On-the-go position sensing and controller predicated contact-type weed eradicator

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This article presents a robust contact-type weed eradicator based on position sensing, digital image processing and microcontroller for weed control in row crops. The imaging system determines the weed density between the crop rows using an image analyser developed in Visual Studio Open computer vision platform for use under varying illumination levels. Graphic user interface was developed for parametric adjustments of the image analyser. The image analyser conducts image analysis after image acquisition and the data is sent via computer serial to microcontroller for pulse width modulation controlled chemical release. Solenoid valves are employed for liquid release on sponge rollers. The contact-type technique overcomes losses due to chemical drift and percolation resulting in an efficient application. The machine locomotion sensing is done through an inductive type proximity switch. The developed system was calibrated in laboratory, followed by extensive field tests. The average weeding efficiency reported was 90.30% with lowest plant damage of 5.74% and 7.91% and high yield coefficients of 26.15 g/plant and 581.74 g/plant in two selected crops of groundnut and maize plantation. The technology saved about 79.50% of herbicide marking it as a robust and eco-friendly technology.

Keywords: Contact application, graphic user interface, image analyser, locomotion sensing, microcontroller, weed density.

WEED control is an important operation in crop cultivation for optimum yield. Excess amount of input chemical pollutes environment by percolating into soil, drift into atmosphere and leaching to damage crop production and human health[1]. The conventional methods of constant herbicide application through spray for weed control are expensive, hazardous and non-eco-friendly[2]. Weeds hamper a major part of crop production[3] and the main issue with the current commercial sprayers is the excessive non-targeted application due to chemical drift. Contact methodology efficiently interacts with weeds and minimizes the chemical drift. A roller-wiper absorbing pad-type contact weed eradicator was therefore developed[4] and tested[5] with crawler tractor at various speeds for woody plant control. The roller-wiper contact applicator was further tested[6] for leafy spurge control. Aiming at glyphosate application for row crops, Cohen and Shaked[7] developed a recirculating carpet applicator. Mayeux and Crane[8] developed a tractor frontal mounted carpet roller for range land applications. Welker[9] developed a roller-wiper contact applicator for broadleaved turf weeds, compared with sprayer and reported a non-significant drift with contact-type roller-wiper, however, with a significantly high drift with sprayer. The contact-type technologies prove contact applications to be better than spray applications. A single row manually drawn contact-type weed eradicator was developed and patented[10], for 100% uniformity with an application rate of 100–120 l/ha.

Drift losses, environment degradation and excess chemical loss in conventional spraying for weed control necessitate the variable-rate contact-type application. Also, the technologies discussed apply herbicide constantly and consume about 50% higher herbicide than variable rate contact application technology as reported by Tewari *et al.*[11]. The estimation of site-specific weed information predicts the variable rate application analogy and in this regard many researchers have tried colour detection technique like Bulanon *et al.*[12] developed and tested a machine vision for apple detection with expensive charge coupled device (CCD) cameras. Graniatto *et al.*[13] also applied machine vision technique to determine the weed and seed infestation by incorporating R, G, B wavelengths and illumination to produce a resulting colour to be detected in luminance colour difference model (LCD) and the hue saturation intensity (HSI) method.

Several studies have reported application methodology for the inter-row region which hosts the maximum amount of weed. Carrara *et al.*[14] designed a system which applied herbicide in variable amount but proportional to the forward speed rather than weed infestation. Some researchers studied the effects of the spatially differentiated herbicide spraying which was a map-based

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approach rather than being real time[15,16]. Tian[17] developed a sensor-based herbicide sprayer which integrated machine vision and variable technology; however, the chemical drift was very high and not suitable for smaller weed patches. Thorp and Tian[18] navigated the variable-rate herbicide applications based on weed species and site specific information for herbicide doses using remote sensing imagery. Various researchers worked out fine techniques to electronically control flow line discharge and inferred[19] that the regulation of pressure drop as the best technique to control the nozzle discharge but this was limited by slow system response, less flow control range and poor nozzle performance. Further, pulse width modulation (PWM) was utilized for flow control with conventional sprayers. Han *et al.*[20] employed correlations and characteristic curves for PWM behaviour to determine the flow rate and error in its calibration through solenoid operated sprayer nozzles.

This article presents the development of a robust contact-type precise variable rate weed eradicator for weed control. The system adopts hue saturation value (HSV)-based image analysis in Visual Studio which incorporates illumination parameter for accurate weed information. Contact-type methodology with sponge rollers was adopted for a uniform, no drift and eco-friendly application. PWM technique was further employed in predication with image analysis for high precise application through solenoid valves.

Materials and methods

Contact-type weed eradicator

The contact-type weed eradicator was designed and developed with main components such as storage tank, pipelines, camera mounting bracket, field separators-cum-deflectors, ground wheel and sponge rollers connected to adjustable telescopic linkage. The applicator was developed for all such crops with row to row spacing ranging between 350 and 450 mm such as groundnut planted at a spacing of 450 mm. The applicator intends for parallel herbicide application in six rows and thus individual camera and application units were fabricated and assembled. The six cameras were mounted on six telescopic mounting brackets for each row and the field of view (FOV) width of camera set for particular type of crops was 300 mm. FOV was separated from main crops by deflectors of dimension 600 × 300 × 600 mm around the camera. These deflectors restrict main crop plants into FOV, thereby contribute for accurate weed estimation, avoiding main crop damage and herbicide wastage. The recommended operation speed is 2.1 km/h, appropriate for intercultural operation and also covering a FOV length of 600 mm. The camera and sponge rollers were spaced on the basis of time lag between image capture and liquid release on sponge rollers. The first captured frame/sec was processed and analysed whereas other subsequent frames were rejected till the next 600 mm patch arrived. An inductive-type proximity switch was installed on the ground wheel to witness the applicator movement and distance coverage. Five iron strips equally placed in the peripheral vicinity of the proximity switch indicated 600 mm coverage on the ground. A fixed displacement pump was employed while spraying.

