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Comparative evaluation of different sensors for foliage detection to assist in intra-row weeding applications

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Abstract
Accurate detection of plants foliage is essential criteria for the development of efficient intra-row weeding mechanism to prevent crop damage. This study evaluated the detection performance of three sensors- ultrasonic, infrared and camera, to identify the most suitable sensor to assist intra-row weeding applications. The sensors were tested under laboratory conditions at varying distances (30, 60 and 90 cm), sensor heights (10, 20, 30 and 40 cm) and angular positions (45°, 60°, 75° and 90°). Plants were classified as large, medium and small based on foliage density and height to assess sensor response under different canopy conditions. A custom sensor-holding setup was fabricated, and embedded programs were developed using an Arduino platform for ultrasonic and infrared sensors, while image acquisition and processing for the camera were carried out using OpenCV. Sensor performance was evaluated based on the number of successful detections across all test combinations. The camera sensor recorded the highest number of detections (84 out of 144), followed by the ultrasonic sensor (68) and the infrared sensor (47). The camera consistently detected plants across varying foliage densities due to its rich visual information and precise localization capability. Ultrasonic and infrared sensors showed reduced performance, particularly for small plants, due to weak signal reflection and sensitivity to environmental factors. The results indicate that camera-based sensing is the most reliable approach for foliage detection and is well suited for integration into automated intra-row weeding mechanisms.

Keywords: Intra-row weeding, foliage detection, ultrasonic sensor, infrared sensor, camera sensor, sensor evaluation, precision agriculture, weed detection

1. Introduction

Mechanical weeding is an effective alternative to chemical weed control and plays a vital role in promoting sustainable agricultural practices. Although a wide range of mechanical weeding equipment is currently available, most are limited to the removal of inter-row weeds, with very few designed for effective intra-row weed control. Intra-row weeds, which grow in close proximity to crop plants, compete directly for nutrients, water and light, thereby severely hindering crop growth and productivity. Consequently, there is a critical need for the development of efficient intra-row weeding equipment. However, the performance of intra-row weeding systems largely depends on the accurate detection and localization of crop plants to prevent unintended crop damage. This challenge is further intensified during the early growth stages of crops, when variations in plant height, foliage density and field undulations make reliable differentiation between crop plants and weeds particularly difficult.

Sensor-based detection systems offer a promising solution for automating intra-row weeding operations. Among the available sensing technologies, ultrasonic, infrared and camera sensors have been widely used in agricultural and industrial applications for object detection. Ultrasonic sensors measure distance based on sound wave reflection, infrared sensors rely on reflected infrared light for object detection, while camera sensors provide rich visual information that can be processed for object recognition and localization. Each of these sensors has distinct advantages and limitations when deployed under agricultural conditions.

Despite extensive use of these sensors individually, a comparative evaluation of their detection performance under varying distances, heights and angular orientations is limited. Therefore, selecting an appropriate sensor based on detection ability and response under realistic operating conditions is essential for the successful development of an intra-row weeding mechanism. The present study was undertaken to systematically evaluate ultrasonic, infrared and camera sensors for foliage detection and to identify the most suitable sensor for accurate crop-weed discrimination in real fields.

2. Materials and Methods

2.1 Selection of suitable sensor for the development of intra row weeding mechanism

Crop and weed foliage detection is the critical part in the development of any intra row weeding mechanism to avoid damaging of crop plants. Selection of suitable sensor is the first step in the development of any intra row weeding mechanism. From the review of literature, it was being dealt that the three major sensors which were vastly being used in object detection field was ultrasonic sensor, infrared sensor and camera. Ultrasonic sensors are widely used for measuring distances by emitting sound waves and calculating the time taken for the echo to return. Infrared sensors, on the other hand, detect objects or motion based on infrared light reflection, making them suitable for close-range obstacle detection. Camera sensors provide visual data that can be processed for image recognition, object tracking or video recording. There is necessity to select the best sensor among these sensors for proper detection of crop and weeds in field to assist intra row weeding mechanism. The best sensor among these was selected based on detection ability. These sensors were tested at different distances, at different heights and at different angles from the target to judge the detection ability. To know the distance adoptability of these sensors, the sensors were tested for 3 different distances *i.e.*, 30, 60 and 90 cm and for 4 heights *i.e.*, 10, 20, 30 and 40 cm. Based on the earlier studies, the sensors were tested for angles 45°, 60°, 75° and 90°. The plan of experiment for evaluation of these three sensors is given in Table 1.

