Weed discrimination using ultrasonic sensors

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Summary

A new approach is described for automatic discrimination of grasses and broad-leaved weeds, based on their heights. An ultrasonic sensor was mounted on the front of a tractor, pointing straight downwards to the ground in the inter-row area, with a control system georeferencing and registering the echoes reflected by the ground or by the various leaf layers. Static measurements were conducted at locations with different densities of grasses (*Sorghum halepense*) and broad-leaved weeds (*Xanthium strumarium* and *Datura* spp.). The sensor readings permitted the discrimination of pure stands of grasses (up to 81% success) and pure stands of broad-leaved weeds (up to 99% success). Moreover, canonical discriminant analysis revealed that the ultrasonic data could separate three groups of assemblages: pure stands of broad-leaved (lower height), pure stands of grasses (higher height) or mixed stands of broad-leaved and grasses (medium height). Dynamic measurements confirmed the potential of this system to detect weed infestations. This technique offers significant promise in the development of real-time spatially selective weed control techniques, either as the sole weed detection system or in combination with other detection tools.

Keywords: Weed species discrimination; site-specific weed management; wide-row crops.

Introduction

Although numerous studies have been conducted in the past to develop ground detection methods to assess weed infestations, none of these methods have been yet introduced commercially. Therefore, there is a need for precise, low cost sensors that can be incorporated into already available commercial equipment for real time weed patch spraying.

Optical sensors have been used in the past to map and/or spray weed patches present in fallow sites and in various wide-row crops (Biller 1998; Andújar *et al*. 2011). Although these sensors are not able to differentiate weed species from crops, this does not represent a major problem if the sensor is operated only in the inter-row area and the infested areas are treated with broad spectrum herbicides or herbicide mixtures. However, though some of these systems are already commercial (WeedSeeker®, Weed-IT®) the lack of discrimination power and the relatively high cost of these sensors are serious deterrents to wider acceptance. In recent years, numerous studies have used machine vision techniques to detect and identify plant species (either crops or weeds) based on their shape, colour and texture features (Gerhards & Oebel 2006; Slaughter *et al*. 2008). Sonar technologies could even describe weed geometry and discriminate different weed species (McKerrow & Harper 1999). Although it has been proved to be possible, these approaches require relatively long computing time and may be costly.

Plant height and biomass are reliable parameters for the assessment of weed stands. Previous studies have shown that these parameters can be estimated using ultrasonic sensors (Shibayama *et al*. 1985; Reusch 2009). Consequently, it was hypothesized that these sensors could also be used for weed detection and discrimination. Standard ultrasonic sensors are robust and relatively cheap compared to other sensors. However, their performance is affected by the target to be detected, in this case, the canopy structure (Escolà *et al*. 2011).

A study was conducted to assess the use of ultrasonic sensors to detect weeds in the inter-rows of maize, exploring their capabilities and limitations to discriminate weed species of different heights.

Materials and methods

Weed detection system

Ultrasonic sensors provide an estimation of the distance from the sensor to the first obstacle generating an echo according to the time-of-flight method. A Pepperl+Fuchs UC2000-30GM-IUR2-V15 ultrasonic sensor (technical characteristics: http://www.pepperl-fuchs.com/global/en/classid_186.htm?view=productdetails&prodid=4221) was mounted on the front of a tractor, pointing straight downwards to the ground. This sensor has an approximate beam angle of 10º, leading to an effective footprint diameter of approximately 0.30 m when placed at a height of 0.80 m. The transducer ultrasound frequency is approximately 180 kHz with a sensor resolution of 0.48 mm when working in full evaluation range (80 mm to 2000 mm). A deflective shield was installed around the sensor to avoid maize leaves interfering with the readings of inter-row weeds. The response delay of the sensor was set up to 195 milliseconds so that its frequency coincided with the global positioning receiver. Geopositioning was obtained from a differential global positioning system (DGPS) receiver (Hemisphere Crescent R130), with an Omnistar correction signal capable of sub-meter accuracy (about 0.6 m), working at 5 Hz update frequency. The DGPS antenna was located on top of the sensor. Dedicated software was developed using National Instruments LabVIEW graphical language to acquire and process ultrasonic sensor and DGPS receiver data using a compact FieldPoint (National Instruments) device. The program was designed to acquire the output voltage of the sensor and convert it into a distance using an experimental linear regression model equation. System calibration was conducted in a weed free area in the field to be mapped in order to establish the distance from the sensor to the ground in working conditions and save it as the reference distance. After the calibration, the height of weeds was estimated by subtracting the actual estimated distance from the reference distance. The program can work in a single (static) measurement mode or in a continuous (dynamic) recording mode, the latter was used along with DGPS coordinates to identify and map weed patches in the fields.