Image analyser and graphic user interface

The image acquisition and processing unit consists of laptop with digital image analyser application, cameras of high resolution (640 × 480) for each row. The frame grab interval of 30 frames per second/patch is set in the application as per the operation speed of 2.1 km/h. Among 30 frames, the first image frame is acquired from a land patch of 600 mm and the rest 29 are discarded, continuing the same for the next patches. Further, digital image was analysed through HSV image analyser built in Visual Studio C^{++} with Open CV in the laptop. The net greenness in the acquired image is calculated through this colour-based HSV analyser using eq. (1), where the HSV components of every pixel are analysed for green colour. The total number of such green pixels is counted based on the HSV image analysis and highlighted as white colour in the binary image as shown in Figure 1. A graphic user interface (GUI) is constructed with HSV range bars for adjustments according to the green colour and illumination. GUI also presents the original acquired images in each row and their corresponding binary images after analysis. An intermediate output window is generated where the weed infestation degree is displayed along with the corresponding controller action signals for the precise herbicide application. After the image analyser and intermediate outputs, there appears the role of the controller operation where programmed Arduino with Atmega 328P chip takes the necessary actions for the precise application of herbicide. The controller action signals for each row are stored in an array string and transferred to the interfaced controller from laptop. Figure 2 shows the functions comprised in the image analyser. Figure 3 presents the components of image processing and controller circuit.

$$\text{Weed density (\%)} = \frac{\text{Total green pixels in captured image}}{\text{Total pixels in captured image}}. \quad (1)$$

Controller and precise application system

The controller interfaced with laptop image analyser comprises a Arduino microcontroller (Atmega 328P chip), relay switches, solenoid valves and proximity switch. The controller receives the action signal string based on image analyser output from the laptop and takes relevant action for precise application. The weed density ranges from 0 to 1, and separate signals are allotted to the 21 sub-ranged weed densities such as 0–0.05, 0.05–0.1 and so on. The control signal is a basic PWM actuation for a particular duty cycle. The first part is zero weed density where Arduino commands no herbicide application, the next weed density sub-range is 0–0.05 and based on this a control signal in Arduino is validated and through relay switches the solenoid valves are actuated for that particular duty cycle time and the corresponding herbicide amount is released for application. Similarly for every range of weed density, solenoid actuates for the relevant duty cycle time and the corresponding herbicide is released on sponge coated rollers which roll over the weeds for herbicide application between the crop rows. Solenoid valves are timely operated by relay switches as actuated by Arduino for the assigned duty cycle control signals for the six row application. The actuation of one solenoid valve is kept totally independent of the other solenoid. In this manner through image analyser and controller system the herbicide application is directly related to the amount of weed infestation between the crop rows. Most importantly, the controller system functions only when the machine is under locomotion in field which is indicated by sensing signals of the inductive-type proximity switch. Individual components in the weed eradicator from image analyser, controller unit and sponge roller application are synchronized with appropriate FOV, camera roller spacing, time lag and operation speed for maximum field capacity and minimum input. The entire process flow of the application system is shown in Figure 4. Figure 5 depicts the circuit diagram of the fabricated controller unit. This system is unique as the herbicide application is varied for every 5% variation in weed infestation which amounts to better savings of herbicide along with better weeding efficiency as compared to the existing system for an efficient application. This system also contributes towards quick sensing of response as per the expectation in the desired region of weed infestation.

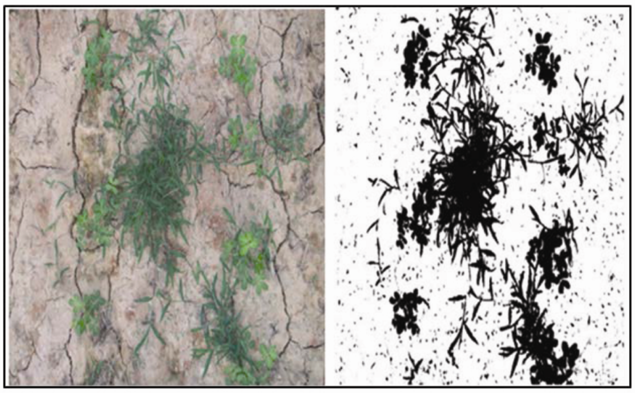

Figure 1. Original and binary weed images from the tests.

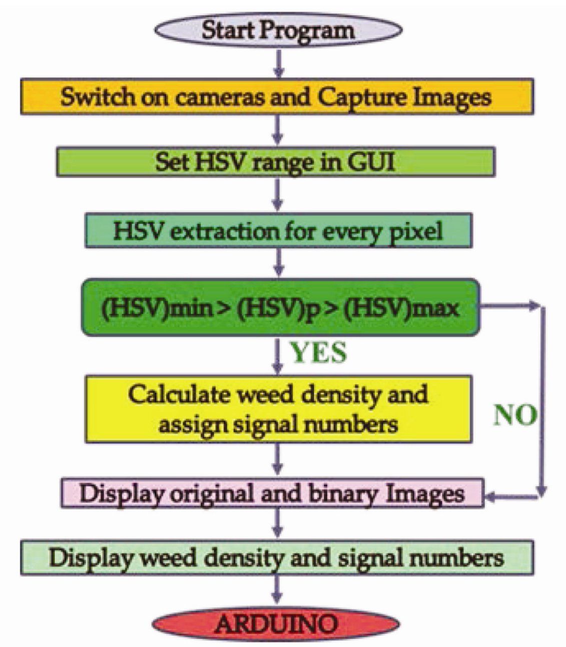

Figure 2. Image analyser process.

