TOWARDS VISUALIZING CANAL CROSS-SECTION USING DATA ACQUIRED FROM TELEOPERATED BOAT

Supannee Tanathong[1], Kurt T. Rudahl[2] and Sally E. Goldin[3]
[1,3]KMUTT Geospatial Engineering and InnOvation Center (KGEO),
Institute of Field Robotics, King Mongkut's University of Technology Thonburi
[2]Department of Computer Engineering, King Mongkut's University of Technology Thonburi
126 Pracha Uthit Road, Bangmod, Thungkhru, Bangkok, 10140, Thailand,
Email: [1]stanathong@yahoo.co.uk, [2]rudahl@rsgis.net, [3]seg@goldin-rudahl.com

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ABSTRACT: Floods are the most frequent hazard in Thailand and have become a common occurrence over the past three years. To reduce the severity of flooding and minimize the area affected by floods, an effective flood diversion plan is necessary. Field surveys can provide profiles of canals and rivers which are critical inputs to develop such a plan. However, they are a slow endeavor and usually provide a discontinuous picture of surveyed area. To overcome these problems, this study equips a teleoperated boat with a 2D laser scanner, a single-beam depth sounder, and GPS/IMU sensors to make it possible to measure canal profiles during navigation along the waterway. In order for these data to be used for flood preparedness, they must be presented as graphical images. This paper describes the development of an application that enables the visualization of the cross-sections of the canals from the laser scanner, depth sounder, and geolocation data. The experimental results have been shown to be promising. Given that sensor data are reliable, the proposed application to visualize the cross-sections of waterways will effectively support flood management officers in issuing adequate water diversion plans for flood preparedness.

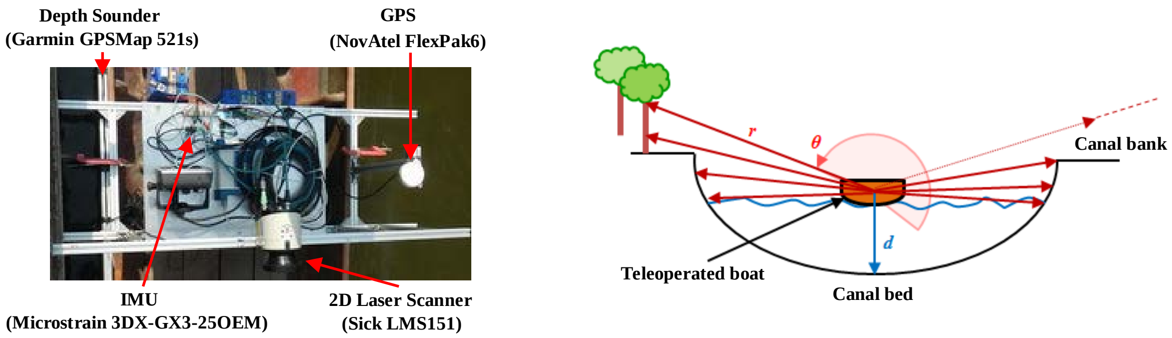
1. INTRODUCTION

Floods are the most frequent hazard in Thailand and have become a common occurrence over the past three years. In fact, flooding has always been a recurring hazard in Thailand, but recently, due to rapid urban development and deforestation, flooding has become more severe. In 2011, floods resulted in more than 680 losses of lives, affected more than 13 million people, inundated more than 5.5 percent of total landmass and accounted for 46.5 billion USD losses in Thai economy (The World Bank, 2012). To reduce the extent of damage and minimize the area affected by floods, a flood diversion plan is necessary. In order to develop an effective plan, flood management officers need to understand the profiles of waterway. These profile data should, at least, include physical descriptions of canal banks, width between two sides of canal, depth of canal bed and water level.

