INTRODUCING THE AGRI-ROVER: AN AUTONOMOUS ON-THE-GO SENSING ROVER FOR SCIENCE AND FARMING

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Abstract
Grazed pastoral systems exhibit high levels of within-paddock variability in soil and pasture properties. Precision agriculture (PA) is frequently touted as a high-tech opportunity to manage this variability for production and environmental improvements, but it is not yet widely applied in pastoral systems. There is no affordable, easy to use PA technology that can map and regularly monitor within-paddock variation in a way that does not create an extra workload for the farmer. Autonomous ground vehicles (AGVs) are a promising option to accommodate the apparent niche between remote and conventional labour-intensive proximal sensing platforms. AgResearch is developing a small, low profile, battery-powered AGV that is intended to deploy from a central base station, navigate to a paddock (pre- and post-grazing), autonomously traverse the paddock while collecting soil and pasture data at high spatial detail, and then return to the base station for recharging and further deployment. Two prototypes have been built and a third is currently in construction. While this is a small proof-of-concept scoping project, the long-term view is a set-and-forget PA tool for future farming applications.

Introduction
Precision agriculture is a technology-rich approach to farming that has the potential to achieve markedly improved production efficiencies through the identification and management of soil and pasture variability (Schellberg et al., 2008; Trotter, 2010). However, precision technologies can be expensive and complicated to use, and there is a lack of agriculturally-robust sensor delivery systems that can achieve regular, affordable, high resolution data-collection across individual paddocks.

This paper examines the potential of automated ground vehicles (AGVs) as one promising option for delivering a wider variety of sensor technologies for pastoral farming, and reports on a prototype agri-rover AGV being developed by AgResearch.

Within-paddock variability
The often uniform appearance of an actively growing pasture can belie the level of spatial variation or heterogeneity present within a single paddock. Landscape variation can be present in the underlying resource, such as within-paddock differences in soil type, topography and climate, most notably in hill country. Many practical tools are available to help pastoral farmers and consultants identify and manage this type of variation at paddock and sub-paddock scales (e.g. Dairy NZ, 2012; Lynn et al., 2009; Grogan et al., 2008; Manderson et al., 2007).

Less readily manageable variation occur at finer scales. This is particularly true with soil properties, which can exhibit significant variations over very short distances, often less than a metre. Indeed, up to half the soil variance within a field may be present within any given square metre (Beckett and Webster, 1971). Morton et al. (2000) in a study of 20 NZ hill country farms found the majority of total farm variance for soil potassium, sulphur and pH occurred within 1 m of a fixed point. Table 1 provides an indication of paddock-scale variability according to coefficients of variation (CV) where CV percentages less than 15% are considered least variable, while those greater than 25% exhibit high levels of spatial variation (Wilding & Drees, 1983).

Table 1: Variability of soil properties that occur in landscape units of a few hectares, or less, in size (adapted from Wilding & Drees, 1983).

Variability of property	**Soil properties**
Least variable (CV <15%)	Soil colour (hue and value); pH; A horizon depth; silt percent; plastic limit.
Moderately variable (CV 15-35%)	Sand percent; clay percent; CEC; base saturation; structure/aggregation (grade and class); liquid limit; depth to minimum pH; $CaCO_3$ equivalent.
Most variable (CV >35%)	B2 horizons and solum thickness; soil colour (chroma); depth to mottling; depth of leaching (carbonates); exchangeable H, Ca, Mg and K; fine clay percent; organic matter; soluble salt content; hydraulic conductivity.

Spatial variation in soil fertility is particularly pronounced in grazed pastoral systems relative to other land use types (Speir et al., 1984; West et al., 1989). The primary cause is excreta return from the grazing animal. This is a well-recognised process resulting in small, relatively discrete patches of high fertility (Haynes & Williams, 1993), which can affect a significant area of a paddock in a non-uniform pattern, and contributing to the 'mosaicked' appearance that is characteristic of grazed swards at certain times of the year. Saunders (1984) reported 27-40% of a paddock can be affected by the patchwork return of dung and urine, but this will vary according to stocking rate, grazing duration, and other management factors (White et al., 2001).

