Proceedings of the 2018 Design of Medical Devices Conference
DMD2018
April 9-12, 2018, Minneapolis, MN, USA

DMD2018-6964

REAL-TIME ROBUST 3D PLANE EXTRACTION FOR WEARABLE ROBOT PERCEPTION AND CONTROL

Ran Duan
Department of Mechanical Engineering,
City College of New York
New York, NY, USA

Shuangyue Yu
Department of Mechanical Engineering,
City College of New York
New York, NY, USA

Guang Yue
Kessler Foundation and Rutgers University New Jersey Medical School,
East Hanover, NJ, USA

Richard Foulds
Department of Biomedical Engineering,
New Jersey Institute of Technology,
Newark, NJ, USA

Chen Feng
Mitsubishi Electric Research Labs
Cambridge, MA, USA

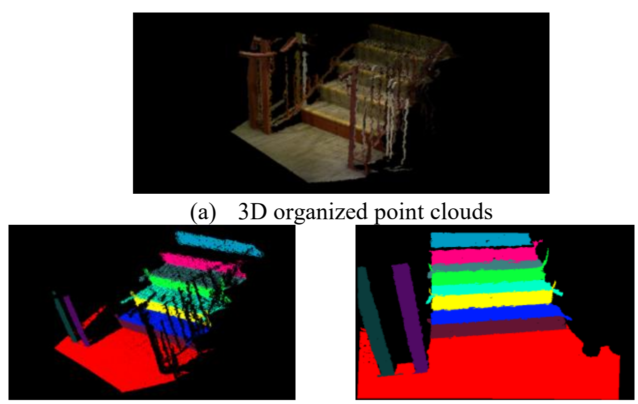
Yingli Tian
Department of Electrical Engineering,
City College of New York
New York, NY, USA

Hao Su
Department of Mechanical Engineering,
City College of New York
New York, NY, USA

BACKGROUND

Wearable environment perception system has the great potential for improving the autonomous control of mobility aids [1]. A visual perception system could provide abundant information of surroundings to assist the task-oriented control such as navigation, obstacle avoidance, object detection, etc., which are essential functions for the wearers who are visually impaired or blind [2, 3, 4]. Moreover, a vision-based terrain sensing is a critical input to the decision-making for the intelligent control system. Especially for the users who find difficulties in manually achieving a seamless control model transition.

Terrain sensing is widely demanded by mobility aid devices such as lower limb exoskeleton system. Without the assistance of intelligent system, the users are usually required to go through intensive training to learn how to switch the locomotion for different types of terrain such as ramp, level grounds with different surface properties, stair, etc. It is even more difficult for the user who cannot see. Although being investigated for years and much progress in detection accuracy and robustness has been made [5, 6], the wearable terrain sensing system remains a challenging problem. While the laser distance sensor in conjugation with inertial measure unit (IMU) [7] has shown the limited yet efficient perception of terrain, the variation of environment may cause suboptimal estimation and the IMU errors are unfortunately inevitable. Recently notable work [8] reported favorable performance using monocular vision and depth sensor for identifying stair terrains. However, these methods are highly sensitive to the setup of the RGBD camera.



(a) 3D organized point clouds

(b) 3D extracted planes

(c) 2D sketch map

Fig. 1 The terrain sensing result using fast plane extraction method. (a) shows the stairs terrain obtained by RGBD camera. (b) and (c) show plane extraction results in 3D point clouds and 2D image plane.

This paper proposes an RGBD camera-based wearable visual perception system. The novelty of this work is the development and evaluation of a 3D environment sensing by performing a fast and accurate plane extraction algorithm [9] (see Fig.1). Compared with the algorithm in [8] that suffers from performance degradation due to the increasing of angle of intersection and lateral distance, the proposed algorithm is immune to the change of camera location and orientation during human locomotion. Experimental results using this method conducted on a wearable camera system show that the proposed method outperforms the state-of-the-art perception methods in terms of accuracy, robustness, and efficiency.

METHODS

3D vision systems play an important role to assist stair terrain perception in performing multiple planes segmentation/extraction. First and foremost, the algorithm must be applicable to organized point clouds obtained by an RGBD camera and extracts planes in real-time. The camera device must be wearable and low-cost. In this design, the RGB image with registered depth information is obtained from a wearable RGBD sensor.