Table 1: Plan of experiment for evaluation of three sensors

Sl. No.	Independent parameters	Levels	Dependent parameters
1)	Type of sensors	3 [Ultrasonic, Infrared, Camera]	Detection ability
2)	Distance from target	30, 60, 90 cm	
3)	Angular position from target	45°, 60°, 75°, 90°	
4)	Height from ground	10, 20, 30, 40 cm	
5)	Replication	3	

2.2 Fabrication of sensor holding setup

For proper evaluation of sensors, there is a need of sensor testing platform to select the appropriate sensor for detection and localization of cotton crop and weeds. Therefore, a sensor holding setup was fabricated in the workshop of College of Agricultural Engineering, UAS, Raichur, Karnataka to study different sensor parameters under laboratory conditions. A length of 3 m square pipe (50 × 50 × 2 mm) was cut and a platform of plus shape was welded at one end of square pipe column to make it stand in vertical position when sensor readings were taken. Further, a piece of iron sheet (100 × 50 × 0.5 mm) was cut into semicircle shape with angles marked on it with the help of punch and on these marks, holes were made as shown in Fig.1a. A sensor holding section was fitted to semicircular section whose angles can be changed based on the requirement as shown in Fig.1b. This angular section was further fitted into a vertical square pipe platform as shown Fig.1c.

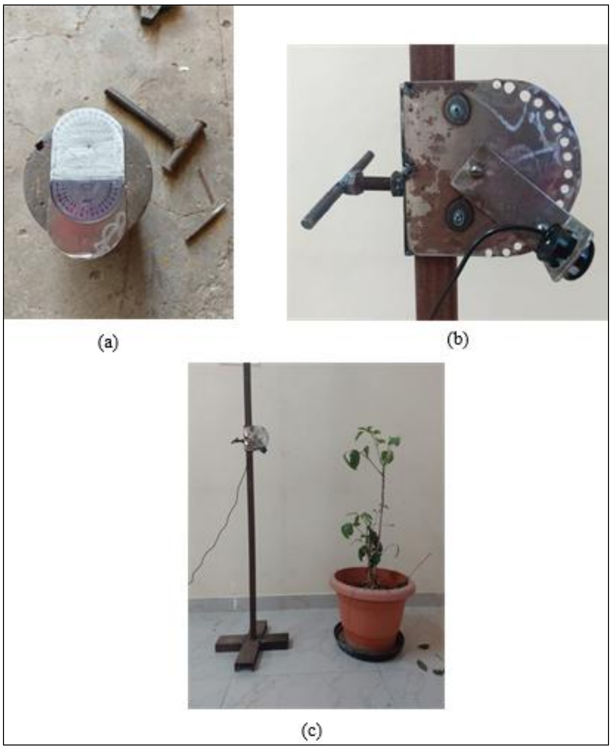

Fig 1: a) An iron sheet marked with angles and cut into semicircular shape b) Adjustable sensor holding section c) Developed sensor holding setup

2.3 Development of embedded programs for Ultrasonic, Infrared and Camera sensors

The integration of sensors in embedded systems enables intelligent decision-making and real-time interaction with the obstacles. This section focuses on the development of embedded programs for ultrasonic, infrared and camera sensor. Each of these sensors plays a crucial role in sensing distance, detecting obstacles or capturing visual information.

2.3.1 Ultrasonic sensor (JSN-SR04T)

A software program was developed to connect ultrasonic sensor to arduino board which was given in Appendix A1. This board was further connected to laptop to execute the code. The ultrasonic sensor detects distance and sends it to the arduino, which then transmits the data to the PC through a USB connection for monitoring or processing. Hardware connections of JSN-SR04T ultrasonic sensor to arduino board was shown in Fig.2. The specifications of JSN-SR04T ultrasonic sensor was mentioned in Appendix A2.

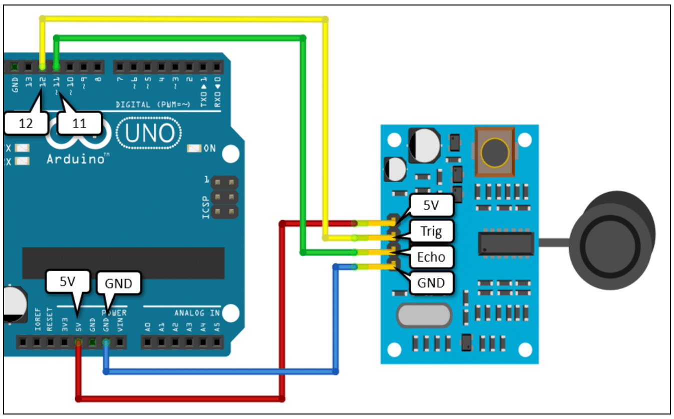

Fig 2: Hardware connections of JSN-SR04T ultrasonic sensor to Arduino board

2.3.2 Infrared sensor (E18-D80NK)
A program was developed to connect infrared sensor to Arduino board which was given in Appendix A3. The IR sensor detects nearby objects, the Arduino reads the detection signal, and the PC receives this information through USB for monitoring or processing. Hardware connections of E18-D80NK infrared sensor to Arduino board was shown in Fig.3. The specifications of E18-D80NK infrared sensor was mentioned in Appendix A4.

