control both the Autosteer and the Air Seeder Cart with the one screen.

It is generally accepted that full implementation of ISOBUS needs to be completed within the next 5 years and manufacturers are making a genuine effort to reach that goal. The feeling is that those who aren't compatible just won't have a market.

2.2 Vehicle Telemetry

There is a general feeling among equipment manufacturers that a move toward wireless data transmission is inevitable. This would offer many benefits over the current system of data cards. John Deere, among others, is developing various vehicle telemetry packages whereby real time machine statistics can be viewed from a web page. Users with appropriate access can monitor engine and vehicle parameters, fault codes and even vehicle location. John Deere even has a system called Curfew, whereby if a vehicle is moved when it shouldn't be, a text message can be sent to a phone. Several farmer co-operatives in the US Mid-West use these systems to co-ordinate their fleets of fertilizer spreaders and sprayers. A list of jobs is

uploaded to the vehicle and its progress tracked in real time from the company office. If a change in plan is required then new job plans can be instantly downloaded to the vehicle.

Wireless networking will also allow yield and application maps as well as prescription maps to be wirelessly transferred between vehicles and the farm management software. This is particularly important as more farmers move toward variable rate inputs and utilize the services of consultants to create these prescription maps. For this to work effectively it would be ideal to have a certain degree of standardisation between different manufacturers of Precision Agricultural equipment.

2.3 Precision Agriculture Data Standardisation

In 2008 The EU funded the “Future Farm” project, a three year collaborative research project between fifteen Universities, Research Centres and Private Companies from ten European countries.



Future Farm Logo (source www.futurefarm.eu)

The full project title is “Meeting the challenges of the farm of tomorrow by integrating farm management information systems to support real-time management decisions and compliance to standards”. The project’s overall aim is to better understand how new technologies can be used to better manage European farms through the collection and transmission of data in real-time, across networks. It aims to develop a standardised platform for this data, in the same way that ISO11783 is standardising the agricultural electronic equipment. It is also looking at how advances in robotics technology can be effectively introduced into farming systems. This is integrated with analysis on how future agricultural developments will impact the entire European community.

3.0 Better Boomsprays

There are many economic and environmental reasons to increase the effectiveness in which agri-chemicals are used. Increasing use efficiencies and reducing off target applications lead to a better outcome for the environment and a better economic outcome for the farm business. Developments in sprayer technology including better nozzles, booms and controllers combined with a better understanding by operators of the interaction between spray pressure and the proportion of fine, drift prone droplets has all contributed to reducing the incidence of agri-chemicals moving off the site of application.

The introduction of GPS technology to agriculture has allowed the development of automatic boom section control, whereby the controller will map the areas sprayed and if any part of the boom passes over that area again the controller automatically shuts off the appropriate sections of the boom. As with Autosteer technology, this technology reduces overlap and operator fatigue, particularly with larger booms and irregularly shaped fields.

