

An Automated Robot-assisted 3D Reconstruction System for Adit

Yang Lei^{1,2}, Li En¹, Liang Zize¹

1. The State Key Laboratory of Management and Control for Complex Systems,
Institute of Automation Chinese Academy of Sciences, Beijing 100190, China
2. the University of Chinese Academy of Sciences, Beijing 100049, China
{leiyang2014,en.li,zize.liang}@ia.ac.cn

Abstract—In the geological exploration of the Adit, the texture, section, joint and other rock structural information are important factors to determine the stability of the Adit. Therefore, the collection and analysis of rock data information are the premise work and the key process of the safe production. Faced with the actual requirements of Adit 3D reconstruction, an automatic 3D reconstruction system is designed to replace human work. Aimed at and the special structure of the Adit, a novel mobile robotic platform is designed to realize the automatic image collection of the Adit. At the same time, this paper combines with SFM(Structure from Motion) algorithm and PMVS(Patch-based Multi-view Stereo) algorithm to realize automatic Adit 3D reconstruction. The experimental results show that this system can better replace human work to finish the task of Adit 3D reconstruction without any prior knowledge.

Keywords—Adit; robotic; 3D Reconstruction; SFM; PMVS;

I. INTRODUCTION

In recent years, the basic construction occupies a large proportion in the national life and production. The engineering geological exploration is the foundation work of the infrastructure construction, and it plays a key role in the promotion of the engineering progress^[1]. During the actual production, the Adit is a horizontal channel on the ground and it bears much important functions in the production and construction, such as material transport, pedestrian, drainage, ventilation and so on. Therefore, the Adit plays a very crucial role in the entire production process and the geological exploration of the Adit is very necessary.

In the geological exploration of the Adit, the texture, section, joint and other rock structural information are important factors to determine the stability of the Adit. So the collection, measurement and analysis of rock data information are the essential link of the safety production. Meanwhile, the 3D information could provide much information about the Adit structure. Therefore, to ensure the project progress and safe production, realizing the automated and fast 3D reconstruction of the Adit is a key issue of the engineering construction. However, the Adit has the poor and complex working environment, and it also has much uncertain dangerous situations for the builders in the Adit. The traditional measurement methods are mostly based on the artificial field measurement. These methods are more complex and they need huge workload to finish the measurement task. And these methods have the disadvantages of low efficiency, high labor intensity and so on. Therefore, a novel mobile robotic platform

is designed to replace human work and realize the automatic 3D measurement of the Adit.

With the development of computer vision and photogrammetry technology, these methods are gradually applied into the geological exploration to serve the infrastructure construction. During much researches of geological exploration, there are two common methods: laser scanner^[2] and photogrammetry^[3]. The laser scanners have the advantages of high precision and simple characteristics. However, the laser scanners cannot obtain the color information of the scene surface and the cost of the laser scanners is relatively high. The photogrammetry methods have many advantages than laser scanners, such as abundant information, low cost, flexible operation and so on. Based on the processing and analysis of a series of overlapping images or video sequences, a 3D model with texture is extracted to realize the 3D reconstruction of the object or the environment scene. Therefore, the photogrammetry is applied into this paper to serve the structure analysis of the Adit.

At present, there are mainly three kinds of photogrammetry methods: depth-map merging^[5], volumetric-based method^[4] and feature-based method^{[6]-[8]}. During the depth-map merging method, the image sets are divided into some small image sets to calculate the depth maps, and the 3D reconstruction is realized by merging a series of depth map. However, this method also has some certain limitations. Especially when the image number inside the image set is relatively small, it will lead to the failure of 3D reconstruction. The volumetric-based method is realized by the way of discretization of the space, but this method has the disadvantage of the finite precision and it is only suitable for on the 3D reconstruction of small objects. Feature-based approach achieves the 3D reconstruction through the extraction and matching of a series of feature points. During the much researches of 3D reconstruction based on feature points, the common algorithms are Bundler^[9], CMP-MVS^[10] and PMVS^[11]. The output results of Bundler are sparse point cloud, and this sparse point cloud is sufficient for robot applications, measurement applications and so on. However, it is not suitable for the visualization requirements of the Adit. The PMVS algorithms and CMP-MVS algorithms could get a dense point cloud of the object or scene information through the input of a series of images and the camera pose information.

