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Technological Development of Automated Harvesting for Cultivated Button Mushroom Using Image Processing

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Abstract

The amount of mushrooms cultivated around the world is constantly increasing, and the most commonly consumed species in Europe is the white button mushroom (Agaricus bisporus). Mushroom producers are facing a permanent challenge to provide the labour for harvesting, with increasing wage demands. Due to high market quality requirements, early automatized technologies are currently not able to replace manual picking. Our research therefore aims at facilitating the automated picking of button mushrooms and improving the technology via image processing. We aim to develop a method that can select the right size of mushrooms from field images and produce their picking position. We used Python programming language, along with the OpenCV and NumPy libraries, to implement image processing on real scenario images. The development considered factors such as fused- or overlapping mushroom heads, emergence of mushrooms from under caps, fallen or laterally visible stumps, cover soil contamination, and white mycelia which make detection significantly more difficult. We managed a solution for handling fruiting bodies that extend beyond the edge of the image due to the small field of view. The results indicated that the quality of photographs is crucial for the program's performance, as improper lighting, the presence of shadows. The efficiency of the algorithm was significantly affected by the 82% accuracy of the OpenCV Watershed segmentation algorithm, which in some cases could not separate objects. The program processed the images at an average speed of 0.78 seconds and produced the coordinates with a 92% success rate.

Keywords

mushroom picking, automation, image processing, opencv, button mushroom

1 Introduction

The amount of mushrooms cultivated annually in the world is increasing year by year [1], with the majority of cultivated mushrooms being only a few species of the genera Pleurotus, Lentinula, Agaricus. Among the latter genus, one of the most commonly consumed edible mushrooms is the Agaricus bisporus, alias white button mushroom [2]. World-wide per capital consumption is continuously increasing [3], which trend may become even more significant in the future, as mushroom cultivation is not affected by weather conditions, providing a reliable food source. One of the most significant variable costs of intensive mushroom cultivation technologies is picking, which is a particularly large part of the costs for fresh mushrooms market [4, 5]. Mushroom producers are constantly facing challenges in recruiting and retaining labour for picking, with estimated fluctuation rates up to e.g. 50% in Canada [6]. Due to low salaries and monotonous working conditions, the challenging work is often performed by migrant labourers [7]. Due to the exposure to pickers and increasing wage demands, growers worldwide have been attempting for decades to mechanize production and to switch to automated picking, to reduce their costs and labour exposure. Currently, there is no reliable, fully automated mushroom picking solution on the fresh market that can fully replace manual picking. Therefore, our research is focused on the technological development of automated picking of fresh market button mushrooms.

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The first and one of the most important step in automated mushroom picking is the detection of the mushrooms to be picked by an electronic device and the determination of the position of the picking head. Our aim is to develop a method to detect mushroom fruiting bodies in images of the cultivatation surface, estimate their size, select the appropriate mushrooms and define their picking position. Furthermore, the program displays the result of image processing, labelling the mushrooms suitable for picking and the positions of their picking heads. Limited studies have focused on the detection of Agaricus bisporus in professional fields using cost-effective and competent tools. The aim of the research was to create an easily accessible, cost-effective solution, because automatic machinery in mushroom cultivation is hampered by the extremely high cost of the technology and equipment [8].

2 Literary research

2.1 Available harvesting methods

The shelf system technology for cultivating white button mushrooms has undergone significant advancements in recent years [9]. Professional control systems regulate the production processes [9] and the environmental parameters in modern mushroom farms [10]. The compost is conditioned and handled using highly mechanized methods [11], ensuring consistently high-quality mushroom production [12]. Due to high market quality requirements, there is still a lack of technology to replace manual picking. For this reason, the picking is still performed by human labour, which contributes to a significant part of the cost, up to one third. The most widespread picking method is single handed picking, which provides exceptional quality and in some extreme cases can reach 45–50 kg/person/hour [13]. However, this picking efficiency is rarely achieved on most mushroom farms due to factors such as the size of harvested mushrooms, logistic capabilities, and the efficiency of work organization. To improve picking conditions, complex tiltable and movable shelving systems have been introduced, but these are expensive and lower productivity can be achieved due to their large space requirements [14].