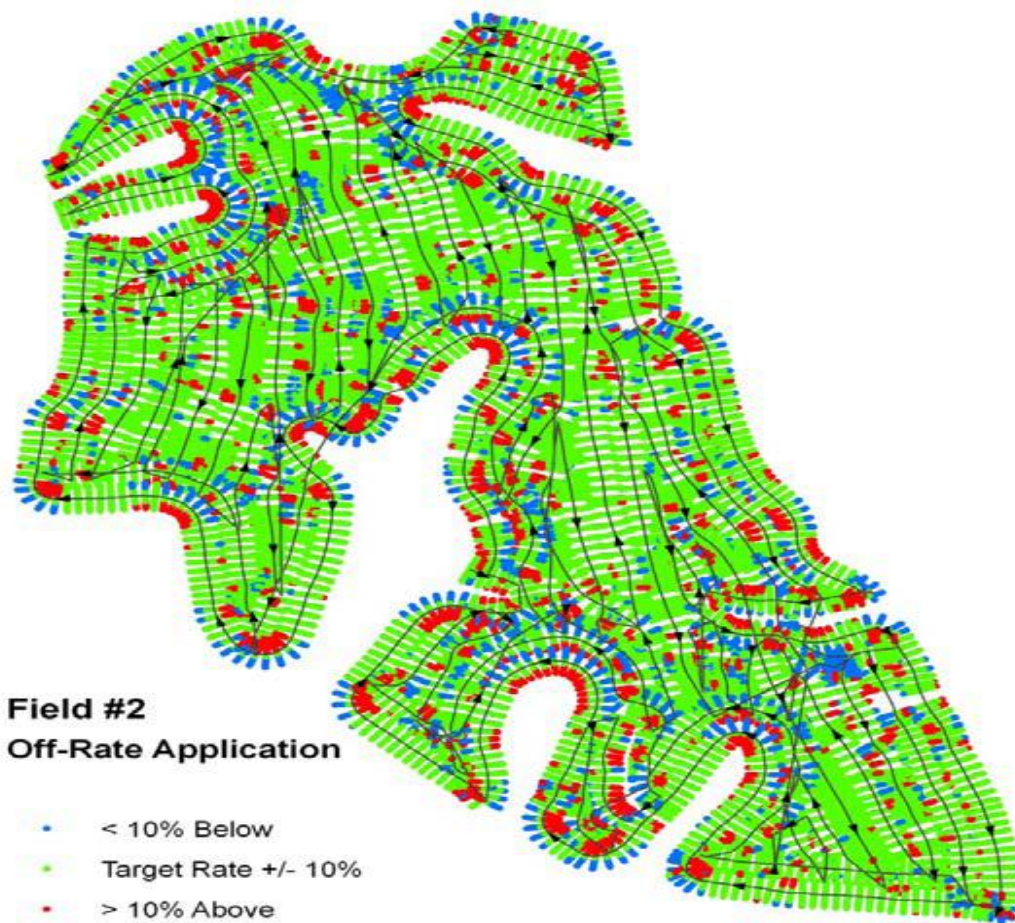
3.1 Improving boomspray performance

The development of more robust and reliable boomsprays has allowed farmers to operate over a greater range of speeds, improving efficiencies by travelling faster over straight, flat areas and slowing around obstacles and when cornering. This has presented issues for drift control, as automatic rate controllers increase the boom pressure, as speed increases, in order to maintain a consistent application rate.

Capstan has commercialised a technology developed at the University of California, Davis Campus, whereby individual nozzle bodies are fitted with a solenoid valve. The nozzle bodies are fitted with the appropriate nozzle for the maximum speed and flow rate required. When the boom is travelling under this speed, the solenoid valves on each nozzle will pulse, simulating the flow of a smaller nozzle. The overall effect is to hold the spray pressure, pattern and average droplet size at a predetermined level over a much larger speed range than is usually possible. For small and irregularly shaped fields, there are typically many speed changes as a large boom negotiates the contours in its path. Maintaining the predetermined boom pressure and droplet size is important to ensure effective coverage is maintained while the production of fine, drift prone droplets is minimized.

This technology could be further enhanced with integration with the automatic boom technology, whereby instead of the automatic boom controller activating valves to control sections of the boom, it could interface with the Capstan controller and direct individual nozzles to turn on or off.

As boom widths continue to increase there is a significant issue of over and under application of chemical as the boom rounds corners with the inside boom slowing significantly and the outside boom speeding up.



Simulation of actual spray applied in an irregular field (source Joe Luck)

Joe Luck and his colleagues from the University of Kentucky have been modelling the actual spray application in irregularly shaped fields and are devising methods to overcome it. The Capstan technology could be further developed to account for changes in speed across the boom when cornering. During cornering, as you move further towards the inside end of the boom, the nozzle speed over the ground gradually decreases. To maintain the target application rate per unit area, the flow rate needs to incrementally decrease as you move out

to the point where the nozzle could possibly be turned off, if the nozzles at the end of the boom stop moving forward or even start travelling backwards. As you move further towards the outside end of the boom, the nozzle speed over the ground increases, prompting the controller to increase the flow.

The overall aim is to ensure that a boom applies a fixed volume across the entire field while reducing the incidence of chemical drift. However, there are many situations where an even application isn't actually required.

Automatic spot spraying systems, such as the Weed-Seeker and the soon to be released Weed-IT, can detect chlorophyll and operate individual spray nozzles to only apply chemical to areas which contain plants. While this can significantly reduce the amount of chemical applied to areas not containing weeds, they can still only detect plants from a soil and residue background and therefore can't be used to control weeds in a crop.

