Three-Dimensional Reconstruction of Macroscopic Features in Biological Materials

Michal Krumnikl[1], Eduard Sojka[1], Jan Gaura[1], and Oldřich Motyka[2]

[1] Department of Computer Science, VŠB - Technical University of Ostrava
17. listopadu 15/2172, Ostrava, Czech Republic
{Michal.Krumnikl,Eduard.Sojka,Jan.Gaura}@vsb.cz
[2] Institute of environmental engineering, VŠB-Technical University of Ostrava
17. listopadu 15/2172, Ostrava, Czech Republic
Oldrich.Motyka.st@vsb.cz

Abstract. This paper covers the topic of three dimensional reconstruction of small textureless formations usually found in biological samples. Generally used reconstructing algorithms do not provide sufficient accuracy for surface analysis. In order to achieve better results, combined strategy was developed, linking stereo matching algorithms with monocular depth cues such as depth from focus and depth from illumination.

Proposed approach is practically tested on bryophyte canopy structure. Recent studies concerning bryophyte structure applied various modern, computer analysis methods for determining moss layer characteristics drawing on the outcomes of a previous research on surface of soil. In contrast to active methods, this method is a non-contact passive, therefore, it does not emit any kind of radiation which can lead to interference with moss photosynthetic pigments, nor does it affect the structure of its layer. This makes it much more suitable for usage in natural environment.

1 Introduction

Computer vision is still facing the problem of three-dimensional scene reconstruction from two-dimensional images. Not a few algorithms have been developed and published to solve this problem. These algorithms can be divided into two categories; passive and active [1]. Passive approaches such as shape from shading or shape from texture recover the depth information from a single image [2,3,4,5]. Stereo and motion analysis use multiple images for finding the object depth dependencies [6,7,8,9]. These algorithms are still developed to achieve higher accuracy and faster computation, but it is obvious that none will ever provide universal approach applicable for all possible scenes.

In this paper, we present combined strategy for reconstructing three dimensional surface of textureless formations. Such formations can be found in biological and geological samples. Standing approaches suffer mainly from the following shortcomings: high error rate of stereo correspondence in images with large disparities, feature tracking is not always feasible, samples might be damaged by active illumination system, moreover biological samples can even absorb incident light. Observing these drawbacks we have developed system linking several techniques, specially suited for our problem.

A. Fred, J. Filipe, and H. Gamboa (Eds.): BIOSTEC 2009, CCIS 52, pp. 225–234, 2010.

Presented reconstruction method was tested on bryophyte canopies surfaces. Obtaining three dimensional surface is the first stage of acquiring surface roughness, which is used as biological monitor [10,11].

2 Methods

In this section we will briefly describe the methods involved in our system, emphasizing improvements to increase the accuracy and the density of reconstructed points. As the base point, stereo reconstruction was chosen. Selected points from the reconstruction were used as the reference points for depth from illumination estimation. Missing points in the stereo reconstruction were calculated from the illumination and depth from focus estimation. The last technique provides only rough estimation and is largely used for the verification purposes.

2.1 Stereo 3D Reconstruction

The following main steps leading to a reconstruction of a sample surface are performed by particular parts of the system: (i) calibration of the optical system (i.e., the pair of cameras), (ii) 3D reconstruction of the sample surface itself. In the sequel, the mentioned steps will be described in more details.

In the calibration step, the parameters of the optical system are determined, which includes determining the intrinsic parameters of both the cameras (focal length, position of the principal point, coefficients of nonlinear distortion of the lenses) and the extrinsic parameters of the camera pair (the vector of translations and the vector of rotation angles between the cameras). For calibrating, the chessboard calibration pattern is used. The calibration is carried out in the following four steps: (1) creating and managing the set of calibration images (pairs of the images of calibration patterns captured by the cameras), (2) processing the images of calibration patterns (finding the chessboard calibration pattern and the particular calibration points in it), (3) preliminary estimation of the intrinsic and the extrinsic parameters of the cameras, (4) final iterative solution of all the calibration parameters. Typically, the calibration is done only from time to time and not necessarily at the place of measurement.

