

DESIGN AND EXPERIMENT OF POTATO SEEDLING FILM-BREAKING DEVICE BASED ON MACHINE VISION

基于机器视觉的马铃薯幼苗破膜装置设计与试验

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DOI: <https://doi.org/10.35633/inmateh-71-11>

Keywords: potato, film-breaking, machine vision, improved YOLOv5s, motion control

ABSTRACT

An automatic potato seedling film-breaking device based on machine vision was designed to reduce the labor intensity of potato film-breaking. The device mainly consisted of a motion mechanism, a seedling recognition mechanism, a film-breaking mechanism, etc. Based on single-ridge and single-row potato planting agronomy, the whole structure and key component dimensions of the film-breaking device were determined, the YOLOv5s model was improved to build a potato seedling recognition system, and the film-breaking mechanism based on the parallel CoreXY structure was designed. Potato seedlings at the emerging stage were used as research objects for field film-breaking tests. The results showed that the recognition rate of potato seedlings was 89.7%, the qualified rate of film-breaking was 83.5%, and the damage rate was 2.3%. This paper could provide technical support for the development of intelligent film-breaking equipment for potato seedlings.

摘要

为减轻马铃薯人工破膜劳动强度, 设计了一种基于机器视觉的马铃薯幼苗自动破膜装置。该装置主要由运动机构、幼苗识别机构、破膜机构等组成。基于单垄单行马铃薯种植农艺, 确定破膜装置的整体结构和关键部件尺寸, 改进 YOLOv5s 模型搭建马铃薯幼苗识别系统, 设计基于并联 CoreXY 结构的破膜机构。以出苗期马铃薯幼苗为研究对象进行田间破膜试验, 结果表明: 马铃薯幼苗识别率为 89.7%, 破膜合格率为 83.5%, 幼苗损伤率为 2.3%。本文可为马铃薯幼苗智能化破膜装备研制提供技术支持。

INTRODUCTION

Potato is a food crop with high nutritional value and good production efficiency. At present, China's potato planting area and output are ranked first in the world (Xu et al., 2021; Li et al., 2019). Plastic film mulching cultivation is a widely used technology in the potato planting industry. It has the functions of increasing temperature, water retention, fertilizer retention, and inhibiting the growth of weeds, which can effectively improve the yield and quality of potatoes. However, if the mulching time is too long, the potato seedlings are easy to be burned or grow in a bent state under the film, which will affect the normal growth of potatoes in the later period. Seedling film-breaking is an important link in the normal growth and yield increase of potatoes. At present, artificial film-breaking is mainly used in production. Artificial film-breaking is to use fingers or iron hooks to dig or cut through the plastic film so that potato seedlings are exposed, but this operation process requires manual squatting or bending to operate, and the labor intensity is very high. Therefore, the realization of mechanized film-breaking of potato seedlings is of great significance to the sustainable and healthy development of the potato industry.

Owing to differences in geographical environment and planting patterns, there was almost no research on potato seedling film-breaking machines abroad (Escuredo et al., 2019; Rahaman et al., 2019). In order to meet market demand, China had actively promoted facilities for potato planting in recent years. This planting mode mostly adopted single-ridge and single-row potato planting agronomy, with a ridge distance of about 650 mm, and the furrow width was about 150 mm. It could not only improve potato yield and quality but is also conducive to resource protection.

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However, due to the lack of corresponding machinery for potato seedling film-breaking, it was necessary to manually break the film, which greatly increased labor intensity. Therefore, with the aim of improving work efficiency and reducing labor costs, many scholars had conducted research on potato seedling film-breaking, which mainly includes: Zhang proposed a potato seedling cultivation technology of natural rupture of the covering soil on high ridge film, referring to the soil pressing soil covering technology, through the cultivation of soil on the ridge surface, and covering the soil layer on the mulch to form a high ridge, so as to achieve natural emergence and irrigation and water prevention. Although this method could produce seedlings naturally, the covering soil on the film affected the light transmittance and thermal insulation of the film (Zhang *et al.*, 2019). Hou proposed a potato seeding machine with manual punching on the film, which used manual mode to break the film (Hou *et al.*, 2021). Li invented a film-breaking seedling machine applied to potato black film, which used an infrared spectrum to identify potato seedlings covered with black film, performed film-breaking operations, and was equipped with a waste film recycling device. This machine is currently in the research and development stage, and the actual operation effect has not been verified (Li *et al.*, 2021).