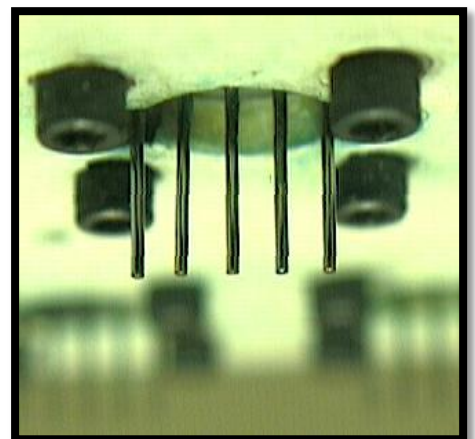
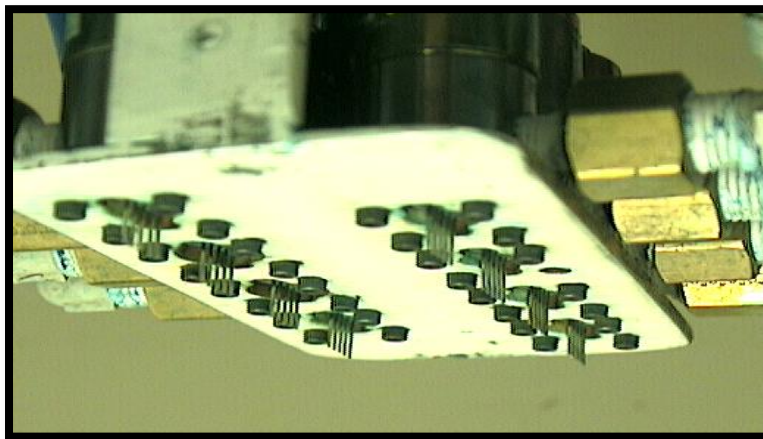
3.2 Image Analysis for the Detection of Weeds and Crop Plants

The mass production of web cams and digital cameras has seen charge-coupled device (CCD) and complimentary metal-oxide-semiconductor (CMOS) image sensor chips increase in resolution while falling in price. This, coupled with the continuing increase in processing power of computers, has resulted in a lot of research being conducted into the development of systems that use image analysis to distinguish between the crop and the weed species.

Several different approaches are taken including systems that have a database of plants in memory to which they compare those in the image. Another system picks out the crop row by the fact that it's in a straight line or known location as defined by its GPS coordinates, then assumes that all inter-row plants are weeds. Others use advanced algorithms and neural networks, which model complex relationships between datasets and look for patterns in data, to classify the plant through its shape, texture and colour. At present these systems can quite accurately classify the plant as long as it doesn't intersect another plant in the image. However, researchers are confident that with more software development, methods will evolve to overcome this limitation.

3.3 Microspray Systems

This concept uses weed detection systems to not only detect the weed, but also determine the most appropriate chemical rate required to kill that particular weed based on its size and other characteristics. The chemical is then applied directly to the leaf of the weed minimising or completely eliminating off target application. Researchers at the University of California, Davis Campus have been working on different chemical application technology including Microspray technology.



Microspray Head developed at UC Davis (source David Savage)

Researchers at the University of Aarhus in Denmark are in the early stages of testing the concept of using a commercial bubble-jet printer head to ‘print’ the chemical onto weed leaves. While this research is only in early development, the technique has many advantages. As the chemical is applied directly to the leaf, drift is negligible. Using different formulations of chemicals, or development of new formulations, should allow application to be carried out in a wider range of conditions, such as higher temperatures or with dew on the leaves. This would allow application over a wider spray window, however it’s unlikely that current boomsprays could be adapted to suite this technology. A completely new type of spray vehicle would be required.

4.0 Automation of Agricultural Equipment

While traditional agricultural machinery has evolved incrementally, it has generally been getting bigger. The question now is ‘how much bigger can machinery realistically get?’ There is some consensus that current equipment is nearing its maximum size limits, particularly with their impact on soils through increased compaction and their limitations in small fields that cannot be combined with others due to topographical or legislative constraints.

4.1 Smaller and Smarter Machines

There are various research projects in automation being carried out in university engineering faculties across the world. There are two main areas researchers are looking into: the physical design of the machine, and its computer control, including navigation and interaction with its surroundings.

Researchers and engineers are looking at the feasibility of replacing one large machine with several smaller ones, all acting together. Initially this would involve an operator sitting in the ‘lead’ machine operating both it and the others. Essentially each machine would mirror the actions of the lead machine. Research into the control systems required to make this work is underway including research being conducted at the University of Kentucky by PhD student Santosh Pitla who is developing control systems for the interaction of multiple vehicles.



Santosh Pitla and his seven autonomous vehicles

There are several advantages to multiple machines including: scalability, where additional units can be purchased or sold as required; and redundancy, where if one machine breaks down the others can keep operating. The move away from the traditional tractor design would allow engineers to completely re-design an agricultural vehicle in order to reduce construction and maintenance costs while increasing its flexibility and efficiency. Many institutions are looking at the ‘Tractor of the Future’ with one prototype design out of the University of Kentucky concentrating on the use of replicated modules throughout the vehicle.



Prototype Autonomous Tractor in development at the University of Kentucky

In this prototype, each wheel ‘leg’ is identical, reducing production and maintenance costs. Efficiency gains will be achieved through the use of computer controlled diesel engines operating at their peak efficiency providing electrical power to modern, highly efficient wheel hub mounted electric motors. Alternative sources of power, such as Hydrogen Fuel Cells, should also be available in the future.