Areas of animal congregation (e.g. areas near troughs, shelterbelts, gateways) are also known to contribute to within-paddock variations in soil fertility (Rowarth et al. 1992; Haynes & Williams, 1999), along with localised compaction (Sigua & Coleman, 2009) and weed infestation (e.g. barely grass, stinging nettle). Similarly, weeds that colonize as anomalous clumps (e.g. californian thistle, variegated thistle) and pests that denudate pasture in a patch-like manner (e.g. grass grub, porina) can represent sources of readily observed variation. Localised dry spots (LDS) associated with patches of hydrophobicity can also result in pasture patchiness, in some cases affecting 30% of paddock area (Muller et al., 2010).

Farmers also introduce spatial variation through management. It is not uncommon for travelling effluent irrigators can have uneven spreads (Houlbrooke et al., 2004), and it is not always possible to achieve complete paddock coverage because of spread geometries and paddock shapes. Fertiliser spreaders can also create variability through uneven uniformity of application. Paddock application CVs of 33% and 43% have been reported for twin-disc ground spreaders (Lawrence & Yule, 2007), while aerial topdressing CVs of 37-67% and 12-20% have been reported for fixed wing aircraft and helicopters respectively (Gillingham, 1981).

Other management factors that could influence within-paddock variations include grazing management (set stock, rotational, break-feeding), paddock design, stock type and age, feeding-out supplements, shade trees and shelterbelts. In effect any management factor that influences livestock behaviour, grazing preference, excreta return, soil compaction, or soil fertility.

Managing within-paddock variability

A rule of thumb used in mapping farm resources is to only delineate the smallest soil or landscape unit that can be managed or treated differently using conventional farming practices (Lynn et al., 2009; Manderson et al., 2007). This recognises the practicality of managing within-paddock variability, where the paddock itself is typically the smallest unit of management, and blanket whole-of-paddock treatments are the norm (i.e. single rate applications of fertiliser, herbicide, pesticide, N-inhibitor. Labour intensive spot-spraying being an exception).

However, as discussed, most of the variation within a paddock is likely to occur at highly detailed scales, well beyond the precision capabilities of most conventional agricultural equipment and practice. Likewise, mapping this variation involves intensive repetitious measurement, which is often too time-consuming and expensive to consider in any practical sense.

A surrogate for intensive measurement is selective sampling according to known variance. For example, Morton et al. (2000) measured the spatial variance in soil phosphorus, potassium, sulphur and pH across 20 hill-country sheep and beef farms. Measured variance was used to design a sampling protocol regarding the number and distance of soil cores recommended for achieving a soil test result for Olsen P with a CV of 15-20%.

Considerable research has been invested in developing similar variance-reducing sampling protocols for soils and pastures, often expressed as a maximum sampling distance. However, while useful, sampling provides an aggregate or average value for a paddock, which can be inadequate or even misleading in some cases (e.g. McDonald & Hodgkinson, 1996). Further, a sampling protocol developed at one place and time may not fully account for different levels of variability under a wide range of environmental conditions, diversity of land resources, and styles and intensities of land use. Most of all, however, low-density aggregate sampling constrains opportunities for site-specific treatment and management offered by precision agriculture technologies.

Precision agriculture is widely touted as the means of mapping, managing and monitoring the fine level variation found within fields. It can be defined for livestock farming as *the use of information and communication technologies for improved control of fine-scale animal and physical resource variability to optimise economic, social, and environmental farm performance* (adapted from Eastwood, 2008 cited in Yule & Eastwood, 2011).

Several practical examples of NZ pastoral PA have emerged in recent years. Mackenzie et al. (2011) used WeedSeeker® optical sensors to locate and avoid pasture 'green patches' (assumed to represent dung and urine patches) to variably apply liquid nitrogen to the non-patch areas. Lawrence et al. (2007) developed a rapid pasture meter that is towed behind a quad-bike to quickly measure sward height for the estimation of pasture mass; this technology is now commercially available as the C-DAX Pasturemeter. Mapping apparent electrical conductivity to represent soil variability has been paired with Variable Rate Irrigation (VRI) for significant improvements in water use efficiency (Hedley et al., 2009); the latter technology is experiencing sound commercial growth (Bradbury, 2011).