Experimental setup and measurements

Assessments were conducted in two maize fields located in La Poveda Research Farm (Arganda del Rey, Madrid, Spain). Maize was planted on April 8 with 0.75 m row spacing and a population of 85,000 plants ha^{-1}. Weeds were assessed on May 6 (static measurements in fields A and B) and May 25 (static and dynamic measurements in field B) at the maize stages BBCH 12–14 and BBCH 16–18, respectively.

Field A was heavily infested with *Sorghum halepense* (L.) Pers., *Datura ferox* L. and *Xanthium strumarium* L., with only occasional weed free areas. Field B was mainly infested with *S. halepense* and *Datura stramonium* L. Weed growth stages at the two sampling dates ranged from BBCH 12 to BBCH 18 for dicotyledonous weeds and between BBCH 32 and BBCH 36 for *S. halepense*. Although the fields had received a pre-emergence treatment with S-metolachlor (1.20 kg ai ha^{-1}) + mesotrione (0.12 kg ai ha^{-1}), residual populations of these four species were still abundant. Static measurements were carried out at 254 different locations (167 locations on the first date and 87 on the second date) which were selected within both fields with different densities of pure and mixed stands of these species. Locations were chosen to achieve at equitable distribution between weed groups, i.e., with approximately similar numbers of locations for pure stands of *S. halepense*, broad-leaved weeds and mixtures. In some cases it was necessary to hand weed the location in order to obtain the desired compositions. These static measurements were made by pointing the sensor to the centre of the sampled area. All readings acquired at the same location within an interval of 5 seconds were averaged and the averaged measured heights and the standard deviations were stored. Immediately after taking ultrasonic readings, average height of the various weed species present was determined using a metre rule. All plants present in a 0.30 m diameter circle, coinciding with the sensor footprint, were harvested and taken to the laboratory for biomass (dry weight basis) determination.

In order to assess the capability of this system for mapping weed infestations, a dynamic study was conducted in the field B on May 25. This field presented an ideal situation for our test, with only two weed species of contrasting heights and marked spatial distribution patterns. Georeferenced points were taken at 0.20 s intervals, by setting this update frequency in the DGPS receiver. As the tractor was travelling at approximately 1.50 m s^{-1}, the distance between points within the same row was approximately 0.30 m, which corresponded with the footprint diameter of the sensor. Thereafter, to verify the dynamic measurements, plant height and biomass were determined at 87 georeferenced sampling points following the same procedure described previously.

Statistical analysis

Multiple linear regressions were used to identify the most significant parameters (e.g., plant height and weed biomass) that explained the observed variations in ultrasonic readings for each individual species and for various species combinations. After testing the normality of the distribution of two independent variables (distance from the sensor and standard deviation of measurements), a univariate analysis of variance (ANOVA) was performed in order to assess the capability of independent variables to discriminate significantly between weed groups. Following this analysis canonical discriminant analysis (CDA) was used to classify and predict the different compositions of weeds (Kenkel *et al*. 2002). In the analyses, two cases were considered: a) the ability of the system to discriminate grasses from broad-leaved weeds; b) its ability to discriminate three types of situations: *i*) grasses (*S. halepense*); *ii*) mixture of grasses and broad-leaved weeds; and *iii*) broad-leaved weeds (*D. ferox, D. stramonium* [hereinafter we will refer to both species as *Datura* spp.] and *X. strumarium*). The same analyses were conducted for static and dynamic measurements, although in the latter no standard deviation values were available (the continuous assessment assigned a single value to each DGPS coordinate).