Cutting blade machines can efficiently harvest mushrooms at a speed of 30 meters per minute (1814 kg mushrooms/h) [15], with the technical support of a few main operators. Thanks to the precise environmental control, the mushrooms grow at nearly the same velocity, if the stumps are elongated the machine cuts all the mushrooms independently of their size [16]. This technology results in many damaged, discoloured mushrooms which need to be processed in a short time, therefore it is mostly used for producing sliced or canned mushrooms [17]. Nowadays, the most reliable and advanced technology for mushroom picking is the double-handed semi-automatic picking [18], where both hands are used to pick the fruiting bodies while the machine handles the cutting of the stems, sorting, and packaging. This method can be used to increase efficiency, but the aesthetic quality of the machine package is not as good as the human hand package [19].

2.2 Completely automated mushroom picking solutions

Currently, several companies are researching harvesting robots that can perform all the steps of mushroom picking simultaneously, which requires solving several technical challenges. These harvesting robots need to be integrated into the standard cultivation racks used in professional mushroom where the maximum available space between shelves is 30 cm [20]. Furthermore, the equipment can not be installed in a permanent position, as it would disturb the technological processes of mushroom cultivation.

Several scientific articles have been published in recent years on technologies for automating mushroom harvesting, focusing on specific subtasks: identification of mushrooms to be picked [21], system design [22], robot development [23], development of soft gripper manipulators [24], mushroom stump cutting and sorting [25], and packaging [16]. Two companies have successfully tested their prototypes in professional mushroom cultivation environments. The company's automated system is based on a gantry structure robot that enters from the side, and laser telemetry scanning the entire growing surface to identify the mushrooms [26]. Their picking method cannot produce a high-quality product, because in many cases the mushrooms were damaged, contaminated and stained [26], and the slow picking speed (20 kg/h [27]) is not able to fully replace manual picking. Another company uses a SCARA articulated robot with a picking speed of up to 36 kg/h [28], which can be integrated into standard shelving systems [29]. The mushrooms to be picked are identified using a 3D vision system [30], the camera and lighting are mounted on the robot arm above the picking head [28]. They use their own image processing algorithm, but in the future, they are interested in developing machine learning-based vision. The technical challenges of the picking machine development task are to pick the mushrooms sufficiently fast and continuously without affecting the quality, which issues are currently unresolved, as mushrooms growing very fast during the cultivation period, more than 1 mm per hour depending on the temperature. A comparison of mushroom picking methods discussed in the literature overview is summarized in Table 1, according to picking speed, mushroom sensitivity, working conditions and costs.

2.3 Software-based solutions for shape recognition in agriculture and mushroom cultivation

Lu et al. used an algorithm based on a convolutional neural network of deep learning method to estimate the number of mushrooms in the images and the size of the caps. This algorithm is capable of predicting the expected growth of the mushrooms and the optimal picking time to maximize the production volume [32]. Another study estimates the diameter from color photographs using Score-Punishment and the YOLOv3 algorithm, because the Hough Circle Transform circle matching was found to be unsuitable [33]. Several studies have applied the Hough Circle Transform, but in many cases it fits false circles to mycelial spots. Additionally, if the mushroom is not perfectly circular, the transform fits an incorrect diameter, or the circle outlines overlap in the case of adjacent mushrooms, introducing errors into the size calculations.

The calculation of the cap diameter can be performed using the Hough transform [34]. The curvature describes how sharply the curve bends at a specified point [35]. The curvature c [dimensionless] can be calculated using the Eq. (1) formula, where u [dimensionless] represents the center position, σ [dimensionless] denotes the deviation, and the functions $X(u, \sigma)$ and $Y(u, \sigma)$ defining the curve have dimensions of length in [m] [35]:

$$c(u,\sigma) = \frac{\dot{X}(u,\sigma)\ddot{Y}(u,\sigma) - \ddot{X}(u,\sigma)\dot{Y}(u,\sigma)}{\left(\dot{X}(u,\sigma)^2 + \dot{Y}(u,\sigma)^2\right)^{1.5}}. \tag{1}$$