Field surveys through direct measurement can provide profiles of canals and rivers which are critical inputs to create such a plan. However, they are a slow endeavor and the collected data are usually spatially sparse. Although Terrestrial Laser Scanner (TLS) offers a rapid acquisition of surveyed data, since it requires a manual placement for every survey stations, it provides a discontinuous picture of surveyed area. In addition, because laser pulses cannot penetrate into water, this technique cannot provide depth of canal bottom. To overcome these problems, this study equips a teleoperated boat with a 2D laser scanner, a single-beam depth sounder, and GPS/IMU sensors to make it possible to measure canal profiles during navigation along the waterway. In order for these data to be useful resources for flood preparedness, we develop an application that enables the graphical visualization of canal profiles from the laser scanner, depth sounder, and geolocation data. In this paper, the implementation of the application is discussed and the focus is on creating cross-section images of the canal. We begin by introducing the data acquisition system which uses a teleoperated as a mobile platform.

2. DATA ACQUISITION AND GEOREFERENCING

In this work, we equip a teleoperated boat with a 2D laser scanner, a single-beam echo sounder, and GPS/IMU sensors. These sensors are installed on the boat as illustrated in Figure 1(a). A 2D laser scanner works by emitting laser pulses to the scanned objects, in which its data include the distance between the scanner and the object surface, denoted as r, and the angle of the laser pulses, θ, measured from the starting angle as presented in Figure 1(b). For Sick LMS151 laser scanner, the starting scan angle is -45° and θ is defined in the range of $-45^\circ \leq \theta \leq 225^\circ$ such that the field of view is 270°. In this study, the scanning frequency is set to 50Hz in which 1080 pulses are emitted per scan round producing a high density of laser pulses. The single-beam echo sounder transmits sonar pulses through water to measure the depth of the canal bed, shown as d in Figure 1(b).



(a) Sensor installation (b) Data acquisition

Figure 1. The mobile data acquisition system.

Since both laser data and depth data are measured independently in their own local coordinate systems, in order for these data to be used complementarily to create the picture of canals, they must be georeferenced into the same coordinate system, principally the world coordinate system (GCS). Using GPS/IMU data, the laser data acquired in the laser scanner coordinate system (LCS) can be transformed into the world coordinate system, defined as LP^{GCS}, using Eq. (1) and using Eq. (2) for the depth data defined in the depth coordinate system (DCS) into GCS, referred to as DP^{GCS}. DCS has the same orientation as the boat coordinate system (BCS) which rotates for ω, ϕ, and κ around the X, Y and Z axis of the North-East-Down coordinate system (NED) (Cai *et al.*, 2011). ω, ϕ, and κ are the rotation angles determined by the IMU sensor.

$$LP^{GCS} = GPS^{GCS} + O^{BCS} + R_{BCS}^{GCS}\left[\left(O^{LCS} - O^{BCS}\right) + R_{LCS}^{BCS} \times \begin{bmatrix} r\cdot\cos\theta \\ r\cdot\sin\theta \\ 0 \end{bmatrix}\right] \quad (1)$$

$$DP^{GCS} = GPS^{GCS} + O^{BCS} + R_{BCS}^{GCS} \times \left[\left(O^{DCS} - O^{BCS}\right) + \begin{bmatrix} 0 \\ 0 \\ d \end{bmatrix}\right] \quad (2)$$

P^{C} denotes a 3D coordinate with respect to the coordinating system *C*, and GPS^{GCS} is the world coordinates of the boat measured at the position of the GPS sensor. R_{A}^{B} refers to a 3D rotation matrix that transforms a point in the coordinating system A into B. Figure 2 illustrates the rotation matrices and the coordinating systems defined in this work. Ideally, GPS, IMU, 2D laser scanner and depth sounder should be installed on the boat at the same position, preferably the centroid of the boat. Since all of these sensors cannot share the same position due to their size, lever arm offsets must be included in the computation. Instead of using the offsets directly, the equations use the positions of IMU (O^{BCS}), 2D laser scanner (O^{LCS}) and depth sounder (O^{DCS}) which are specified with respect to the position of GPS (O^{GPS}), see Figure 3. In order to define these positions, let O^{GPS} be *(0,0,0)*. A sensor that is on the right side of GPS will have a positive X-coordinate and its value equals to the offsets between them. Similarly, a sensor placing front ahead of GPS and above will have a positive Y-coordinate and a positive Z-coordinate, respectively. Since both Eq. (1) and Eq. (2) produce 3D points, laser and depth data collected along a canal while navigating the boat will generate point clouds that picture the canal in 3D.