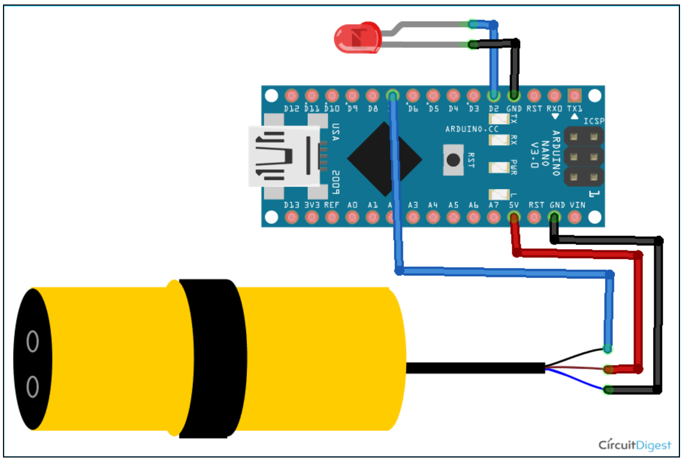

Fig 3: Hardware connections of E18-D80NK infrared sensor to Arduino board

2.3.3 Camera
The webcam was connected directly to the PC via a USB port, as the Arduino does not have the capability to process vedio data. The PC runs OpenCV software which was given in Appendix A5 to capture and process images or vedio from the webcam. The arduino board is connected to the PC via a USB cable, enabling both power supply and serial communication. The PC and arduino communicate through the serial port, allowing the PC to send commands to the Arduino based on the camera’s input. Connections of webcam to Arduino board were shown in Fig.4. The specification of camera was mentioned in Appendix A6.

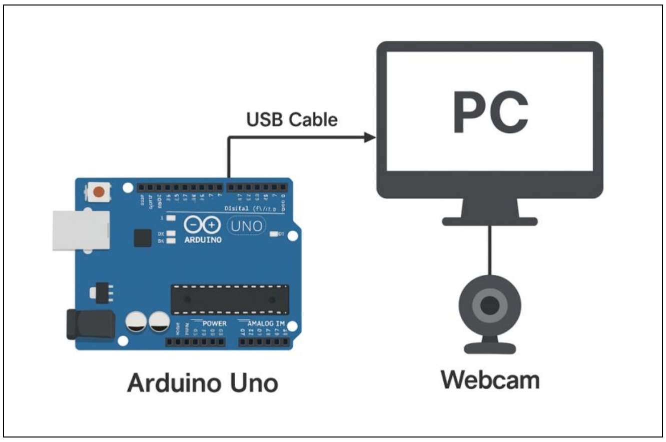

Fig 4: Connections of Webcam, Arduino and PC

2.3.4 Experimental procedure for testing of sensors
Based on the distribution of plant foliage, three categories of plants were selected for testing the compatibility of sensors and they were named as small, medium and large plant. The overall actual setup used for testing sensors was shown in Fig.5. Each sensor was tested by tightening the screw at particular angle by holding the sensor fixed. The procedure followed during the testing of sensor was as follows:

- Initially the sensor testing platform arrangements were done as shown in Fig.6 for taking sensor readings.
- On a firm platform, the three categories of plants were kept and interchanged while taking readings from the sensor.
- Next each sensor was fitted to the sensor holding section and it was connected to the Arduino board.
- This Arduino board was further connected to the PC to write and execute the code according to the selected sensor.
- The distance, height and angle between the sensor and the plants were varied according to the plan of experiment mentioned in Table 1 and simultaneously the data was recorded.