The research on film-breaking of other crops includes: *Mustaqimah* designed a plastic mulch punching machine for punching and recycling plastic mulch during pepper planting (Mustaqimah *et al.*, 2022). Tadeo designed a nylon rope film-breaking mechanism for paddy field operations (Tadeo *et al.*, 2000). Wang used wet felt film-breaking to break the film of garlic buds. Compared with artificial film-breaking, the film-breaking efficiency was improved, but it would cause a higher damage rate to garlic buds (Wang *et al.*, 2019). Chen proposed a cultivation technique for the natural emergence of yam without breaking film (Chen *et al.*, 2018). Liu designed a small electric film-breaking soil covering machine for flue-cured tobacco under film planting technology, which used 3D laser scanning to locate the position of the tobacco seedlings, and then broke the film, but it was only a theoretical study and lacked the test of the whole machine (Liu *et al.*, 2019). Cheng designed a garlic seedling film-breaking machine based on the Delta robotic arm, which used the YOLOv5 network to recognize the unbroken garlic seedlings, and then used the Delta robotic arm to break the film of the garlic seedlings (Cheng, 2019).

In recent years, technologies such as machine vision and deep learning have developed rapidly and have been widely used in the field of agriculture. These research results provide methods and ideas for solving the problems raised in this paper (Fu *et al.*, 2020; Han *et al.*, 2023; Li *et al.*, 2020; Yang *et al.*, 2022; Zong *et al.*, 2021). Aiming at the labor-intensive problem of artificial film-breaking, this paper designs an automatic film-breaking device for potato seedlings based on machine vision to realize the recognition and positioning of potato seedlings and the motion control of the film-breaking mechanism.

MATERIALS AND METHODS

GENERAL DESIGN

Whole structure

The structure of the potato seedling automatic film-breaking device was shown in Fig. 1, which was mainly composed of a frame, a motion mechanism, a seedling recognition mechanism, and a film-breaking mechanism. The frame was composed of aluminum profiles, fixing parts, etc. The seedling recognition mechanism was composed of a computer and an industrial camera, which was installed in the middle of the frame.

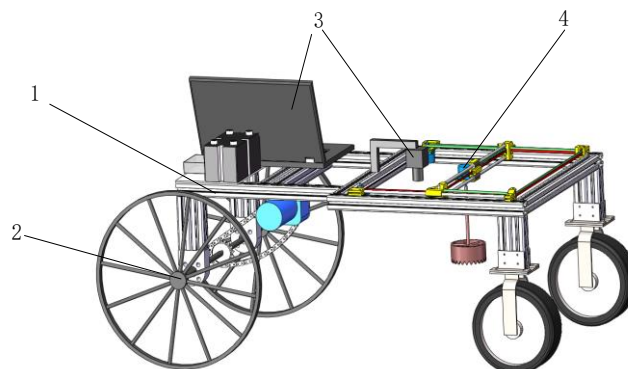


Fig. 1 -Schematic diagram of the whole structure

1-Frame; 2-Motion mechanism; 3-Seedling recognition mechanism; 4-Film-breaking mechanism

Working principle

The film-breaking mechanism was installed at the rear of the frame, the DC geared motor was powered by the battery, and the whole machine was driven forward through the transmission shaft, chain sprocket, and other components. The height of the whole machine was adjusted according to the potato seedling ridge height before work to ensure that the distance between the seedlings and the film-breaking mechanism was within the working range of the film-breaking device. The working process of the film-breaking device was divided into three stages: image acquisition, recognition and positioning, and mobile film-breaking. The industrial camera in the seedling recognition mechanism completed the collection of potato seedling images during the forward process; the potato seedling recognition and control system in the upper computer identified and located the potato seedlings in the image. After receiving the positioning information, lower single chip microcontroller controlled the film-breaking mechanism to move the film-breaking knife quickly to the position directly above the potato seedlings. Then it moved downward to pierce the film to complete the film-breaking work.