For solving the tasks that are included in Step 2, we have developed our own methods that work automatically. For the initial estimation of the parameters (Step 3), the method proposed by Zhang [12,13] was used (similar methods may now be regarded as classical; they are also mentioned, e.g., by Heikilla and Silven [14], Heikilla [15], Bouguet [16] and others). The final solution of calibration was done by the minimization approach. The sum of the squares of the distances between the theoretical and the real projections of the calibration points was minimized by the Levenberg-Marquardt method.

If the optical system has been calibrated, the surface of the observed sample may be reconstructed, which is done in the following four steps: (i) capturing a pair of images of the sample, (ii) correction of geometrical distortion in the images, (iii) rectification of the images, (iv) stereomatching, (v) reconstruction of the sample surface.

Distortion correction removes the geometrical distortion of the camera lenses. The polynomial distortion model with the polynomial of the sixth degree is used. The distortion coefficients are determined during the calibration.

Rectification of the images is a computational step in which both the images that are used for reconstruction are transformed to the images that would be obtained in the case that the optical axes of both cameras were parallel. The rectification step makes it easier to solve the subsequent step of finding the stereo correspondence, which is generally difficult. The rectification step is needed since it is impossible to guarantee that optical axes are parallel in reality. We have developed a rectification algorithm that takes the original projection matrices of the cameras determined during calibration and computes two new projection matrices of fictitious cameras whose optical axes are parallel and the projection planes are coplanar. After the rectification, the corresponding points in both images have the same y-coordinate.

The dense stereo matching problem consists of finding a unique mapping between the points belonging to two images of the same scene. We say that two points from different images correspond one to another if they depict a unique point of a three-dimensional scene. As a result of finding the correspondence, so called disparity map is obtained. For each image point in one image, the disparity map contains the difference of the x-coordinates of that point and the corresponding point in the second image. The situation for finding the correspondence automatically is quite difficult in the given context since the structure of the samples is quite irregular and, in a sense, similar to noise. We have tested several known algorithms [9,7,6] for this purpose. The results of none of them, however, are fully satisfactory for the purpose of reconstruction. Finally, we have decided to use the algorithm that was proposed by Ogale and Aloimonos [6] that gave the best results in our tests.

2.2 Auxiliary Depth Estimators

The depth map obtained from the 3D reconstruction is further processed in order to increase the resolution and fill the gaps of missing data. To achieve this we have implemented several procedures based on the theory of human monocular and binocular depth perception [17]. Exploited monoculars cues were depth from the focus and lighting cues.

Depth estimation based on lighting cues was presented in several papers [18,19,20]. Methods proposed in these papers were stand-alone algorithms requiring either calibrated camera or controlled light source. More simplified setup was proposed in [18] using projector mounted on a linear stage as a light source. These approaches calculate depth from multiple images taken from different angles or with varying lighting.

For our application we have developed slightly modified method based on the previous research which is capable of acquiring depths from just one image. Assuming that we have already preliminary depth map (e.g. disparity map from the stereo matching algorithm) we can find the correspondence of depth and the light intensity.

According to the inverse square law, the measured luminous flux density from a point light source is inversely proportional to the square of the distance from the source. The intensity of light I at distance r is $I = \frac{P}{4\pi r^2}, I \propto \frac{1}{r^2}$, here P is the total radiated power from the light source. Analyzed surfaces were approximated by Lambertian reflectors.

In contrast to [18] we are assuming mostly homogeneous textureless uniform colored surfaces. Observing these assumptions we can omit the step involving the computation of the ratio of intensity from two images and alter the equation in order to exploit already known depth estimation from previous 3D reconstruction based on the stereo matching algorithm. Points that show high level of accuracy in the previous step are used as the reference points for illumination estimation. Look-up table, based on the inverse square law, mapping the computed depth to intensity is calculated.