Of equal interest is the rapid development of sensing technologies, especially on-the-go sensors for mapping variability in soils and pasture. A small selection of examples include TDR determined spatial soil moisture (Jones et al., 2006), electrochemical determination and mapping of soil nutrients and pH (e.g. Sethuramasamyraja, 2008; Schirrmann et al., 2011); spectral-based estimates of soil phosphorous and potassium status (Kawamura et al., 2011); and optical sensors for estimating pasture mass and quality (Pullanagari et al., 2011). Sensors are becoming smaller, faster, more accurate, more efficient, and more intelligent (Viscarra Rossel et al., 2011), and more diverse in terms of soil and pasture properties that can be measured. Worldwide, a vast amount of research is being invested in the development of sensor technologies (*ibid*.).

Despite these advances, the uptake of PA is generally accepted as being low, even within the cropping sector with its numerous examples of successful PA application (Bramley, 2009). Uptake by the pastoral and livestock sector is considered to be even lower (Schellberg et al., 2008; Trotter, 2010). Common barriers include high upfront costs (Yule, 1999) and an unclear level of economic benefit (Betteridge et al., 2008). The technology-rich character of PA can also involve a steep learning curve, and applying the technology can increase rather than decrease workload. At the end of the day farmers want solutions that improve profitability without making life more complex (Yule, 2011).

A sensor platform niche for pastoral farming?

A sensor platform is the carrier vehicle to which a sensor is mounted. Those operated at distances >2 m from the earth's surface are regarded as *remote sensing platforms*, while those <2 m from the surface are *proximal sensing platforms* (after Viscarra Rossel et al., 2011). Remote sensing platforms include orbiting satellites down to ground-based elevators such as hydra ladders, while proximal sensing platforms include people, and ground vehicles such as tractors and quad-bikes.

In their current form, neither type of platform is completely suitable for mapping and monitoring within-paddock variability on a regular basis. As a general statement, satellites and aerial surveys can be limited in the types of variable that they sense; lacking in spatial or spectral detail (low resolution); confined to specific periods of data capture; and depending on the sensor type, can be affected by weather conditions (e.g. cloudiness). There are exceptions, and some limitations become less apparent as the degree of remoteness lessens.

In comparison, proximal platforms can accommodate a wider array of sensor types; can achieve very high levels of spatial accuracy and resolution (<1 cm); can be either weather-independent (e.g. probes) or can be designed to accommodate ambient conditions (e.g. spectral sensors with their own light source); and the operator has greater control over when, or how frequently, the sensor platform is deployed. The main limitation is a very small area of instantaneous data capture. The smaller the area of instantaneous data capture, the more travel required to achieve coverage. For example, a sensor with a capture width of 1 m would need to travel 20 km to achieve full coverage of a 2 ha paddock. For a bike-mounted sensor travelling at 10 $km \cdot h^{-1}$, full paddock coverage would be achieved in 2 hrs, which may be acceptable for once-off mapping purposes, but for regular monitoring (e.g. daily pre-graze pasture covers) this represents an unrealistic investment of time and labour.

Considered together, this represents an inadequately addressed niche between conventional remote and proximal sensing platforms. Some potential exists with ground-controlled low-altitude solutions (kites, balloons, unmanned aerial vehicles) but all-weather use and down-on-the farm practicality has yet to be evaluated. Currently there is no suitable platform for mapping and monitoring within-paddock variability on a regular basis.

Autonomous ground vehicles

An autonomous ground vehicle (AGV) is a vehicle that operates while in contact with the ground without real-time control from an individual. This distinguishes AGVs from remote controlled unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs). Elsewhere some AGVs are referred to as robots (machines capable of undertaking complex actions autonomously) or agribots in a farming context.

