AUT Journal of Mechanical Engineering

AUT J. Mech. Eng., 7(1) (2023) 61-72
DOI: 10.22060/ajme.2023.21775.6045

Machine Vision System for Autonomous Guidance of Raisin-Collection Rover

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ABSTRACT: The development of autonomous vehicles based on machine vision system in various industries and agriculture is a challenging topic. In this study, the active-contour algorithm was utilized for path-tracking of an automatic raisin-collecting rover. For this purpose, the energy difference between the background and foreground levels is utilized to extract the boundary between raisins and the ground surface with good accuracy which is used for navigating the path. This was accomplished by developing a small unmanned rover equipped with four DC motors and a machine vision system. Field tests at the Sunny Raisin Court showed that the system was able to independently detect and navigate its path with an RMS error of 1.57 cm. The results of analysis of variance for accuracy of the path tracking showed that the effect of lighting conditions and speed on the accuracy was significant at the level of one percent.

Review History:

Received: Sep. 16, 2022
Revised: Dec. 09, 2022
Accepted: Mar. 06, 2023
Available Online: May, 05, 2023

Keywords:

Automatic guidance
Image processing
Active contour
Feature extraction
Intelligent control

1- Introduction

The development of computer and electronic technologies and the production of precision sensors have led to the development of automated vehicle navigation systems in recent years [1, 2]. Automatic guidance methods of agricultural vehicles with the above sensors can be classified into seven types: 1. *Mechanical sensors* [3], 2. *Ultrasonic sensors* [4], 3. *Infrared sensors* [5, 6], *4. Laser Sensors* [7-10], 5. *Dead Reckoning method* [11-14], 6. *Satellite Navigation* [15-18] and 7. *Machine vision technology* [19-24] can be categorized. The various sensors commonly used for automatic guidance, each have advantages and disadvantages [25]. Including these sensors, ultrasound sensors are cost-effective to detect obstacles, but they have a low detection range and low accuracy. Infrared sensors are another inexpensive and easy way to detect obstacles. However, their less sensitivity of temperature in hot hours of the day (in outdoor spaces), and also relatively short detection distance (less than a few meters and often a few centimeters), are their disadvantages. Farther distant objects can be accurately detected with laser scanners (2D or 3D), but they are expensive. Satellite sensors have high accuracy in positioning in different weather conditions, but they are not able to detect the spatial conditions around the vehicle (whether there is an obstacle or a hole in the path). Vision sensors have great potential for vehicles to see the surroundings, which can be used as single camera or stereo on the vehicle for automatic guidance, often for localization, by identifying specific markers. Stereo vision is the most natural way of seeing, because humans and animals also use two eyes to obtain information from the environment. In this method, there are many problems in establishing fast communication between images of two cameras that create a three-dimensional space.

The most important part of the machine's vision system is the camera, which is installed on the machine to capture images. The location of the camera on the device depends on the relationship between the camera, the machine and the camera's field of view, and depending on the type of use and application, it can be installed in front, rear, side or even under the machine. Radcliffe *et al*, [23] placed the camera in front of the vehicle in automatic guidance of an orchard unmanned vehicle. In this study, they used a combination of canopy with background sky. By focusing on the tree canopy and sky of an orchard row, the image processing and automatic navigation operations were performed. Han *et al* [24] used single-camera machine vision system in automatic guidance of a tractor to track seed sowing row. They used row separation method by K-means clustering algorithm, row detection by instantaneous algorithm to rout. The results of image processing accuracy evaluation in the proposed method, from two sets of image databases, one of soybean

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fields and the other of corn fields, had good performance accuracy. Mahdavian [19] used a single-camera machine vision system to autonomous guidance of the JD955 combine. They used machine vision system to Image acquisition and determine the lateral and angular deviation of the combine with respect to the forward path. They used fuzzy control system to send the appropriate forward direction correction command as well as the hydraulic extension circuit to receive and apply electric command to steering wheels.

Reviewing the studies done in the field of automatic guidance of vehicles, it is observed that in recent years, machine vision method has made promising progress in this field, which alone or in combination with other methods used in guidance technology.

In this study, the machine vision system was used to navigate and guide the raisin collecting automatic rover. This system is based on the active contour algorithm to detect the path. This algorithm is useful to identify the boundaries in the condition that the image has a lot of noise. Actually, the use of this algorithm for the purpose of routing, is the innovation of this study, in such a way that geometric formable models are used instead of parametric formable models to solve morphological problems. These models use the level set function to detect the boundary, and the evolution of the curve in them is without the need for parameters. The models derived from edge-based methods, the gradient is used as a criterion to stop curvature in cases with fragmented boundaries, or in other words, in cases where the boundaries are not clearly distinguishable. In this study, the edgeless active contour model was used as one of the pioneering and prominent models in this field.