In this paper, an automated robot-assisted 3D reconstruction system for Adit is designed to realize the automatic 3D measurement of the whole Adit, which includes a

novel mobile robot platform and 3D reconstruction system. The main contributions of this paper are described as follows. (1) Faced with the site environment of the Adit, an automated mobile robot platform is designed to realize image collection of Adit. (2) To realize the 3D reconstruction of the Adit, some advanced computer vision tools are adopted in the measurement application of Adit. This paper is organized as follows. The second chapter describes the robotic platform and the style of working. The third chapter describes the algorithm of the 3D reconstruction of the Adit in detail. Finally, the experiments results and summary are described.

II. SYSTEM CONFIGURATION

A. System Platform

Since the Adit is the cave temporary drilled during the process of exploration, the planes of the roads are usually not flat and the internal environment is relatively dark. For the non-engineering person to collect images of the whole Adit, the environment of the Adit is full of uncertainty and much danger. And the images by manual collection are not guaranteed to meet the experimental requirements of 3D reconstruction. Therefore, in this paper, a special mobile robotic system is designed to replace the human labor and realize the automatic image collection of the Adit.

The Adit is a horizontal channel on the ground. Based on the special structure of the Adit, the image collection could be realized by the rotation motion and translation motion. Therefore, the body of the robotic mobile platform is divided into two parts: rotation platform and translation platform. And the digital camera is fixed on the rotating platform for image collection. The picture of the whole system is shown in the Figure 1.



Fig. 1. The Adit mobile platform

According to the structure of the system platform, the working style of the robotic mobile platform is described as follows:

(1) Set the working parameters of the whole system, such as rotation parameters, translation parameters, LED light source brightness and so on;

(2) According to the rotation angle and speed parameters, the rotation platform drives the digital camera to rotate until the

appropriate location and the camera shoots to collect the Adit images. Then the rotation platform rotates to another location to collect Adit image. This step is finished when the images of one circled Adit are collected.

(3) According to the translation distance and speed parameters, the translation platform drives the system platform until the appropriate location and repeats the step two. The work of image collection is finished when the images of the whole Adit are collected.

The motion diagram of the whole system platform is shown in the Figure 2. During the process of image collection, there must be enough coincidence between adjacent Adit images, which is the key of 3D reconstruction. T represents the translation distance of the translation platform and Ω represents the rotation angle of rotation platform. And the values of T and Ω are decided by the real experiments in the Adit.

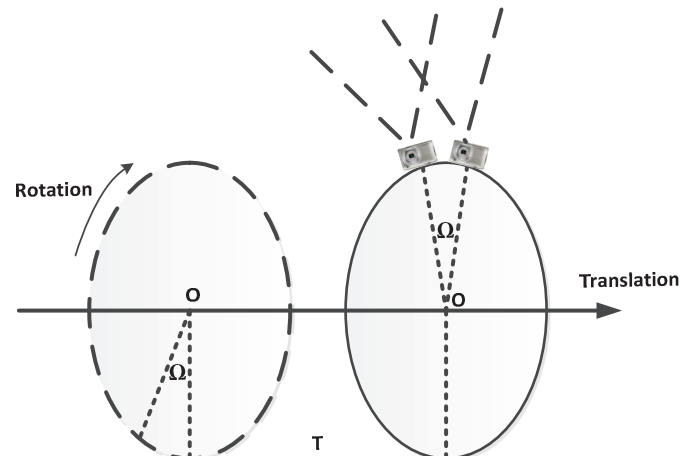


Fig. 2. Schematic diagram of Adit car operation

B. System Structure

To realize the automatic image collection of the Adit, the architecture of the Adit mobile robot platform includes power system, camera, light system, remote controller, track, rotation platform and translation platform.

The power system supplies the energy for the entire system to keep the system working normally. The remote controller can control the working of the system platform and set the values of the system parameters. The digital camera is responsible for image collection and storage. The rotation system and translation system cooperate with each other and work together to finish the task of image collection. Because the brightness of the Adit is relatively dark and greatly affects the quality of images, an auxiliary light system is added into the system. Meanwhile, the roads of the Adit are not flat and the planes of the roads are full of stones, the track is needed to save the battery energy and keep the system working longer time. Therefore, the system block diagram of the mobile robot platform can be simply described in the Figure 3.

During our previous work, the controller of the mobile robot system is based on the fractional order PID controller^[12] and it could realize the precise control of the camera and the

car body, which could provide better control effect than the PID controller.