DESIGN OF KEY COMPONENTS

Design of film-breaking mechanism

The film-breaking mechanism was mainly composed of stepping motors, timing belts, timing pulleys, optical axes, linear bearings, 3D printing fixed parts, a film-breaking knife, etc. The structure was shown in Fig 2. M1 and M2 motors were X and Y axis drive motors respectively, and 2-phase 4-wire 42 stepping motors were selected, and the model was 17HD4800-22B. The Z-axis motor was a fixed screw motor with a stroke of 63.5 mm. Because the stepping motor started too fast, it would stall or lose steps, and if it stopped too fast, it would overstep. Therefore, the trapezoidal model algorithm was used in this paper to control the stepping motor's acceleration and deceleration. The schematic diagram of the algorithm model was shown in Fig. 3. The trapezoidal acceleration and deceleration were divided into three stages: the acceleration stage OA, the constant speed stage AB and the deceleration stage BC. In the acceleration phase, started with a frequency lower than that of the stepping motor, and increased the speed to the target value with constant acceleration; in the constant speed phase, moved at a constant speed at the maximum speed; in the deceleration phase, decelerated to 0 with a constant deceleration.

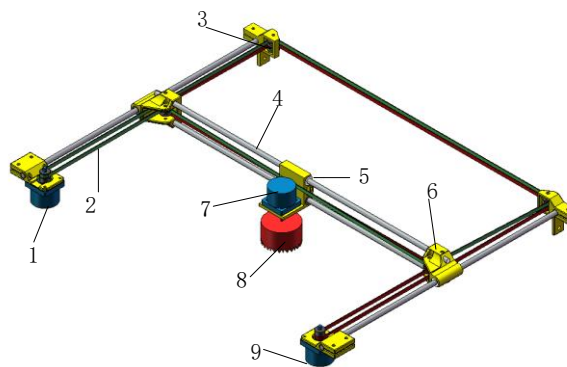


Fig. 2 - Schematic diagram of the film-breaking mechanism

1-M1 stepping motor; 2-Timing belt; 3-Timing pulley; 4-Optical axis; 5-Linear bearing; 6-3D printing fixed part; 7-Z-axis stepping motor 8-Film-breaking knife; 9-M2 stepping motor

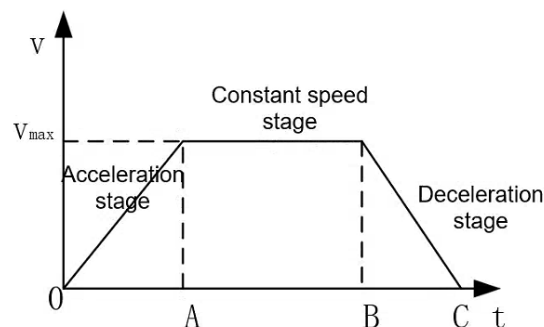


Fig. 3 - Schematic diagram of stepping motor trapezoidal algorithm

The film-breaking mechanism adopted a parallel CoreXY structure, its schematic diagram was shown in Fig. 4, and its kinematic relationship was:

$$\Delta X = \frac{1}{2}(\Delta A + \Delta B) \quad \Delta Y = \frac{1}{2}(\Delta A - \Delta B) \quad (1)$$

where:

$\Delta A, \Delta B$ is the linear displacement of the stepping motors M1 and M2, clockwise is negative and counterclockwise is positive; $\Delta X, \Delta Y$ is the displacement of the film-breaking mechanism along the positive direction of the X-axis and Y-axis respectively.

Since the emerging diameter of potato seedlings was about 30-50 mm, in order not to cause damage to potato seedlings, the diameter of the film-breaking knife was designed to be 60 mm, and its end structure was serrated. The distance between the potato planting ridge was 650 mm, and the maximum stroke of the designed film-breaking mechanism was $650 \times 600 \times 63.5$ mm, which could cover the potato planting ridge surface and realize the film-breaking operation in all aspects.