2- Automatic Guidance of Raisin Collecting Rover

Iran is one of the earliest countries for grape cultivation and one of the largest and most important raisin producing countries in the world. Unfortunately, due to not paying attention to viticulture issues, at the present, the collecting and processing of this product is often carried out by traditional methods using human resources, which is time consuming and tedious work. Therefore, using a machine to collect this product helps a lot in saving time and labor force. Automatic guidance of vehicles, usually includes two concepts: positioning and control. The automatic guidance system for agricultural vehicles must first determine the position and direction of the vehicle and then plan and execute the operations required to move to the specified position. An automated agricultural vehicle must be able to mimic all human actions. In automated vehicles, a microprocessor plays the role of human brain, complex algorithms and programs play the role of decision makers. Sensors play the role of human senses in seeing and perceiving the environment, and actuators play the role of legs and arms in accelerating, braking, and controlling the device. In this study, as can be seen in the block diagram of Fig. 1, the automatic guidance system consists of four general parts: 1- platform (chassis and body), 2- machine vision system, sensors and processor, 3- controller and 4- wheel driver.

2- 1- Unmanned Ground Raisin-Collecting Rover

The construction of this automatic rover included the steps of designing the metal structure of the chassis, selecting and mounting various units such as electric motors, batteries, bearings, wheels, pulleys, belts, axles, and collection platform on the chassis. Different environments of Solidworks 2013 software were used for designing the rover. Part Design and Assembly Design environments were used for modeling, drawing, and assembling device parts. Using the part design environment, the chassis, various parts, and components of the rover with its calculated sizes were designed. Considering that the purpose of constructing the device was to collect 75 kg of raisins in one shift (15 minutes), by considering the density of raisins (1.4 g/cm^3 in moisture content of 0.2), the raisin bin with dimensions of length, width and height of 50, 40 and 40 cm, respectively, and a chassis with dimensions of length, width and height of 60, 40 and 2 cm, respectively, were designed. The other parts and components of the device were also designed according to the actual sizes available in the market (such as the dimensions of the motor and battery, etc.). Then all the designed parts were assembled in the Assembly environment on the chassis. Also displacement, stress, and strain analyzes were performed by the finite element method in the simulation environment of this software. Then different parts were constructed and assembled.

By study about various motion systems [26], it was concluded that four-wheel drive motors is good choice for motion system. Therefore, four 12-volt DC electric motors were used for the four wheels of the rover. Based on the various machine steering systems [26], Skid steering system was used in this study. Fig. 2 shows the overall raisin-collecting rover.

2- 2- Controller System

The control part consists of a control circuit with AT Mega32A microcontroller to guide four motors connected to the wheels, receive signals from sensors and send movement commands to the motor drivers. An ultrasonic sensor was installed on front of the rover to detect obstacles. This sensor actually calculates the distance of an object by calculating the time between sending a signal and receiving a reflection. A USB port was also used to send and receive signals to the computer.

The types of motion defined in the control system include: right-turn, left-turn and forward motion at three different speeds (maximum, medium and minimum), backward motion, as well as the stop or move command. After detecting the path through image processing in MATLAB software, commands are sent from the computer to the controller circuit to create the desired movement. On the other hand, when the device encounters an obstacle, the ultrasonic sensor operates and commands the controller circuit to stop or move backwards, left or right. The device control system algorithm can be seen in Fig. (3).