The last method involved in the reconstruction step is the integration of focus measurement. The depth from focus approaches have been used many times for real time depth sensors in robotics [21,22,23,24]. Key to determine the depth from focus is the relationship between focused and defocused images. Blurring is represented in the frequency domain as the low-pass filter. The focus measure is estimated by frequency analysis. Discrete Laplacian is used as the focus operator. For each image segment, depth is estimated as the maximal output of the focus operator. Since the images were taken from short range, the lens focus depth was large enough to capture the scene with high details. Thus only a few focus steps were used in the experiments.

The final depth is calculated as the weighted average from values given by stereo reconstruction process, light intensity and depth from focus estimation. Appropriate weights were set according to the experimental results gained with each method. The graphical illustration (Figure 1) shows the depth of acquired data. Still the biggest disadvantage of camera based scanning technique is the occurrence of occlusions, decreasing the reconstructed point density.

Fig. 1. Comparison of used methods for depth estimation

3 Bryophyte Structure

Bryophytes are plants of a rather simple structure, they lack of roots and conductive tissues of any kind or even structural molecules that would allow establishment of their elements such as lignin [25]. The water which is generally needed for metabolic processes including photosynthesis is in the case of bryophytes also necessary for reproductive purposes, for their spermatozoids, particles of sexual reproduction, are unable

to survive under dry conditions [26]. This makes them, unlike tracheophytes (vascular plants), poikilohydric – strongly dependent on the water conditions of their vicinity [27] – which led to several ecological adaptations of them. One of the most important adaptations is forming of a canopy – more or less compact layer of moss plants, frequently of a same clonal origin, which enables the plants to share and store water on higher, community level.

Recent infrequent studies concerning bryophyte canopy structure applied various modern, computer analysis methods to determine moss layer characteristics drawing on the outcomes of a research on surface of soil [28]. Surface roughness index (L_r) has been hereby used as a monitor of quality and condition of moss layer, other indices, i.e. the scale of roughness elements (S_r) and the fractal dimension (D) of the canopy profile have been used and found to be important as well [29]. As stated in Rice [10], contact probe, LED scanner and 3D laser scanner were used and compared in light of efficiency and serviceability in 27 canopies of different growth forms. However, none of the methods already assessed have not been found to be convenient for field research, especially due to the immobility of used equipment and therefore needed dislocation of the surveyed moss material into the laboratory. This has great disadvantage in destroying the original canopy not only due to the transfer and excision from its environment, but also due to different much dryer conditions affecting moss surface in laboratory.

4 Bryophyte Canopy Analysis

The former methods [29,10] are suitable and efficient for measuring structural parameters in laboratory, but generally are impracticable in the field. Despite the LED scanner is presented as a portable device, it has high demands for proper settings and conditions that has to be maintained.

The method described in this paper presents a new approach using the pair of images taken by the scanning device. Computer analysis involving 3D reconstruction and soil roughness compensation is used to calculate the canopy surface roughness. The main goal was to create a device that can be used in the field, needs a minimum time for settings and is able to operate in the variety of environments.

Our device is composed of hardware parts – optical system consisting of two cameras and software, analyzing acquired images. The images are acquired from two IDS Imaging cameras (2240-M-GL, monochromatic, 1280x1024 pixels, 1/2" CCD with lenses PENTAX, f=12 mm, F1.4) firmly mounted in a distance of 32.5 mm between them (Figure 2, left). Images has been taken in normal light, no auxiliary lamp was used.

Since the cameras mounted in a given distance produce images with relative big disparity, which might produce difficult scenery for stereomatching algorithm, we have created a laboratory device which is able to take images at variable distance. The camera mounted on a linear motion is moved over the sample, taking the images from different positions. Using Kuroda linear motion SG2605A-250P we are able to achieve position accuracy of 0.02 mm with position reproducibility better than 0.003 mm. Image capture is synchronized with movement. Linear stage is mounted on aluminum chassis with embedded computer, motor driver and additional sensor and light driving units. It was

Fig. 2. The pair of cameras mounted on the tripod for mobile use (left) and camera mounted on linear motion with embedded computer for laboratory use (right)

meant to be used as a laboratory instrument but may be used in the field as well due to battery operation. The device is used for longitudinal studies.