Laboratory and field evaluation

The discussed concept was incorporated to develop a high capacity six-row tractor drawn variable-rate weed eradicator for actual testing and field evaluations. Alphabets from A to U were assigned as ASCII values to different weed density sub-ranges at every 5% infestation starting from 0% to 100%. In case of microcontroller, these ASCII codes assigned to weed ranges were fed as duty cycles as programmed for PWM application. The array of ASCII values as per weed infestations were also displayed in the intermediate output window (Figure 6). Laboratory evaluation of the developed system was

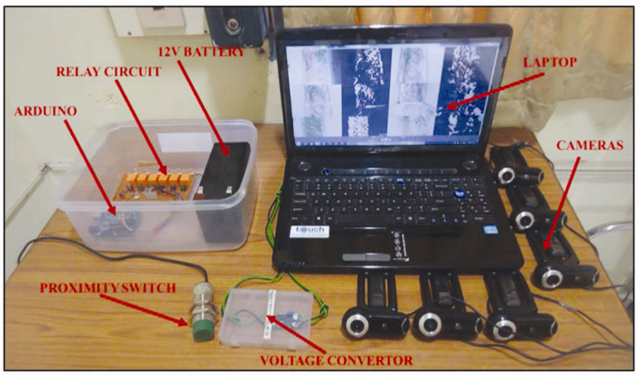

Figure 3. Components of image analysis and controller circuit.

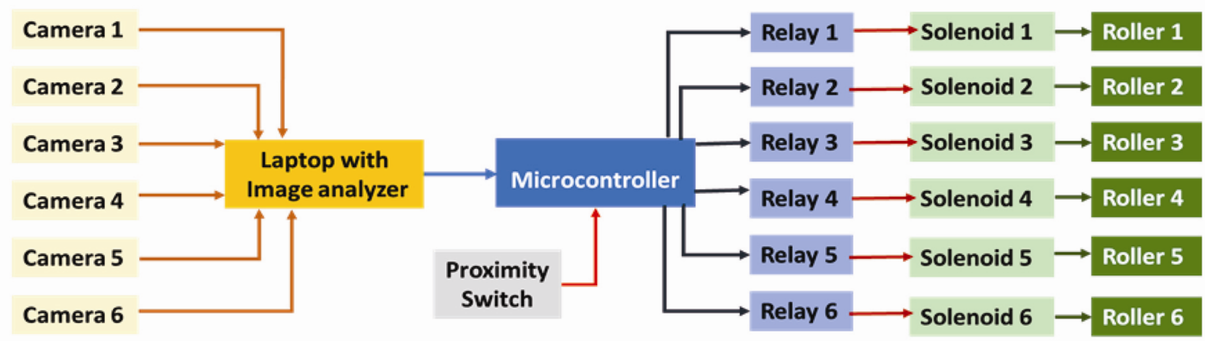

Figure 4. Process flow of the contact-type herbicide application system.