Fig 5: Overall developed setup for sensor evaluation

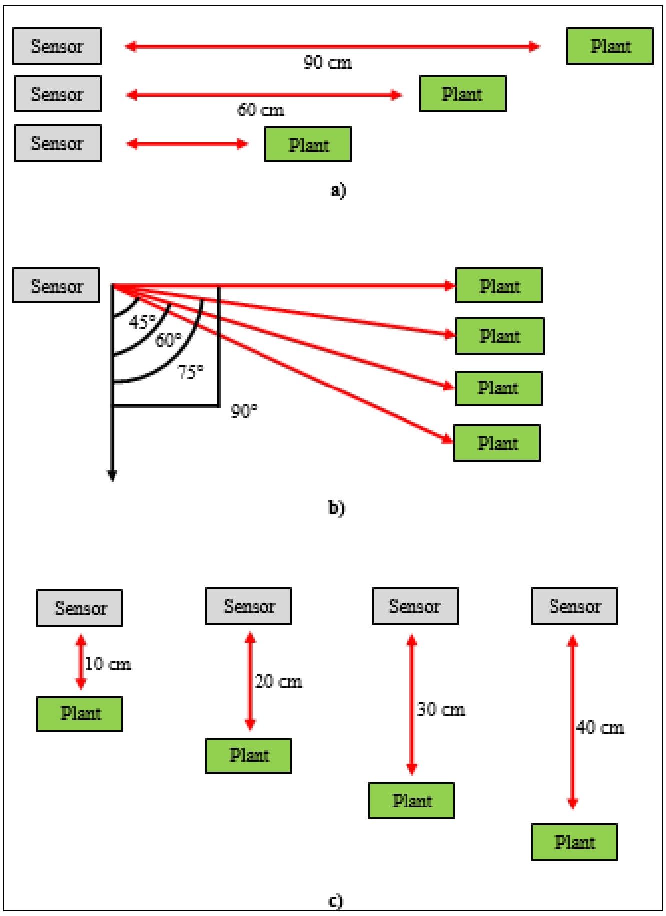

Fig 6: Typical diagram representing different a) distance, b) angle and c) height variations between sensor and the plant while testing.

3. Results and Discussion

The three sensors were evaluated rigorously for their ability to detect the presence of plant under varying distances (30, 60 and 90 cm), heights (10, 20, 30 and 40 cm) and angular positions (45°, 60°, 75° and 90°). The sensors were tested using plants with different foliage distributions and heights to assess it performance. For this purpose, three types of plants were choosen-classified as large, medium and small plant based on their distribution of foliage density and plant height. The sensor which excels with maximum number of detections was further selected for detection of crops and weeds in field conditions. This evaluation was carried out in the Dept. of Farm Machinery and Power Engineering, CAE, UAS, Raichur. The detection performance of each sensor was evaluated based on its ability to detect the plant according to the plan of experiment which was mentioned in the section 2 under different parameter settings. The outcome for each combination of distance, height and angular position was determined based on whether the sensor detected the plant or not, and is presented in terms of number of detections.

The detection response of three sensors measured at different distances (30, 60 and 90 cm), at different heights (10, 20, 30 and 40 cm) and at different angular position (45°, 60°, 75° and 90°) for large size plants were recorded and mentioned in Table 1. The total number of successful detections was 32 for the ultrasonic (US) sensor, 20 for the infrared (IR) sensor and 34 for the camera, indicating that the camera performed the best overall. The number of detections recorded by the ultrasonic (US) sensor was higher than that of the infrared (IR) sensor, primarily because the dense foliage of plants acted like a solid body, enabling ultrasonic waves to reflect effectively back to the receiver. In contrast, the IR sensor achieved less detection since plant surfaces do not provide strong or consistent IR reflections and its performance is further limited by sensitivity to ambient light and restricted detection range. The camera outperformed both sensors, with the highest number of detections, as it was not significantly affected by externally lighting conditions and consistently detected plants across nearly all combinations of distance, height and angular position. These results indicate that the camera was the most effective sensor for detecting large plant foliage. The corresponding heat maps, shown in Fig. 7, visually represent these detection patterns and corroborate the trends reported in Table 2.

Table 2: Detection response of different sensors at different distances, heights and angular positions while testing for large plant

Sl.no	Height (cm)	Angular position (°)											
		Distance from target 30 cm											
		US				IR				Camera			
		45°	60°	75°	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10	N	N	D	D	N	N	N	N	N	N	D	D
2)	20	D	D	D	D	N	D	D	D	N	D	D	D
3)	30	D	D	D	D	D	D	D	D	D	D	D	D
4)	40	D	D	D	D	D	D	D	N	D	D	D	D
Sl.no	Height (cm)	Angular position (°)											
		Distance from target 60 cm											
		US				IR				Camera			
		45°	60°	75°	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10	N	N	N	D	N	N	N	D	N	N	N	D
2)	20	N	N	D	D	N	N	D	D	N	N	D	D
3)	30	D	D	D	D	N	D	D	D	D	D	D	D
4)	40	D	D	D	D	D	D	D	D	D	D	D	D
Sl.no	Height (cm)	Angular position (°)											
		Distance from target 90 cm											
		US				IR				Camera			
		45°	60°	75°	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10	N	N	N	D	N	N	N	N	N	N	N	D
2)	20	N	N	D	D	N	N	N	N	N	N	D	D
3)	30	N	N	D	D	N	N	N	N	N	D	D	D
4)	40	N	N	D	D	N	N	N	N	N	D	D	D