Robotic vehicles down on the farm are neither a blue skies proposition nor a fanciful idea from the realms of science fiction. Indeed, automated vehicles alone are already regarded as one of the top 20 technologies changing agriculture (FIN, 2011). In 2009 it was claimed that over 50 different agricultural robots were being developed worldwide (Blackmore, 2009). Today, much of the technology has been developed (Table 2), and some agribots are either at, or near, full commercialisation. For example, Japan's Ministry of Agriculture, Forestry and Fisheries are currently implementing an $8 million dollar programme aiming to fully automate the farming of rice, wheat and soya production, and to commercialise the agri-robotic technology by 2014 (Noguchi, 2013; Tamaki, 2013).

As with many other aspects of precision agriculture, the development of AGVs and agribots has focused primarily on cropping and horticulture rather than pastoral applications. However, AGVs carry considerable potential as sensor delivery systems for mapping and monitoring within-paddock variability of grazed pastures.

Table 2: Examples of agricultural AGVs and agribots.

Name	Purpose	Source
Cropping robots (ACTV, 'Weedy', Bonirob, Hortibot)	Crop scouting, weed mapping, weeding, micro-spraying	Southall et al. (2002); Klose et al. (2008); Ruckelshausen et al. (2009); Jørgensen et al. (2006).
Robotic spreader	Robotic vehicle for autonomously spreading manure	Murakami et al. (2008)
JD autonomous tractor (prototype)	Orchard spraying, field scouting, grass cutting	John Deere (2013)
Travelling robotic sprinkler	Field irrigation, chemigation	Turker et al. (1998)
NARO rice farming robots	Autonomous rice planting, management and harvesting	Tamaki (2013)
Harvesting agribots	Selective harvesting of fruit, vegetables and flowers	Many

The Agri-rover project

A small 'proof of concept' project has been initiated to test the feasibility of an agricultural rover designed to autonomously collect detailed spatial data within dairy farm paddocks. Ultimately the aim is to build a fully automated agricultural rover that can monitor, treat and condition soil and pasture at the patch scale.

Long term vision (5-10 years)

The vision is for a small, low profile, battery-powered AGV that can deploy from a central base station, navigate to a paddock (e.g. pre- and post-grazing), slowly but progressively traverse the paddock whilst avoiding obstacles, and then automatically return to the base station for recharging and further deployment. The main advantage is one of robotics – being able to take spatial measurements according to preprogramed sampling strategies, at a frequency and intensity that would otherwise be too monotonous, laborious or costly, to undertake using conventional approaches.

Five applications have been considered:

1. Once-off or infrequent paddock mapping of soil properties, similar in principle to how vehicles and proximal sensors are currently used (e.g. bulk electrical conductivity mapping with an EM38 sensor and quad-bike), but with the additional capability of stop-start sampling to utilise probe and penetration type sensors.
2. Spatial and temporal monitoring of soils and pasture. For example, deploying the rover to measure sward heights pre- and post-grazing every day.
3. Generating prescription maps for subsequent treatment using conventional farm machinery and variable rate technology.
4. Real-time treatment or dye-marking of patches.
5. General purpose AGV or remote controlled UGV with video feedback for other farm tasks. For example, Abplanalp (2012) developed a GPS guided robot for the purpose of gathering dairy cows to the milking shed.

All five applications require further development and research. In itself, having an agri-rover capability has also inspired new avenues of research (what can we regularly monitor at the patch scale? If we can identify patch-scale variation regularly, how can we treat that variation to improve paddock performance?).

Design principles

Agricultural robustness, reliability and affordability are fundamental requirements. Many impressive ultra-high-tech robotic platforms have been built by development teams with enviably large budgets, but the designs tend to be unsuitably complex, potentially delicate (many moving parts), overly reliant on leading-edge technologies, and altogether far too expensive to replicate.

AgResearch's Engineering Development Team was engaged to draft up a provisional design (Figure 1). Dimension is primarily a function of space required for the drive components (batteries and electric motors) and sensor payload, along with a low profile necessary for travelling beneath 2-wire electric fences and gates, and a ground clearance sufficient to accommodate uneven paddock surfaces.