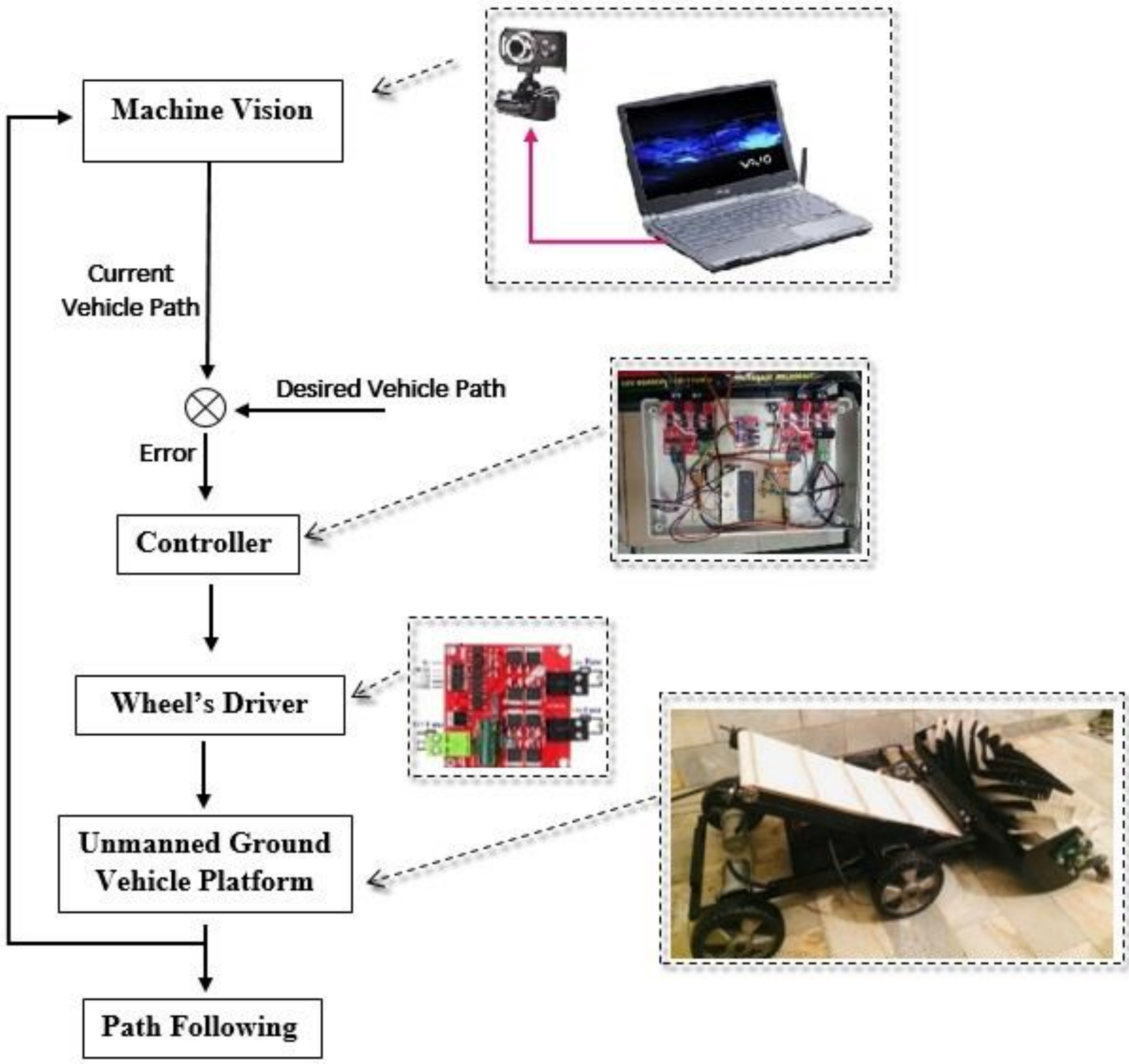


Fig. 1. Block diagram of automatic guidance system

2- 3- Motor-Driver System

In this study, two motor drivers 160 W dual channel XY-160D were used. Each of these drivers was designed to control two motors on each side of the machine with an input voltage range of 6.5 to 27 volts with a maximum current of 7.5 amps per motor, which can be used 30 amps for a total of four motors. The velocity control is applied directly to all four wheels, and all wheels have the same velocity in direct movement or in turning around mode.

The direction of wheels rotation is also such that the right-side drivers, and the left-side drivers are commanded together separately. The steering system accomplished in such a way that, for example, to turning right, the right wheels move backward, and the left wheels move forward, therefore, the radius of turning will be minimal as well as the mechanical and differential parts of steering will not be required anymore. In straight forward or backward motion, both left and right wheel drivers send the same direction command to the motors.

2- 4- Vision System

The desired path of raisin collecting machine, is the boundary between the raisins product surface (foreground) and the ground (background). The machine vision system consists of two parts: Image acquisition and image processing. The image acquisition section consists of a Logitech c920 HD pro Webcam CMOS with a resolution of 480 x 640 pixels at a speed of 30 frames per second, which is installed in front of the machine and connected via cables to the computer. Then, by introducing the camera to MATLAB software and making the necessary settings, color images of the environment in front of the moving machine were sent to the computer.

