Neural Networks in Stereo Vision Evaluation of Road Pavement Condition

Marcin STANIEK
Department of Transport Systems and Traffic Engineering, Faculty of Transport, Silesian University of Technology, Gliwice, Poland; Phone: +48 32603 4150; email: marcin.staniek@polsl.pl

Abstract
This study presents the method for the measurement of road pavement condition based on a stereo vision method of surface representation. The road is represented as a set of points in 3D space. Problems of stereo vision analysis regarding the ambiguity of matching points images, discontinuity depth for neighboring objects registered on the images, etc. were redacted by used neural networks. The author proposed modified Hopfield neural networks in the process of matching pixels in stereo images. The measurement method and construction of test stand presented in the study was developed and implemented by the author of the paper. The test stand allows for inspection of roads according to the requirements of PMS systems. The presented solution would help to identify particularly dangerous places on the road calling for immediate maintenance.

Keywords: Road inspection, road pavement condition, stereo vision, image processing, neural networks,

1. Introduction

Diagnosis of road pavement is a key element of the system to maintain road infrastructure and road safety. Evaluation methods allow the identification of road sections which are a real danger for safe movement of vehicles on the road network. Carried out in accordance with Polish guidelines the evaluation of the state of road surfaces requires the determination of operational parameters, such as: surface conditions with identification i.e. potholes, deformations, patches, cracks, transverse equality, longitudinal equality or skid resistance. Evaluation and analysis of received measurement parameters allows the development of conclusions on the state of the tested road network in order to determine the timing and scope of the repair and overhaul procedures. In terms of strategic it allows planning and distribution of necessary funds for the proper performance of road infrastructure.

The measurement precision, their performance and complexity are main elements of the diagnostic system of road infrastructure. This requires the use of the latest solutions for measuring operational parameters of the road. Such solutions must be able to conduct measurements without hindrance to other road users and be of a non-destructive i.e. not interfering with the construction of the road during the measurement. For such group of devices can include laser profilers designed to identify equality of the road surface, vision systems to record the state of the road surface deflectometer to measure the impact FWD load capacity, radar systems GPR intended for research volatility of the construction of the road, and vision systems for the registration area of the roadway.

A large group of equipment used in the diagnosis of road pavement are the vision systems of pavement condition evaluation. They allow for the identification and registration of such road surfaces distresses like: potholes, deformations, patches, many kind of cracks. This group of devices using image processing and pattern recognition including operations: morphology, segmentation, binarization, measures matching, and image mapping in 3D space. Used vision techniques despite the process automation of identifying are burdened with the necessity of proper calibration of the measurement system due to the variable scaling parameters, lighting, filtration of road pavement of the analyzed image.
In the literature can be find some interesting work on the use of vision techniques in the diagnosis of road pavement. Due to the subject matter of this article, the author will present solutions based on processing and matching the images in stereo vision systems.

The authors of [1] used the stereo vision technology to assess the condition of the road surface. Their method allows to determine the longitudinal and transverse profiles of roads and identify underlying damage to the road surface as bumps, cracks. The measure used in the matching of the proposed solution is based on a cross correlation of stereo-images windows. A similar solution wherein the measurement of matching the pictures is calculated on the basis of the average of the sum of squares of windows stereo-images. The authors work to identify defects and to eliminate distortions in the image used morphological image processing operations. They took effective try to correct uneven lighting of the tested road surface.

In [2], the authors to the stereo vision measurement system introduced the laser lighting in the form of line, which allowed the identification of micro and macro texture of the road surface. However, the disadvantage of the presented solution is time-consuming and complex calibration procedure of measuring equipment. Application of linear LED lighting and projector displaying a specific pattern on the tested surface is shown in [3]. The principle of this solution consists in determining the difference between the theoretical light information and the actual deformed line or pattern. Another solution was proposed in [4] where was used recording the state of the surface by linear cameras and surround cameras system. In addition, the measurement system used a laser illumination system. This arrangement provides the data connection in description 2D and 3D, which in turn increased the accuracy of the mapping surface at 1 mm.

2. Stereo vision test-bench and problems of depth analysis

Based on the study of literature concerning the use of modern diagnostic tools in assessing the state of the road surface, observations and comments of inspectors carrying out measurements of the surface condition, the author of the work proposed his own solution of the test stand. The proposed solution uses the method of stereo vision mapping of the tested road surface. The resulting model of the road surface in the description of spatial allows the use of fault detection procedures it's parameterization and record.