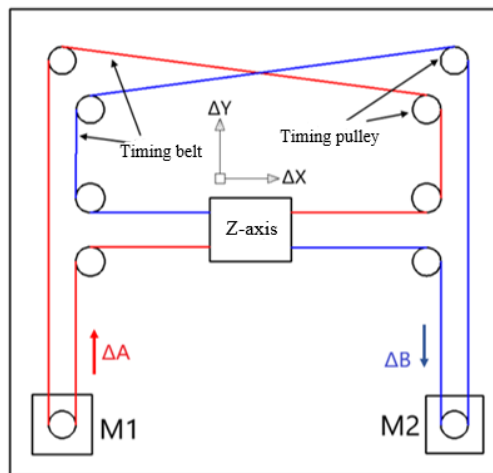


Fig. 4 - Schematic diagram of CoreXY structure

Design of motion Mechanism

The motion mechanism was mainly composed of batteries, DC geared motors, relays, governors, proximity switches, driving wheels, driven wheels, etc., as shown in Fig. 5. The model of the DC geared motor was XD6D300-24GU21S, the reduction ratio was 1:1.75, and the maximum load was 5.2 N.m; the battery specification was 12V20AH, and the DC geared motor was powered by connecting two batteries in series. When working, the DC geared motor drove the driving wheel to rotate through the gear and chain, and the motor speed was adjusted through the governor to control the forward speed of the motion mechanism.

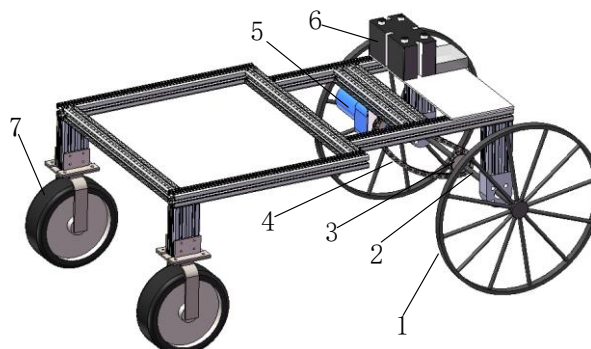


Fig. 5 - Motion mechanism

1-Driving wheel; 2-Driving shaft; 3-Gear; 4-Chain; 5-DC geared motor; 6-Battery; 7-Driven wheel

Design of other components

HF868_2.8-12 industrial camera was used for image acquisition of potato seedlings. The highest image resolution was 1920 pixels \times 1080 pixels, and the maximum frame rate was 30fps. It was connected to the computer through the USB Type-c interface.

The upper computer used a computer to recognize and position seedlings; the lower computer used Arduino UNO single chip microcomputer and Arduino CNC expansion board to receive signals from the upper computer. The external circuit was powered by 12V DC, and UART was used for communication between the upper and lower bits. The development board was connected to the USB port of the upper computer to transmit signals through the USB interface. At the same time, the parallel data was converted into serial data for transmission. The baud rate was set to 115200b/ s.

POTATO SEEDLING RECOGNITION AND COORDINATE TRANSFORMATION

Potato seedling recognition

Improved YOLOv5s seedling recognition model

Among the existing target recognition algorithms, YOLOv5 has the advantages of fast recognition speed and high accuracy, and has a wide range of applications (Huang et al., 2022; Sami et al. 2023). Therefore, this paper improved the potato seedling recognition algorithm based on the original model of YOLOv5s, mainly through the fusion of Coordinate Attention Mechanism, replaced the Coupled Head with a Decoupled Head and replaced the loss function with Focal-EIOU Loss to strengthen the learning ability of the network model for seedlings and reduce false detection and missed detection (Liu et al., 2020; Xiu et al. 2022). Specifically, improvements were made in the following three aspects:

1) Coordinate Attention Mechanism

To obtain the key feature information of potato seedlings from complex features, and considering that water vapor and weeds under the film would interfere with seedling recognition, this paper introduced a Coordinate Attention Mechanism to strengthen the target information of potato seedlings and suppress redundant features. Compared with the traditional channel attention, the CA attention mechanism integrated the location information into the attention, used the acquired location information to locate the target location faster, and improved the algorithm's performance without consuming additional computing resources.

The CA attention mechanism divided two channels of attention into two parallel one-dimensional features, which were aggregated along the two spatial directions respectively. Its module structure was shown in Fig. 6.