Fig. 2. Raisin-collecting rover

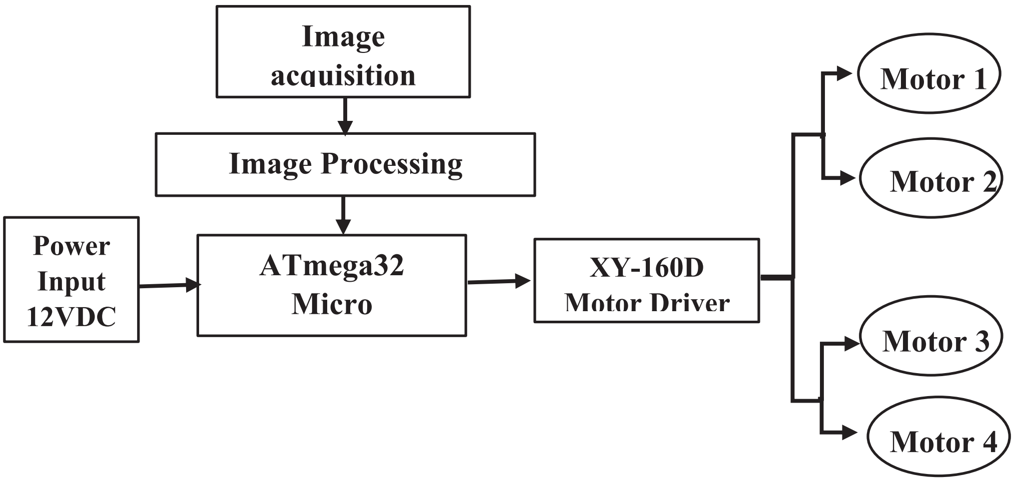
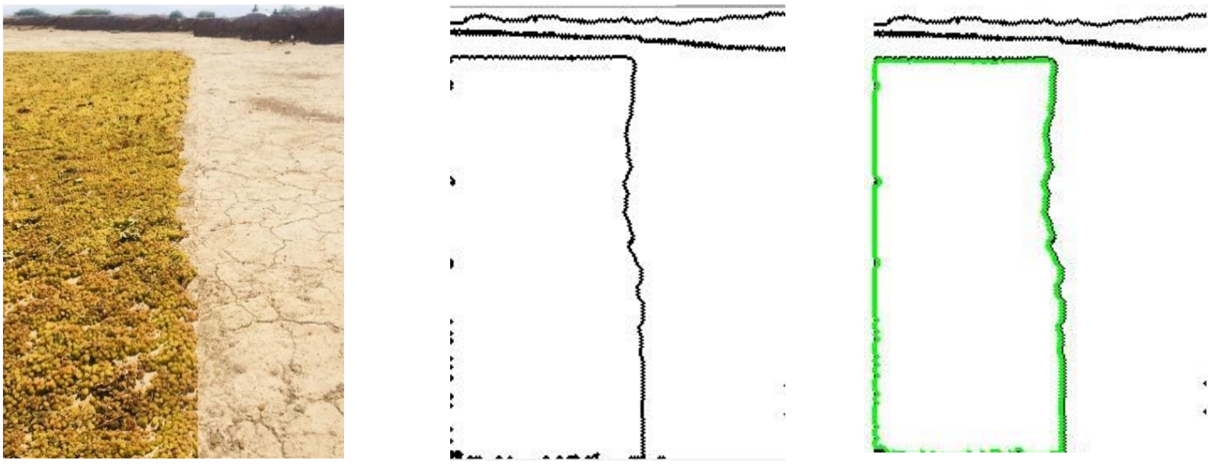


Fig. 3. The device control system algorithm



(a) **(b)** **(c)**

Fig. 4. Automatic machine path detecting and tracking image: a) initial image, b) binary image for path detection and c) path tracking image by the algorithm

After sampling images (Fig. 4.a) from the Sunny Raisin Court, in image processing section, first, the most widely used algorithms in the field of navigation were researched [19], [27-29]. The four most widely used methods in this field are: **1- Huff transform** algorithm, which detects the boundary between objects by thresholding and recognizing points with maximum threshold and converting these points to line. **2- Edge detection** algorithms such as (Sobel, Canny, Log, Perwit …), which act based on differentiation to identify the boundary**. 3- Deep learning** method, which is based on training and evaluating a series of pattern images, in order to identify boundaries and routing. **4-Active contour** algorithm, which operates based on detecting energy differences at the boundary of different objects.

After investigating this field and observing the shortcomings and sensitivities to noise in the first three cases, in the end, by observing the results of using the active contour algorithm as a real-time algorithm in object tracking or routing [30-33], the active contour algorithm due to low sensitivity in different conditions, high detection accuracy and high processing speed in detecting the boundary between raisin product and ground was used. The active contour, or snakes, is an energy-reducing, shapeable spline influenced by constraint and image forces that pull it toward object boundaries and internal resistance to deformation. In other words, snakes can be understood as a special case of the general technique of matching and deformable model to an image using energy minimization [29].

In machine vision, contour models describe the boundaries of shapes in an image. Snakes in particular are designed to solve problems where the approximate shape of the boundary is known. In addition, compared to classical feature extraction techniques, this method can find Illusory contours in the image by ignoring missing information of boundary. A simple elastic snake is defined by a set of points $v_i\,(i = 1,2,...,n-1)$, in which E_{internal} is internal elastic energy term, $E_{external}$ is energy term based on the outer edge. The purpose of internal energy term is to control the deformations of snake, and the purpose of external energy term is to control the contour connections on the image. External energy is usually a combination of forces that are introduced due to the existence of the image E_{image} and the user fore E_{con} .

The energy function of the snake is the sum of its external energy and internal energy (Eq. 1):

$$E^*_{snake} = \int_0^1 E_{snake}(v(s))ds = \int_0^1 (E_{\text{internal}}(v(s)) + E_{image}(v(s)) + E_{con}(v(s)))ds \quad (1)$$