In the developed test bench can be divided into two modules. First module is a set of CCD cameras for stereo-image acquisition of the road surface. This module is essential to mutual geometric parameterization of camera locations, their view area and to define the same parameters for focal length, aperture and focus optical systems of each camera. Second module includes equipment: for determine the position of the measuring vibrations during vehicle movement measurement, for identify the distance traveled based on measuring vehicle wheel rotation and GPS receiver to obtain current information about the vehicle location. Developed measurement test-bench is shown in Fig. 1 and described in details in the paper [5].

The basic problem of depth analysis of stereo-images is the ambiguity of matching points, pixels of images. Analysis of all the points of the stereo-image is a complex problem, impossible for all points (pixels) due to the perspective projection and the shift of the stereo-vision camera system. To the depth analysis of stereo-image problems joined problems connected with digital imaging processing problems like noise, distortion or uneven lighting. They result from imperfections of the image acquisition system and test-bench constriction and they are difficult to eliminate or limit due to the randomness of its kind and scope.
The depth discontinuity, which occurs in adjacent of objects is the next problem of stereo-images analysis, exactly where is a significant change in intensity of the image. This results in the problem of discontinuity of the depth determined by the blurring disparity map. This problem is particular noticeable for algorithms based on measures of matching areas, however, the use of diffusion algorithms allows to significantly reduce the blurring disparity map [6]. In case of road pavement diagnostics the depth discontinuity problem it is not dominant. It can be assumed that the recorded road surface is characterized by continuity with the exception of damage to the type of road cracks and deep potholes.

Another problem of depth analysis of stereo-image concerns the partial obscuring of objects. The common configuration of the real objects, seen in the system stereo vision system may not be able to acquire full information about a facility for images recorded from various measurement points. In depth analysis of the stereo-image there is also the problem of discontinuity of border fragments of images (frames stereo-image). This problem results from a distance relative to each other stereo-image recording cameras in the stereo-visual system. The solution is to define an area smaller than the size of the analyzed image (disable parts of the images from the process of matching points).

Encountered problems in the analyzed received test material forced to undertake proper work on the elimination or significant reduction of the above-described problems of depth analysis of stereo-images. In the next part, the author proposed a method of correcting procedure currently being used measures of matching stereo-images. The proposed solution is based on neural network with Hopfield structure in stereo-visual matching procedure.

2 NEURAL NETWORK FOR CORRECTION OF MATCHING STEREO-IMAGES

For the appropriate matching the stereo-image points, obtaining the optimal solution, author of the paper proposed the use of Hopfield neural network. The solution is based on minimizing the total energy of the neural network, where the inputs are two stereo-images with a $w \times h$ size. Applied neural network has a size $w \times w \times h$ of neurons $\text{neu}_{ijk}$, wherein the potential value of the neuron $v_{ij}$ corresponds to the degree of matching of the i-th point in the left image and the j-th point in the right image on the determined height k from set of $h$ [7]. Fig. 2 presents the assignments matrix of...
potential neural network on the height $k$. The one in the assignment matrix for the $i$-th row, $j$-th column is equivalent to the assignment of the left and right image.

\[ \begin{array}{ccccccc}
1 & 2 & 3 & 4 & 5 & 6 & \cdots w \\
1 & 0 & 0 & 0 & 0 & 0 & 1 \\
2 & 0 & 1 & 0 & 0 & 0 & 0 \\
3 & 0 & 0 & 1 & 0 & 0 & 0 \\
4 & 0 & 0 & 1 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 1 & 0 & 0 \\
6 & 1 & 0 & 0 & 0 & 0 & 0 \\
\end{array} \]

Figure 2. The assignments matrix (potentials of neural network) for stereo-image pixels

Solution of the matching pixels of stereo-images is a multi-criteria problem [8], [9]. The criteria are the components of the energy function of the neural network $\hat{E} = (\hat{E}_1, \hat{E}_2, \hat{E}_3, \hat{E}_4)$, where the value of the minimum of components corresponds to fulfilling the criterion. The need to define the energy equations, acceptable in neural network, enforces transformation of energy vector $\hat{E}$ for a scalar values of the sum of weighted energy components:

\[ \alpha_1 E_1 + \alpha_2 E_2 + \alpha_3 E_3 + \alpha_4 E_4 \quad (1) \]

where:
\[ \alpha_i \] - requires the prioritization of outlined above criteria, solving the multiple criteria problem, including the appointment of weight $\alpha_i$ components of energy function achieved empirically.

