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Steering the line following robot using fast Monte Carlo image analysis and the Gravity Center binary image

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Abstract

The application of Monte Carlo analysis for controlling the line following robot is discussed in the paper. Proposed approach is compared with popular algorithms based on image analysis as well as the use of a line of optical sensors. The most typical image analysis approach based on the Centre of Gravity has been compared with our fast Monte Carlo technique described in earlier publications. Finally, the extension of Monte Carlo control by the use of the binary Centre of Gravity is proposed.

Keywords: line following robot, Monte Carlo method.

Sterowanie robota śledzącego linie z wykorzystaniem szybkiej analizy obrazu metodą Monte Carlo i środka ciężkości obrazu binarnego

Streszczenie

W artykule omówiono zastosowanie analizy Monte Carlo do sterowania robota śledzącego linie. Zaproponowane podejście zostało odniesione do popularnych algorytmów opartych na analizie obrazu, jak również użycia linijki czujników optycznych. Najbardziej typowe podejście wizyjne oparte na wyznaczaniu środka ciężkości zostało porównane z szybką techniką Monte Carlo przedstawioną w naszych wcześniejszych publikacjach. W artykule zostało ponadto zaproponowane rozwinięcie sterowania opartego na metodzie Monte Carlo poprzez wykorzystanie dodatkowej informacji dostępnej po wyznaczeniu środka ciężkości obrazu binarnego. Obraz ten jest uzyskiwany w wyniku zastosowania binaryzacji metodą Monte Carlo z podziałem obrazu na bloki w celu wyznaczenia podstawowego sterowania. Ze względu na możliwą utratę sterowania za pomocą tego algorytmu dla linii przerywanych zaproponowano korektę kierunku ruchu na podstawie trendu wyznaczonego za pomocą estymacji środka ciężkości obrazu binarnego. W wyniku zastosowania proponowanego hybrydowego podejścia do sterowania uzyskano dodatkową możliwość sterowania prędkością ruchu robota oraz wzrost odporności algorytmu na zakłócenia, w szczególności dotyczące przerwania linii.

Slowa kluczowe: robot śledzący linie, metoda Monte Carlo.

1. Introduction

One of the most typical applications of mobile robots is related to transport purposes in industrial warehouses or factories. Navigation of such robots is usually based on the line tracking. Typically, such lines are painted on the floor and not necessarily clearly visible. In such environment the most popular approach to the control of such robots, based on the line of optical sensors, may be unreliable. Such sensors, containing a limited number of cells determining the resolution of the optical system, gather information about the position of the traced line located underneath the robot. The spacing between sensors is also important for the smoothness of the robot's motion.

Considering the disadvantages of such optical systems the short time for the reaction limited by the distance between the sensors and the steering centre should be pointed out, as well as relatively low resolution.

The increase of the resolution has been the main reason of development of vision systems for the robot motion controlling. Another advantage of such approach is the availability of data acquired from the front [1, 2]. For industrial purposes the full analysis of obtained images can be time consuming and unnecessary from the steering point of view, especially assuming the presence of some obstacles, changing lighting conditions, possible line intersections etc.

For the simplification of the image analysis, required for the line following robot control, the use of the Monte Carlo method is proposed. In such approach the analysis of binary image is performed so the computational complexity is much lower. Additionally, the number of pixels used in the computations is also limited.

2. Classical steering based on the Center of Gravity

A typical algorithm used for machine vision based steering of line following robots consists of several steps. The first one is the image normalization used for the reduction of the effects of bad lighting. It usually requires the construction of image histogram or the calculation of extreme intensity values. Then, the edge detection is applied (many various algorithms are available) followed by a simple lower thresholding.

For the robot located over the straight line (its center is between the two obtained edges) the sum of the pixel values on its left side should be the same as on its right side. Each significant disturbance should cause turning assuming that no additional elements, except two line edges, are present on the image. A simple and efficient method used for robot steering is based on the image's Center of Gravity calculated for a grayscale image as:

$$x_C = \frac{\sum_{i,j} i \cdot X_{i,j}}{\sum_{i,j} X_{i,j}}, \quad y_C = \frac{\sum_{i,j} j \cdot X_{i,j}}{\sum_{i,j} X_{i,j}}, \tag{1}$$

where $X_{i,j}$ denotes the value of the specified pixel and *i,j* are its coordinates.

Steering the robot motors can be implemented using the calculated coordinates x_c and y_c by turning towards the image's Center of Gravity. The vertical coordinate can be also helpful for the speed control of the robot. All the artifacts and noise contaminations may cause the steering errors, so they should be filtered out by some additional algorithms.

3. Statistical approach – the Monte Carlo method

The basic steering algorithm used in the paper is related to the idea of fast image processing methods dedicated to the real-time systems supplied by the Monte Carlo method.