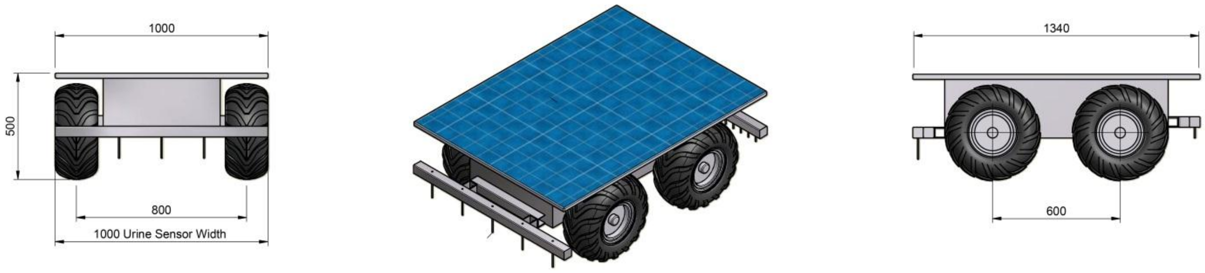

Figure 1: Basic preliminary sketch of the agri-rover (Scott Sevier, AgResearch Engineering Development Team).

Using existing ‘off-the-shelf’ technologies was specified as a critical design component to minimise cost. In the initial design the drive system was based on well-established technologies used in motorised wheel chairs (gearmotors and controllers). Given the abundance of wheelchairs available, an assumption was made that parts would be easy to source, affordable (due to economies of scale), and performance details would be transferrable.

Options for steering were reviewed, and differential ‘skid steering’ was selected as the most robust and simple option from both a mechanical and control perspective. Conventional car-like steering and 4-wheel steering would result in wide turning circles, and components would take up space better allocated to sensor payload. Differential turning used in wheelchairs is not particularly suitable for muddy ground where the opposing 2-wheel drive has limited surface area (cf. 4-wheel drive) and supporting dolly wheels can become bogged.

Four DC gearmotors, one for each wheel, where selected over a two motor system running belt or chain drives. Again, the main reason being simplicity of control, but also because of considerations regarding reliability, space, and the level of engineering precision and ‘trial and error’ required to identify the most suitable system. However, the two-motor chain drive system may be revisited as it carries a large potential for efficiency gains and cost reduction.

Target speed and operational duration are dependent on sampling strategy. For example, achieving full surface area coverage of a 2 ha paddock at 4 $km \cdot h^{-1}$ (slow walking pace) with a 1 m wide rover would take at least 5 hrs. This would be acceptable for once-off mapping of soil properties (even a full day would be acceptable - this is the advantage of robotics and automation), but perhaps too long for daily monitoring purposes. However, complete paddock coverage is not required for monitoring. Rather, several much quicker passes or transects can be performed when the paddock average is of most interest (e.g. pasture mass). Ten 1 m wide passes across a 2 ha paddock at 7 $km \cdot h^{-1}$ would only take 30 minutes.

Maximum operational duration is also dependent on motor draw and battery capacity. Initial design used four 180 watt wheelchair motors with an operational 24 amp draw (net), 110 amp-hour batteries, and an 8 $km \cdot h^{-1}$ speed, all of which equates to a theoretical 3.9 hr operation time and a potential distance of over 30 km on a single charge. This is without factoring in augmented power supply from two marine grade 50 W solar panels. For comparison, average motorised wheelchair top-speed is 7 $km \cdot h^{-1}$ and average maximum range is 25 km (calculated from manufacturer specifications for 28 top selling wheelchairs). Wheelchairs tend to have two larger motors (e.g. 240-350 W) and smaller 66 amp-hour batteries.

Design weight is 150 kg which is comparable to smaller wheelchairs carrying a 100 kg person. Four 180 W gearmotors, each producing 6.8 Newton metres of rated torque (100% duty), is more than adequate for pushing a 150 kg rover over flat terrain. Increased torque demand associated with turning and small slopes can be accommodated for short periods by drawing on peak torque (up to 25 N·m per gearmotor).