Results and Discussion

Weed species considered in this study had contrasting heights, with *S. halepense* being significantly taller at both sampling dates (Table. 1). Although heights of *Datura* spp. and *X. strumarium* were relatively uniform, a wider range of values was obtained for *S. halepense*.

Static measurements showed the potential of this technique to assess plant height and biomass. Readings taken in pure stands of *S. halepense*, were well correlated with the biomass of this weed at both sampling dates and with plant height at the later date (Table 2). In the case of *Datura* spp., correlations were good at the second date but not at the first one. Correlations of *X. strumarium* height and biomass with ultrasonic readings were poor at the May 6 evaluation (this species was not present in field B, used for the dynamic evaluation of May 25). In species mixtures, ultrasonic readings were good predictors of *S. halepense* height and/or biomass in most cases but they did not show good relationships with the parameters of both broad-leaved weeds. The baseline to assess the various plant situations was recorded on bare soil, where ultrasonic readings provided a fairly accurate measure of the distance between sensor and ground, despite small fluctuations due to soil irregularities and to the position of the vehicle.

Table 1. Average heights in cm (in brackets the range of values) of weed species at two sampling dates.

	May 6	May 25
Sorghum halepense	15.2 (8.0–27.0)	32.9 (20.0–49.0)
Datura spp.	4.6 (3.0–6.0)	12.9 (8.0–18.0)
Xanthium strumarium	6.7 (4.0–10.0)	19.0 (14.0–22.0)

Table 2. Multiple regression analysis between ultrasonic readings and measured height and biomass for weed species (*S. halepense*, *Datura* spp. and *X. strumarium*) and paired species mixtures at two different dates. Results of the static measurements. *Xanthium strumarium* was not found in the sampling of the field B on May 25.

	May 6			May 25		
		Coefficient*	*P*-value**		Coefficient	*P*-value
S. halepense	Height		n.s.	Height	0.68 (0.17)	< 0.001
	Biomass	2.29 (0.4)	< 0.001	Biomass	0.36 (0.16)	0.029
	$R^2 = 0.51$***			$R^2 = 0.73$		
Datura spp.	Height		n.s.	Height	0.99 (0.30)	0.003
	Biomass		n.s.	Biomass	0.33 (0.18)	0.075
				$R^2 = 0.70$		
X. strumarium	Height	1.54 (0.6)	0.021			
	Biomass		n.s.			
	$R^2 = 0.37$					
S. halepense & *Datura* spp.	Height (*S. halepense*)	0.73 (0.3)	0.010	Height (*S. halepense*)	0.72 (0.17)	< 0.001
	Biomass (*S. halepense*)	1.51 (0.4)	0.002	Biomass (*S. halepense*)		n.s.
	Height (*Datura* spp.)		n.s.	Height (*Datura* spp.)		n.s.
	Biomass (*Datura* spp.)	3.32 (1.3)	0.021	Biomass (*Datura* spp.)		n.s.
	$R^2 = 0.55$			$R^2 = 0.40$		
S. halepense & *X. strumarium*	Height (*S. halepense*)		n.s.			
	Biomass (*S. halepense*)	2.38 (1.0)	0.026			
	Height (*X. strumarium*)		n.s.			
	Biomass (*X. strumarium*)		n.s.			
	$R^2 = 0.20$					
Datura spp. & *X. strumarium*	Height (*Datura* spp.)		n.s.			
	Biomass (*Datura* spp.)		n.s.			
	Height (*X. strumarium*)		n.s.			
	Biomass (*X. strumarium*)		n.s.			

* Regression coefficients with standard errors in parenthesis. ** *P*-value: significance level; n.s.: not significant at the 5% level. *** R^2 of the model, including dependent (ultrasonic reading) and independent variables (height and biomass).