In their research, Nadim et al. use the k-nearest neighbor algorithm to categorize mushrooms into 5 quality classes based on their estimated size, weight, color, defective areas. The mushrooms were photographed and inspected on a dark background in an artificial environment and with illumination [36], but the method does not handle the image recognition problems that can occur in real cultivation environments. Quality control of mushrooms is often performed using image processing techniques. A common method for detecting mushrooms is contour and edge detection, which is performed on a grayscale image by identifying intensity differences where continuum differences are explored using the gradient and Laplace operators [37]. The result of edge detection is a binary image, where the white pixels represent the sharp changes and the gradient points in the direction of the change, indicating the maximum intensity rise direction [38]. The gradient and the second derivative (Laplace) of a two-dimensional intensity function (f) can be calculated using the in Eq. (2) and in Eq. (3) formulas [37]:

$$\nabla f \equiv \mathrm{grad}(f) = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \end{bmatrix}, \tag{2}$$

$$\nabla^2 f(x,y) = \frac{\partial^2 f(x,y)}{\partial x^2} + \frac{\partial^2 f(x,y)}{\partial y^2}. \tag{3}$$

Common methods are sobel and canny edge detection, but these techniques do not result in closed contours for images with many details, which could be filled to obtain the area of the mushroom [39]. Several studies demonstrated the efficiency of object separation using flooding-based segmentation algorithms [40, 41]. Deep Learning-based methods provide a more efficient detection, but these methods require a significant amount and high quality of data, longer learning times and high processing capacities [41], which might

Table 1 Comparison analysis of available methods of mushroom picking

Picking method	Speed (depends on mushroom size)	Sensitivity and quality of the mushrooms	Labour conditions	Operating costs	Cost of acquisition
One-hand picking with human labour	30–50 kg/h/person	low, high quality	unpleasant	high	low
Semi-automatic two-hand picking [31]	up to 100 kg/person 8000 pcs/h	standard, slightly stained	average	medium	high
Automatic slicing blade harvesting [14]	outstanding 1814 kg/h	many damaged pieces, low quality	very good	low	medium
Full automated machine A [25, 26]	20 kg/h/machine	medium damage, soil contamination	excellent	low	very high
Full automated machine B [27, 28]	max 36 kg/h/machine	high damage, stained mushrooms	excellent	low	very high

not be available on the edge. In agriculture, Python [42] and OpenCV [43] based image processing programs are used in many cases with very good efficiency, e.g. for apple [44], tomato [45], strawberry detection [46] or for vegetable disease prediction [47]. Various further imaging and detection methods are available in agriculture and vegetable cultivation, such as thermal imaging [48], 3D point cloud LiDAR sensors [49], and 3D Kinect [50], however their application might be an overshoot for the given task.

3 Materials and methods

3.1 Programming tools

Based on literature, the Python programming language and the OpenCV and NumPy [51] libraries were used to implement image processing program on Windows 10 64-bit platform in V.S. Code editor, which versions are included in Table 2. Based on literature, the Python programming language and the OpenCV and NumPy libraries were used to implement image processing on Windows 10 64-bit platform in V.S. Code editor. The image processing was performed on a MacBook Pro (15-inch, 2016) equipped with an Intel I7-6820HQ processor, 16 Gb DDR3 RAM, SSD, and Radeon Pro 450 video card.

3.2 Images to be processed

To develop and validate the algorithm, a 60 image dataset was compiled that include pictures from professional bag and shelf cultivation growing surfaces, some of them taken in the mushroom growing laboratory of the Department of Vegetable and Mushroom Production of the MATE Institute of Horticultural Sciences. The data set included 15 images downloaded from the internet for testing the program. The complete dataset is available through request.

3.3 Difficulties in mushroom detection

The software was tested on photos that simulate even the worst conditions that can occur during image processing. The importance of correct photograph capture in image processing is crucial, as incorrect lighting, shadows, blurriness due to depth of field, object aliasing and incorrect angles complicate identification. In case of inappropriately applied mushroom cultivation technology, parameters and inadequately managed harvesting areas, problems will occur, such as joined, merging mushroom caps, mushroom starts emerging from below the caps, laterally growing visible stumps, or cover soil contamination, or white mycelia, which make detection significantly difficult. In a properly functioning professional mushroom growing environment, these issues are only rarely found. They must be avoided, as they negatively affect the production volume and the quality of the product.