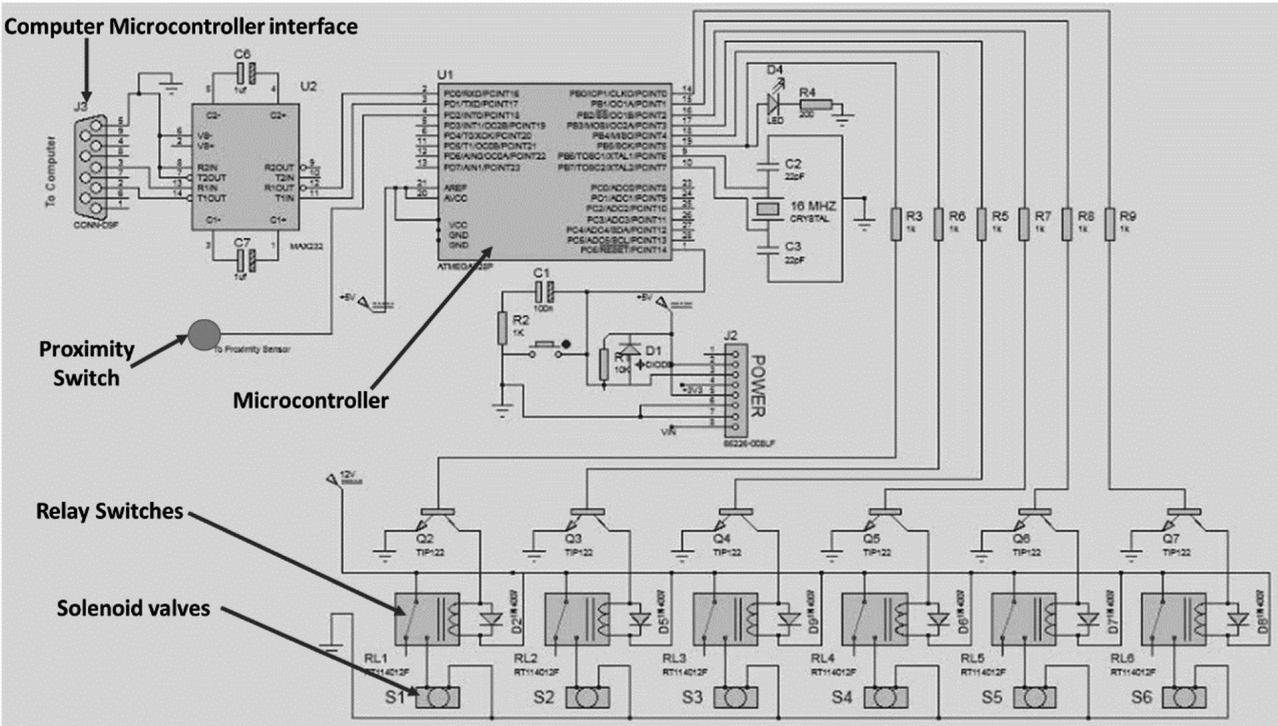

Figure 5. Circuit diagram for the precise herbicide application system.

carried out by a two-stage solenoid valve calibration, first by individual actuation and then by simultaneous actuation at all duty cycles. Green painted card boards were used in FOV as in Figure 7 to observe the discharge variation in the laboratory. Figure 7 displays the actual and binary images of the painted boards at a particular illumination. Figure 6 shows the intermediate output window that presents the ASCII values based on the weed density of the captured images in each camera's FOV. These are the same ASCII values sent as an array to microcontroller as duty cycles for each solenoid valve.

For field performance evaluation, the variable-rate weed eradicator was mounted on the tractor. The weed variation along rows together with the discharged herbicide liquid was recorded using Hall-effect flow meter sensor. The performance of weed eradicator was evaluated and compared for contact-type and spray-type applications for the two selected groundnut and maize plantations. The damaged plants along with weeding efficiency, application rate and herbicide savings were recorded. Weeds were sampled using a frame of 300 × 600 mm at multiple locations within crop rows, 48 hours before and after the herbicide application. Figure 8 shows the GUI window during weeding operation between the crop rows at a particular illumination setting and displaying the original and binary images of weed infestation. A fixed displacement pump and six flat fan nozzles were employed for evaluation with spray applications as in Figure 9. Figure 10 shows the field tests performed with the variable applicator in contact-type mode. Cameras

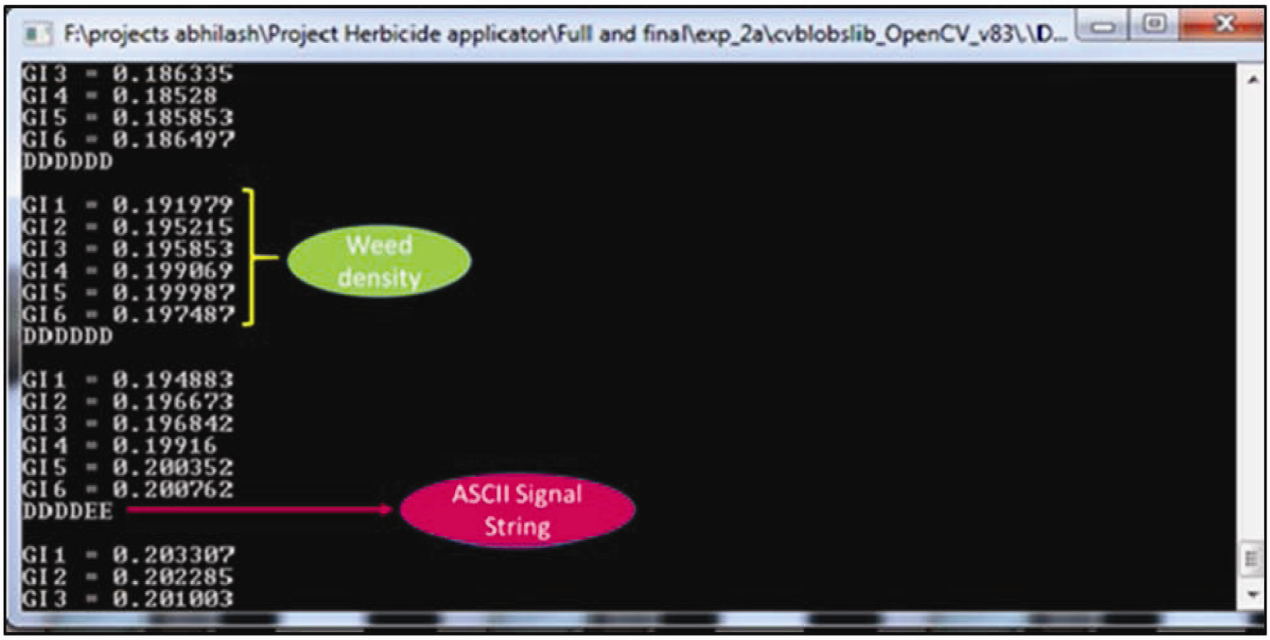

Figure 6. Primary output window to display weed density and signal string.