Guidance will include both remote control operation (for manual override) and an automated navigation system. The latter will initially utilise a Trimble R6 GNSS differential GPS capable of 8 mm positional accuracy in RTK mode. Navigation systems using similar systems on tractors have achieved 1° accuracy in heading and 2.5 cm accuracy in line tracking (O'Connor et al., 1996) – errors are further reduced when GPS is paired with other tracking sensors (summarised in Li et al., 2009). Tractor speed and steering responsiveness influences accuracy, so even better performance may be possible with a small slow moving rover.

High-end GPS is not an ideal solution because of the associated high cost, but it may be the only option when very high precision mapping is required. However, other relatively inexpensive options exist for less precise applications (e.g. pasture monitoring), such as low cost GPS receivers (as used by Alonso-Garcia et al., 2011 for tractor guidance), encoders for measuring relative distance, electronic compasses for holding a straight bearing (corrected for local magnetic disturbance), relative positioning sensors (e.g. lasers, ultrasound), and sensors that respond to fixed within-field references (e.g. buried magnets, bottom fence-wires set up as circuits). Furthermore, relative to the cost of differential RTK GPS, it may also be feasible to establish farm-dedicated local positioning systems that draw on principles of line-of-site triangulation (minimum of three transmitters and a receiver on the rover).

Prototype models

Selecting motor and gearbox combinations for robotic vehicles is both an art and a science, and calculated performance is often less than that achieved in real-world conditions (Piccirillo, 2009). Two prototype rover models were built to evaluate and refine aspects of design (Figure 2). Both used the same drive and control system – x4 second-hand 180 W 1:32 ratio 24 V Fracmo gearmotors (2-pole) salvaged from old wheelchairs and mounted to 406 mm turf wheels and tyres. Motor management is achieved through a 30 amp wheelchair controller, while power is provided by two 110 amp-hour 12 V deep-cycle gel batteries in series (24 V system). In being second-hand the motors were showing their age, and had variable individual levels of output performance.

Figure 2: Mk I and II prototypes for design testing and development.

The first design had a large payload bay positioned in the centre of the vehicle, with batteries positioned at each end. The wheelbase was long and the centre of gravity was poorly positioned, both of which affected turning performance. Both issues were fixed with the second prototype, but a different mounting system for sensors had to be developed.

Maximum straight-line speed was 9 $km \cdot h^{-1}$ on pasture (jogging pace) at a modest 20 amp draw, with speed being adjustable down to 5 $km \cdot h^{-1}$. Incline performance stopped at 10°, although with momentum an incline of 20° could be achieved. In most respects testing indicated that the Mk II design would fulfil requirements for traversing a dairy paddock for an extended period. However, turning was a critical issue. While turns could be performed on gravel and concrete, the Mk II prototype failed on grass. The problem was traced to the controller, which would not allow the motors to achieve peak torque because of a preset 30 amp draw limit. Further, when the controller was bypassed to achieve turns, the high gear-ratio resulted in rapid bouncing rotations, which while fun to watch, carries the potential to damage sensor equipment.

In itself this is readily solved through a better wheelchair controller, reduced gearing, and a more rigid chassis structure. However, further investigation into wheelchair components disproved earlier assumptions of affordability, availability, and in the case of controllers, adaptability and capability.

Project status

The third prototype is currently being assembled. Motor management issues have been addressed with the purchase of a fully programmable Roboteq HDC2450 controller with a 300 amp capacity.

Functionality has overridden the pursuit of efficiency as the project has a small budget and cannot afford the luxury of mistakes. For example, the chassis design is now steel rather than aluminium to maximise strength and rigidity at low cost, but this results in a sizeable increase in weight and thus power draw. Similarly, excessively powerful gearmotors are used to offset any risk of underperformance. Motors are industrial 24 V 260 W DAGU 4-pole units, paired with 1:40 ratio worm-type gearboxes. Rated output torque is high at 23 N·m per gearmotor (at peak efficiency – Figure 3), which is considerably greater than the 6.8 N·m used in the Mk II prototype. An expected 58 N·m will be available at peak power for short periods (20% duty). However, output speed is reduced to 5.7 $km \cdot h^{-1}$ (top speed) and the continuous rated amp draw effectively doubles. Expected operational duration decreases to 1.7 hours (if operated continuously at top speed).