4.1 Surface Roughness

Surface roughness is a measurement of the small-scale variations in the height of a physical surface of bryophyte canopies.

For the statistical evaluation of every selected bryophyte, we fitted all measured z-component values that we obtained from the 3D reconstruction (2.1) with a polynomial surface. This surface then represents the mean value of measured z-component. For this step, we have already a full set of x-, y-, and z-components (in meters) from the previous reconstruction process (Figure 3). Bottom figure shows another reconstructed sample of the same species in the original coordinates of the image.

In order to calculate the surface specific parameters, we have to minimize the impact of subsoil segmentation. We have performed a regression using the polynomial expression above to interpolate the subsoil surface. Thus we have obtained the surface that represents the average canopy level. The distances from the reconstructed z-coordinates and the fitting surface were evaluated statistically.

Canopy structure can be characterized by the surface characteristics. The most common measure of statistical dispersion is the standard deviation, measuring how widely z-values are spread in the sample.

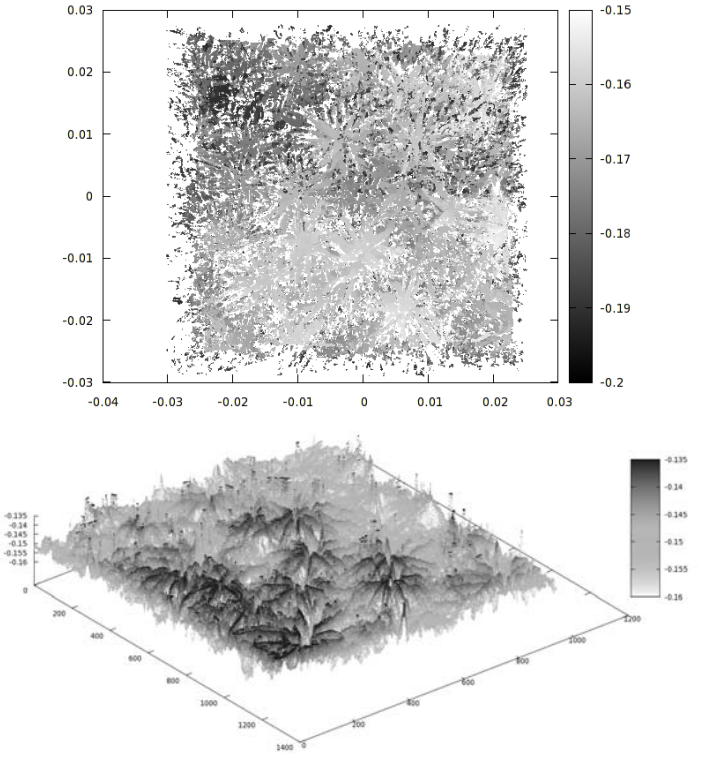

Fig. 3. Z-components from reconstructions (*Polytrichastrum formosum*)

Bryophyte canopy structure is also described by L_r parameter defined by Rice as the square root of twice the maximum semivariance [29]. Semivariance is described by

$$\widehat{\gamma}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} (z(x_i + h) - z(x_i))^2, \tag{1}$$

where z is a value at a particular location, h is the distance between ordered data, and $n(h)$ is the number of paired data at a distance of h [30].

The real surface is so complicated that only one parameter cannot provide a full description. For more accurate characteristics other parameters might be used (e.g. maximum height of the profile, average distance between the highest peak and lowest valley in each sampling length).

5 Results and Discussion

When applied in a study of six bryophyte species [11] surface structure (*Bazzania trilobata*, *Dicranum scoparium*, *Plagiomnium undulatum*, *Polytrichastrum formosum*, *Polytrichum commune* and *Sphagnum girgensohnii*), both in laboratory and *in situ*, mentioned approach was found to be able to obtain data suitable for surface roughness index

calculation (Figure 4). Also, indices calculated in eight specimen per each species (four in laboratory and four in field measurements, total 48 specimens) were found to significantly distinguish the specimens in dependence on species kind; one-way analysis of variance showed high significance ($p = 0,000108$) when data were pooled discounting whether derived from laboratory or from field measurements. Laboratory measurements separate gave not that significant outcomes ($p = 0,0935$), for there were found distinctively different indices of *Dicranum scoparium* specimens in laboratory and in field caused probably by disturbance of their canopies when transferring and storage in laboratory. This is supported by the fact that independent two-sample t-test showed significant difference between laboratory and field measurements outcomes only in case of this one species ($p = 0,006976$). This approach was then found to be suitable to be utilized even under *in situ* conditions which is according to the outcomes of the mentioned study considered to be much more convenient way to study bryophyte canopy structure.