There is also a general feeling that, for the western world at least, there will continue to be a need to find engineering solutions to the diminishing semi-skilled farm labour supply. The recent success of Autosteer technology has been put down to two main factors: Firstly, with equipment continually getting bigger and input prices increasing, farmers could see the immediate economic benefits in reducing/eliminating overlap. The widespread adoption of automatic boom and planter section controllers, where a section of a boomspray or the individual row of a row-crop planter will disengage when it crosses into an area which has already been treated, has directly cut down on overlap and the associated wastage of inputs such as fuel, seed, fertilizer and chemical, as well as time and wear on machinery. Secondly, it has reduced the fatigue associated with long hours performing monotonous tasks and given a more consistent outcome. This has not only allowed farmers to more effectively utilize less skilled operators, but it allows older operators to continue to effectively operate machinery over a longer periods. According to the farmers and dealers I spoke to in the USA, this has been one of their biggest selling points.

More mentally demanding tasks, such as harvesting or spraying with large booms at higher speeds or challenging terrain, also benefits from this technology. Autosteer systems on combine harvesters allow operators to concentrate on operating the machine more efficiently. As sensor technology improves there is the opportunity to further improve the operational efficiency of combine harvesters through better measurement of grain and straw loads within the machine. Dr Rasmus Jorgensen from the University of Southern Denmark suggested that a late season Normalised Difference Vegetation Index (NDVI) map, which gives a good indication of spatial biomass and yield potential across a field, would give the operator prior indication as to the best speed to operate the harvester. Ultimately a harvester would use an array of onboard sensors measuring such parameters as crop height and density, harvester input loads, separator drum load, cleaning shoe loads, grain loss rates, cleaning shoe return levels, yield, screenings, admixture and so on to automatically adjust machine settings such as forward speed, cleaning fan speed, sieve settings in order to establish and maintain peak machine efficiency. Ultimately the operator would only be responsible for overseeing the operation of the machine to ensure systems are functioning effectively and to manage any unusual circumstances. This data would also be recorded for later analysis to determine interactions between that season's crop yield and quality characteristics (protein, screenings, test weight and admixture), the variable rate management of nutrition and other management practices over the growing season and underlying soil characteristics. As large and reliably

collected datasets become available it will allow crop models to be fine-tuned from their current 'broader scale' or regional crop models, down to individual farm, field and soil type within a field scale. Localized crop models allow managers to better plan the management requirements of the following season's crop to achieve the desired outcomes of higher gross margins through increased crop input and equipment use efficiencies.

Communication between vehicles and the control of one machine based on the actions of another is now also possible. Using high accuracy RTK-GPS, cross referenced with other dead-reckoning and proximity sensors, a vehicle such as a modern tractor and chaser bin, where all steering, engine and transmission controls are via the electronic CANBUS system, can be automatically guided and positioned under the unloading auger of the moving combine harvester. This position can also be maintained automatically through the interaction between the combine and tractor's autonomous operation systems with one vehicle, probably the combine, being designated the master, with the chaser bin tractor designated as a slave, taking its instructions, including speed, from the master. Once unloading is finished, or cancelled by either operator (the tractor operator could also stop the unloading process if required), the control link between the two is cancelled and control of the individual machines returns to each operator.

Dr Dionysios Bochtis from Aarhus University in Denmark is working on path planning algorithms, where the most efficient path is taken by all vehicles in a field. While ultimately this research is aimed at controlling fully autonomous vehicles, it is also applicable to operations which require the interaction of many machines, such as multiple harvesters and chaser bins. With inputs such as the number and capacities of combines, number, capacities and cycle times of chaser bins and biomass variability within the field, the most effective routes can be determined for the combines automatically. This would not only ensure that the combines themselves are operating at peak efficiency but the most effective unloading sequences are achieved through path planning for the chaser bins as well. Using biomass variability as a prediction for yield potential, the overall control system will be able to predict at what point the combine's bin will be full and plan a path to ensure the unloading auger is accessible to the chaser bin. The chaser bin will also know in advance, where in the field that point will be, and can plan a path to be at that point when required. When multiple combines are operating in large fields, the combine's paths can be planned so that each can be unloaded when they are close together to reduce travel times by the chaser bin. If a full tramline system is in place, then paths can be planned, for example if a change of tramline is unavoidable

outside the usual headlands then this can be planned for the most suitable part of the field such as around trees or other areas where vehicles are forced off tramlines anyway, or dedicated crossing areas such as cross field roadways or on lower quality soils. Crossings can also be pre-planned for the appropriate time, for example if a crossing was required in a less appropriate area. An underlying soil classification map showing the soils ability to support various loads would also be an integral part of the decision tree. The spatial variability in the soils ability to satisfactorily support heavy loads will also vary with moisture content. If rainfall events occurred prior to and/or through the harvest period, then the areas within the field most suitable for infield tramline changes would also change. Paths would be planned to ensure the tramline changes also happen at the most appropriate time. The system would also have the ability to react to any changes in circumstances in real-time. Should a combine break-down, a chaser bin be held up, or other unforeseen circumstances arise, the system would adapt its plans to manage the situation.