Table 2 Versions of programming libraries

	Visual Studio Code	Python	NumPy	OpenCV
Version	1.71	3.10.5	1.23.0	4.6.0.66

3.4 The method of image processing

As an initial step of the image processing, the image was converted from sRGB to a grayscale image, and then Gaussian smoothing to reduce noise and grayness. The contour lines carry the useful information in mushroom detection, so finding the right brightness threshold in binarization is crucial due to the different intensities of illumination. The parameters were optimized to minimize unnecessary details, while preserving the circularity of the shapes avoiding the merging of components. Discolorations and soil fragments on the mushroom caps were removed using the custom developed algorithm, because OpenCV's floodFill function and Morphological Closing also removed the closed areas between the mushrooms in many cases. The removal of black spots is essential because they would complicate segmentation and the calculation of mushroom size would result in incorrect values. The result of removing small black spots is shown in Fig. 1 (a–c) where the soil particles are marked by red circles on the mushroom caps.

Fig. 1 (a–c) illustrates a section of the processed image where (a) visualises the original image, (b) presents the image following binarization, and (c) the image resulting from the removal of soil particles using a custom algorithm.

Our method was based on inverting the binary image and searching for connected components. A filtering routine was used to check which elements need to be deleted, and then

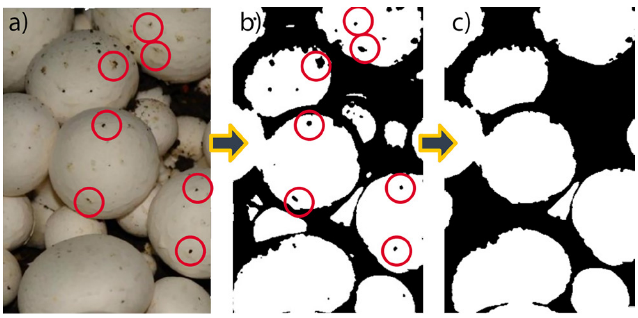


Fig. 1 (a–c) The figure illustrates (a) the original image, (b) the binarized image, and (c) the final image with the removal of soil particles.

the elements of the multidimensional matrix were formed into an image and inverted back. The binarization resulted in some merged shapes, which were segmented using the OpenCV Watershed algorithm. Afterwards, the algorithm estimated the size of the mushrooms and select the right pieces. The position of the picker head was determined by calculating the contour line of the object and then its central moment. The OpenCV's Central Moment mu_{ji} are computed [52] as Eq. (4) where $\bar{x}$ and $\bar{y}$ are calculated as Eq. (5) and as Eq. (6). The complete operation of the program is summarized in Fig. 2 and illustrated on Fig. 3 (a–d).

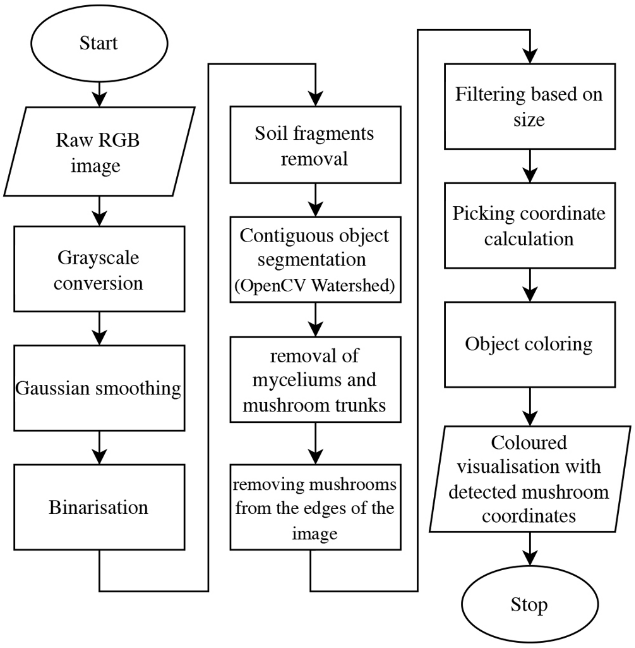


Fig. 2 Flowchart illustrating the image processing workflow

$$mu_{ji} = \sum_{x,y}\left(\text{array}(x,y)\times(x-\bar{x})^j\times(y-\bar{y})^i\right), \tag{4}$$