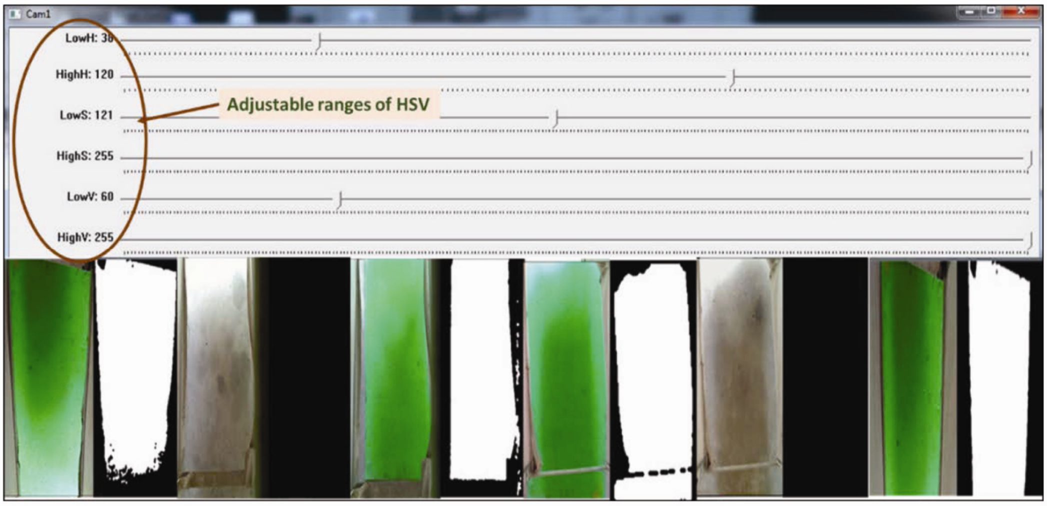

Figure 7. GUI for original and threshold image analysis in laboratory condition with HSV adjustments.

were switched off during constant contact-type application. The reduction in herbicide application with respect to constant spray application (HR1) was determined using eq. (2) and reduction with respect to constant contact application (HR2) was determined using eq. (3)

$$HR1 = (CSA - VCA)\%/(CSA), \quad (2)$$

$$HR2 = (CCAR - VCA)\%/(CCA), \quad (3)$$

where HR1 is the herbicide reduction with respect to constant spray application (%); HR2 the herbicide reduction with respect to constant contact-type application (%); CSA the herbicide application rate during constant spray application (l/ha); CCAR the herbicide application during constant contact-type application (l/ha); VCA is the herbicide application during variable contact-type application (l/ha).

Results and discussion

Solenoid valve tests

Solenoid valves discharged herbicide at a rate of 2.08–16.25 ml/s at 5% (0–5% weed density) to 100% duty

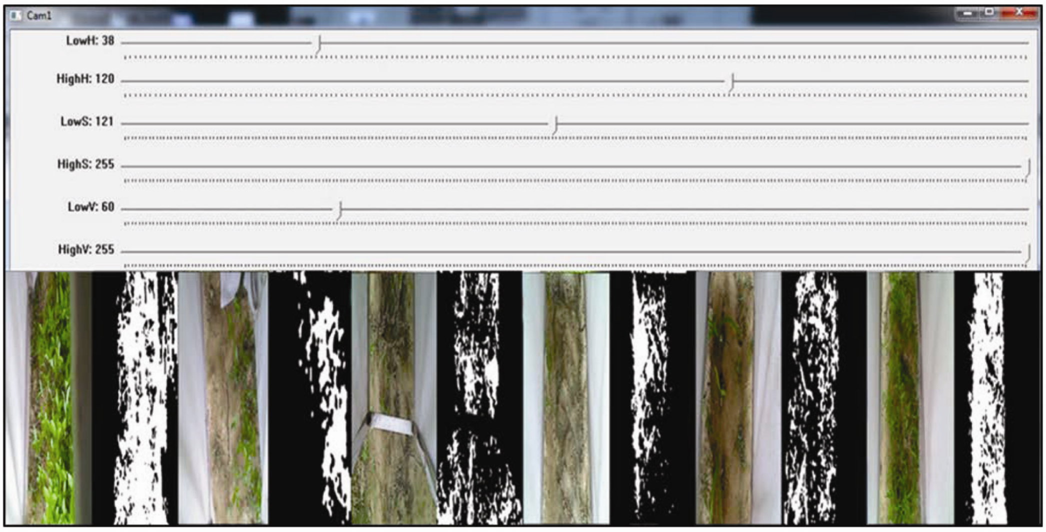

Figure 8. GUI window with original and threshold images during field operation.

Figure 9. Field evaluation with the spray-type mode of herbicide application.

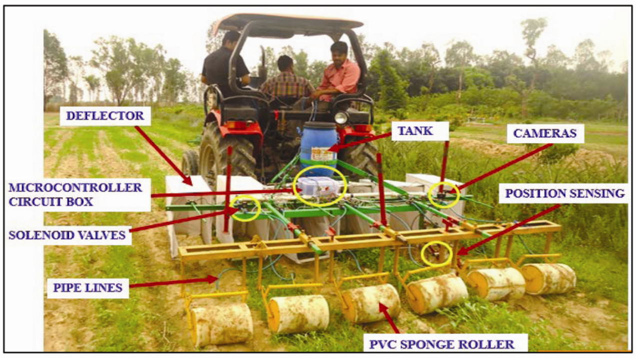

Figure 10. Field tests of the developed variable rate weed eradicator at maize field.