The following criteria for the most favorable matching-points of stereo images and image mapping in spatial model of road surface were defined. The first criterion relates the matching factor of stereo-images, where the highest obtained factor value corresponds to the best matching of the stereo-image points. To activate neurons of the best matching were applied the minimization of the energy component of formula: [10]

\[ E_1 = -\sum_{i}^{n} \sum_{j}^{n} \sum_{i'}^{n} \sum_{j'}^{n} C_{ij,i'j'} v_{ij} v_{i'j'}', \quad (2) \]

where:
\[ C_{ij,i'j'} \] - correlation of coefficient pairs of point $(i,j)$ of the right image to the point $(i',j')$ of the left image.
\[ v_{ij}, v_{i'j'} \] - output potential of neurons $\text{neu}_{ij}$ and $\text{neu}_{i'j}$.

The second criterion, unambiguous of assignment of pixels stereo-image, forces according to "the matching direction (matching the pixel of the left image to right image, or matching the pixel of
right image to the left image) for each column, respectively in row, there was at most one non-zero element, signifying association of pixels. In adopted criterion there is possible the lack of allocation of pixels in the stereo-images which means no non-zero elements. Implementation of the criterion ensures minimization of the energy component of the formula:

\[
E_2 = \sum_{i} \sum_{j} \sum_{i'} \sum_{j'} v_{ij} v_{ij'} + \sum_{i} \sum_{j} \sum_{i'} \sum_{j'} v_{ij} v_{ij'}.
\]  

(3)

The third criterion for maintaining order of matching, means, that for neurons \(\text{neu}_{ij}\) and \(\text{neu}_{(i+1)i'}\) contained in the same area, corresponding matching exists for the condition \(i < i'\). Implementation of criterion requires energy minimization using the following:

\[
E_3 = \sum_{i} \sum_{j} \sum_{j'} v_{ij} v_{i+1,j} \sigma_{i,i+1},
\]  

(4)

where:

\(\sigma_{i,i+1} = 1\) for pixels in the same area, \(\sigma_{i,i+1} = 0\) – otherwise.

Fourth criterion, continuity of disparity map, has the task of eliminating sudden changes in the value of disparity map and assumption of the kind of pavement distresses in detection and recording procedures. Implementation of criterion is to minimize the sum of the differences between the disparity in the analyzed area bounded by the edges:

\[
E_4 = \sum_{i} \sum_{j} \sum_{j'} v_{ij} v_{i+1,j} \sigma_{i,i+1} \xi_{i,j',j},
\]  

(5)

where:

\[
\xi_{i,j',j} = \begin{cases} 
((j'-i)-(j-i)) - \alpha & \text{for } j' > j \\
\beta & \text{for } j' \leq j 
\end{cases}
\]  

(6)

where:

\(\beta\) - the value defining the increase of energy while criterion is not accepted,

\(\alpha\) - the value defining tolerable deviation in the accepted criterion.

Comparing the overall pattern for the Hopfield network energy with function of the total energy as a sum of its components, weights of synaptic connections and external currents are shown below formula: [11]

\[
\begin{align*}
t_{ij,i'} & = a \cdot C_{ij,i'} - b \cdot \delta_{ii'} (1 - \delta_{ii'}) - b \cdot \delta_{jj'} (1 - \delta_{ii'}) - c \cdot \rho_{j < j} \delta_{i+1,i} \sigma_{i,i+1} - d \cdot \delta_{i+1,i} \sigma_{i,i+1} \xi_{ij,i'} \\
I_{ij} & = 0
\end{align*}
\]  

(7)
This relationship shows the effect of a recursive neural network Hopfield type.

3. Evaluation of the proposed solution

Implementation of the proposed method for correcting mismatches of stereo-images using a recursive neural network Hopfield type, made it possible to achieve reasonable results of a proper matching of pixels of images. A key element of properly functioning solutions was the problem of local minima of the energy function. According to the theory of neural networks [12] in a particular state network evolution occurs when a neighboring condition has a lower energy value or the network is excited by asynchronous simulation. For the proposed solution is possible only the movement between the hypercube vertices of solutions [11].

The evaluate of used neural network consists in carrying out the process of matching corresponding points on selected fifty pairs of stereo-images in two cases:
- using the only CoVar method [6]
- using the proposed neural network.

In the first case after the matching procedure [13] the corresponding pixels in the stereo-images, which erroneously determining the disparity map, were identified and counted. The numbers of incorrectly corresponding points were presented in the Table. 1, column A. In the second case, the corresponding pixels on the same stereo-images were matching using a neural network. The pixels incorrectly identified using first case were compared with the same pixels for second case. During the comparative analysis the correct changes of matching pixels (column B in Tab.1), the incorrect changes (column C in Tab.1) and also no changes were observed (column D in Tab.1) were noted.

Moderate effectiveness of networks at level of 66% identification the pixels of invisible stereo-images of analyzed potholes in road network enforces modification or application a different solution. In subsequent studies author of the paper will propose a modification of the network structure Hopfield.

