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Ultrasonic Remote Sensing for Precision Agriculture

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ABSTRACT

Precision Agriculture makes use of quantitative measurements as input to sophisticated farm management software. For management of grazing animals, such as dairy cows, a key input is pasture biomass, so that pasture is not over-grazed nor have too much or too little application of fertilizer. Aside from destructively cutting, drying, and weighing the pasture, current measurement methods are slow and/or unreliable. We describe a new ultrasonic sensor which is compact and low-power, and which senses pasture properties remotely from a moving farm bike or UAV. The sensor comprises co-located log-spiral arrays of transmitters and receivers, giving high spatial resolution transverse to the propagation direction without excessive component counts. A pulsed, radar-like linear-FM chirp and matched filter gives high along-axis spatial resolution. With CLEAN image deconvolution, mm resolution is obtained through the pasture layer. This methodology allows detailed profiles of pasture density to be obtained at rates of 100 profiles per second. We present results retrieved via modelling of the complex acoustic scattering occurring in the pasture layer.

Keywords: sensor arrays, ultrasonic sensor, scattered sound, chirp pulse

1. INTRODUCTION

Modern farming is an intensive business in which optimization of resources through observation-based farm management software is an important component of 'precision agriculture'. For management of grazing animals such as dairy cows, the quantity of economic interest is the biomass, or the mass of 'dry matter' (DM) per unit area of ground, which is the mass of pasture per unit area when the pasture has been cut and dried. It is this dry matter which contains the food value for the livestock. Current methods for estimating biomass include: cutting, drying, and weighing; measuring the compressibility of pasture using a 'rising plate meter' (RP); measuring the depth of pasture using a 'CDaX' or ultrasonic sensor; and using multi-spectral satellite image data. Cutting, although an absolute measure, destroys the pasture. The biomass is

$$DM = \int_0^H \rho dh = \left(\frac{1}{H}\int_0^H \rho dh\right) H = \bar{\rho} H \quad (1)$$

where ρ is the bulk density and H is the depth of the pasture. The bulk density includes the empty space between grass blades. Underlying the use of pasture height H as a measure of biomass DM is the assumption $\bar{\rho}$ is constant for a range of farm pasture conditions. In practice, it is found that this is not true and the correlation between DM and H is not strong (1, 2).

The use of an ultrasonic sensor mounted on a motorized farm bike or UAV and remotely sensing pasture properties is attractive because of potential low cost, low power, compactness, and the ability to both sense the depth of the pasture as well as pasture density information within the pasture layer. The backward scattered acoustic power, dP, from a depth dh is

$$\frac{dP}{P} = \alpha_{bs} dh \quad (2)$$

where P is the power incident on the area at depth h, and α_{bs} is the acoustic backscatter cross section area per unit volume, as in, for example, Hodges (3). An ultrasonic ranging system can potentially

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sense depth h as well as α_{bs}, a measure of pasture interception of sound, hence providing more information than height alone. This is the essence of the new ultrasonic remote sensing tool for precision agriculture (4).

2. SENSORS AND RESOLUTION

2.1 Choice of frequency

Ultrasound is used for several reasons. There is very little background noise at high frequencies and short-wavelengths are reflected well from the thin grass blades. For example, Fricke et al. (5) used 180 kHz. However, such frequencies are strongly scattered by the pasture and do not penetrate well through to the ground, so the instrument can only measure the distance from the sensor to the pasture tops. The depth of pasture must be then found from another measurement of distance from sensor to the ground. This secondary measurement is typically based on the distance from sensor to ground when the farm bike or other platform is at rest. This is a potential source of error, since the platform will generally have a suspension system and the sensor-ground distance will vary.

In general, scattering cross-sections depend on the size parameter, ka, where k is the wavenumber and a is a typical dimension of the scattering object. A typical half-width of a blade of rye grass is a = 2 mm and for ka = 1, the frequency is 27 kHz. A common piezo-electric transducer operating frequency is 40 kHz for operating in air, so the decision was made to use ultrasonic frequencies between 20 kHz and 40 kHz.