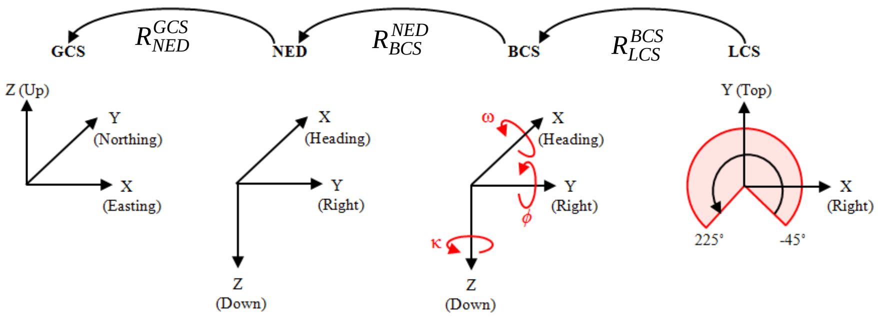


Figure 2. Transformation of coordinating system.

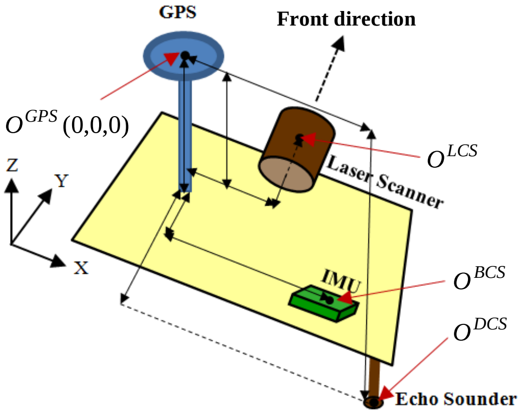


Figure 3. Installation positions of sensors with respect to the position of GPS.

3. APPLICATION DEVELOPMENT

The application to reconstruct canals in 3D and visualize the cross-sections of canals was developed in the C/C++ language. We used the OpenGL library to facilitate graphical image rendering, and used the Qt library to create graphical user interface that allows the users to interact with the application and adjust the visualization results. This section discusses the input data and the process to convert them into georeferenced 3D points. We explain the data structure and the detail of creating cross-section images. The general system architecture and the point cloud coloring method were discussed in our recent paper (Tanathong *et al*., 2014).

3.1 Input Data

The application requires the GPS/IMU data as mandatory inputs in conjunction with either one or both of laser data and depth data depending on the expected results. If a complete 3D view of a canal is expected, both laser and depth data must be input into the application. If only canal bank is to be visualized, laser data must be entered while inputting only depth data for canal bed. The format for each data file used in this work is presented as Figure 4. Note that these three sources of data are synchronized by acquisition time.

%Time	East	North	Height	Roll	Pitch	Yaw
0:0:52.868	659676.04	1506158.68	11.5984	0.0133	0.0195	-2.9249
0:0:54.985	659675.90	1506157.67	6.6245	-0.0314	0.0200	-2.9155
0:0:57.861	659673.24	1506158.00	5.5789	0.0016	0.0206	-2.9006
0:0:57.861	659672.73	1506157.55	5.8967	-0.0373	0.0206	-2.9058
0:0:57.861	659675.61	1506155.17	9.0289	0.0058	0.0225	-2.9233
0:1:2.852	659677.63	1506155.60	11.0524	-0.0215	0.0209	-2.9335
0:1:4.932	659674.60	1506154.99	11.8582	-0.0263	0.0212	-2.9577
0:1:7.808	659673.61	1506154.56	13.0270	-0.0477	0.0236	-2.9755
0:1:9.925	659674.91	1506154.22	10.5578	-0.0098	0.0223	-2.9702
0:1:12.45	659675.28	1506154.00	8.9303	-0.0046	0.0221	-2.9635

(a) GPS/IMU data file

%Time	Distance	Laser angle
0:0:52.868	5475	- 45.00°
0:0:52.868	5514	- 45.25°
0:0:52.868	5518	- 45.50°
......		
0:0:52.868	5520	225.00°
0:0:54.985	5481	- 45.00°
0:0:54.985	5485	- 45.25°
0:0:54.985	5484	- 45.50°
......		
0:0:54.985	5494	225.00°

(b) Laser data file

%Time	Depth
0:0:52.868	0.78
0:0:54.985	0.76
0:0:57.861	0.81
0:0:57.861	0.76
0:0:57.861	0.79
0:1:2.852	0.78
0:1:4.932	0.76
0:1:7.808	0.82
0:1:9.925	0.79
0:1:12.45	0.76

(c) Depth data file

Figure 4. Data file format.