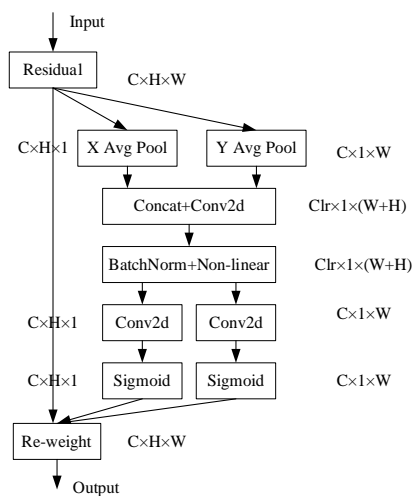


Fig. 6 - CA attention mechanism structure

2) Decoupled Head

To solve the conflict between the seedling recognition and classification problem and the regression task, accelerate the convergence speed of the model, and improve the overall performance, this paper introduced the Decoupled Head to replace the Coupled Head in YOLOv5s. Considering that the classification problem of the target recognition algorithm and the regression task were mutually exclusive, the focus of classification and regression were different. Classification paid more attention to the texture content of the target, and regression paid more attention to the edge information of the target. The Coupled Head combined the classification problem and the regression task for calculation, and the classification and regression branches shared parameters, which could not balance positioning and recognition, causing the problem of slow convergence in the training process. The Decoupled Head was introduced to separate the classification problem and the regression task as two branches, so that the focus of the two tasks was clearer and the convergence speed was accelerated. Its structure was shown in Fig.7.

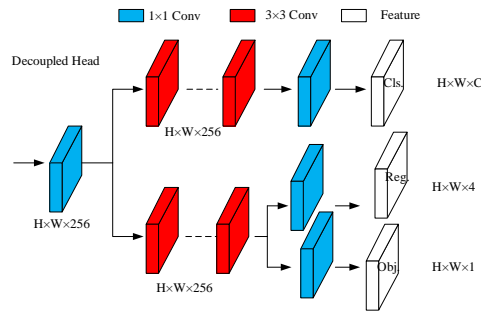


Fig. 7- Decoupled Head structure diagram

3) Focal-EIOU loss function

Aiming at the CIoU Loss function in YOLOv5 could not deal with the optimization similarity problem of the model well, this paper proposed to improve the penalty item based on CIoU, and disassembled the influence factor of aspect ratio based on CIoU's penalty item to calculate the length and width of the anchor box respectively, and then became EIOU Loss, the calculation formula was shown in formula (2).

$$Loss_E = 1 - IOU + \frac{\rho^2(b, b^{gt})}{c^2} + \frac{\rho^2(w, w^{gt})}{c_w^2} + \frac{\rho^2(h, h^{gt})}{c_h^2} \tag{2}$$

where: IOU represents the intersection ratio between the predicted box and the real box, b, b^{gt} respectively represents the center point of the predicted box and the real box; ρ represents the calculation of the Euclidean distance between the two center points; c represents the diagonal distance of the minimum closure area that can contain both the predicted box and the real box ; w, w^{gt} represents the width of the predicted box and the real box, respectively; c_w is the width of the minimum bounding box covering the predicted box and the ground truth box; h, h^{gt} representing the width of the predicted box and the real box, respectively; c_h is the height of the minimum bounding box covering the predicted box and the ground truth box. Combining Focal Loss based on f EIOU to synthesize a new type of Focal-EIOU Loss, the calculation formula is:

$$Loss_F = IUO^\gamma Loss_E \tag{3}$$

Where: γ is a parameter to control the degree of outlier suppression. According to the above formula, the higher the IOU, the greater the loss, which was equivalent to the weighting effect, and the better the regression target, the greater the loss, which helped to improve the regression accuracy and strengthen the sensitivity of the network to information such as the direction and position of potato seedlings.

The improved overall network architecture was shown in Fig. 8.