Ultimately, the aim is to complete the harvest operation capturing maximum efficiencies out of all equipment with minimal compaction damage to the soil. The entire system, which includes acceptable combine grain loss and percentage of infield tramline changes, can be monitored and altered by the manager in real time, depending on other circumstances and time pressures. If, for example, the forecast is for rain in three days time, parameters can be altered by the manager to achieve an acceptable balance between combine grain losses and infield tramline changes in order to get an appropriate amount of the harvest completed.

As future equipment would already have ISOBUS as standard and probably already fitted with telemetry equipment, the system would be compatible with any brand and make of equipment. The manager would be able to access and operate the overall management software from any terminal, in any vehicle or remote computer logged into the network. Operators would be restricted to limited management functionality, typically functions relating to that vehicle only and limited management of other associated vehicles if carrying out a joint operation. For example, the operator of a chaser bin could manually initiate or prematurely cancel a combine unloading run which would include stopping the unloading auger, perhaps retracting it as well, on the combine.

Recording and analysing the telemetry data from the machinery, in particular the periods that required human intervention will allow the system's engineers to develop more intelligent software with the ultimate aim of slowly reducing the number of people required to manage the operation successfully and safely.

4.2 Field Robotics

The ultimate goal in increasing the level of computer control of agricultural machinery is to remove the operator altogether with the machines operating completely autonomously.

As the vehicle's environment sensor systems and control software matures and becomes able to operate reliably and safely in an open environment we will see more autonomous vehicles enter the field. This opens a whole new range of possibilities for finer scale crop management. Precision Agriculture has so far allowed farmers to manage field scale variability on a fairly coarse scale with variability grouped into a number of zones. The smallest area an input can be varied over is usually set at the width of the implement and the reaction time of the controllers.

Research work conducted by Bill Raun, John Solie, Marvin Stone and others from Oklahoma State University suggested that significant variability can exist at less than 1m² therefore current techniques cannot fully capture and manage this variability. Shibusawa (1996) used the term 'Phytotechnology' to describe machines that can manage individual plants. The management of plants, rather than fields becomes the central focus. Crop sensors which can detect crop nitrogen fertilizer requirements, such as the Greenseeker, Crop Circle and N-Sensor, are already commercially available but the sensors are set-up in a manner to suit the traditional application equipment and fertilisation practices. When the Greenseeker concept was initially developed at Oklahoma State University it was envisaged that a completely new liquid nitrogen fertilizer application system would be developed around it, whereby each crop sensor head, with a field of view of around 0.6m, controlled the flow through a corresponding nozzle. However this system was ultimately considered commercially unfeasible and a system which produced an average fertilization rate, across a farmers existing boom width, was ultimately commercialised.

The development of smaller autonomous vehicles could potentially see the concept of Phytotechnology become a reality with finer scale crop management creating overall field productivity gains. How this would work in practice was the focus of the Green Robotics conference held in Odense, Denmark that I attended. Researchers from across Europe met to discuss what form field robots should take. It was generally felt that the robots needed to be quite small as this would reduce soil compaction and allow fields and crops to be managed on a finer scale. The problem of logistics was discussed, in particular, how would small planting and harvesting robots carry enough product efficiently? It was felt that a tramline system

could be used whereby a large vehicle carrying inputs or harvested crop could supply a number of smaller robots running perpendicular to the main tramline.

The use of small autonomous robots which can operate continuously, as required, opens up a whole range of new possibilities for field and crop monitoring and management. Australian arable agriculture is somewhat unique when compared to farming systems in the Northern Hemisphere in that Australia has a fallow period in which the aim is to control weeds and build soil moisture reserves. Currently the standard practice for no-till farming systems is to control weeds by applying a uniform rate of herbicide across a field; the chemicals used and application rate determined by the weed species which is the hardest to control. This system is highly inefficient as these 'hard to kill' weeds may only occupy a relatively small percentage of the field with the majority of weeds requiring a significantly lower dose. The introduction of the Weedseeker system has allowed a number of new fallow weed control practices to be developed whereby a combination of uniform and spot-spraying passes, sometimes with different herbicides, can be used dramatically decreasing overall herbicide use.