For a static image of analyzed scene a constant value can be defined, which denotes the number of pixels fulfilling specified logical condition. Such condition may be used for thresholding in further processing and can be defined e.g. as the presence of a pixel's value within a specified range. Such algorithm behaves as an area estimator for the objects satisfying the specified criterion, since the created binary image containing "ones" for the samples which fulfill the condition (and "zeroes" for the others) gives the quantitative information about the object's features.

The area estimation can be done by summation of all "ones". Using the Monte Carlo method the limited number of randomly drawn pixels is used, so the area estimator $\hat{A}$ is given as:

$$\hat{A} = \frac{k}{n} \cdot N, \tag{2}$$

where: k is the number of drawn "ones", n denotes the number of draws and N stands for the total number of pixels on the image.

The same approach can be also used assuming the division of the image into blocks. In such case some object's motion parameters, such as direction and velocity, can be estimated [3] as well as some additional geometrical parameters such as e.g. moments. For each block the local area estimator $\hat{A}$ is used as the input for the "cut-off" operation in order to obtain the simplified binary representation used for steering the robot. The proper choice of the "cut-off" value decreases the influence of noise and some other artifacts. The idea of the algorithm is presented in Fig. 1.

The considerations presented above are correct for the generator with uniform distribution having good statistical properties in order to prevent the error's increase. More detailed explanation of the fundamentals of the Monte Carlo base image analysis and its application for machine vision can be found in our earlier papers [3, 4]. The Monte Carlo estimation can also be successfully applied for fast image quality estimation [5].

Steering of the line following robots is based on the differential motion controlling. Steering signal for each motor is dependent on the values in the lowest row of the low resolution binary image obtained after the "cut-off" operation. This row of the image can be treat as equivalent to the classical line of sensors.

The image based control algorithm should lead to the situation when the line is present in a single block of the bottom image row. It can be obtained using the prediction based on the analysis of the other rows of the image. If the line occupies the two or more neighboring blocks the analysis of the current trend should be performed.

The control algorithm for each frame consists of the following operations:
– binarization of the frame,
– removal of the orphan blocks,
– filling gaps in the detected line using approximation methods,
– counting the blocks with "ones" for each column (summation),
– control operation:
  - the detection of the possible crossing lines,
  - speed control.

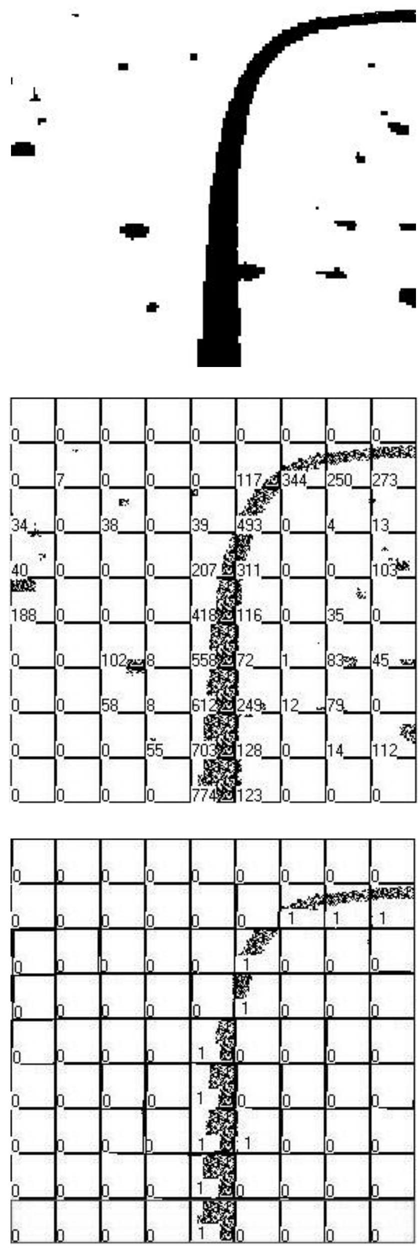

Fig. 1. Example tracked curve with estimated areas for each block and the final effect after the "cut-off" operation
Rys. 1. Przykładowa śledzona linia z estymowanymi polami powierzchni dla każdego bloku oraz wynik końcowy po operacji „odcięcia"

In the case of detected crossing line the control depends on the symmetry. For the symmetrical line-crossing (Fig. 2e) the robot should move forward with the maximum speed or the additional speed control. If the maximum value is not in the middle block the line-crossing is not symmetrical and the robot should turn left (Fig. 2f) or right and decrease it speed. The speed of the robot should be proportional to the sum of the values in the middle blocks of each horizontal line. If that sum is equal to zero (Fig. 2h), the minimum speed should be set before the turning. In that case the additional flag should be set, which informs the system about the current state (0 – moving forward or turning, 1 – turning with detected crossing lines).

A fundamental advantage of the Monte Carlo based algorithm is a significant reduction of the amount of processed data. In comparison to the classical Center of Gravity method its implementation is much simpler and the 8 times reduction of the computation time has been verified for the same route with identical lighting conditions.