Where, D: Detected, N: Not Detected US: Ultrasonic, IR: Infrared

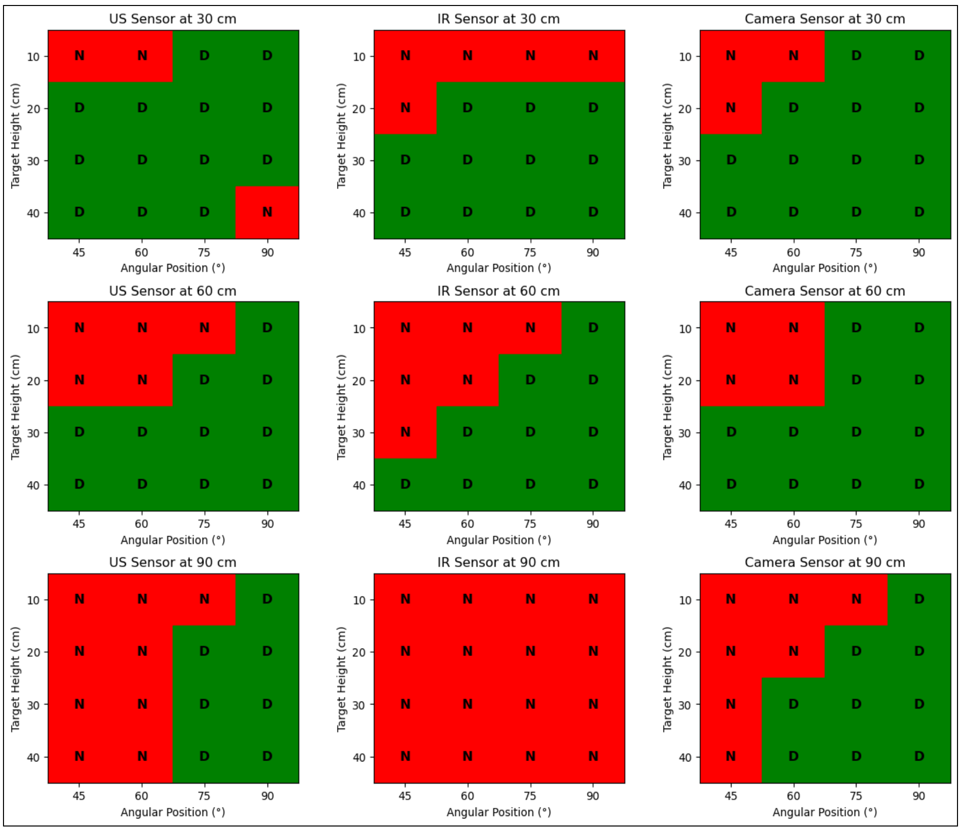

Fig 7: Heat maps of detection results of sensors across heights, angles and distances while testing for large plant

The detection responses of the three sensors for medium-sized plants, measured at different distances (30, 60 and 90 cm), heights (10, 20, 30 and 40 cm) and angles (45°, 60°, 75° and 90°) are presented in Table 3. The total number of successful detections was 21 for the ultrasonic (US) sensor, 15 for the infrared (IR) sensor and 24 for the camera, indicating that the camera performed best overall. Due to the insufficient plant foliage of medium size plant compared to large plant the number of detections were reduced by all the three sensors. Among these sensors, once again camera recorded the highest number of detections. This confirms that the camera was the most effective for detecting medium-sized plants. The corresponding heat maps of sensors across distances, heights and angular positions while testing for medium plant was shown in Fig. 8.

Table 3: Detection Response of different sensors at different distances, heights and angular positions while testing for medium plant

Sl.no	**Height (cm)**	**Angular position (°)**											
		Distance from target 30cm											
		US				**IR**				**Camera**			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	D	N	N	N	D	N	D	D	D
2)	20 cm	N	D	D	D	N	D	D	D	N	D	D	D
3)	30 cm	D	D	D	D	D	D	D	N	D	D	D	N
4)	40 cm	D	D	N	N	D	N	N	N	D	N	N	N
Sl.no	**Height (cm)**	**Angular position (°)**											
		Distance from target 60cm											
		US				**IR**				**Camera**			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	D	N	N	N	D	N	N	N	D
2)	20 cm	N	N	D	D	N	N	D	D	N	N	D	D
3)	30 cm	N	D	D	N	N	D	D	N	N	D	D	N
4)	40 cm	D	D	N	N	D	D	N	N	D	D	N	N
Sl.no	**Height (cm)**	**Angular position (°)**											
		Distance from target 90cm											
		US				**IR**				**Camera**			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	D	N	N	N	N	N	N	N	D
2)	20 cm	N	N	N	D	N	N	N	N	N	N	D	D
3)	30 cm	N	N	D	N	N	N	N	N	N	D	D	D
4)	40 cm	N	D	N	N	N	N	N	N	N	D	N	N