$$\bar{x} = \frac{m_{10}}{m_{00}} \tag{5}$$

$$\bar{y} = \frac{m_{01}}{m_{00}} \tag{6}$$

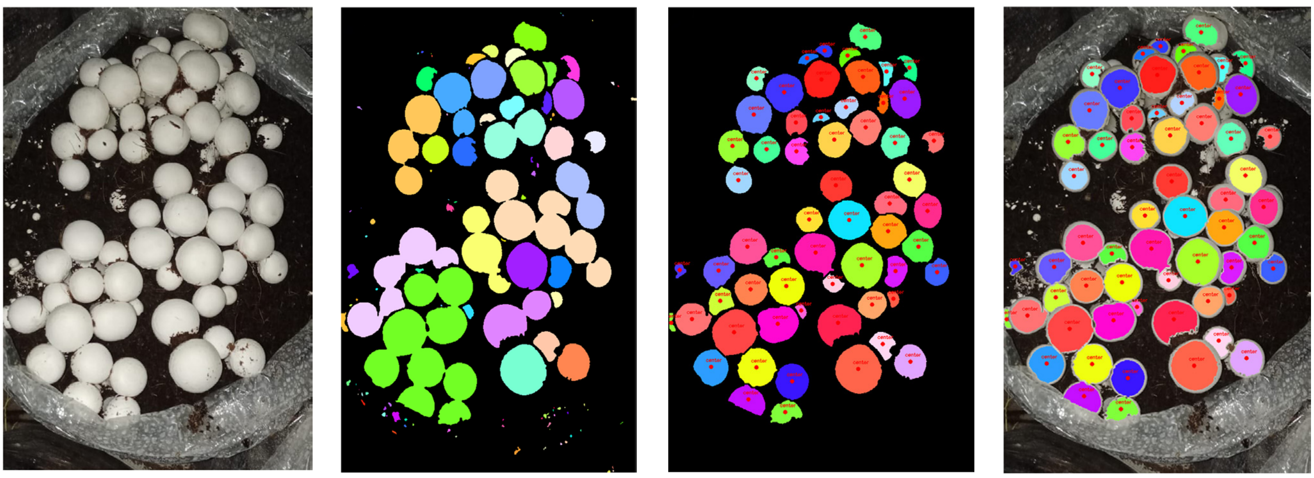
3.5 Method for verifying the separation of objects

The development of the program required verification of the performance of object segmentation using the Watershed algorithm. It is difficult to discern when two shapes are connected by a pixel in the case of incorrect separation, and therefore different colours have been assigned to the independent objects. This solution makes easier and faster to monitor and validate the operation of the programme. After identification of connected components, a multidimensional matrix was created, which stores the RGB color codes generated for the pixels of the components and black color for the background.

Fig. 4 illustrates the state before and after segmentation to demonstrate the practical importance of the verification algorithm, as some pixels connect the purple objects. On the Fig. 4(a) illustrates objects before segmentation without colouring and on the Fig. 4(b) after segmentation the coloured objects.

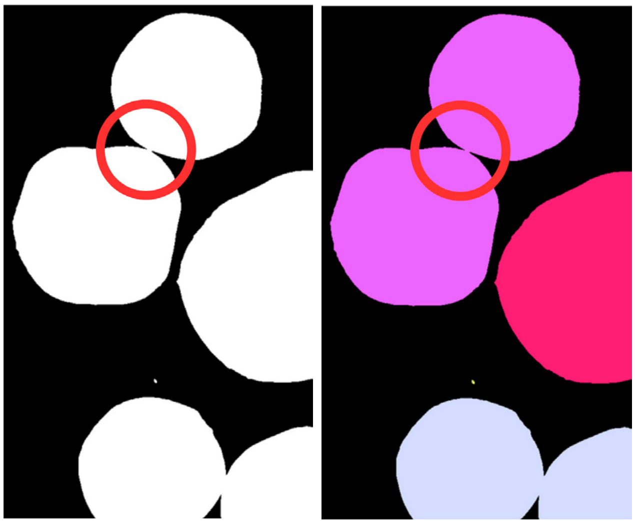
3.6 Method for detecting mushrooms along the edges of the image

The standard shelving systems used in mushroom cultivation have a narrow space (~30 cm) between the shelves, due to the small field of view it is not possible to fully photograph the



(a) (b) (c) (d)

Fig. 3 (a-d) Illustration of the operation of the image processing program: (a) the initial image, (b) the binarized image before segmentation, (c) the image after segmentation with generated coordinates, and (d) the detected mushrooms visualized on the original image.