Tab. 1. Comparison of the properties of discussed algorithms
Tab. 1. Porównanie właściwości prezentowanych algorytmów

Problem	Center of Gravity	Monte Carlo method
lighting conditions	good conditions required or correction necessary	good conditions required or correction necessary
noise and small artifacts	cause control disturbances	filtered out
discontinuous line	does not interrupt the robot's motion	wrong steering or motion interrupt
objects near the line	wrong steering or motion interrupt	wrong steering but the motion may be continued
computational complexity	high (multiple analysis of all image points required)	low (limited to randomly selected points only)

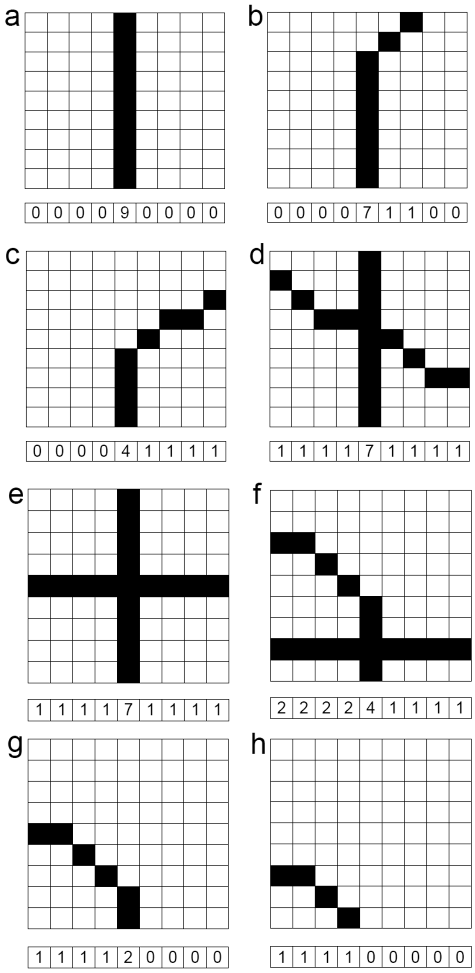

Fig. 2. The illustration of the image based prediction and control (a – forward with maximum speed, b – fast forward and turn, c – forward and turn, d – crossing, e – crossing, f – crossing and turn, g – slow forward and turn, h – start turning)
Rys. 2. Ilustracja predykcji i sterowania opartego na analizie obrazu (a – ruch prosto z maksymalną prędkością, b – szybki ruch prosto i skręt, c – ruch prosto i skręt, d – skrzyżowanie, e – skrzyżowanie, f – skrzyżowanie i skręt, g – ruch powoli do przodu i skręt, h – rozpoczęcie skrętu)

4. Proposed hybrid algorithm

In order to eliminate the drawbacks of both presented steering methods the hybrid motion control algorithm, the idea of combining their advantages is proposed. Similarly as in the previously discussed approach, a single image is considered with the use of the Monte Carlo method in order to obtain the simplified binary images similar as presented in Fig. 2.

Next, the Center of Gravity (also known as the Center of Mass) is calculated for such prepared image and the test of the presence of additional artifacts near the line is performed. If the row containing the sums of the values (counted blocks with "ones") has more than one local minimum (e.g. 1 3 0 1 7 0 0 0 1), some additional objects are present on the image. In such situation the Center of Gravity is ignored and the motion control is based on the previous value. Otherwise, the Center of Gravity can be used for the verification of the correctness of the steering set using the Monte Carlo method.

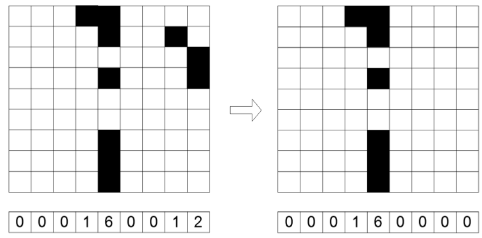

Fig. 3. The illustration of the discontinuous line with artifacts and their elimination
Rys. 3. Ilustracja linii przerywanej z zakłóceniami oraz ich eliminacji

Another problem may occur in the situation when some additional artifacts are present as well as the discontinuity of the line, which is illustrated in Fig. 3 (there is more than one local maximum in the bottom row containing the sums of the values). In such case the additional modification of our method is proposed, which is based on the elimination (e.g. using conditional morphological erosion) of the blocks not connected to the line represented by the maximum sum in the bottom row. Next, the Center of Gravity can be calculated in order to determine the current trend. In such sense, the Center of Gravity is used for the verification of the steering determined using the Monte Carlo method.

5. Conclusions

As the results of the performed experiments, one of the main drawbacks of the statistical approach related to the discontinuity of the line has been eliminated using the Center of Gravity. Thus, the robustness of the proposed method increases, preserving also the main advantages of the fast Monte Carlo method related to the reduction of the number of analyzed pixels. Additionally, the knowledge of the Center of Gravity, even its estimated location, can be helpful for the speed control of the line following robot.

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