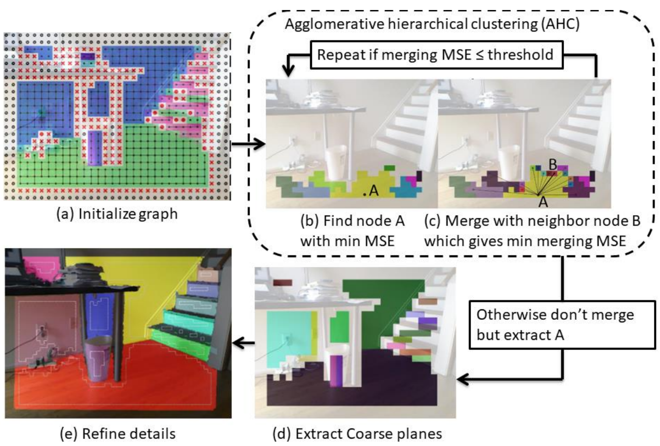


Fig.2 Algorithm overview. In (a), each node colored by its normal; black dot and line showing graph node and edge; red 'x', black 'o', and red dot showing node rejected by depth discontinuity, missing data, and too large plane fitting MSE, respectively. Regions with random colors in (b) and (c) show graph nodes merged at least once, where the black lines in (c) show all edges coming out from the node A, in which the thick line shows the edge to the node B that gives the minimum plane fitting MSE when merging the node A with one of its neighbors.

Figure 2 shows the overview of the fast plane extraction algorithm. The proposed plane extraction method consists of three phases and runs on each frame independently. Initially, the point clouds are uniformly divided into non-overlapping groups in the image space. An initialized graph is subsequently constructed, whose nodes (black dots) and edges (black lines) represent the groups aforementioned and their neighborhood, respectively. Meanwhile, the nodes rejected by depth discontinuity, missing data, and large plane fitting mean squared error (MSE) are plotted by red 'x', black 'o', and red dot respectively. Then the algorithm extracts the coarse planes, i.e., systematically merges nodes belonging to the same plane, by performing an agglomerative hierarchical clustering (AHC) on this graph. The AHC repeats the two steps until the plane fitting MSE exceeds a threshold: (1) finding the region that has the minimum plane fitting MSE and (2) merging it with one of its neighbors such that minimize the plane fitting MSE of merge results. The last phase is the segmentation refinement. While coarse segmentations are already useful in many applications, a pixel-wise region growing approach is employed to refine artifacts in the coarse segmentation when necessary.

RESULTS

We have extensively evaluated the plane extraction method on the same stairs throughout the multiple walking trials. Fig. 3 illustrates the perception results of approaching and walking up/down stairs.

Average processing time using different initial nodes are shown in Table 1 (frame resolution: 640*480). Starting from node size 10*10 pixel, the proposed plane extraction method achieves real-time processing (FPS > 30 Hz) on an ordinary laptop with Intel Core i7-2760QM CPU of 2.4GHz and RAM of 8GB.

Table 1. Average processing time in different initial node size

Initial Node Size (pixel)	Initial Graph	AHCluster	Refine	Total Time (ms)
4*4	18	62	19	98
8*8	9	13	14	36
10*10	8	8	10	26
16*16	7	3	10	20
20*20	6	1	10	17

The accuracy evaluation results on two SegComp [10] datasets are shown in Table 2, where the image datasets are acquired using ABW structured light scanner and a Perceptron laser range finder. The ground truth of each database is given by average number of connected instances.

Table 2. Accuracy evaluation on SegComp datasets

Property	ABW	PERCEPTRON
Regions in ground truth	15.2	14.6
Correctly detected	12.8 (84.2%)	8.9 (60.9)
Orientation deviation (°)	1.7	2.4
Over-segmented	0.1	0.2
Under-segmented	0.0	0.2
Missed (not detected)	2.4	5.1
Noise (non-existent)	0.7	2.1

Compared with the results in [5], the stair sensing using the proposed method demonstrates significantly improved accuracy, robustness, and time efficiency. We also observe that the scenes of stair terrain (include stairs and walls) have been properly reconstructed by our plane extraction approach. The precise bounders of stair and wall regions are critical information for the accurate motion control of a wearable robot. Moreover, the algorithm runs in real time such that only minor delay is caused by our vision feedback. This allows the devices deal with more complex events. For instance, the falling-down avoidance of the lower limb exoskeletons requires the immediate response of the control system, of which the feedback can be obtained by the abrupt visual motion.