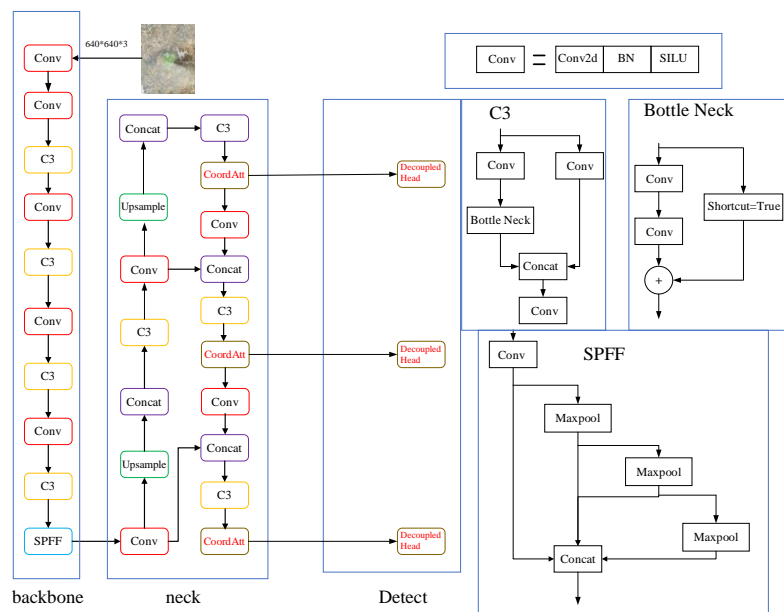


Fig. 8 - Improved YOLOv5s framework diagram

Potato seedling recognition test

(1) Dataset making

The collection location of potato seedlings was Qixiang Potato Planting Cooperative in Tengzhou City, Shandong Province. The collection time of the dataset was set into three stages, namely 6:30-7:30, 12:00-1:00, 4:00-5:00. The collected dataset had 800 potato images in total after manually eliminating redundant and poor pixel quality images. To avoid too few samples in the dataset from affecting its model training effect and generalization performance, this paper used mirroring, rotation, brightness adjustment, and adding noise to enhance data. After expansion and processing, the dataset had a total of 2,400 images. Some sample images as shown in Fig. 9. The images of potato seedlings were labeled using Labellmg software. The labeled dataset was divided into a training set (2160 images) and a verification set (240 images) at a ratio of 9:1.

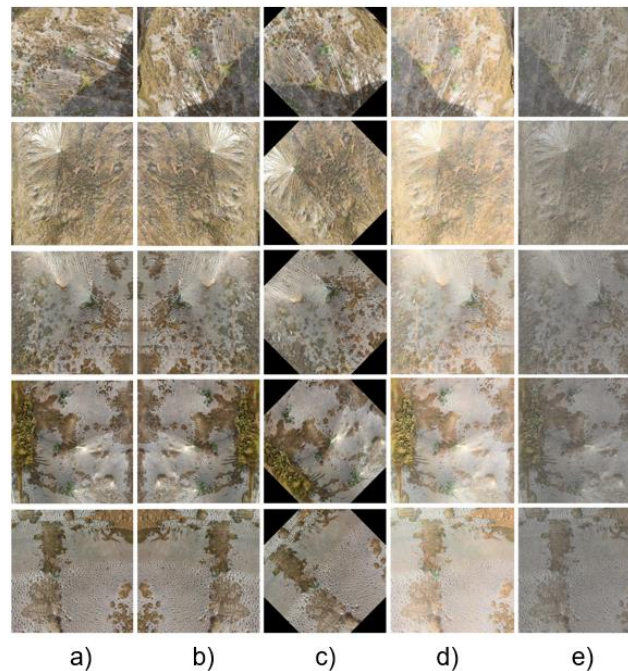


Fig. 9 -Some seedling image enhancement samples

a) Original image; b) Mirror; c) Rotation; d) Brightness adjustment; e) Add noise

(2) Test environment and evaluation indicators

The model training process was carried out under the Win11 operating system, the computer processor was 2nd Gen Intel(R) Core(TM) i7-12700K 3.60 GHz, the graphics card model was Nvidia GeForce RTX 3080Ti, the deep learning framework was Pytorch, and CUDA11.6 was installed in parallel Computing framework and acceleration library of CUDNN8.0.5, using Python3.9.13 programming language. To evaluate the recognition performance of the model for potato seedlings, recognition accuracy (P, Precision), recall rate (R, Recall), mean average precision (mean Average Precision, mAP) were used as evaluation indexes (Kim *et al.*, 2022).