(a) (b)

Fig. 4 (a, b) Part of a picture demonstrating the practical importance of verification by colouring objects

cultivation area. Photographs may contain mushrooms with caps that hang off the image. The algorithm filters mushrooms that touch the edge of the photo. Without the filtering, it is possible to have two coordinates for the same fruit body, with inaccurate size calculations, ignoring the part that hangs off the picture. In order to correctly estimate the position and size of all mushrooms, overlapping should be used when taking photographs. The amount of overlap should be selected to avoid having a mushroom that touches the edge of both images, which can be adjusted by experience. If there is a mushroom intersected by the edge of an image in one photo, it can certainly be assumed that it is not touching the frame in the next photo. Mushrooms that are located on the overlap of the images, but not touching the edge of either image, will appear twice in the list of coordinates. For this reason, these coordinates must be filtered out. In order to accelerate data collection and image processing, it is recommended to stitch parts of the photo to reduce the number of images to be taken, as overlap is not necessary. This can be done by Image stitching method in Python using for example OpenCV, which can be implemented by aligning images or by using a SIFT (scale-invariant feature transform) algorithm [52].

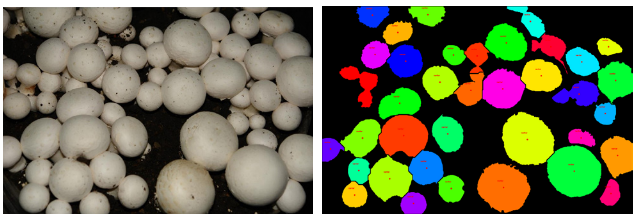
4 Results and discussion

4.1 Image processing results

The image processing was tested on a dataset of 60 photographs, where the samples were from different cultivation methods (bagged, standard shelving), with many different or unique properties, e.g.: different lighting conditions, different brightness and contrast values. In the evaluation, we checked the produced mushroom coordinates validity manually, analyzed the errors that occurred and investigated their causes. The main difficulty in image processing was the different lighting conditions, due to different illumination conditions from above, which caused shadows on some mushrooms and their outlines. In the samples examined, the intensity of illumination in different parts of the image was different in several cases, which affected the binarization process, causing the outlines of the mushrooms to become irregular, with small protrusions appearing on them due to the inhomogeneous illumination as Fig. 5 (a, b). We also explored how image processing is affected by different lighting conditions for images of the same cultivated area. The images were taken from the same height and position, changing the direction, intensity and character of the light source. The results showed that the lower angle the light came from, the less efficient the mushrooms could be separated. The best detection results were achieved by photographing and illuminating the growing area from a 90 degree angle.

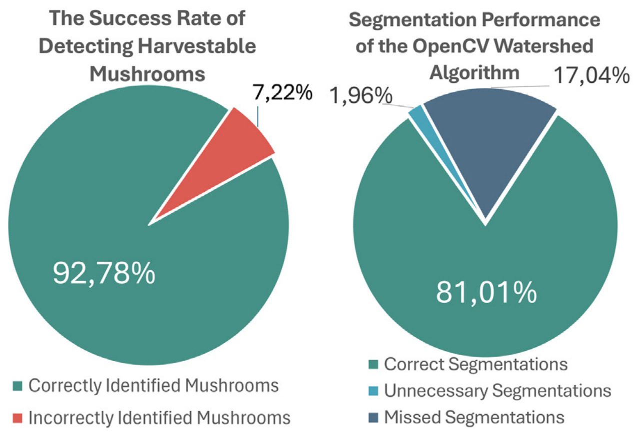
Some of the samples analyzed were taken from the side, from about 40 degrees, and the mushroom caps appeared to be elliptical rather than circular. This is especially significant if the mushroom is growing tilted in the opposite direction, as the Watershed algorithm is less capable of separating the objects, and the calculation of the mushroom size will be incorrect. For this reason, in 13 cases, incorrect coordinates were determined, because the algorithm incorrectly detected the mushroom stump as a cap or failed to filter out mycelial spots. There were difficulties in identifying when the mushrooms touched each other. OpenCV's Watershed algorithm was able to separate the shapes 351 out of 290 times, with a success rate of 82.62%. The failures occurred mostly when the mushrooms touched the edge of the image, which caused 18 failures, or when small mushrooms needed to be separated (Fig. 6(b)).