3.2 Data Structure

The GPS/IMU records must be stored in an internal storage, defined as an array of GPSIMU_RECORDs, such that the application can immediately retrieve these data for drawing the trajectory line of the boat to aid the interpretation of visualized canal scenes. On the contrary, the laser and depth data are not kept as raw inputs but converted into 3D points and stored into an array of 3DPOINTs to be visualized as 3D point clouds.

```
struct GPSIMU_RECORD
    { TIME_FORMAT tTimestamp; float gpsX; float gpsY; float gpsZ; float roll; float pitch; float yaw; }

struct 3DPOINT { float X; float Y; float Z; int C; }
```

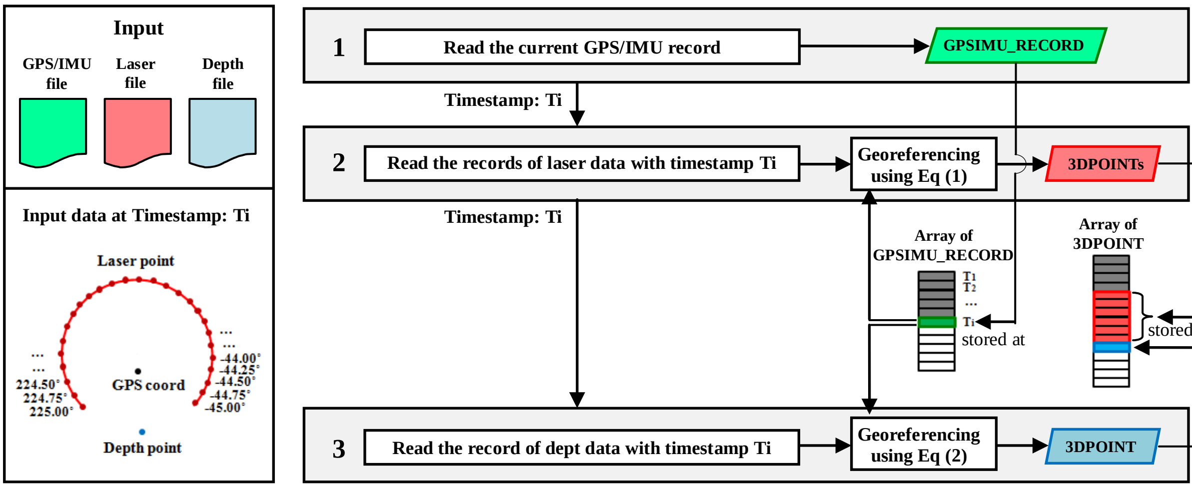


Figure 5. Input data processing procedure.

3.3 Input Data Processing

When the input data files are entered into the system, the application processes the data according to the procedure summarized in Figure 5. First, a record from the GPS/IMU file is read and stored into the array of GPS/IMU records. Second, the laser file is read and only the records with their timestamp corresponding to that of the previously processed GPS/IMU record are georeferenced using that GPS/IMU record. The second step results in a number of 3D points and they are stored in the array of 3D points according to the order that they are processed. In the third step, the depth record with timestamp *Ti* is converted into a 3D point using the read GPS/IMU data, and then stored into the 3D point storage. These three steps are repeated until there is no record in the GPS/IMU file remained unprocessed. This processing procedure intuitively sorts the 3D points in the point cloud storage by the acquisition time.