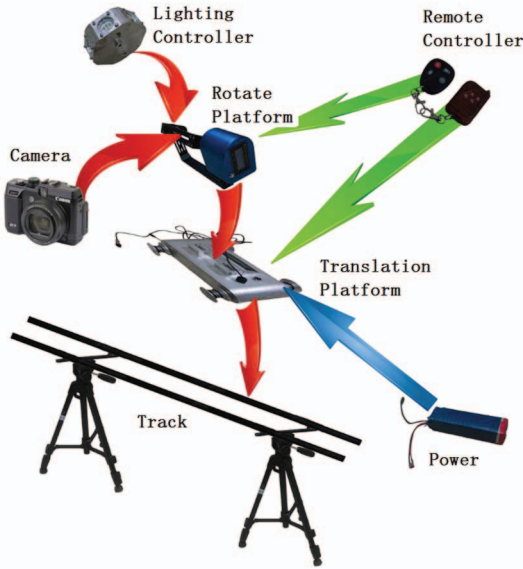


Fig. 3. The block diagram of Adit mobile platform

III. ADIT RECONSTRUCTION

A. Feature extraction and Matching

During the process of 3D reconstruction, the core problem is to solve the 3D coordinates of the matched feature points. Not only that, the effect of the 3D reconstruction is closely related to the number of the feature points. Therefore, feature extraction and matching are the basic and important task of 3D reconstruction.

At present, the common operators have Harris^[13], SIFT^[14], Brisk^[15] and so on. The Harris operator has the advantages of simple calculation, fast calculation speed, but it is sensitive to rotation and scale change. The BRISK operator has the most outstanding performance in the larger blurred image registration. The SIFT operator is invariant to image scaling, rotation and affine transformation. Therefore, the SIFT operator is adopted to finish the feature extraction and matching in this paper.

After the initial matching of the feature points based on SIFT operator, there must be some false matches due to the influence of the noise factors. These false matches will affect the solution of 3D reconstruction and camera position. The RANSAC robust algorithm is adopted in this paper to remove the false matching in the images.

B. Structure From Motion

The SFM algorithm is to recover the 3D coordinates and camera parameters according to the 2D images. It begins by two images to get camera position and structure information. Then, the initial reconstruction could be realized by the principle of the triangulation. Finally, the bundle adjustment algorithm is applied to optimize 3D information of camera position and camera parameters through the non-linear minimization function of the re-projection errors^[16]. The

objective function of the minimization error is shown as follows.

$$M = \min_{P_i, X_i} \sum_{i=1}^m \sum_{j=1}^n d(x_{ij}, P_i X_i) \quad (1)$$

where x_{ij} is the coordinate of the j -th feature point in the i -th image. P_i is the camera projective matrix of the i -th image and X_i is the 3D coordinate of the feature point.

The SFM algorithm is an iterative computation process. And the spare reconstruction could be realized by adding the remaining images one by one. Here, the experimental results of SFM algorithm based on 48 Adit images are shown in the Figure 4.

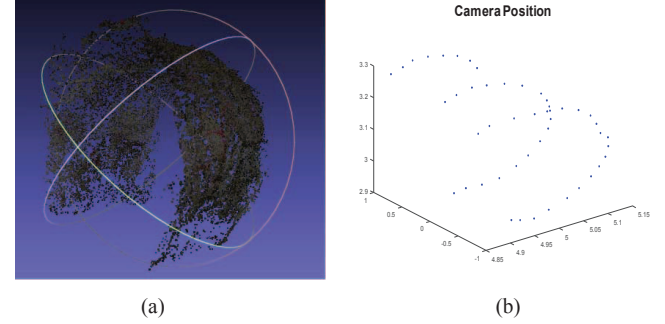


Fig. 4. (a)The spare point colud of Adit; (b) Camera trajectory

According to the above experimental results, the spare point could better reflect the structure of the Adit. But the details of the Adit cannot be clearly displayed, such as texture, section, joint and so on. Therefore, this spare point cloud cannot be directly applied into the geological analysis of the Adit. However, the SFM algorithm could better solve the camera trajectory and the camera trajectory is consistent with real camera motion.