And the internal energy of the snake consists of the continuity of the contour E_{cont} and the smoothness of the contour curve E_{curve} (Eq. 2):

$$E_{\text{internal}} = E_{cont} + E_{curve} \quad (2)$$

The external energy is defined in the form of a potential energy P(x,y) along the curve as Eq. (3). This potential energy obtains its minimum values at the location of the desired boundary. Assuming that I(x,y) is an image with gray levels, a common potential energy function to drive the formable model towards the boundary is expressed as Eq. (4):

$$E_{external} = \int_0^1 P(X(s))ds \qquad (3)$$

$$P(x,y) = \left|\nabla[G_\sigma(x,y) * I(x,y)]\right|^2 \qquad (4)$$

where, $G_\sigma(x,y)$ is a two-dimensional Gaussian function with standard deviation σ, ∇ gradient operator and * is convolution operator. Finally, the curve that minimizes the E_{total} energy function is minimized by the Euler-Lagrange theorem, and the evolution equation of the active boundary is obtained as (Eq. 5):

$$\frac{\partial}{\partial s}\left(\alpha\frac{\partial x}{\partial s}\right) + \frac{\partial^2}{\partial s^2}\left(\beta\frac{\partial^2 x}{\partial s^2}\right) - \nabla P(x,y) = 0 \qquad (5)$$

Usually, in the active contour algorithm, parametric formable models have a series of morphological problems, such as not breaking and merging the boundary, which is caused by the definition of the integrity of the active boundary in these models. To deal with these problems in parametric models, geometric formable models were used. In these models, unlike the parametric formable models, the active boundary is implied, and the deformation and metamorphosis of the active boundary are introduced with geometric criteria such as the normal vector and the degree of curvature. For this purpose, the level set function is used in geometric models. The use of the level set function caused the curves to be introduced as zero level and a scalar function. Curvature evolution in the level set function method works implicitly, without the need for parameters, and intrinsically. This process is such that the desired level is placed as the level of zero, and the points of the figure that are lower than it is marked with a negative sign, and the upper points of it are marked with a positive sign.

In this way, to describe the level set, there will be a matrix of the same dimensions as the matrix of the original image, whose values will show the distance of different areas of the surface from the zero level set, instead of showing the gray light levels. In general, instead of following the curve over time, the evolution of the curve is obtained by updating the level set function. The advantage of using a level set in the description of the active contour is that by using the component perpendicular to the surface, the problem of not changing the boundary shape despite the change of its parameters in parametric models is solved, and in addition, by changing the morphology, the level set function remains valid. The models were derived from edge-based methods, the gradient is used as a criterion to stop curvature in cases with fragmented boundaries, or in other words, in cases where the boundaries are not clearly distinguishable. To solve this problem, the edgeless active contour model was used as one of the pioneering and popular models in this field. This model uses the area-based term in its energy function. In this method, the level set function is used to implicitly describe the active boundary *C*. In fact, in this method, the average brightness of the areas inside and outside the active border is used for the segmentation process. The energy function of the model is expressed as Eq. (6).

$$E(f,C) = \sum_{i=1}^{N} \lambda^2 \iint_{R_i} (\lambda[c_i(x,y) - I(x,y)]^2 + \mu|C| + vC)dxdx \qquad (6)$$

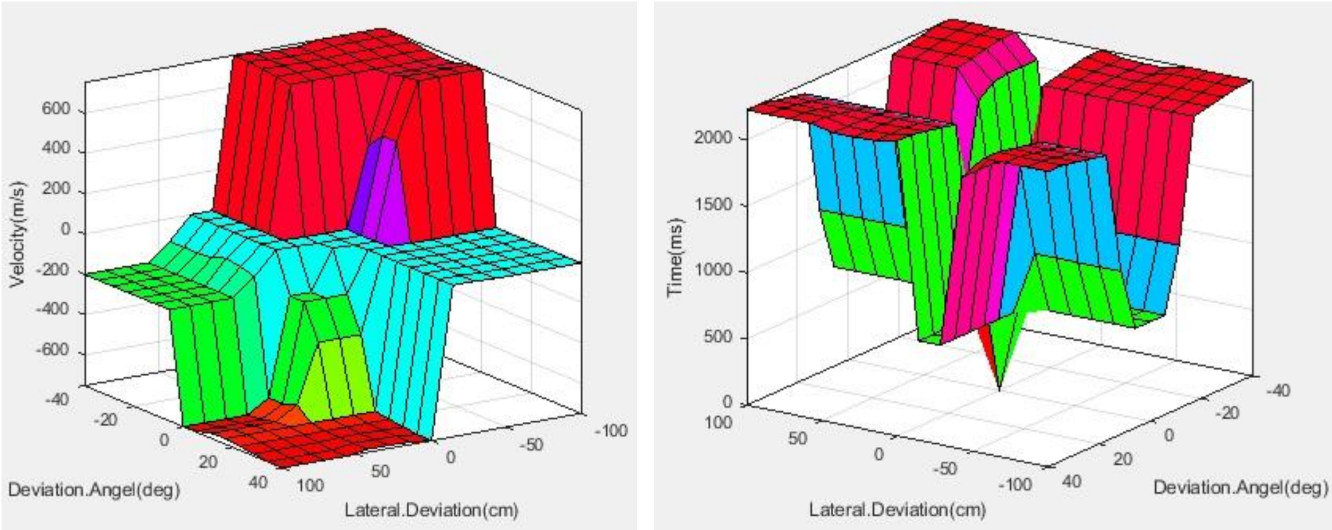
where, Ri covers the discrete areas of the entire *R* area and *N* is the total number of image areas. λ, μ and *v* are setting parameters. Using the Euler-Lagrange theorem, the evolution Eq. is obtained from the above relation in the form of (Eq. 7):

$$\frac{\partial\phi}{\partial t} = \delta(\phi)[\mu div(\frac{\nabla\phi}{|\nabla\phi|}) - v - \lambda(|c_1 - I|^2 + |c_2 - I|^2)] \qquad (7)$$

In this equation, δ is the Dirac function. Therefore, the energy minimization process will depend on the areas C_i and the level surface function.