ANOVA showed that there were significant differences between weed groups in both static and dynamic measurements (data not shown). Subsequently, CDA provided relatively good results (Table 3) when weeds were classified in two pre-defined groups (grasses vs.

broad-leaved weeds). Indeed, the number of cases classified correctly for pure stands of grasses was 80 to 81%. All misclassified cases were associated with very low *S. halepense* biomass. In addition, 97 to 99% of the cases of pure stands of broad-leaved weeds were classified correctly. When weeds were classified in three pre-defined groups, (grasses, broad-leaved and mixed stands of both weed types), CDA resulted in poorer predictions. At the first sampling date, pure stands of grasses and broad-leaved weeds were correctly classified in 58 and 97% of the cases respectively. These predictions improved at the second sampling, with 71% of the cases being well classified as grasses and 94% as broad-leaved weeds. The presence of mixed stands was predicted in 38 to 46% of the cases, with better results at the second sampling date. In spite of the better discrimination obtained at the later stage, it is not advisable to delay weed detection and herbicide application until this date because of the higher risks of poor weed control and higher yield losses. Further work should focus on improving weed discrimination at early stages.

Table 3. Classification results showing the percentages of original grouped cases correctly classified into two or three weed type groups based on ultrasonic readings. Measurements were taken on two different dates with both static and dynamic mode.

	Predicted group membership				
	Two groups:		Three groups:		
Measurement (date)	Pure stands of grasses	Pure stands of broad-leaves	Pure stands of grasses	Mixed stands	Pure stands of broad-leaves
Static (May 6)	81.1	98.5	57.5 (17.5*)	38.2 (20.0*)	97.0 (0.0**)
Static (May 25)	79.6	97.0	71.4 (7.1*)	46.2 (26.9*)	93.9 (0.0**)
Dynamic (May 25)	77.8	97.0	71.4 (10.7*)	53.8 (23.1*)	87.9 (0.0**)

* % of cases misclassified as “pure stands of broad-leaves”. ** % of cases misclassified as “pure stands of grasses”

The canonical discriminant function plot (Fig. 1) identifies differences between groups based on sampling date. At the earlier date, the centroid of the pure broad-leaved group separates from the centroids of the other two groups, but some overlapping was observed between the position of the pure stands of grasses and mixed stands (Fig. 1a). In contrast, at the second sampling date the centroids of the three weed groups were clearly separated by the first canonical discriminant function which differentiated grasses, broad-leaves and mixed stands (Fig. 1b).