C. Dense Reconstruction

The output of SFM algorithm is sparse point cloud of the scene, this sparse point cloud is sufficient for robot applications, measurement applications and so on. However, the point cloud is not enough for the visualization requirements of the scene. Therefore, the dense reconstruction algorithm is needed to improve the results. The current common methods of dense reconstruction are PMVS and CMP-MVS. The CMP-MVS algorithm can get a relatively dense point cloud. However, the reconstruction result contains a lot of noise information, which seriously affects surface reconstruction of the scene. Compared with CMP-MVS algorithm, the PMVS algorithm has more prominent performance on accuracy and integrity of 3D reconstruction. Therefore, the PMVS algorithm is adopted in this paper to finish dense reconstruction of the Adit.

The PMVS(Patch-based Multi-view Stereo) algorithm is based on patch model to finish the dense reconstruction. To better explain the PMVS algorithm, the following definitions are given in the Figure 5.

1).Patch Model: The shape of Patch is a rectangle and it includes the center of the patch $c(p)$ and the unit normal vector $n(p)$. And $R(p)$ is the reference image of the patch. Therefore, the models of patch and image model are shown as follows. Due to the factors of light, occlusion, motion blur and so on, some patches cannot be identified and these patches are set as

quasi visual patches $S(p)$ and the real visible patches are set as $T(p)$. The initialization of these variables is shown as follows:

$$R(p) = \min_{I \in T(p)} h(p, I, J) \quad (2)$$

$$S(p) = \{I | I \in I_m, n(p) \cdot \frac{c(p) \cdot o(I)}{|c(p) \cdot o(I)|} > \cos(\pi/3)\} \quad (3)$$

$$C(p) = \{C_i(x', y) | p \in Q_i(x, y), |x - x'| + |y - y'| = 1\} \quad (4)$$

$$T(p) = \{I | I \in I_m, S(p), h(p, I, R(p)) \leq \alpha\} \quad (5)$$

where the function $h(p, I, J)$ represents the evaluation function of gray consistency between image I and image J .

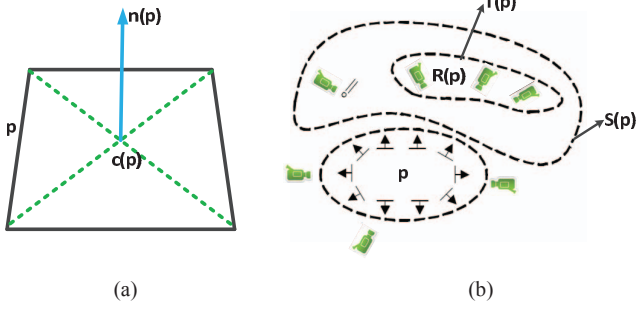


Fig. 5. (a)The model of patch; (b) Image Model

2).Photometric Consistency Constraint: For the patch p , the NCC normalization algorithm is used to evaluate the photometric consistency.

$$\tilde{N}(p) = 1/(|T(p) - 1|) \sum_{I \in T(p), I \neq R(p)} N(p, R(p), I) \quad (6)$$

3).Visibility Consistency Constraint: The visibility size of patch p is decided by the patch set of $T(p)$ and $S(p)$. During the different stage, the definition of the patch set of $T(p)$ and $S(p)$ is different.

A. Matching Stage: The patch p is decided from the spare matching.

$$S(p) = T(p) = \{I | N(p, R(p), I) > \alpha_0\} \quad (7)$$

B. Expansion stage: The definition of the patch set $S(p)$ is based on the threshold of depth map.

$$S(p) = \{I | d_I(p) \leq d_I(i, j) + \rho_1\} \quad (8)$$

where the function $d_I(i, j)$ represents the cell depth of image I and the patch p . ρ_1 is decided according to the distance between the cell depth and β_1 pixel in the patch $R(p)$. The definition of $T(p)$ could be derived based on the patch $S(p)$.

$$T(p) = \{I \in S(p) | N(p, R(p), I) > \alpha_1\} \quad (9)$$

The processes of the PMVS algorithm could be divided into three steps and these steps are feature extraction and matching, diffusion and filtering. The diffusion is the core part of the PMVS algorithm. Therefore, the main process of the PMVS algorithm is described as follows:

1. Feature extraction and matching: According to the operators of Harris and DOG, the feature points of all the images could be extracted. Then the matched feature point could be realized by the epipolar constraint. Finally, the final patch set is decided by the optimal feature set through the method of minimize gray difference.