Considering that the output image of the camera is an RGB image, there are three color components R, G, and B. To calculate the contour average for each component, as in grayscale images and according to the above explanation, there were two forces (one tending to shrink the border and the other tending to expand the border), in RGB images instead of having only one component, now there are three components. Therefore, first, the components of the forces in these three images of two-dimensional should be found and then their resulting forces are calculated. Finally, the resulting forces control the motion of the contour. This approach is very useful for many noisy images (where some or many pixels of the image have been added to the noise). In general, many edge detection algorithms mistakenly pick up those noises in these cases. As a result, these noisy pixels cannot be distinguished from those informative pixels. However, this algorithm (unless noise contaminates all three components in a single pixel) performs well against the effect of noise in edge detection.

After detecting the boundary between the raisin product and the ground, the path was marked as a binary image (Fig. 4. b). To speed up image processing operation, no need for preprocessing and noise removal (which are time-consuming tasks). Also, since the image acquisition speed of the webcam



(a) (b)

Fig. 5. Graph of output values for different inputs in the fuzzy control system: a) Motor velocity values for inputs, b) Steering time values for inputs

was 30 frames per second. By defining steps in the image processing operation, only one frame was processed every 4 seconds. In other words, out of every 120 frames, only one frame was processed. This speeded up image processing operations in path detection. Then, using the contour tracing algorithm and identifying closest point of the path to the center of the machine's head as a first point of the path, path tracking began to trace the enclosed ring around raisin and the raisin product was collected by automatic machine (Fig. 4.c). Since in this system, instead of measuring the distance between the machine and the product, the route is identified. Therefore, when the rover reaches the corners of the product surface, ie where there is no path to identify in front of the rover, a 90-degree left turn was defined by default.

2- 5- Route Correction Feedback

Control systems that are used to process control or performance control of a set, are two types: classic or fuzzy control. In classic control, dynamic equations of system are usually used. But recently, intelligent control methods are used in which classic control is combined with artificial intelligence. One of the intelligent control methods is fuzzy control, whose operation is based on fuzzy logic. In other words, the fuzzy control is a system that operates based on scientific knowledge.

By comparing fuzzy and classic controllers, a fuzzy controller was used to correct the machine route and sending a feedback command to the electrical circuit of the controller and drivers. In this method, using the fuzzy editor function in MATLAB 2017b software by a laptop with specifications (CPU: Intel core i5-4200. 1.6GHz, RAM: 8GB), first, the inputs (lateral and angular deviations) and outputs (motors velocity in steering and steering time) was introduced. Then the number of variables of each as well as their membership functions were defined. In the next step, in the Rule editor section, the relationship of the defined rules was expressed so that in different situations, the fuzzy controller can make decisions and send the correction command to the automatic machine. The graph of output values for different inputs can be seen in Fig. 5.

2- 6- System Evaluation

To determine the performance of the control system as well as the image processing algorithm, an initial evaluation of the device was performed in the laboratory on several samples of the recorded image, measuring the lateral deviation of the machine manually at different distances from the boundary for a length of 10 meters. After the initial evaluation of the control system in the laboratory, the machine was evaluated in the Sunny Raisin Court in Malayer, Iran. Measurement of the lateral deviation from the boundary between raisins and the ground was such that first a straight line was drawn at a distance of one meter from the boundary and parallel to it as the baseline. In the next step, the boundary distances from the baseline along the boundary were measured at different points. Then, during navigation, at the corresponding points of measured distances from the baseline, deviations from the baseline were also measured.

The performance of the designed algorithm was evaluated at three speeds of the rover (1, 2, and 3 km / h), in five lighting conditions (at 7, 10, 13, 16, and 19 o'clock) and in three repetitions. The results of the factorial completely randomized design were analyzed by SPSS v. 21 software. The accuracy rate index was used to evaluate the results

Table 1. ANOVA of path detection accuracy in different conditions

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Time	3999.682	4	999.921	85.123	0
speed	583.633	2	291.816	24.842	0
Time * speed	182.843	8	22.855	1.946	0.089
Error	352.405	30	11.747		
Total	334615.261	45			

a R Squared = .931 (Adjusted R Squared = .899)