2.2 Sensor array design and lateral resolution

The height above ground of the mounting on a farm bike is typically 800 mm and pasture can be 200 mm deep. The range to the top of the pasture is then typically R = 600 mm. Using the far-field approximation, the diameter D of the sensor array should satisfy $D^2 \leq cR/f_{max}$ where c is the sound speed and f_{max} is the maximum frequency transmitted. In practice we choose f_{max} = 35 kHz to avoid the transmitting element resonance at 40 kHz, and also D = 60 mm to better satisfy the far-field condition.

In order to keep transmitted and received beam side-lobe levels low, a sparse spiral array of sensors is used. In figure 1, the transmitters are the square objects and the receiving microphones sense through the small holes which lie on the white spiral lines. The power consumption is sufficiently low that the instrument can be run from a smart phone for 24 hours.

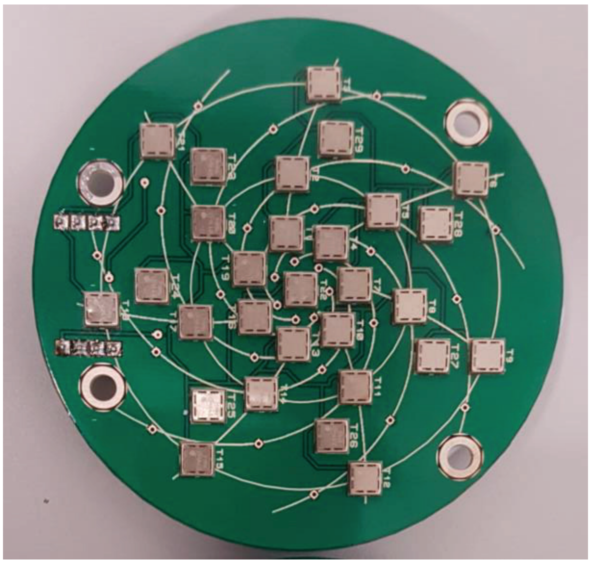

Figure 1 – The ultrasonic array.

The resulting lateral resolution is equivalent to a half-power footprint of around 140 mm at a range of R = 780 mm, or a circular area of 0.06 m^2. This is finer than the 0.1 m^2 of the RP while providing reasonable averaging over multiple grass blades.

2.3 Chirp pulse design and vertical resolution

The typical depth of rye grass pasture is 100 – 200 mm. A typical calibration equation for the Rising Plate Meter is DM (kg m^{-2}) = $1.5x10^{-3}$ h (mm) + 0.05 where h is the pasture depth. For a mean DM = 0.2 kg m^{-2}, a 10% error occurs if h is in error by 13 mm. This gives a rough guide of the required along-range (vertical) resolution (rough, because the correlation between pasture depth and biomass DM is not consistently strong). This is comparable to the wavelength at 35 kHz. The usual approach to obtaining high spatial resolution while maintaining high output power, is to use a coded pulse and a matched filter receiver (5). A commonly used coding is a linear FM chirp pulse where the frequency is linearly swept from f_0 to f_0+B over a time T. This provides a very distinctive echo signal which can be detected by correlation with the original transmitted signal. The result is a range resolution $\Delta R = c/(2B)$, which depends only on bandwidth B and not on pulse duration T, hence allowing for longer pulses and transmitting greater power. We use f_0 = 20 kHz and B = 15 kHz, giving an along-path range resolution of 11 mm.

2.4 CLEAN deconvolution

Since the shape of the matched filtered echo signal is well-known, the CLEAN deconvolution method can be used to identify 'point' scattering elements. The basic method is to find the highest peak intensity in the echo signal, multiply that by the matched filter sinc function, and subtract that from the echo time series. This is repeated until only noise remains. Each peak intensity identified is then considered to be the intensity from a point scatterer, resulting in a mm-scale along-path resolution.

The difficulty with CLEAN is interpretation, giving the complex scattering environment of typical pasture (see figure 2). Grass blades extend obliquely through the scattering volume, with typically a number of blades present at any time. For this reason, we currently have not been using CLEAN in regressions to obtain DM.