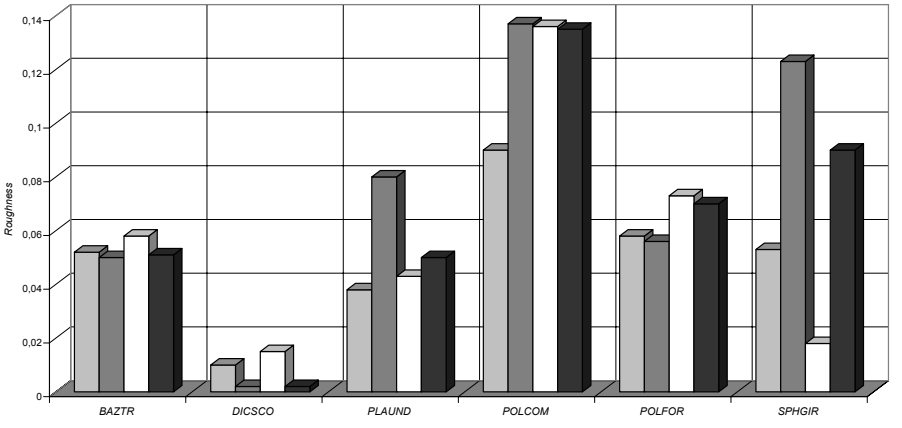

Fig. 4. Obtained roughness in field conditions, the variability between samples of the same species is quite high, especially in the case of *Polytrichum commune*

6 Conclusions

By comparing the results of pure stereo matching algorithms [9,7,6] and our combined approach we have found out our method to be more suitable for homochromatic surfaces. Biological samples we have been working with were typical by the presence of rather long narrow features (leaves or branches). Heavy density of such formations in the images is more than unusual input for the stereo matching algorithms supposing rather smooth and continuous surfaces. Segmentation used by graph cut based stereo matching algorithms usually lead in creating a great many regions without match in the second image.

Without using additional cues, described in this paper, results of reconstructed image was poor, usually similar to noise without and further value for bryophyte analysis.

Meanwhile our reconstruction process produce outputs that are sufficient for further biological investigation. Both number of analyzed specimens and number of obtained z-values for statistical analysis are unprecedented and this approach is so far the only one successfully used in field. Further research will be carried out in order to describe the surface more appropriately for biological purposes.