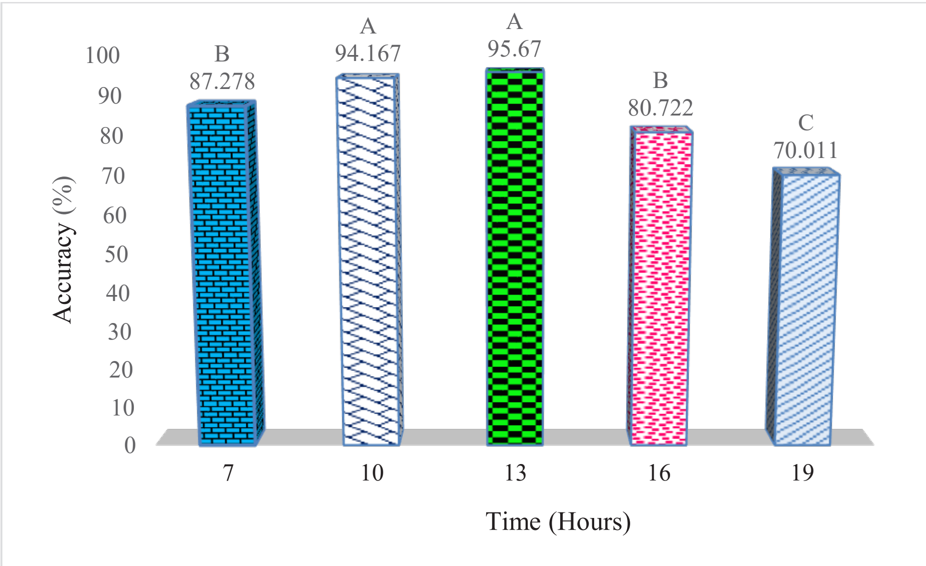


Fig. 6. Accuracy of the proposed algorithm in different lighting conditions

and compare the performance of the algorithm in different conditions. The accuracy index is shown in Eq8. ..

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \times 100 \quad (8)$$

where, TP is the number of path detections in which paths were correctly identified; TN is the number of non-path detections in which non-path were correctly identified; FP is the number of detections in which the non-path was incorrectly identified as the path, and FN is the number of detections in which the path was incorrectly identified as the non-path.

3- Results and discussion

The results of the analysis of variance for the accuracy of the proposed algorithm are shown in Table 1. It was observed that the effect of lighting conditions and speed on the accuracy of the proposed algorithm was significant ($p<0.01$). While the interaction of these two factors was not significant. In other words, these two factors do not affect each other's performance.

The results of the performance accuracy of the proposed algorithm in different lighting conditions (at 7, 10, 13, 16, and 19) can be seen in Fig. 6.

The accuracy of the active contour algorithm in the middle hours of the day (hours 10 and 13) had better results than other hours of the day, due to the presence of shadows in the early hours and at the end of the day, which caused the error, and reduced the accuracy of image processing. The results of the accuracy of the proposed algorithm at different speeds of the rover are shown in Fig. 7. As observed, by reducing the speed of the rover, the accuracy of the image processing algorithm increases, due to reduced noise and impressions of images at lower speeds.

According to the results obtained from the evaluation of the device, it was found that the performance of the image processing algorithm in identifying and tracking the path

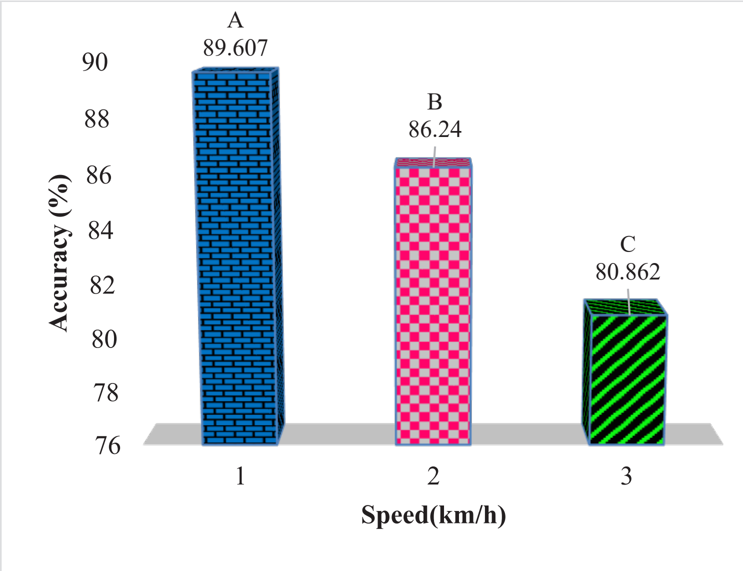


Fig. 7. Accuracy of the proposed algorithm in different speeds

Table 2. Comparison of widely used routing algorithms in image processing

Algorithm	sensitivity to light conditions	noise sensitivity	detection accuracy	processing speed
Hough Transform [19]	High	High	Middle	High
Sobel Edge Detection [27]	High	High	Middle	Middle
Deep Learning [28]	Middle	Low	Middle	Low
Active Contour [29]	**Low**	**Low**	**High**	**High**

is acceptable. After sampling images of the raisin court, in the routing section by using image processing, some used algorithms in this field were evaluated. Four widely used methods in this field were studied and compared (Table 2). The shortcomings like high sensitivity of light conditions, high noise sensitivity, and middle detection accuracy in the first three cases were observed., In the end, the active contour algorithm was used to detect the boundary between the raisin product and ground due to low sensitivity to work in different conditions of light, shadow, and noise, high detection accuracy, and high processing speed. As a result, the image processing speed was acceptable.