3.4 Implementation of Visualizing Cross-Section

Plotting onto the display screen the 3D points retrieved from the 3D point storage presents the image of canal profiles in 3D. Although these 3D points are said to be presented in 3D, since the display screen is flat and has only two dimensions, they, in fact, are positioned as 2D points on screen. The process that converts the 3D coordinates into their corresponding 2D positions on a flat screen is known as *projection* (consult Shreiner *et al.* (2013) for more detail), while the reversed process is unofficially referred to as *unprojection*.

Prior to documenting canal cross-section profiles, field surveyors have to locate good positions to survey (Harrelson *et al.*, 1994). These surveyors either walk along the stretch of canals in search of those positions or obtain them using maps. Similarly, in order to visualize a cross-section image of the canal reconstructed from the data acquired from the teleoperated boat, the users browse along the 3D canal by customizing the viewing parameters, then mark a good position by clicking on the display screen. The user-click action unprojects the 2D screen coordinate at the clicked position (x′,y′) into its corresponding 3D coordinate (X,Y,Z). The obtained coordinate is then searched through the array of 3D points to find the closest matched point. *N* number of 3D points stored in the array adjacently to the matched points are retrieved to produce the cross-section image of the selected position. According to the OpenGL specification, the screen coordinate system is that the X axis moves from left to right of the screen, the Y axis moves towards the top of the screen, and the Z axis comes out of the screen (Hearn and Baker, 2004). Therefore, the cross-section view of the canal is presented by rotating the X axis by -90° such that the Z axis will direct towards the top of the screen hiding the Y values in display. The procedure to visualize cross-sections is summarized as Figure 6.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The application offers users functionalities to visualize, in different perspectives, canal images reconstructed from data collected by the teleoperated boat, as illustrated in Figure 7. To have a better understanding of the surveyed canal, the users may present the results as a top-view image to extract the width of the canal or, possibly, pinpoint where along the canal that may block the water flow. The side-view shows users depths at each position along the navigation path, while, in 3D mode, users may rotate the scene to measure the height of canal banks. In addition, the user can export the 3D point clouds into files for use with commercial GIS applications.

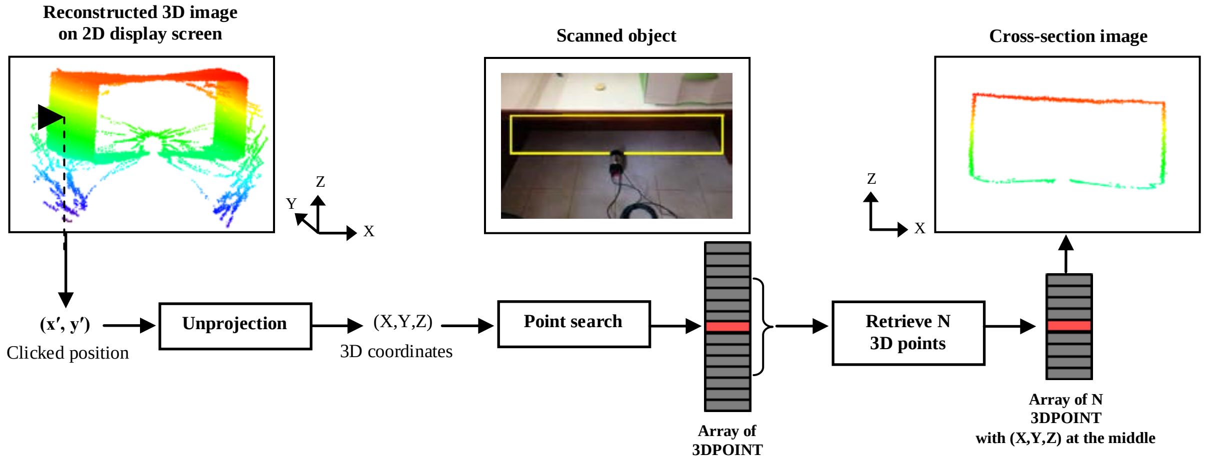
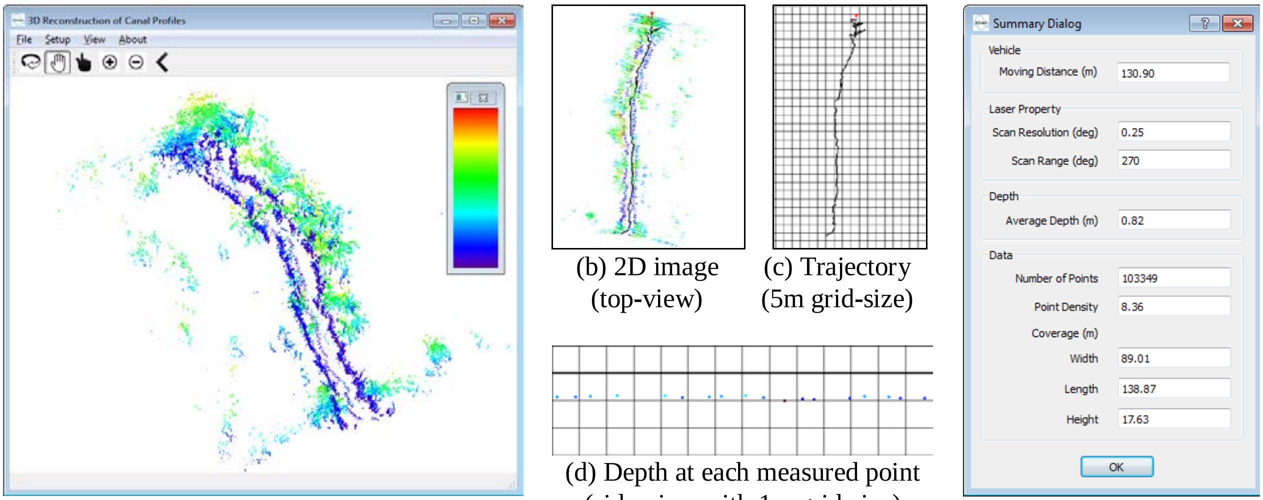