Figure 2 – The complex scattering matrix of typical pasture.

2.5 Calibration

The measured beam pattern for a target disk of radius a = 20 mm is shown in figure 3, together with the Airy diffraction pattern for a 60 mm diameter circular aperture (the diameter of the speaker and microphone arrays). This is a plot of the normalized square of the output voltage, together with the standard deviation from around 40 transmissions of a 20-35 kHz chirp. The central beam pattern closely follows the Airy pattern for a tonal 35 kHz signal.

Measurements were made of echoes from a range of small disks, as shown in figure 4. Also shown is the echo from a 24.5 mm length trimmed from a 4.5 mm wide grass blade (equivalent area to a circular disk of radius 6 mm), and the theoretical backscatter from disks using the quoted sensitivities from speaker and microphone specifications together with the array beam pattern. The agreement between measurements and theory is very close.

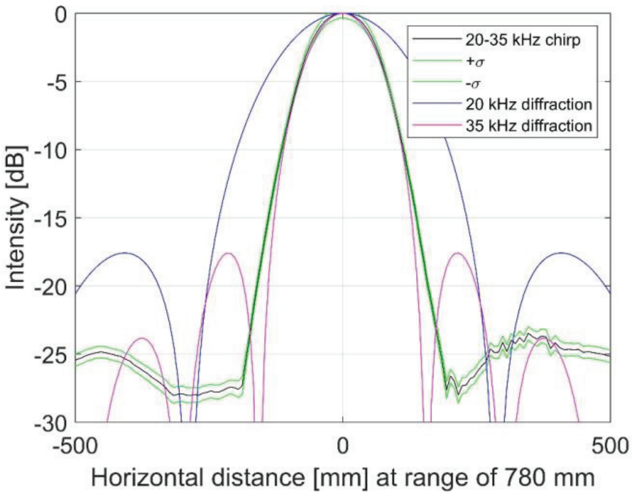

Figure 3 – The measured beam pattern (black) and experimental variation (green) compared with theoretical disk diffraction at f0 (blue) and f0+B (magenta).

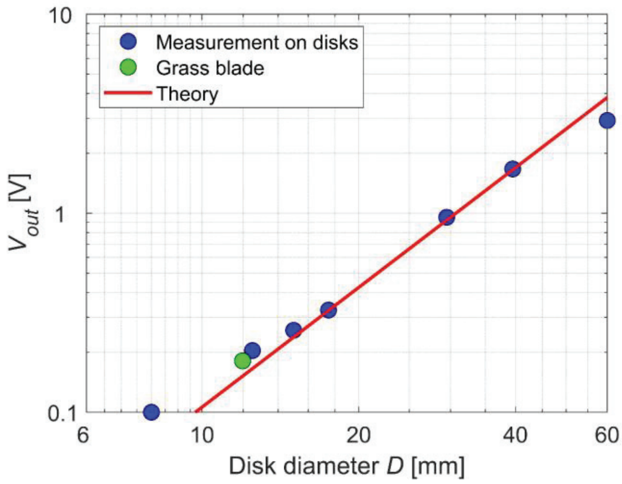

Figure 4 – Measured echo strength from small disks (blue dots) and a segment of a blade of grass (green dot). Also shown (red line) is the theoretical dependence, at the range of 780 mm.

3. FIELD RESULTS

Figure 5 shows some echo profiles with the ultrasonic pasture meter mounted at the front of a farm bike moving at 10 km h^{-1} (2.8 m s^{-1}). The background noise in ranges above the pasture (above the solid green line), is low compared with the signals from within the pasture. Also, there is good penetration to the ground (the solid red line). Echoes at ranges further than the direct distance to the ground come from multiple reflections within the pasture layer. The pasture top is estimated by a simple signal threshold and the ground position from the highest signal peak. While both methods work well much of the time, there are some failures. For pasture top, isolated high blades or stems can give a false impression of the real depth of the bulk pasture, whereas sometimes a pasture echo will masquerade as a ground echo. More complex algorithms have been developed, but are not discussed here.