A fallow weed control robot which utilizes the latest technology could improve fallow weed control a great deal more. A small solar powered robot could be continually monitoring weed populations using cameras and image analysis software to map weed species and densities. It could also be fitted with micro-spray equipment which could apply the most appropriate herbicide to the weed detected. The herbicide would be in a concentrated form to reduce the overall weight of the robot and better formulations could be developed to allow the robot to operate in more adverse conditions such as heavy dew or higher temperatures. The robot could also be fitted with other sensors which could monitor other field characteristics such as soil moisture and nitrate levels on a fine scale. The robot could also be used in-crop to monitor and control weed populations as well as monitor crop vigour and nutritional status.

Conclusions and Recommendations

The invention of the transistor sixty years ago has seen digital technology revolutionise every industry sector, including agriculture. While the introduction of simple counting devices found initial acceptance in agriculture, the development of GPS and a subsequent range of agriculture specific equipment, such as guidance and mapping systems, now allows farmers to effectively boost productivity through greater precision.

The planned upgrades to the global navigation satellite system will see it's accuracy and robustness continually improve over time and should also result in the overall cost of obtaining higher accuracy decrease. There has been considerable investment by farmers across the developed world in satellite guidance and auto-steer systems and this should continue to foster the continual enhancement of systems by manufacturers. This new demand for complex electronics in agriculture has also seen the development and adoption of the ISOBUS system by equipment manufacturers as a means of standardising communication protocols which will allow different systems to operate together. Farmers need to be aware of this evolution and while the upgrades to GNSS is some time off it shouldn't overly effect receiver purchasing decisions in the short term. Farmers need to encourage satellite position receiver manufacturers to utilize the receiver test track developed by the University of Kentucky in order to standardise performance data.

Compatibility between brands is a current issue and it is therefore recommended that farmers ensure that any new equipment purchased is ISOBUS 11783 compatible.

Wireless data transfer is also currently being implemented by several manufacturers and this technology will offer many advantages as the systems evolve. This will ultimately be offered as an additional service, most likely with annual subscription fee's over and above the costs of having additional wireless internet connections, one for each vehicle. Farmers need to weigh up these additional costs against the potential benefits to determine if it suits their particular enterprise.

The development of Agro-chemistry in the form of selective and non-selective herbicides and, more recently, the introduction of GMO's has seen boomsprays become the most utilized and probably the most important implement in modern farming systems. Spray technology continues to evolve and will continue to include more electronics to improve the application

accuracy. Australia needs to be part of this research effort given our farming systems rely heavily on agro-chemicals, particularly for fallow weed control.

A keen interest in digital systems, satellite guidance, advanced electronic sensors and robotics by today's young engineering students is resulting in a whole new wave of research into ways this technology can be utilized in agriculture. Considerable research is being conducted into the development of a whole range of smaller and smarter agricultural machines that can manage agricultural systems more efficiently and on a finer scale than could ever be achieved with the equipment commercially available today. This technology would also go a long way toward overcoming Australia's limited agricultural labour supply.

Australian farmers need to be made aware of this research and it's potential benefits in order to foster this innovation. A well informed farming community, that has already demonstrated it's ability to think outside the square and become some of the most innovative and efficient farmers in the world, has the ability to effectively define the future direction of agricultural research.

Appendix A: The Development of Navstar GPS.

GPS was originally conceived and designed as a precise weapons guidance and asset monitoring system for the USA's Department of Defence (DoD) that could operate effectively across a number of different platforms. It was based on several earlier satellite navigation systems developed in the 1960's.

The Navy had sponsored two programs aimed locating ballistic missile submarines and other ships on the ocean's surface. TRANSIT was developed by the Johns Hopkins Applied Physics Laboratory (APL) and was a two-dimensional system which utilized 7 low altitude, polar-orbiting satellites that broadcast very stable radio signals. The original concept was conceived in 1957 after APL scientists were able to determine the USSR's Sputnik satellite orbit by analysing the transmitted radio signals Doppler shift. Development of the system began in 1958 and entered Naval service in 1964 and while it proved effective for naval navigation, it was too slow to be used for aircraft or other faster moving vehicles. It did, however, prove the concept of satellite based navigation. The United States Naval Research Laboratory then started working on their TIMATION system in 1964 and was based on the use of highly stable and accurate clocks. The first satellites launched in 1967 used quartz-crystals, similar to those used by all electronic clocks and watches today. They then moved to higher accuracy atomic clocks and the last two satellites launched in 1969 were also used as prototype GPS satellites.