Out of the 817 coordinates produced, 758 were produced correctly, with a success rate of 92.78% as Fig. 6(a).



(a) (b)

Fig. 5 (a–b) The figure represents the original image (a) and the result of the image processing (b) without filtering out the coordinates of the mushrooms at the edges of the image



(a) (b)

Fig. 6 (a, b) The results and efficiency of image processing

Among the generated coordinates, 28 were produced incorrectly due to non-segmentation, and 18 coordinates were deleted incorrectly by the algorithm due to lack of segmentation of the mushrooms at the edge of the image as Fig. 7. It is important to mention, that normal, thinning picking (graze picking) does not typically contain the same amount of merged mushrooms [53] as the samples used to test the efficiency of the separation. Thinning picking means that the mushrooms are picked before they are able to reach each other and block further development, thereby significantly increasing productivity. Therefore, when applied to the thinning method, our method is expected to result in fewer defects than in the tests. Out of the 1243 mushrooms in the photos, 429 of them were touching the edge of the image. The algorithm filters out all shapes that touch the edge of the image as Fig. 8, but it cannot handle cases where the segmentation algorithm failed to separate the objects. This resulted in objects being removed that were not supposed to be removed, which resulted in 4.2% of the total number of

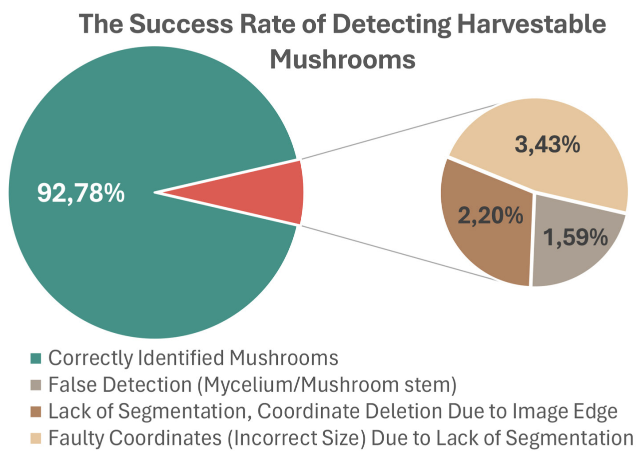


Fig. 7 The accuracy rate of the produced coordinates, and the causes of incorrect coordinates

Fig. 8 The figure shows the result of the image processing, filtering out the coordinates of the mushrooms at the edges of the image.

objects that needed to be removed. During the picking process, it is common that soil falls on to the cultivation area from the stumps that the algorithm has been able to remove efficiently. The slightly darker, brownish mushrooms were correctly detected. In many cases, the images examined were out of focus, or only some mushrooms were protruding and becoming sharp due to their varying height and depth of field, but this did not affect the accuracy of detection. In images afflicted by poor lighting conditions and varying luminance levels, the image processing was less efficient.

4.2 Accelerating image processor program run time

In order to reduce the runtime of the image processing program, by switching from Python arrays to NumPy arrays, and after further optimizations, managed to reduce the running time by several seconds. By performing operations on Numpy arrays, the average code runtime has been accelerated to 0.78 s thanks to efficient matrix operations as Fig. 9. The program included several functions that helped to

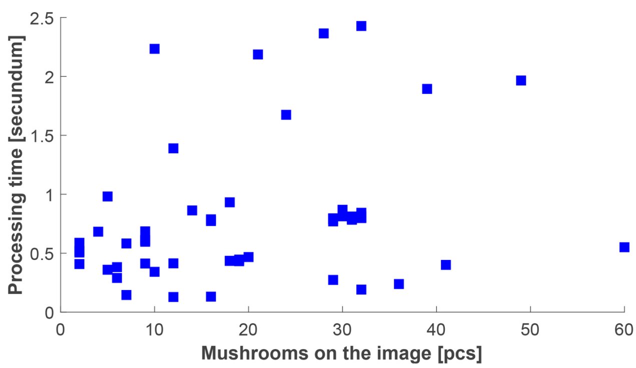


Fig. 9 Image processing time compared to the number of mushrooms in the image.