Figure 6 shows a 20 m section of a farm bike traverse at 15 m s^{-1}, comparing DM obtained by cutting, drying and weighing, and the pasture depth estimated entirely from ultrasound. A simple linear regression between DM and depth H over a range of platform speeds up to 20 km h^{-1} gives a coefficient of determination of 0.65. This is high compared with other pasture DM estimation methods.

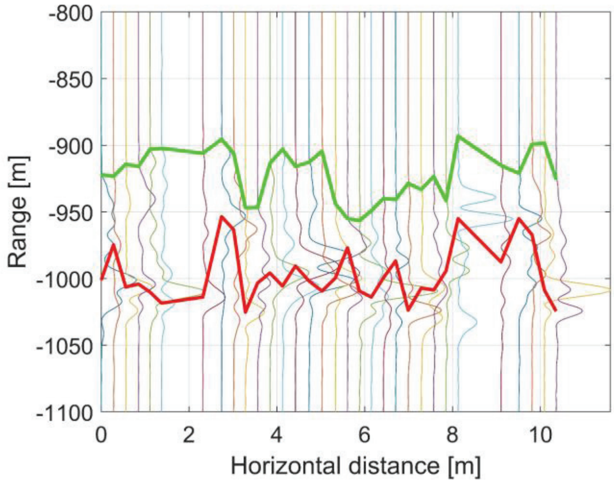

Figure 5 – A succession of echo profiles recorded (thin lines), together with estimated top of pasture (solid green line) and ground location (solid red line).

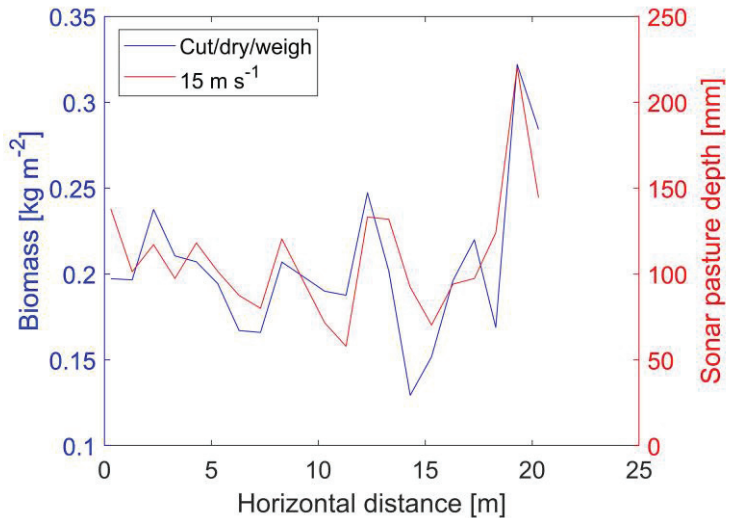

Figure 6 – Comparison between measured DM and acoustically-estimated pasture depth along a 20 m horizontal traverse at 15 m s^{-1}.

4. CONCLUSIONS

A compact and low-power remote sensing instrument has been designed to ultrasonically profile through pasture from a moving platform. The design has ensured that blades of grass are sensed and also that there is penetration to the ground. This allows the pasture layer to be identified independently of the instantaneous height of the sensor above ground. Information is obtained about the strength of scattering from within the pasture layer (but not discussed in detail here). Judicious design of the antenna gives a lateral spatial resolution appropriate to averaging over representative areas of pasture, while use of a linear FM chirp pulse gives along-path spatial resolution sufficient to determine pasture depth accurately. The design is confirmed by detailed calibration.

Field measurements have been conducted at platform speeds up to 20 km h^{-1} (5.5 m s^{-1}) which show good signal-to-noise performance. DM obtained by cutting, drying and weighing the pasture has been compared with the pasture depth estimated from the ultrasonic echoes. Linear regression gives a coefficient of determination (often written R^2) greater than 0.65, which is higher than generally achieved with other methods of DM estimation.

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