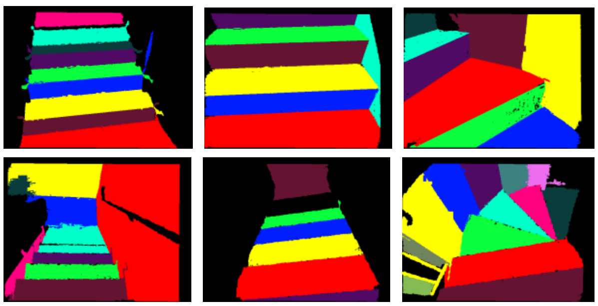


Fig.3 Plane extraction results. Top images: environment plane segmentation during stair descending; Bottom images: environment plane segmentation during stair descending. The results indicate that the proposed method is able to provide accurate segmentation for both ascending and descending stairs and is robust to the change of camera pose and different types of stair. In contrast, the state-of-the-art method [5] is susceptible to the angle and height of the camera during human locomotion. Furthermore, it does not handle ramps or descending stairs.

INTERPRETATION

In this paper, we presented a RGBD camera based wearable environment perception system for 3D terrain sensing. A fast plane extraction algorithm is employed to extract multiple planes from the organized point clouds. The experiments showcased the proposed system's ability of real-time stair perception. The produced results demonstrated that our method outperforms the start-of-the-art stair segmentation methods in terms of accuracy, robustness, and time efficiency. Our system provides a real-time 3D visual feedback that could benefit the intelligent control and system decision-making of the wearable robot.

The major limitation of this perception method is that it is only applicable to flat planes. Although man-made structures mainly consist of planes, it is desirable to be able to sense curved surfaces. In addition to terrain sensing, the scenes understanding, for example, could be developed for navigation, obstacle avoidance, falling-avoidance, etc., which have a wide range of applications in helping people in their daily life. Especially for the visually impaired people or senior citizens, the capability of informing user through biofeedback for fall prevention will significantly reduce the risk of serious injury. For the environmental perception applications, future work involves the data collection about real scene such as stair height, length, and amount for visual estimation enhancement. Thus, the system will be able to have a better measurement of the real world to increase accuracy of control. Other sensors can also be integrated into our system to provide prior information. The proposed perception system makes wearable robot more flexible, versatile and intelligent in real environment.

REFERENCES

[1]. Y. Tian, W. R. Hamel and J. Tan, "Accurate Human Navigation Using Wearable Monocular Visual and Inertial Sensors," in *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 1, pp. 203-213, Jan. 2014.

[2]. R. Munoz, X. Rong, and Y. Tian, Depth-aware Indoor Staircase Detection and Recognition for the Visually Impaired, The 3rd IEEE International Workshop on Mobile Multimedia Computing (MMC 2016) in conjunction with ICME 2016.

[3]. S. Wang, H. Pan, C. Zhang, and Y. Tian, RGB-D Image-Based Detection of Stairs, Pedestrian Crosswalks and Traffic Signs, Journal of Visual Communication and Image Representation (JVCIR), Vol. 25, pp263-272, 2014.

[4]. J. P. Mũnoz, B. Li, X. Rong, J. Xiao, Y. Tian, and A. Arditi, An Assistive Indoor Navigation System for the Visually Impaired in Multi-Floor Environments, IEEE Int. Conf. on CYBER Technology in Automation, Control, and Intelligent Systems (IEEE-CYBER), 2017.

[5]. N. E. Krausz and L. J. Hargrove, "Recognition of ascending stairs from 2D images for control of powered lower limb prostheses," *2015 7th International IEEE/EMBS Conference on Neural Engineering (NER)*, Montpellier, 2015, pp. 615-618.

[6]. S. Wang and H. Wang, "2D staircase detection using real AdaBoost," *2009 7th International Conference on Information, Communications and Signal Processing (ICICS)*, Macau, 2009, pp. 1-5.

[7]. M. Liu, D. Wang and H. Helen Huang, "Development of an Environment-Aware Locomotion Mode Recognition System for Powered Lower Limb Prostheses," in *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 4, pp. 434-443, April 2016.

[8]. N. E. Krausz, T. Lenzi and L. J. Hargrove, "Depth Sensing for Improved Control of Lower Limb Prostheses," in *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 11, pp. 2576-2587, Nov. 2015.

[9]. C. Feng, Y. Taguchi and V. R. Kamat, "Fast plane extraction in organized point clouds using agglomerative hierarchical clustering," *2014 IEEE International Conference on Robotics and Automation (ICRA)*, Hong Kong, 2014, pp. 6218-6225.

[10]. A. Hoover *et al.*, "An experimental comparison of range image segmentation algorithms," in *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 18, no. 7, pp. 673-689, July 1996.