4. Conclusions

The presented method of diagnostics of road pavement allows for rapid implementation of measurements, and the complexity of the research. The main problem of stereo-visual solutions is the ambiguity of matching pixels of stereo-images. Proper matching pixels is a composite problem due to the distortion and simplification of operations of optics transformation and optoelectronic systems displacement of developed measuring system. In addition, the impact on the results of measurements has the depth discontinuity occurring in the connection places (in the picture) where there is a large change in intensity of the image - on the brink of a real object.

In the case of diagnosis of road pavement it is assumed that the recorded road pavement is characterized by continuity with the exception of road damages to the type of cracks and deep potholes.

The use of neural networks as a method for correcting the pixel matching in stereo-images has defined the direction of work on a significant reduction or elimination of existing problems in the area of stereo-vision. The structure of the pavement damages, their representation in the digital image and specifics of stereo-visual measuring station of road pavement diagnosis indicates as a
proper the application of neural networks. Further work will consider the modified neural networks, based on the architecture of Hopfield i.e. a deterministic modification of Hopfield networks as the maximum neural network.

Table 1. Results of implemented Hopfield neural network

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>57</td>
<td>33</td>
<td>10</td>
<td>26</td>
<td>37</td>
<td>73</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>55</td>
<td>23</td>
<td>22</td>
<td>27</td>
<td>45</td>
<td>62</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>36</td>
<td>67</td>
<td>25</td>
<td>8</td>
<td>28</td>
<td>28</td>
<td>64</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>66</td>
<td>18</td>
<td>16</td>
<td>29</td>
<td>38</td>
<td>63</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>72</td>
<td>22</td>
<td>6</td>
<td>30</td>
<td>31</td>
<td>68</td>
<td>26</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>60</td>
<td>32</td>
<td>8</td>
<td>31</td>
<td>34</td>
<td>65</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>68</td>
<td>22</td>
<td>10</td>
<td>32</td>
<td>33</td>
<td>61</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>63</td>
<td>31</td>
<td>6</td>
<td>33</td>
<td>41</td>
<td>68</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>73</td>
<td>14</td>
<td>13</td>
<td>34</td>
<td>22</td>
<td>68</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>29</td>
<td>62</td>
<td>24</td>
<td>14</td>
<td>35</td>
<td>36</td>
<td>61</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>11</td>
<td>37</td>
<td>68</td>
<td>22</td>
<td>10</td>
<td>36</td>
<td>41</td>
<td>66</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>12</td>
<td>44</td>
<td>68</td>
<td>18</td>
<td>14</td>
<td>37</td>
<td>44</td>
<td>59</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>34</td>
<td>62</td>
<td>26</td>
<td>12</td>
<td>38</td>
<td>32</td>
<td>75</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>28</td>
<td>71</td>
<td>15</td>
<td>14</td>
<td>39</td>
<td>34</td>
<td>65</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>15</td>
<td>28</td>
<td>68</td>
<td>21</td>
<td>11</td>
<td>40</td>
<td>43</td>
<td>60</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>16</td>
<td>46</td>
<td>52</td>
<td>24</td>
<td>24</td>
<td>41</td>
<td>26</td>
<td>65</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>17</td>
<td>15</td>
<td>67</td>
<td>27</td>
<td>6</td>
<td>42</td>
<td>27</td>
<td>70</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>18</td>
<td>42</td>
<td>67</td>
<td>26</td>
<td>7</td>
<td>43</td>
<td>35</td>
<td>69</td>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td>19</td>
<td>38</td>
<td>66</td>
<td>18</td>
<td>16</td>
<td>44</td>
<td>23</td>
<td>65</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>63</td>
<td>21</td>
<td>16</td>
<td>45</td>
<td>34</td>
<td>71</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>21</td>
<td>18</td>
<td>78</td>
<td>11</td>
<td>11</td>
<td>46</td>
<td>35</td>
<td>74</td>
<td>17</td>
<td>9</td>
</tr>
<tr>
<td>22</td>
<td>28</td>
<td>75</td>
<td>14</td>
<td>11</td>
<td>47</td>
<td>28</td>
<td>71</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>23</td>
<td>29</td>
<td>69</td>
<td>24</td>
<td>7</td>
<td>48</td>
<td>38</td>
<td>58</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>24</td>
<td>25</td>
<td>76</td>
<td>16</td>
<td>8</td>
<td>49</td>
<td>29</td>
<td>59</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>57</td>
<td>30</td>
<td>13</td>
<td>50</td>
<td>44</td>
<td>70</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>
References