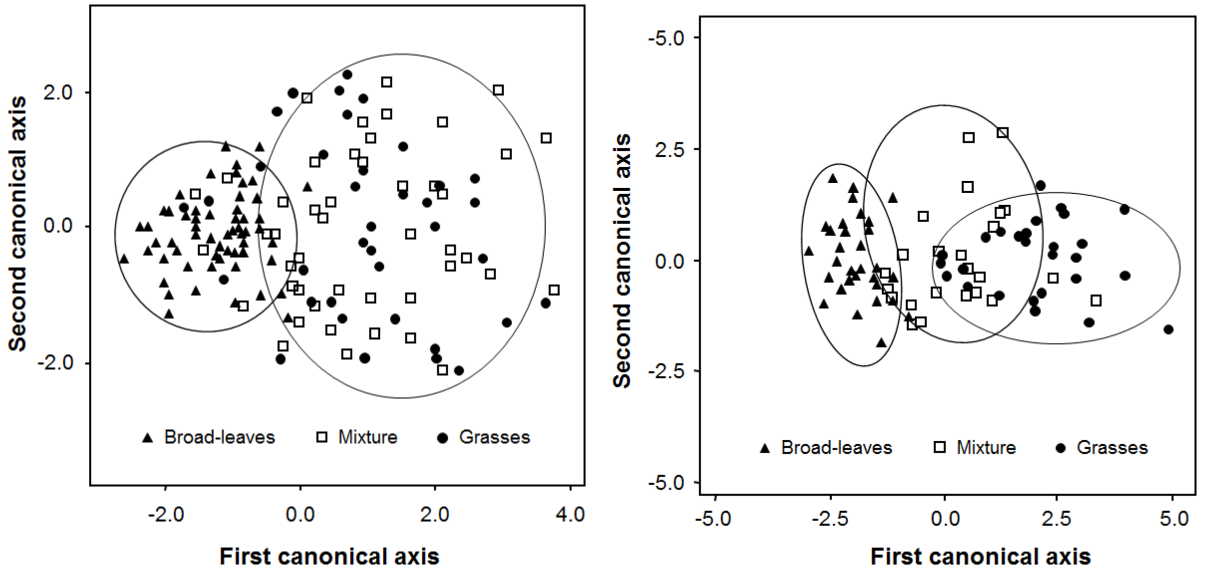

Fig. 1. Canonical discriminant function plot of ultrasonic readings in three groups representing pure stand of grasses, pure stand of broad-leaved and mixed weed stands. a) Sampling on May 6; b) Sampling on May 25.

Dynamic measurements confirmed the capability of this system for weed detection and weed mapping (Fig. 2). When weeds were classified in two groups, pure stands of grasses and broad-leaved weeds were correctly classified in 78 and 97% of the cases respectively (Table 3). When weeds were classified in three groups, the percentages of cases well classified were 71, 88 and 54% for grasses, broad-leaved weeds and mixed stands, respectively.

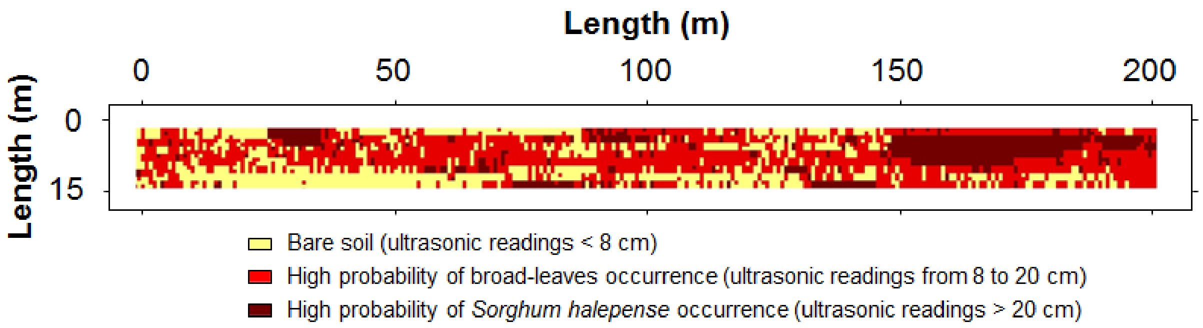

Fig. 2. Weed map derived from the data collected in the dynamic assessment on 25 May in field B.

It seems that the tall erect, *S. halepense* plant canopies produced signals clearly different from those of *Datura* spp. or *X. strumarium* canopies, which were much lower and with horizontal leaves. This discrimination power represents a clear advantage over optoelectronic methods that can only provide an estimate of the presence/absence of weeds on the ground (Andújar *et al*. 2011). Although this approach did not permit the differentiation of species with similar height characteristics (e.g., *Datura* spp. from *X. strumarium*), it may be adequate for deciding on the use of grass or broad-leaved herbicides in situations where these two types of weeds have marked height differences. The map generated in Fig. 2 suggests that spatially selective treatment might be feasible for *S. halepense* as well as for both broad-leaved weeds as a whole.

The low cost, robustness and relatively fast reaction of ultrasonic sensors make them a promising tool to be integrated into real time patch sprayers in situations where crops are grown on wide rows and the major weed species have clearly distinct heights. Additionally, data retrieved by these sensors may reveal useful information on weed biomass and canopy structure. However, further work is needed to explore these possibilities.

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