cycle (95–100% weed density) respectively, when tested separately with an average relative deviation of 2.03%. Thus, herbicide release was directly dependent on weed density eq. (4) as in Figure 11 with R^2 as 0.99. However, the valves discharged 1.56 ml/s at 5% duty cycle (0–5% weed density) and 15.51 ml/s at 100% duty cycle (95–100% weed density) when tested simultaneously with an average relative deviation of 3.78%, follows direct relationship with weed density eq. (5) in Figure 11 with R^2 as 0.99. On a two-stage statistical analysis at 5% significance level and 20 degrees of freedom, the variances of two tests were significantly close with F-statistic of 1.18 (< F-critical) and P-value of 0.36 (>0.05) and a similar trend was observed at second stage analysis. Hence it is evident that there was no significant difference in discharge values of solenoid valves in the two tests and the behaviour of one solenoid valve does not affect the other.

$$Y = 0.15X + 1.72, \quad (4)$$

$$Y = 0.14X + 1.46. \quad (5)$$

Field performance of contact type variable-rate weed eradicator

The variable-rate contact-type applicator with saturated sponge rollers applied the chemical herbicide paraquat dichloride at a concentration of 1 : 10 in water with prime mover as tractor at an operating speed of 2.1 km/h. The variation in weed density was captured in the groundnut and maize field as shown in Figure 12, averaged between 418.72 weeds/m^2 and 357.19 weeds/m^2 respectively, before weeding. This variation in weed density indicates the appropriate functioning of imaging and processing devices in the variable-rate weed eradicator. To observe accurate functioning of herbicide application and record the non-uniform liquid released through solenoid valves, the Hall-effect flow meters were interfaced to the microcontroller and plotted through PLX-DAQ application as

Table 1. Compared application rates and weeding efficiency in groundnut and maize plantation

Sr. Col.	CSA (l/ha) (A1)	WE (CSA)% (B1)	CCA (l/ha) (C1)	WE (CCA)% (D1)	VCA (l/ha) (E1)	WE (VCA)% (F1)	HR (1)% (G1)	HR (2)% (H1)
Groundnut plantation								
1	733.70	90.00	298.85	89.87	163.76	90.63	77.68	45.20
2	666.67	89.96	302.72	91.25	155.53	89.96	76.67	48.62
3	688.89	91.25	295.24	90.87	169.94	90.41	75.33	42.44
4	720.74	93.58	297.45	89.83	151.76	88.47	78.94	48.98
5	719.80	94.05	301.78	92.15	145.85	91.33	79.74	51.67
Avg.	705.96	91.77	299.21	90.80	157.37	90.16	77.67	47.38
SD	27.45	1.95	3.08	0.98	9.57	1.07	1.76	3.59
RD%	3.89	2.12	1.03	1.08	6.08	1.18	2.26	7.58
Col.	(A2)	(B2)	(C2)	(D2)	(E2)	(F2)	(G2)	(H2)
Maize plantation								
1	725.90	94.03	305.45	90.45	133.77	89.78	81.57	56.21
2	696.78	91.25	303.58	89.56	158.65	91.35	77.23	47.74
3	708.15	92.24	299.75	91.66	125.78	90.75	82.24	58.04
4	715.85	89.86	300.15	90.75	119.47	90.75	83.36	60.02
5	689.35	90.85	291.43	92.23	121.35	89.15	82.40	58.36
Avg.	707.21	91.65	300.07	90.93	131.80	90.36	81.36	56.07
SD	14.59	1.58	5.39	1.04	15.99	0.88	2.39	4.85
RD%	2.06	1.73	1.79	1.15	12.13	0.97	2.94	8.65

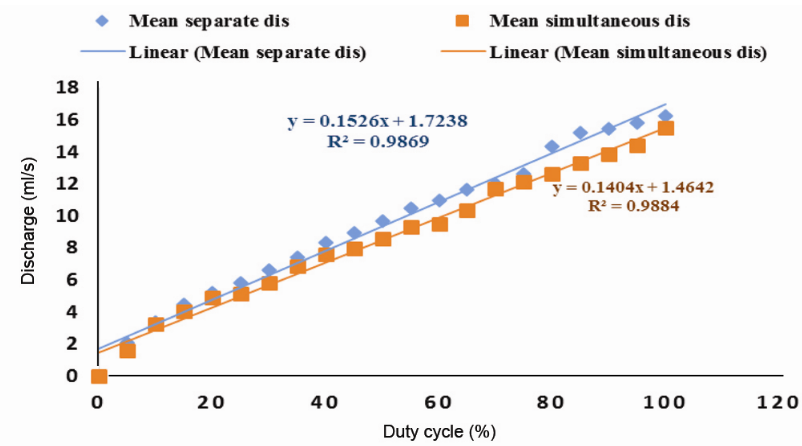

Figure 11. Discharge regression for separate and simultaneous solenoid valve calibration.

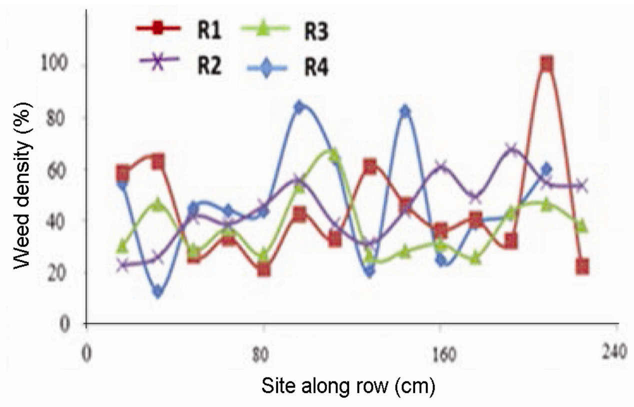

Figure 12. Variation of weeds along the alternate row in 300 mm × 300 mm area.

in Figure 13. The maximum herbicide released was 17 ml during 100% weed infestation and none released during 0% weed infestation at some patches.