monitor the program's behavior, the software development and the evaluation of the result, although these increased the runtime. Further runtime reductions could be achieved by running the program on an industrial computer (albeit increasing costs) and further optimising and eliminating the mentioned elements. The results show that the image processing time was mostly influenced by the size (resolution) of the photo. In addition, the complexity of the image also influenced the image processing time, but to a lower extent, with the biggest factors being the amount of micelles in the photo and the stains on the caps appearing during the process of binarization. No clear relationship was found between the number of mushrooms in the image and image processing time as Fig. 9. According to the current work, the optimal image size is between 1–2.5 megapixels (Table 3), which is sufficient to perform the vision application efficiently and to support the mushroom picking machine at an adequate operational speed. The cost-effective approach could be maintained, if the process finishes within the range of seconds on portable, adaptable hardware, as the range of seconds is still in line with the time constraints of the process. To accelerate the speed of image processing, further optimization of the program is required, as well as additional extensive data processing and testing to find the most optimal image resolution and settings.

5 Conclusion

Mushroom farms are facing a constant challenge in providing the labour for mushroom picking, with increasing labour costs. However, currently there is no reliable, fully automated mushroom picking solution available that could replace the manual picking of high quality. Therefore, this research aims to improve the technology for automated picking of button mushrooms. The image processing algorithm was tested on a 60 photo sample, which detected and generated the picking coordinates of the mushrooms with the 92.78% accuracy. The best recognition results were achieved by photographing and illuminating the cultivation area from a 90° angle. The performance of the algorithm was significantly affected by the accuracy of OpenCV's Watershed algorithm, which was able to separate the objects with 81.01% efficiency. Failed separations occurred mainly when the mushrooms were close to the edge of the image or when small mushrooms had to be separated. To increase the efficiency of the program, it would be useful to test other separation algorithms. The algorithm incorrectly identified 13 times a mycelium spot or stump as a mushroom as Fig. 10, to reduce this it would be useful in the future to introduce further shape validation to improve the accuracy of the generated coordinates to near 100%.

The research could be continued by collecting a large number of samples of photographs from cultivation and moving on to machine learning-based detection. The developed algorithm could be used to support more effective training of the AI-based program. In the future, it would be beneficial to select the mushrooms to be picked on the basis of the thinning method, which would increase productivity. The developed program gives promising results and seems suitable for use in a mushroom picking machine after further optimization and testing in real applications.

In the future, with more advanced techniques (and moving above the cost-effective applications regime) the recognition will require the application of artificial intelligence and learning methods, whereby the automated systems could not only assist the picking, but also provide information about the condition and quantity of the production. By analyzing the collected data, the software could make autonomous decisions and communicate with the automated system that controls the cultivation to independently modify the technological parameters of cultivation, alerting to diseases and defective areas, thereby introducing Industry 4.0 to mushroom cultivation and facilitating production management and controlling.

Table 3 The average image processing time as a function of the resolution of processed images

Resolution [megapixel]	Average processing time [secundum]	Number of processed images
0–0.5	0.5074	7
0.5–1	0.3940	5
1–1.5	0.5965	15
1.5–2	0.7769	2
2–2.5	0.7657	25
3–5	1.5320	2
5 <	2.1876	4

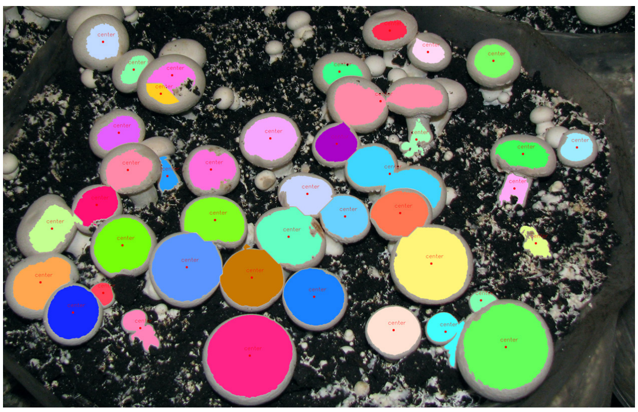


Fig. 10 The figure shows the result of the image processing, with some incorrect segmentation and lack of object removal

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