Where, D: Detected, N: Not Detected US: Ultrasonic, IR: Infrared

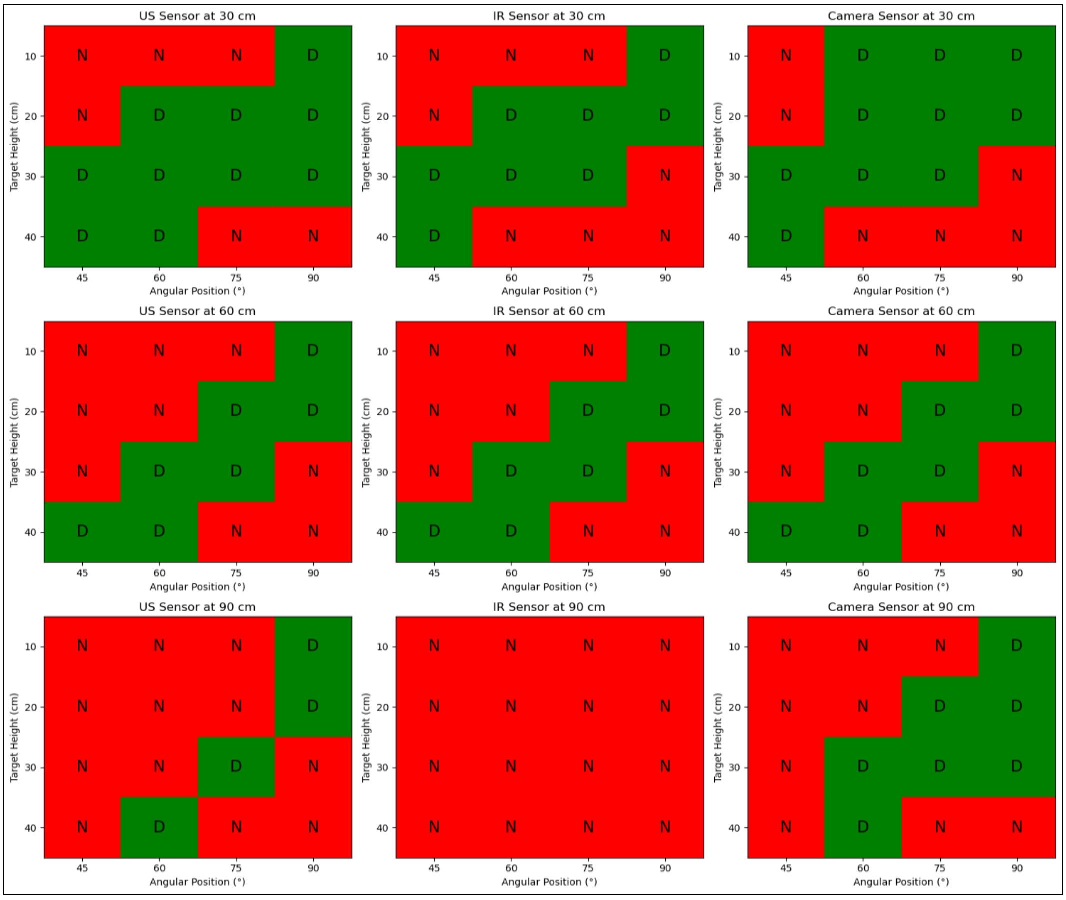

Fig 8: Heat maps of detection results of sensors across distances, heights and angular positions while testing for medium plant

The detection responses of the three sensors for small plant, measured at different distances (30, 60 and 90 cm), heights (10, 20, 30 and 40 cm) and angles (45°, 60°, 75° and 90°) are presented in Table 4. The total number of successful detections for each sensor for small plant was 15 for the ultrasonic (US) sensor, 12 for the infrared (IR) sensor and 26 for the camera, indicating that the camera performed the best overall. Due to the small size of plant, the detection performance of ultrasonic (US) sensor has decreased very much because the US sensor waves were unable to reflect back to the receiver because of less plant foliage instead they just passed through the plant and never reflected back to the transmitter. Infrared (IR) sensor also performed very poorly due to the fact that it was unable to detect because plant foliage is very thin which hinders the waves to reflect back to the receiver and moreover the plant foliage absorbed and scattered the infrared light. Compared to US and IR sensor, the number of detections made by camera was the highest. Thus camera proves to be the best for detection of small plant foliage. The corresponding heat map of detection performance of three sensor for small plant was shown in Fig. 9.