All herbicide application modes were carried out for two fields planted with maize and groundnut (TG-22 type) and divided into 4 parts of 5 × 20 m each for different modes and control. Tables 1 and 2 present the comparative analysis between the chemical application rates during constant spray application (CSA), constant contact application (CCA) and variable contact application (VCA) and respective weeding efficiencies (WE). The average application rate of 157.37 l/ha with relative deviation (RD) of 6.08% during VCA in groundnut field resulted in an average WE of 90.16% and RD of 1.18%. Similarly, the average application rate of 131.8 l/ha and

Table 2. Stat-analysis of herbicide dose and weeding efficiency in two fields at various modes

Col.	*F*-Stat	*F*-critical	*P*-value	Result	*t*-Stat	*t*-critical	*P*-value	Result
(A1)(C1)	79.51	6.389	<0.05	S	32.92	2.13	<0.05	S
(C1)(E1)	9.66	6.39	<0.05	S	31.55	2.01	<0.05	S
(A1)(E1)	8.23	6.39	<0.05	S	50.07	2.13	<0.05	S
(B1)(D1)	3.95	6.39	0.11	NS	0.99	1.86	0.17	NS
(D1)(F1)	3.52	6.39	0.12	NS	0.98	1.86	0.18	NS
(B1)(F1)	1.12	6.39	0.46	NS	1.62	1.86	0.07	NS
(G1)(H1)	4.18	6.39	0.1	NS	16.93	1.86	<0.05	S
(A2)(C2)	7.35	6.38	0.04	S	58.50	2.01	<0.05	S
(C2)(E2)	8.81	6.38	0.03	S	22.30	2.01	<0.05	S
(A2)(E2)	1.20	6.38	0.43	NS	59.43	1.86	<0.05	S
(B2)(D2)	2.29	6.38	0.22	NS	0.84	1.86	0.21	NS
(D2)(F2)	1.08	6.38	0.47	NS	0.94	1.86	0.19	NS
(B2)(F2)	2.13	6.38	0.24	NS	1.59	1.86	0.07	NS
(G2)(H2)	4.11	6.38	0.10	NS	10.45	1.86	<0.05	S

S, Significant difference; NS, Non-significant difference.

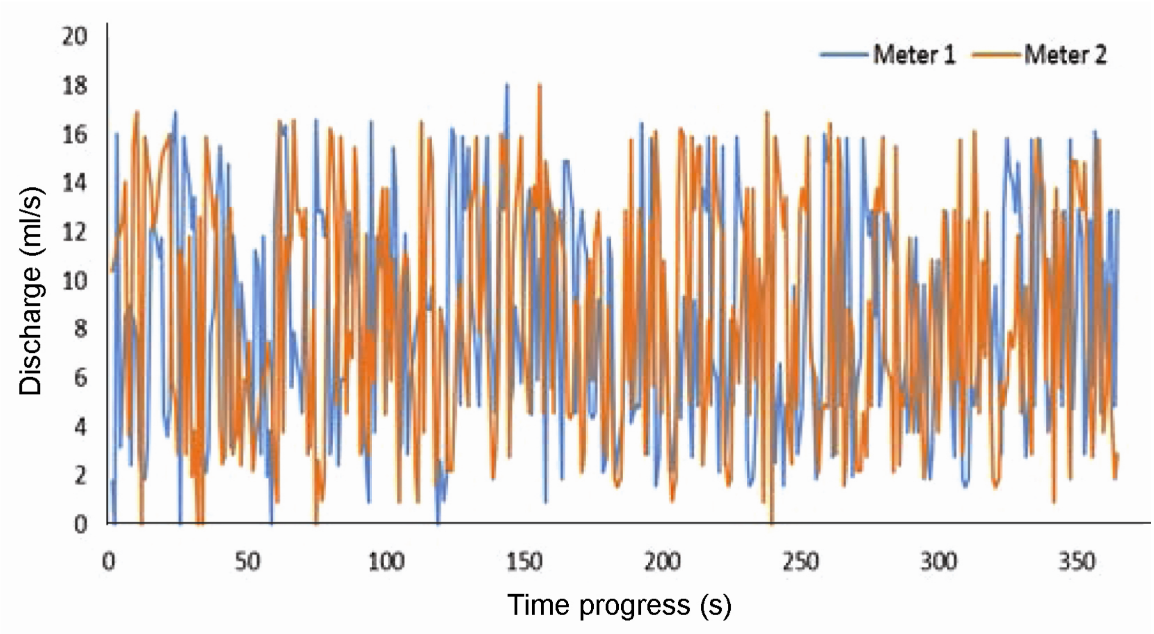

Figure 13. Flow variation recorded by the Hall Effect flow meter per variation in weed density.