In the meantime, the US Air Force was working on a similar concept called System 621B, from studies conducted by the Aerospace Corporation in 1963. By 1972 the system was using a new type of satellite ranging signal based on pseudorandom noise (PRN) which allowed all the satellites to transmit on the same frequency and had better interference handling capability. It provided three-dimensional (latitude, longitude and altitude) navigation at high speed and with continuous service.

The US Army had also proposed its own system called Sequential Correlation of Range (SECOR) so in 1968 the DoD established a joint tri-service steering committee called the Navigation Satellite Executive Group (NAVSEG) in an attempt to coordinate the development of a universal system. NAVSEG was charged with defining what the specifics of a satellite navigation system should be and the cost. In 1973 the Air Force was appointed as the lead agency to consolidate the various satellite navigation concepts into a single comprehensive DoD system to be known as the Defence Navigation Satellite System (DNSS). They worked on creating a system which utilized the best parts of each of the systems that had

been developed so far. The signal structure and frequencies were taken from the Air Forces 621B system and the satellite orbits were based on the Timation configuration, but at higher altitudes, as well as the use of atomic clocks. In December 1973 the DoD commissioned the development of the system to be known as NAVSTAR GPS. Testing was originally done with the last two Timation satellites launched in 1974 and 1977, before the first Block I GPS satellite was launched on the 22nd February 1978. In all 10 Block I satellites were successfully launched and tested, with one lost due to a launch failure. While they all eventually failed due to deterioration of their atomic clocks or failure of other control systems, many of the satellites continued to operate much longer than their original design life of just three years, several for 13 years or longer. GPS Receivers were also being developed and tested, even before the launch of the Block I satellites, using radio transmission towers acting as pseudosatellites across the Arizona desert. With initial testing proving successful, the go-ahead was given for the full-scale development of GPS in 1979.

On September 1, 1983, at the height of the Cold War, the USSR shot down Korean Air Lines Flight 007 over the Sea of Japan, after it drifted of course into prohibited Soviet Airspace due to a navigational error by the pilots. On the 16th September, US President Ronald Reagan announced that GPS, once operational, would be made available for civilian use, free of charge in order to improve navigational methods and avert such errors in the future. In 1987 the DoD formally requested the Department of Transport to outline the requirements of a civilian GPS system and the US Coast Guard was given the responsibility of working with the DoD to ensure proper implementation.

After initial setbacks due to funding problems and the Challenger disaster, the first Block II satellite was eventually launched on the 14th February 1989. An additional 19 Block II and Block IIA satellites were launched up until the system was given Initial Operational Capability (IOC) on the 8th December 1993. It was subsequently declared fully operational on the 27th April 1995. In all 40 Block II, IIA and IIR satellites have been launched to 2004 with 24 still operational.

While the DoD provided a freely available civilian GPS signal, it deliberately degraded the accuracy of the signal through a feature called Selective Availability (SA) in order to prevent an enemy from using civilian GPS receivers for precision weapons guidance. Errors could be up to 100m, however as the error affected every GPS receiver in a given area almost equally, a fixed station with an accurately known position could determine the distance and bearing of the error and then transmit a correction to other local GPS receivers via a radio link. This is

called Differential GPS (DGPS) and it will also correct for other signal errors such as those induced by the signal travelling through the earth's atmosphere, particularly the ionosphere. With the growing ineffectiveness of SA due to the use of DGPS and with growing pressure from the Federal Aviation Administration (FAA), SA was switched off on the 1st May 2000.

In 1998 the US government announced that the GPS system would be upgraded to meet the additional civilian and military demands on the system. The upgrades involves new satellites with additional frequencies and ranging codes as well as new ground stations to better track and manage the satellites. The first of the new Block IIR-M satellites was launched in September 2005 and in all 8 satellites have been launched. Twelve Block IIF satellites are due to be launched starting February 2010 with the first stage of the upgrade due for completion by 2013. Block IIR-M and Block IIF will transmit a new civilian ranging code on the L2 frequency call L2C (L2 civilian). This will improve the initial speed of signal acquisition and overall accuracy of receivers capable of receiving and processing the signal. This should bring the accuracy of these receivers to levels similar to today's single frequency DGPS receivers, typically around 1m.

Block IIF satellites will also include a new frequency (1176.45 MHz) and associated ranging code called L5, Safety of Life. This is a civilian signal which will have improved signal strength and the ranging code will be transmitted 10 times faster than the current C/A code transmitted on L1. This will make it more tolerant to radio signal interference, and the receiver will be better able to detect and rectify the effects of multipath. This is a situation where the ranging code is reflected off another surface before reaching the receiver instead of coming straight from the satellite. This makes the satellite appear further away causing position errors. Receivers that use a combination of the L1, L2C and L5 frequencies will have accuracy similar to today's Dual Frequency receivers, with improved signal acquisition times, without the need for an external correction signal.