2. Diffusion: During the adjacent image blocks $C_i(x, y)$ of patch p , the adjacent patch p' of the patch p is extended. The initialization of the patch p' is realized

from the information of the patch p . The variables of $c(p')$ and $n(p')$ are solved by the optimization process and a new patch could be generated. These processes are repeated until these patches can recover the entire object surface.

3. Filtering: In order to remove the erroneous patches in the reconstruction process, the filtering process is done after the diffusion process is over. And the erroneous patches could be eliminated through the visibility consistency constraint and photometric consistency constraint. Through the iterative process of diffusion and filtering, the dense patches could be got and the dense reconstruction could be realized.

Therefore, according to these analysis of the propose methods, the entire processes of the whole system are shown in the Figure 6. It mainly consists of image collection, feature extraction and matching, spare reconstruction and dense reconstruction.

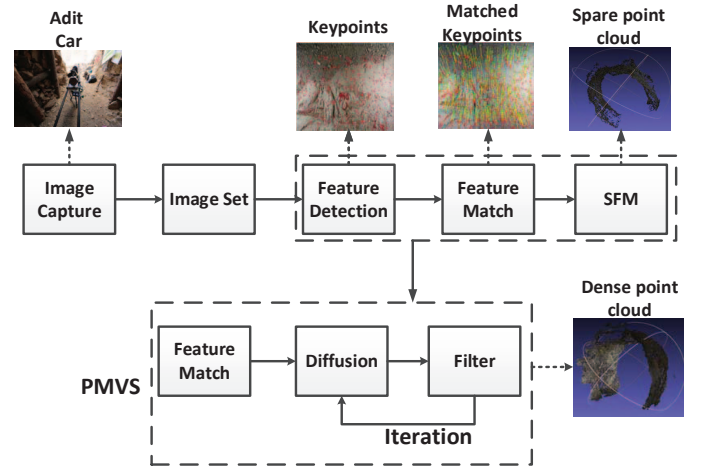


Fig. 6. The system flow of the Adit measurement

IV. EXPERIMENTS

To better verify the performance of the proposed methods, some experiments are done in the Adit. The picture of the system platform in the Adit is shown in the Figure 7.



Fig. 7. The experiments of Adit measurement

A. 3D Reconstruction

Aimed at the requirements of Adit 3D measurement, the Adit images are collected by the Adit mobile robot platform automatically. Then the 3D reconstruction of the Adit is realized by the proposed method. The specific experimental results of Adit 3D measurement are shown in the Figure 8.

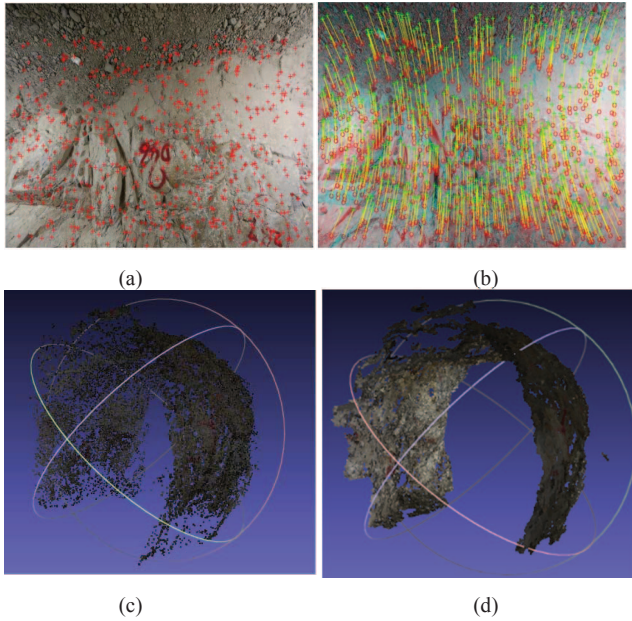


Fig. 8. (a)Feature extraction; (b) Feature matching; (c) The spare point cloud;(d)The dense reconstruction of the Adit;

According to the above experimental results, the proposed method could better finish the task of Adit reconstruction. The SIFT operator could detect much feature points in the Adit images. And it also could realize the feature matching and the matched feature points are consistent with real camera motion. Meanwhile, aimed at the spare point cloud of the Adit, the PMVS algorithm could better finish the dense reconstruction.

To better verify the performance of the proposed method, some common methods are set as the comparison test in this paper. The Bundler and CMVS-PMVS algorithm are applied into the Adit reconstruction and the specific experimental results are shown in the Figure 9.