References

1. Jarvis, R.A.: A perspective on range finding techniques for computer vision. IEEE Trans. Pattern Analysis and Machine Intelligence 5, 122–139 (1983)
2. Horn, B.: Robot Vision. MIT Press, Cambridge (1986)
3. Horn, B., Brooks, M.: The variantional approach to shape from shading. In: Computer Vision Graphics and Image Processing, vol. 22, pp. 174–208 (1986)
4. Coleman Jr., E., Jain, R.: Shape from shading for surfaces with texture and specularity. In: IJCAI 1981, pp. 652–657 (1981)
5. Prados, E., Faugeras, O.: Shape from shading: a well-posed problem? In: Computer Vision and Pattern Recognition, vol. 2, pp. 870–877 (2005)
6. Ogale, A., Aloimonos, Y.: Shape and the stereo correspondence problem. International Journal of Computer Vision 65(3), 147–162 (2005)
7. Kanade, T., Okutomi, M.: A stereo matching algorithm with an adaptive window: Theory and experiment. IEEE Transactions on Pattern Analysis and Machine Intelligence 16(9), 920–932 (1994)
8. Sun, J., Li, Y., Kang, S.B., Shum, H.Y.: Symmetric stereo matching for occlusion handling. In: CVPR 2005: Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2005), Washington, DC, USA, vol. 2, pp. 399–406. IEEE Computer Society, Los Alamitos (2005)
9. Kolmogorov, V., Zabih, R.: Computing visual correspondence with occlusions using graph cuts. In: ICCV, vol. 2, p. 508 (2001)
10. Rice, S.K., Gutman, C., Krouglicof, N.: Laser scanning reveals bryophyte canopy structure. New Phytologist 166(2), 695–704 (2005)
11. Motyka, O., Krumnikl, M., Sojka, E., Gaura, J.: New approach in bryophyte canopy analysis: 3d image analysis as a suitable tool for ecological studies of moss communities? In: Environmental changes and biological assessment IV., Scripta Fac. Rerum Natur. Univ. Ostraviensis (2008)
12. Zhang, Z.: Flexible camera calibration by viewing a plane from unknown orientations. In: International Conference on Computer Vision (ICCV 1999), Corfu, Greece, pp. 666–673 (1999)
13. Zhang, Z.: A flexible new technique for camera calibration. IEEE Transactions on Pattern Analysis and Machine Intelligence 22, 1330–1334 (2000)
14. Heikilla, J., Silven, O.: A four-step camera calibration procedure with implicit image correction. In: IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 1997), pp. 1106–1112 (1997)
15. Heikilla, J.: Geometric camera calibration using circular control points. IEEE Transactions on Pattern Analysis and Machine Intelligence 22(10), 1066–1077 (2000)
16. Bouguet, J.Y.: Camera calibration toolbox for matlab (2005), `http://www.vision.caltech.edu/bouguetj/calib_doc/index.html`
17. Howard, I.P., Rogers, B.J.: Binocular Vision and Stereopsis. Oxford Scholarship Online, 212–230 (1996)

18. Liao, M., Wang, L., Yang, R., Gong, M.: Light fall-off stereo. In: Computer Vision and Pattern Recognition, pp. 1–8 (2007)
19. Magda, S., Kriegman, D., Zickler, T., Belhumeur, P.: Beyond lambert: reconstructing surfaces with arbitrary brdfs. In: ICCV, vol. 2, pp. 391–398 (2001)
20. Ortiz, A., Oliver, G.: Shape from shading for multiple albedo images. In: ICPR, vol. 1, pp. 786–789 (2000)
21. Wedekind, J.: Fokusserien-basierte rekonstruktion von mikroobjekten. Master's thesis, Universitat Karlsruhe (2002)
22. Chaudhuri, S., Rajagopalan, A., Pentland, A.: Depth from Defocus: A Real Aperture Imaging Approach. Springer, Heidelberg (1999)
23. Nayar, S.K., Watanabe, M., Noguchi, M.: Real-time focus range sensor. IEEE Transactions on Pattern Analysis and Machine Intelligence 18(12), 1186–1198 (1996)
24. Xiong, Y., Shafer, S.: Depth from focusing and defocusing. Technical Report CMU-RI-TR-93-07, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA (1993)
25. Crum, H.: Structural Diversity of Bryophytes, p. 379. University of Michigan Herbarium, Ann Arbor (2001)
26. Brodie, H.J.: The splash-cup dispersal mechanism in plants. Canadian Journal of Botany (29), 224–230 (1951)
27. Proctor, M.C.F., Tuba, Z.: Poikilohydry and homoiohydry: antithesis or spectrum of possibilites? New Phytologist (156), 327–349 (2002)
28. Darboux, F., Huang, C.: An simultaneous-profile laser scanner to measure soil surface microtopography. Soil Science Society of America Journal (67), 92–99 (2003)
29. Rice, S.K., Collins, D., Anderson, A.M.: Functional significance of variation in bryophyte canopy structure. American Journal of Botany (88), 1568–1576 (2001)
30. Bachmaier, M., Backes, M.: Variogram or semivariogram - explaining the variances in a variogram. Precision Agriculture (2008)