Appendix B: ISOBUS 11783 Development

Electronic communications require significantly more standardisation than was needed in earlier tractor-implement mechanical standards. Not only do the wiring, plugs and sockets need standardisation, but compatibility between the electronic messages sent between the different systems is also required. The rapid development of precision farming has seen a large increase in the amount of electronic based equipment further increasing the need for standardisation.

The amount of electronics and its associated wiring has been increasing over time in all vehicles. In a typical modern tractor there are separate computers for the engine, transmission, and hydraulics. The cab will typically also have its own computer which gets input from the driver via the usual levers and pedals as well as displaying information on the dash. In order to facilitate communication between each of these computers Bosch developed an electronics communications protocol called Controlled Area Networks (CAN) in the early 1990's. This system is based around a single pair of wires called a 'BUS' to which all the computers are connected.

Each computer on the BUS places information onto the BUS and/or looking for information placed on the BUS by other computers. Information is sent in packets and each packet has two parts, the identifier and the data. The identifier tells all the computers what the number contained in the data actually is. For Example a packet may have the identifier 'Current Engine RPM' and data '1500'.

Computers can also request information from the other computers or give commands to other computers simply by placing a data packet on the BUS. For Example, after the driver moves the throttle, the cab computer places this message on the BUS; 'Requested Engine RPM', '1800'. The BUS can only transmit one message at a time so the CAN protocol also includes a message priority system whereby if two computers try to place a message on the BUS at the same time, the message with the highest priority goes first and the other computer waits until the BUS is free again.

While Bosch's CAN protocol defines how the computers should be connected together and the overall structure of the messages placed on the BUS, this protocol doesn't outline the message identifiers or their priorities. For two or more computers to be able to communicate, they all need to know what the packet identifiers actually mean. The computers software

needs to know what the message ‘Current Engine RPM’ means, what the unit of measure is and so on.

In 1988 LAV, the German Farm Machinery and Tractor Association, set up a committee to work on an agricultural machinery CAN protocol. In 1991 the initial standard had been developed and Germany requested that ISO (International Organization for Standardization) begin an effort to standardise an agricultural bus system. In North America a combined group was organised to represent agricultural equipment industries, composed of the ASABE (American Society of Agricultural and Biological Engineers), the SAE (Society of Automotive Engineers) and the EMI (Equipment Manufacturers Institute). The group eventually named itself the Construction and Agriculture Multiplexing Task Force and its aim was to develop a CAN communications protocol standard that would meet the needs of the North American agricultural and construction equipment manufacturers and confirm to and/or influence the developing ISO standard.

Today the ISOBUS protocol is administered in Europe by VDMA, the German Engineering Federation and in North America by the NAIITF, an organisation formed with members of the ASABE and the AME, Association of Equipment Manufacturers. The term ISOBUS is the marketing term for equipment which conforms to the ISO 11783 standard. The organisations are responsible for approval of entries into the data definition dictionary, specifying the ISOBUS compliance protocol and approval of laboratories to test equipment.



ISOBUS Logo (source www.isobus.net)

Plain English Compendium Summary

Project Title: Future Trends in Precision Agriculture	
Nuffield Australia	
Project No.:	0906
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Objectives	To research the future trends in Precision Agricultural Equipment. This includes looking at developments in the GPS system, getting the opinions of equipment manufacturers as to the likely direction of their product lines and research being conducted by university agricultural engineering faculties.
Background	I have been heavily involved with Precision Agriculture over the past 12 years both as a farmer and consultant. I have collaborated on research projects conducted by the University of Sydney and others and have presented my experiences to fellow farmers and consultants at various conferences over the past five years. I was keen to broaden my understanding of the future direction of Precision Agriculture from an international perspective.
Research	My studies were conducted in the USA, Canada, UK, The Netherlands and Denmark. I attended several conferences including the Joint International Agricultural Conference at Wageningen University, The Netherlands, InfoAg at Springfield, Illinois, USA, The Nitrogen Use Efficiency Conference at Purdue University, Indiana, USA and the Green Robotics Conference at Odense Denmark. I also visited equipment manufacturers, universities, consultancy firms and progressive farmers across the USA and Europe.
Outcomes	I have gained a good understanding of the future direction of Precision Agricultural equipment development and its implications for farmers. I have also gained new insights into automation and robotics and how the research could be modified to better suite Australian farming systems.
Implications	Gaining new ideas from across the world, especially in new technologies such as Precision Agriculture, allows farmers to remain innovative and progressive. It also allows them to effectively influence the future direction of agricultural research.