RD of 12.13% during VCA in maize field resulted in an average WE of 90.35% and RD of 0.98%. The average application rate during CCA in two fields was observed as 299.65 l/ha (maximum RD, 1.79%), much closer to 297.61 l/ha, as reported[21], with an average WE of 90.87% (maximum RD, 1.15%) in the two fields. However, the average application rate during CSA in two fields was observed as 701.58 l/ha (maximum RD, 3.89%), leading to an average WE of 91.71% (maximum RD, 2.12%). Table 2 presents the statistically compared herbicide dosage, WE and herbicide reduction in all three modes of application in the two fields. As shown in Table 2, WE in VCA was significantly similar to that of in CCA and CSA but the herbicide dose in case of VCA was significantly lower than that of in CCA and CSA modes of herbicide application. A significant reduction in herbicide dose of 47.38% and 77.67% was found in groundnut field with VCA mode compared to CCA and CSA and was significantly high in the latter case. Similarly, a significant reduction in herbicide dose of 56.07% and 81.36% was found in maize field with VCA mode compared to CCA and CSA and was significantly high in the latter case. All the statistical tests were conducted at significance level of 5% in two steps – first, the *F*-test was carried out to determine whether there was any significant difference in variances of application rates and WE and later, Student's *t*-test was carried out depending on the results of *F*-test for significantly equal and unequal means. The results of weed eradicator were also analysed using RD as

$$RD = (SD/Mean) \times 100. \quad (6)$$

Weeding efficiency was significantly the same (*S*) in all modes of application but the application rate was significantly lowest (S). Herbicide reduction was significantly highest (S) with VCA mode of application in both the fields. Extra dose of herbicide was observed in CSA and CCA mode which was considerably lost to pollute the ground water, soil and atmosphere. The system stands unique for its quick response, robustness and efficient application and most importantly it was able to vary the herbicide application amount at every 5% weed infestation variation, making it a good option for eco-friendly and smart weed eradication.

Plant damage and production

The results of plants damaged and yield coefficients for groundnut and maize plantations are shown in Figures 14 and 15 respectively. Both figures indicate that the plant damage was highest in the case of CSAs (20.73% and 21.5%), whereas the damage during different modes herbicide application mode was minimum for VCA (5.74% and 7.91%). The groundnut yield coefficient (g/plant) was observed to be minimum for control plot (13.96) followed by CSA (19.21) and CCA (23.12) and was maximum for VCA (26.15) mode of herbicide application. The maize yield coefficient (g/plant) was observed to be minimum for control plot (329.89) followed by CSA (444.28) and CCA (511.12) and was maximum for VCA (582). Groundnut plant damage after VCA was 3.6 times less than CSA and 1.37 times less than CCA. Also, VCA amounted to a maximum yield coefficient, among all modes of herbicide treatments. In case of maize, the plant damage after VCA was 2.72 times less that CSA and 1.33 times less than CCA. Here also VCA showed a maximum yield coefficient. Yield was comparatively less in case of CSA mainly due to plant damage by drift and liquid percolation that might have affected plant roots and their nutrient uptake capacity. The control plot reported minimum yield for all types of application which is one of the well justified reasons in various studies on how weeds affect crop production by competing against them and hosting insects and pests. The results were analysed statistically stating the application rate, WE, damage and grains produced during different modes of herbicide treatment like CSA, CCA, VCA and the control to be significant at 5% level ($\alpha = 0.05$).

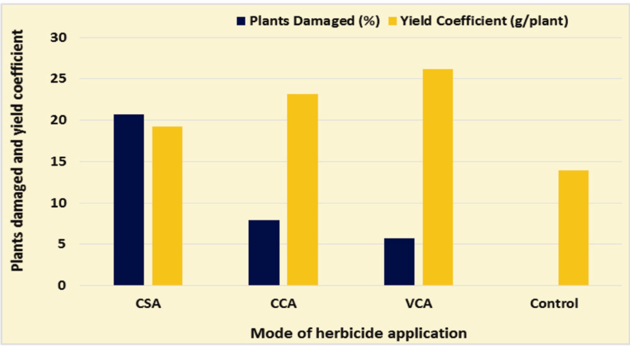

Figure 14. Plant damage and yield coefficient for groundnut plantation under different modes of application.

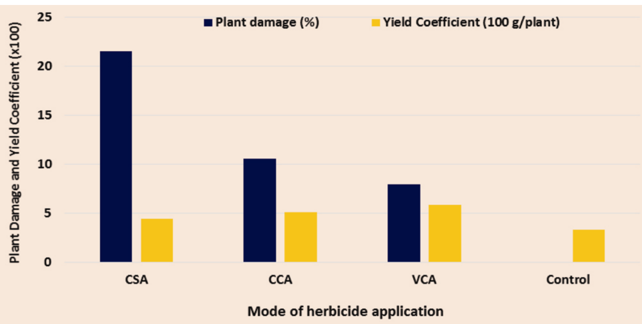

Figure 15. Plant damage and yield coefficient for maize plantation under different modes of application.

Conclusions

The system provides an unavoidable approach and answer towards such situations when system events are required to be in synchronization with the location of stationery objects in the captured images relative to a mobile and sensing control unit.

A user friendly GUI was developed for robust application which can be used effectively with minor adjustments.

The technology was rigorously tested to address effortless and robust intercultural operations in the dry land.

All plots of 5 × 20 m for each application mode and control in both plantations were under similar conditions when evaluated. The two-stage statistical tests and analysis were performed for the analysis of significance in performances of VCA and other modes.

The incorporated mechatronic system and novel design of application unit were satisfactorily able to reduce the herbicide use and thereafter avoided potential environmental hazards.

Variable-rate contact-type herbicide application system was able to significantly save herbicide amount by about 79.5% over conventional method of constant spraying, while maintaining a fine weeding efficiency of 90.26%.

Most importantly the plant damage in VCA was lowest for groundnut (5.74%) and maize (7.91%) plantations and was significantly less than that of CSA and CCA mode of herbicide application.

The variable-rate contact-type application marked the highest yield coefficient of 26.15 g/plant for groundnut and 581.74 g/plant for maize plantation among all modes of herbicide application.

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