The machine control system also had a good performance in tracking the route and sending the motion command to the DC motor drivers according to the signals received from the images. According to the use of DC motors in the machine, precise control of wheel movement is more difficult compared to servo motors, but since DC motors are cheaper and more economical, this type of motor was used. To simplify the operation of the machine, some restrictions such as the presence of obstacles in the route, the complexity of the route, and special environmental conditions (such as rain and fog) did not into account.

Comparing the results with two samples of similar studies [19, 23], observed that the RMS error in the proposed method had better values (Table 3). Since the PI controller was used in all three methods, the better performance of the proposed method was due to the use of active contour algorithm in routing. Because, this algorithm is less sensitive to noise and different light conditions, which was one of its advantages. As can be seen in Table 3, the performance of the proposed method and also the research of Radcliffe *et al.* [23] have

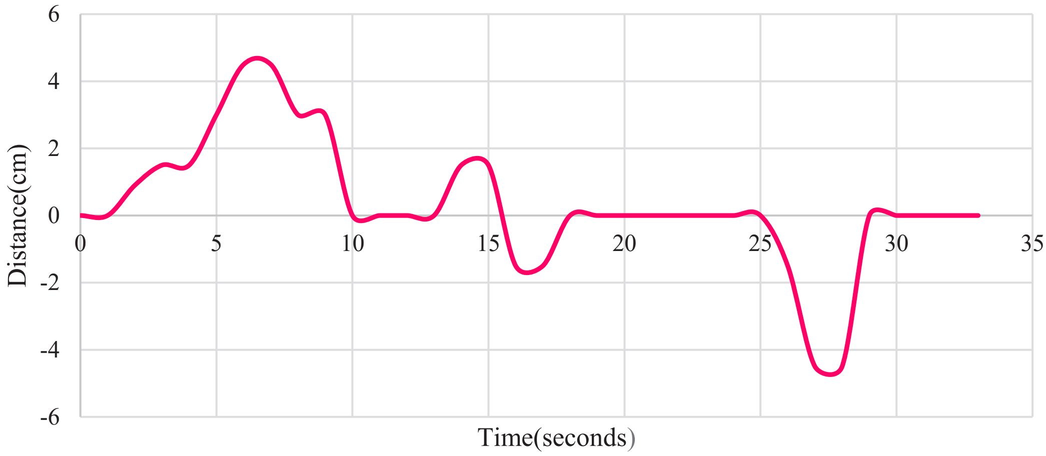


Fig. 8. Lateral deviation from the boundary between raisins and the ground surface

Table 3. Comparison of RMS error results of the proposed method with two similar studies

Research	Path Detecting Algorithm	Controller	RMSE (cm)
Proposed method	Active contour	PI	**1.57**
Radcliffe *et al* [23]	The centroid of the Path plane	PI	2.13
Mahdavian *et al* [19]	Hough Transform	PI	6.7

better performance compared to the research of Mahdavian [19], which was due to the use of Skid steering system in the first two studies. Fig. 8 shows the lateral deviation of the machine from the boundary using the proposed algorithm. The vertical axis is the lateral deviation and the horizontal axis shows 35 seconds of the movement time of the machine. As it is seen, the maximum lateral deviation measured from the baseline was 4.5 cm.

4- Conclusions

In this study, an automatic rover was constructed to collect raisins from the ground surface. The rover consisted of four motors on four wheels and a skid-steering system. The machine-vision system consisted of a webcam installed in front of the rover, which began processing images by sending them to a computer. In image processing, the active contour algorithm (snakes) was used for routing, which was based on the difference in energy between the levels. The initial starting point of the movement was introduced to the system upon which, the identified path was subsequently tracked. To correct the route, the Mamdani fuzzy control system was used, which issues corrective commands from the control system as soon as the rover deviates from the desired path, thus returning it to the main route. The maximum lateral deviation measured from the baseline was 4.5 cm, and the RMS error was also calculated to be 1.57 cm. The results of the analysis of variance accuracy of the proposed algorithm also showed that the effect of light conditions and speed on path detection accuracy was significant ($p<0.01$). According to the obtained results, the use of active contour algorithm in route detection and fuzzy control in route correction has promising potential for unmanned vehicle navigation.

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HOW TO CITE THIS ARTICLE

H. Ramezani, M. H. Khoshtaghaza, S. Minaei, Gh. Akbarizadeh, Machine Vision System for Autonomous Guidance of Raisin-Collection Rover, AUT J. Mech Eng., 7(1) (2023) 61-72.

DOI: 10.22060/ajme.2023.21775.6045