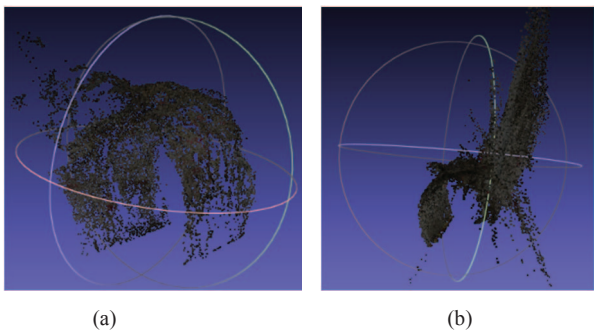


Fig. 9. (a)Bundler; (b) CMVS-PMVS;

From the experimental results, it could be clearly seen that the result of the Bundler algorithm is a sparse point cloud and the point cloud could not meet the real measurement

requirements of Adit. The CMVS-PMVS algorithm generates the error reconstruction results and it could not be applied into the Adit measurement. While the point cloud of the Figure 9_d generated by proposed algorithm contains less noise point and the structure and details could be seen clearly. Therefore, the proposed method has a better performance than other 3D reconstruction methods.

To better finish the visualization of the Adit, the Poisson algorithm can create a very smooth surfaces based on that point cloud with noisy data and it is widely applied into the surface reconstruction^[17]. Therefore, the Poisson algorithm is adopt in this paper and the specific experimental results of surface reconstruction are in the Figure 10.

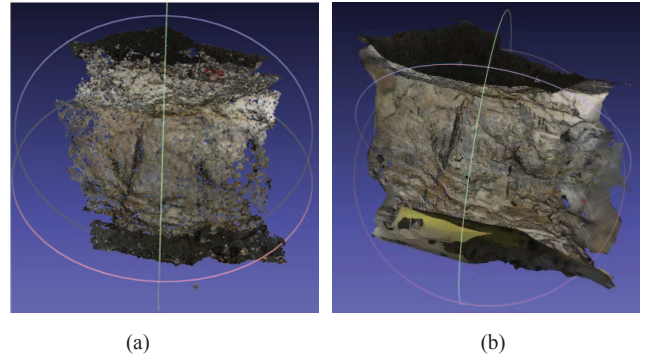


Fig. 10. (a)The point cloud; (b) The mesh of the Adit;

According to the above experimental results, the details of the Adit are clearly displayed. Through the data analysis of the point cloud, it could better serve in the geological exploration. Therefore, the propose method could better realize the Adit measurement.

B. System Parameters

During the 3D reconstruction of the Adit, the efficiency of the 3D reconstruction and the number of images are closely related. When the number of the image gets increased, the time of 3D reconstruction will become longer. In the process of data collection, the number of the Adit images could be decided by the rotation parameter of the system platform. However, in the process of 3D reconstruction, there must be enough overlap between adjacent images. For keeping the quality of 3D reconstruction, it is very important to determine the proper motion parameters of the system platform to ensure the efficiency of the 3D reconstruction.

Here, two group experiments are done to test the effect of the sparse reconstruction and dense reconstruction with different system parameters. The specific experimental results are shown in the Table I.

TABLE I. THE RESULTS OF 3D RECONSTRUCTION

Case	Angle	Image Size	Image Number	Point cloud	Time(min)
SFM	8°	1200*800	48	34772	158
SFM	16°	1200*800	24	11852	62
PMVS	8°	1200*800	48	106101	256
PMVS	16°	1200*800	24	77806	81

From the above experimental results, it could be seen that when the rotation angle of system platform becomes larger, the image set become less and the speed of 3D reconstruction has been significantly improved. Due to the decrease of image count, some details of the Adit are loss. Through the test of many experiments, the suitable system parameters are shown in the Table II and it could meet the real requirements of Adit measurement.

TABLE II. THE SYSTEM PARAMETERS

System Platform	System parameters
Rotating platform	20cm
Moving platform	10°

CONCLUSION

In this paper, faced with the real requirements of Adit measurement, an automatic 3D reconstruction system is designed for the Adit. The system includes an automatic robotic mobile platform and a 3D reconstruction system. It could realize the automatic image collection and 3D reconstruction without any prior knowledge. The following conclusions are drawn as follows.