Table 4: Detection response of different sensors at different distances, heights and angular positions while testing for small plant

Sl.no	Height (cm)	Angular position (°)											
		Distance from target 30 cm											
		US				IR				Camera			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	D	N	N	D	D	N	D	D	D
2)	20 cm	N	N	D	D	N	D	D	D	D	D	D	D
3)	30 cm	N	D	D	D	D	N	N	N	D	D	D	N
4)	40 cm	D	N	N	N	N	N	N	N	D	N	N	N
Sl.no	**Height (cm)**	**Angular position (°)**											
		Distance from target 60 cm											
		US				**IR**				**Camera**			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	D	N	N	N	D	N	N	D	D
2)	20 cm	N	N	D	N	N	N	D	D	N	D	D	D
3)	30 cm	N	D	D	N	N	D	D	N	N	D	D	N
4)	40 cm	N	D	N	N	N	D	N	N	N	D	N	N
Sl.no	**Height (cm)**	**Angular position (°)**											
		Distance from target 90 cm											
		US				**IR**				**Camera**			
		45°	60°	75^0	90°	45°	60°	75^0	90°	45°	60°	75^0	90°
1)	10 cm	N	N	N	N	N	N	N	N	N	N	N	D
2)	20 cm	N	N	N	D	N	N	N	N	N	N	D	D
3)	30 cm	N	N	D	N	N	N	N	N	N	D	D	N
4)	40 cm	N	D	N	N	N	N	N	N	N	D	D	N

Where, D: Detected, N: Not Detected US: Ultrasonic, IR: Infred

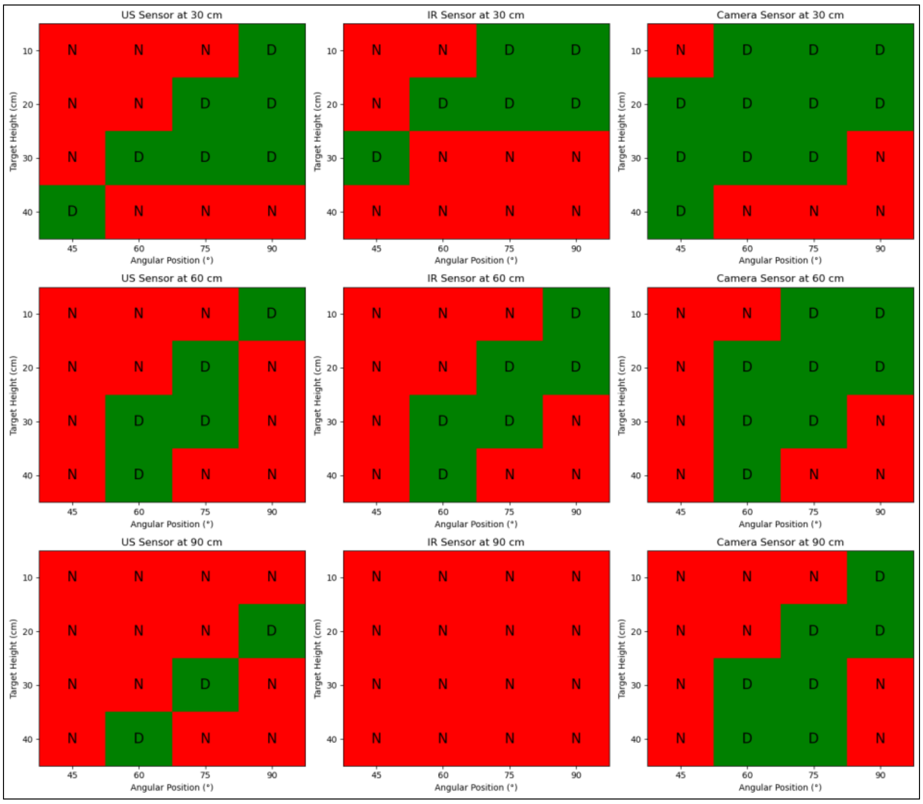

Fig 9: Heat maps of detection results of sensors across distances, heights and angular positions while testing for small plant

From the observed outcomes of the three sensors tested under different plant foliage conditions, the ultrasonic (US) sensor recorded 68 detections, the infrared (IR) sensor recorded 47 detections and the camera recorded 84 detections out of 144 possible combinations each. These results indicate that the camera achieved the highest number of detections across varying distances, plant heights and sensor angular positions. A generalized summary of the features of these sensors is presented in Table 5.