(3) Test results and analysis

To test the recognition effect of the model, the verification sets were recognized by YOLOv5s and the improved YOLOv5s algorithm respectively. The results showed that the P, R and mAP of the improved YOLOv5s model were 93.2%, 92.7%, and 95.5%, which were 3.5 percentage points higher than the original model mAP, while P and R were increased by 1.5 and 1.7 percentage points, respectively. The above results showed that the improved model introduces the CA coordinate attention mechanism, which could strengthen the model's attention to potato seedlings and effectively avoid the influence of redundant features such as water vapor and weeds under the film; the improved model Coupled Head was replaced by a Decoupled head, which could solve the conflict between the seedling recognition classification problem and the regression task, and speed up the convergence speed of the model; the improved model loss function was changed to the Focal-EIOU Loss function, which could optimize the sample imbalance problem in the bounding box regression task and strengthen the sensitivity of the network to information such as direction and position.

Partial results of potato seedlings were shown in Fig. 10. From top to bottom, the recognition effect was compared under strong exposure, water vapor occlusion and weed interference respectively. For the seedling

recognition in the three special environments, the YOLOv5s model had missed or false detections, but the recognition effect of the improved YOLOv5s model had been significantly improved.

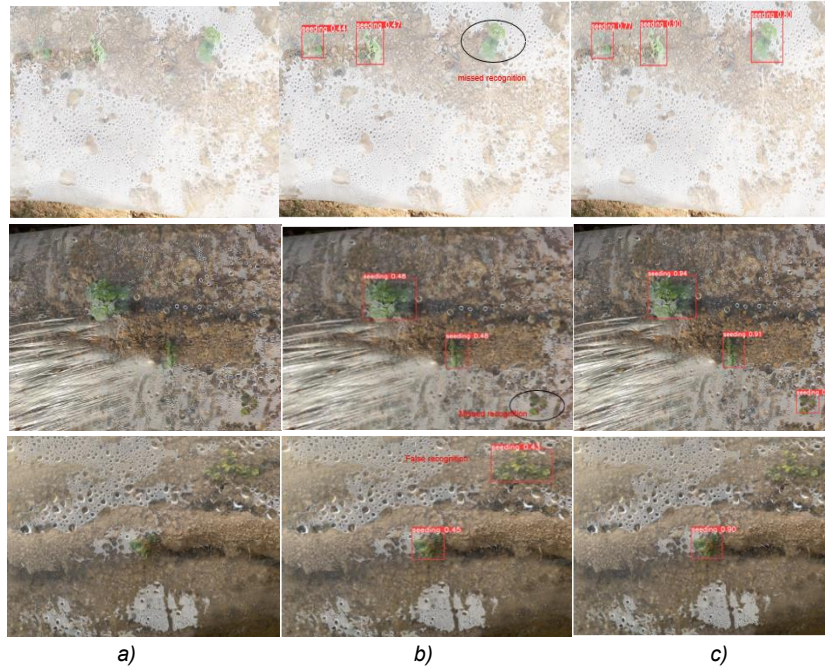


Fig. 10 - Comparison of recognition results
a) Original image; b) YOLOv5s; c) Improved YOLOv5s

Potato seedling coordinate transformation

The seedling coordinates of potato seedlings were given under camera coordinates, which needed to be converted to the film-breaking mechanism coordinate system. The height of the potato planting ridge was relatively fixed, and the potato seedlings could be regarded as being in the two-dimensional plane of the ridge surface. Therefore, the transformation between the pixel coordinates of the potato seedlings in the camera coordinate system and the coordinate system of the film-breaking mechanism could be expressed by affine transformation. That is, the conversion from the camera coordinate system to the film-breaking mechanism coordinate system could be regarded as the translation of the film-breaking mechanism coordinate system by x_0 units along the X direction, the translation of y_0 units along the Y direction, and the transformation of the rotation angle around the Z axis to the camera coordinate system, which the conversion matrix could express:

$$H = \begin{bmatrix} 1 & 0 & x_0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & y_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & x_0 \\ \sin \theta & \cos \theta & y_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where:

H is the transformation matrix. The coordinates of the point $p(u, v)$ in the plane of the camera coordinate system in the coordinate system of the film-breaking mechanism could be expressed as:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & x_0 \\ \sin \theta & \cos \theta & y_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \cdot \alpha_x \\ v \cdot \alpha_y \\ 1 \end{bmatrix} \quad (5)$$

where: (x, y) is the point in the coordinate system of the film-breaking mechanism; α_x, α_y is the scale factor of the camera coordinate system. According to formula (6), the affine transformation equation could be obtained as:

$$\begin{cases} x = a_2 \cdot u + b_1 \cdot v + x_0 \\ y = a_1 \cdot u + b_2 \cdot v + y_0 \end{cases} \quad (6)$$