1. Aimed at the structure of the Adit environment, a novel robotic mobile platform is designed to replace human work and realize the automatic collection of Adit images.

2. Through the analysis and experiment, the 3D reconstruction system for Adit is proposed which includes some advanced computer vision tools, such as SIFT operator, SFM algorithm, PMVS algorithm and so on. Through the experimental verification, it has better performance than Bundler and CMVS-PMVS algorithm.

3. This system could better finish the task of Adit 3D reconstruction without any prior knowledge and the experimental results meet the real requirements of Adit measurement.

In the future research, we will improve our current work and try to construct a complete geological analysis system for the geological exploration.

ACKNOWLEDGMENT

This work is supported by National Science and Technology Support Program of China (2015BAK06B01) and the National Natural Science Foundation(NNSF) of China (61403372 and 61403374).

The author is grateful to the anonymous reviewers as well as to the Editors for their valuable suggestions. Meanwhile, the author is also thankful to the lab of Institute of Automation, Chinese Academy of Sciences for providing the excellent research facilities and environment.

REFERENCES

- [1] Gong J, Cheng P, Wang Y. Three-dimensional modeling and application in geological exploration engineering[J]. Computers & Geosciences, 2004, 30(4): 391-404.
- [2] Xiong X, Adan A, Akinci B, et al. Automatic creation of semantically rich 3D building models from laser scanner data[J]. Automation in Construction, 2013, 31: 325-337.
- [3] Javernick L, Brasington J, Caruso B. Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry[J]. Geomorphology, 2014, 213: 166-182.
- [4] Vogiatzis G, Hernández C, Torr P H S, et al. Multiview stereo via volumetric graph-cuts and occlusion robust photo-consistency[J]. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2007, 29(12): 2241-2246.
- [5] Li J, Li E, Chen Y, et al. Bundled depth-map merging for multi-view stereo[C]//Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on. IEEE, 2010: 2769-2776.
- [6] Ling L, Burrent I S, Cheng E. A dense 3D reconstruction approach from uncalibrated video sequences[C]//Multimedia and Expo Workshops (ICMEW), 2012 IEEE International Conference on. IEEE, 2012: 587-592.
- [7] Seeger M, Gronz O, Klaes B, et al. The effect of object characteristics and image quality on 3D-modelling by Structure-from-Motion[C]//EGU General Assembly Conference Abstracts. 2014, 16: 7293.
- [8] Yang Y, Chang M C, Wen L, et al. Efficient large-scale photometric reconstruction using Divide-Recon-Fuse 3D Structure from Motion[C]//Advanced Video and Signal Based Surveillance (AVSS), 2016 13th IEEE International Conference on. IEEE, 2016: 180-186.
- [9] Snavely N, Seitz S M, Szeliski R. Modeling the world from internet photo collections[J]. International Journal of Computer Vision, 2008, 80(2): 189-210.
- [10] Jancosek M, Pajdla T. Multi-view reconstruction preserving weakly-supported surfaces[C]//Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference on. IEEE, 2011: 3121-3128.
- [11] Furukawa Y, Ponce J. Accurate, dense, and robust multi-view stereopsis[J]. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2010, 32(8): 1362-1376.
- [12] Yang L, Li E, Liang Z. The novel control method for the adit data collection system[C]// IEEE International Conference on Mechatronics and Automation. 2016.
- [13] Chen L, Lu W, Ni J, et al. Region duplication detection based on Harris corner points and step sector statistics[J]. Journal of Visual Communication and Image Representation, 2013, 24(3): 244-254.
- [14] Leutenegger, S., M. Chli and R. Siegwart. "BRISK: Binary Robust Invariant Scalable Keypoints", Proceedings of the IEEE International Conference, ICCV, 2011.
- [15] Wang S, Cui C, Niu X. Watermarking for DIBR 3D images based on SIFT feature points[J]. Measurement, 2014, 48: 54-62.
- [16] Pradeep V, Konolige K, Berger E. Calibrating a multi-arm multi-sensor robot: A bundle adjustment approach[C]//Experimental robotics. Springer Berlin Heidelberg, 2014: 211-225.
- [17] Orts-Escolano S, Garcia-Rodriguez J, Morell V, et al. 3D surface reconstruction of noisy point clouds using growing neural gas: 3D object/scene reconstruction[J]. Neural Processing Letters, 2016, 43(2): 401-423.