Table 5: Generalised summary of features of ultrasonic (US) sensor, infrared (IR) sensor and camera

Feature	US sensor	IR sensor	Camera
Object classification	None	Limited	High
Localization Precision	Low (distance only)	Low	High (bounding box)
Environmental robustness	Moderate (wind)	Low (sunlight)	Moderate (light)
Data richness	Very low	Low	Very high
AI/ML integration	Poor	Limited	Excellent

Appendix

A1: Program to connect JSN-SR04T ultrasonic sensor to arduino board

```
const int trigPin = 12;
const int echoPin = 11;

void setup() {
 Serial.begin(115200);
 pinMode(trigPin, OUTPUT);
 pinMode(echoPin, INPUT);
}

void loop() {
 digitalWrite(trigPin, LOW);
 delayMicroseconds(5);

 digitalWrite(trigPin, HIGH);
 delayMicroseconds(10);
 digitalWrite(trigPin, LOW);

 long duration = pulseIn(echoPin, HIGH);
 long distance = duration * 0.034 / 2;

 Serial.print("Distance:");
 Serial.println(distance);
 delay(100);
}
```

A2: Specifications of Ultrasonic Sensor (JSN-SR04T)

Particulars	specifications
Operating voltage	DC 5V
Quiescent current	5mA
Total current draw	30mA
Frequency	40khz
Range	25 cm to 450 cm
Beam angle	≤50 degrees
Response time	100 ms

A3: Program to connect HC-SR04 to arduino board

```
#define TRIG_PIN 12
#define ECHO_PIN 11
void setup() {
 Serial.begin(115200); // Start the serial communication
 pinMode(TRIG_PIN, OUTPUT);
 pinMode(ECHO_PIN, INPUT);
}
void loop() {
 long duration, distance;
 // Send a 10us pulse to trigger the sensor
 digitalWrite(TRIG_PIN, LOW);
 delayMicroseconds(2);
 digitalWrite(TRIG_PIN, HIGH);
 delayMicroseconds(10);
 digitalWrite(TRIG_PIN, LOW);
 // Read the echo pin
 duration = pulseIn(ECHO_PIN, HIGH);
 // Calculate the distance in cm
 distance = duration * 0.034 / 2;
 // Print the distance to the serial port
 Serial.println(distance);
 delay(100); // Wait a bit before the next reading
}
```

A4: Specifications of E18-D80NK infrared sensor

Features	Specifications
Input voltage	5V
Current consumption	25-100mA
Response time	2ms
Range	3-80 cm
Beam angle	30° to 35°

A5: Specifications of webcam

Features	Specifications
Frame rate	30 fps
Field of view	60 degrees
Compatibility	Mac
connectivity	USB
Brand	Logitech
Feature	HD resolution
Color	Grey
Model number	7B45035100400

A6: Program to connect webcam to laptop and Arduino

```
import cv2
import serial
import time

# Connect to Arduino (check your COM port or '/dev/ttyUSB0' for Linux)
arduino = serial.Serial('COM3', 9600)
time.sleep(2) # wait for Arduino to initialize

# Open webcam
cap = cv2.VideoCapture(0)

while True:
 ret, frame = cap.read()
 if ret:
cv2.imshow('Webcam', frame)
```

```
# Example: send a command to Arduino every frame
 arduino.write(b'L') # Send 'L' to Arduino (like 'LED ON' or 'Move left')

 if cv2.waitKey(1) & 0xFF == ord('q'):
 break

cap.release()
cv2.destroyAllWindows()
```

4. Conclusion

The comparative evaluation of ultrasonic, infrared and camera sensors under varying distances, heights and angular positions clearly established the camera sensor as the most effective technology for foliage detection in agricultural applications. While the ultrasonic sensor performed reasonably well for plants with dense foliage, its detection capability declined significantly for small plants due to poor wave reflection. The infrared sensor showed the lowest detection performance, primarily because of its sensitivity to ambient light and limited reflective response from plant surfaces. In contrast, the camera sensor consistently achieved the highest number of detections for large, medium and small plants, owing to its superior object recognition capability, precise localization and compatibility with advanced image-processing techniques. Based on the overall detection performance and functional advantages, the camera sensor was identified as the most suitable sensing system for integration into an intra-row weeding mechanism aimed at accurate crop–weed discrimination under field conditions.

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