Sacrificing operational duration to achieve 'proof of concept' was deemed acceptable because considerable opportunity exists for major efficiency gains later on. Aluminium construction of the chassis and wheel hubs would provide significant weight savings. Replacing lead-acid gel batteries with lithium iron phosphate (LiFePO4) equivalents would further decrease weight and space requirements (same power capacity for half the space). Using helical rather than worm-type gearboxes would improve gearmotor efficiencies from 65% (current) to upwards of 90%. Lastly, we have yet to identify the best combination of motor power and gearbox ratio for the types of terrain the rover will encounter. We still suspect the initial 180W motor choice paired with lower gearing and improved motor management would still achieve most requirements. This would halve the amp-draw and extend the duration of operation.

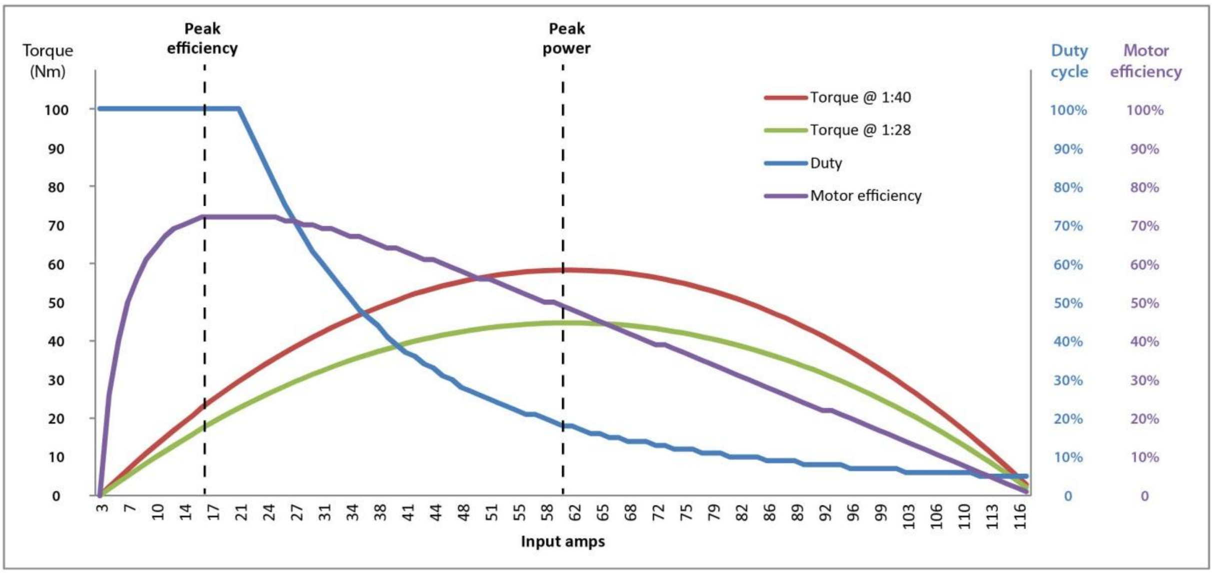

Figure 3: Modelled performance curves for DAGU ME63-066 DC motor with a STM UMI 40 gearbox at 1:40 and 1:28 ratios.

Conclusion

This paper has set out the background for a new approach to mapping and managing the high level of variation found within pastoral paddocks, through the use of AGVs. Ultimately the aim is to develop affordable, easy to use precision-agriculture technologies that have clear benefits for pastoral farming, and do not create an extra workload for farmers. Toward this end we are aiming to achieve proof of concept through the development of our own agri-rover AGV.

AGVs down on the farm may still be several years away in any practical sense. However, given the compounding production and environmental challenges facing farmers, coupled with an increasingly technology-rich world, we see them as an almost unavoidable, if not essential, part of the future farming landscape.

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