Where:

$a_1 = \alpha_x \cdot \sin \theta$, $a_2 = \alpha_x \cdot \cos \theta$, $b_1 = \alpha_y \cdot \sin \theta$, $b_2 = \alpha_y \cdot \cos \theta$. In this paper, the nine-point calibration method was used to solve the parameters of the affine transformation equation (Zhang et al., 2021), and the

transformation matrix H could be obtained, In the actual film-breaking process, the potato seedling coordinates in the film-breaking mechanism coordinate system could be obtained in the camera coordinate system through the transformation matrix H , as shown in Fig.11. Fig.11(a) was the result of potato seedling recognition, and Fig.11(b) was the result of coordinate transformation.



Fig.11 - Potato seedling recognition results and coordinate transformation

a) Potato seedling recognition results

b) Coordinate transformation results

RESULTS

FIELD TESTS

Test conditions and methods

To verify the operating performance of the film-breaking device, a field test was conducted at the potato planting base of Shandong Agricultural University in March 2023. The potato planting mode was single-ridge and single-row, the ridge distance was 650 mm, the ridge height was 250 mm, the ridge top width was 300 mm, the ridge bottom width was 500 mm, and the film thickness was 0.008 mm. Before the start of the test, the vertical distance between the seedling recognition camera and the plastic film was adjusted to 250 mm to ensure that the recognition range covered the entire ridge top. The initial height of the film-breaking knife from the ridge surface was 30 mm, and the forward speed of the motion mechanism was set to 0.2 m/s. Three ridges were randomly selected, and 200 potato seedlings were selected from each ridge for film-breaking test. The test process was shown in Fig.12.



Fig.12 - Field test and film-breaking results

In the experiment, the seedling recognition rate, film-breaking qualified rate, and seedling damage rate were selected as evaluation indicators, and the calculation formula was as follows

$$Q = \frac{q}{M} \times 100\% \quad (7)$$

$$I = \frac{F}{M} \times 100\% \quad (8)$$

$$K = \frac{N}{M} \times 100\% \quad (9)$$

where: Q is the seedling recognition rate q is the number of potato seedlings correctly recognized; I is the qualified rate of film-breaking; F is the number of completed film-breaking; K is the damage rate of seedlings, N is the number of potato seedlings damaged by film-breaking knife, M is the total number of potato seedlings.

Test results

The results of film-breaking of potato seedlings were shown in Table 1. It could be seen that the recognition rate of potato seedlings was 89.7%, the qualified rate of film-breaking was 83.5%, and the seedling damage rate was 2.3%. The results showed that the film-breaking device designed in this paper could complete the film-breaking work of potato seedlings well.

Table 1

Test results						
Line number	Number of potato seedlings	The number of potato seedlings correctly recognized	The number of completed film-breaking	The seedling recognition rate /%	Film-breaking qualified rate /%	Seedling damage rate /%
1	200	183	170	91.5	85.0	2.5
2	200	176	165	88.0	82.5	2.5
3	200	179	166	89.5	83.0	2.0

CONCLUSIONS

An automatic film-breaking device for potato seedlings based on machine vision was designed. Based on the single-ridge and single-row potato planting agronomy, the film-breaking device's whole structure and key component sizes were determined. The potato seedling recognition system was built using the improved YOLOv5s model, and the film-breaking mechanism based on the parallel CoreXY structure was designed.

The field film-breaking tests were carried out on potato seedlings at the emerging stage. The results showed that the recognition rate of potato seedlings was 89.7%, the qualified rate of film-breaking was 83.5%, and the seedling damage rate was 2.3%. The film-breaking device designed in this paper could complete the film-breaking work of potato seedlings well. It can provide technical support for the development of intelligent film-breaking equipment for potato seedlings in the next step.

ACKNOWLEDGEMENT

This work was supported by Shandong Province Potato Industry Technology System Agricultural Machinery Post Expert Project (SDAIT-16-10) and Shandong Province Key R&D Plan (Major Scientific and Technological Innovation Project) Project (No. 2022CXGC020703).

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