Figure 6. Procedure to visualize cross-sections.



(a) Main application displaying a 3D canal

(b) 2D image (top-view)

(c) Trajectory (5m grid-size)

(d) Depth at each measured point (side-view with 1m grid-size)

(e) Data properties

Figure 7. Application results.

This section focuses on analysing the results of producing cross-section images. The experimental data set is obtained by navigating the teleoperated boat along a canal in the outskirts of Bangkok. The canal has concrete banks stretched along its left side while the banks on its right side are part of agricultural land. There are sparse bushes and trees along both sides of the canal. Due to unreliability of the elevation (Z) values measured using GPS, we discard the elevation values (by substituting them with zero, thus effectively using the surface of the water as the vertical reference).

Figure 8 shows the 3D visualization result of the surveyed data and its cross-sections at the marked positions. The 3D result on the left image is rotated in which the Y-axis aligns with the navigation path and the X-axis spans across the canal on the right side of the boat while the Z-axis directs towards the sky. The dark blue colored areas represent the two banks of the canal, with the white area in between being the canal itself. The line of the points in the middle of the two banks corresponds to the depth positions of the canal bed. The light green, yellow and red scattered around the canals are bushes and trees that grow beyond the banks.

The left sub-images present the cross-section images of the selected positions marked by four numbers on the right image. Grid lines are presented on the background to assist users in estimating the scale of the image. The dimension of a grid cell is 5×5m. The sub-image (1) presents the cross-section image at the position (X: 659673.85, Y: 1506141.65, Z: -0.35). Two short lines of dark blue points correspond to the banks of the canal with approximately 6-7m wide. The yellow and the green above the blue points are trees that grow above the banks. The two blue dots between the two banks are the points on the canal bottom. Although the canal bottom points are expected to be located lower than the positions of canal banks, because the GPS's Z values are discarded, they appear almost at the same elevation as the banks. For this case, users may instead select to visualize the depth points with respect to the positions of the boat presented as the trajectory path, see Figure 7(d). The sub-image (2) and (3) presents the cross-sections at the positions (X: 659664.26, Y: 1506094.65, Z: 0.87) and (X: 659660.62, Y: 1506084.29, Z: -0.55), where trees are only appeared on the left side of the canal. The sub-image (4) shows that the canal at this position (X: 659661.01, Y: 1506058.17, Z: -0.99) is more narrow than other part of the canal. The cross-section shows the width of the canal to be less than 5m.

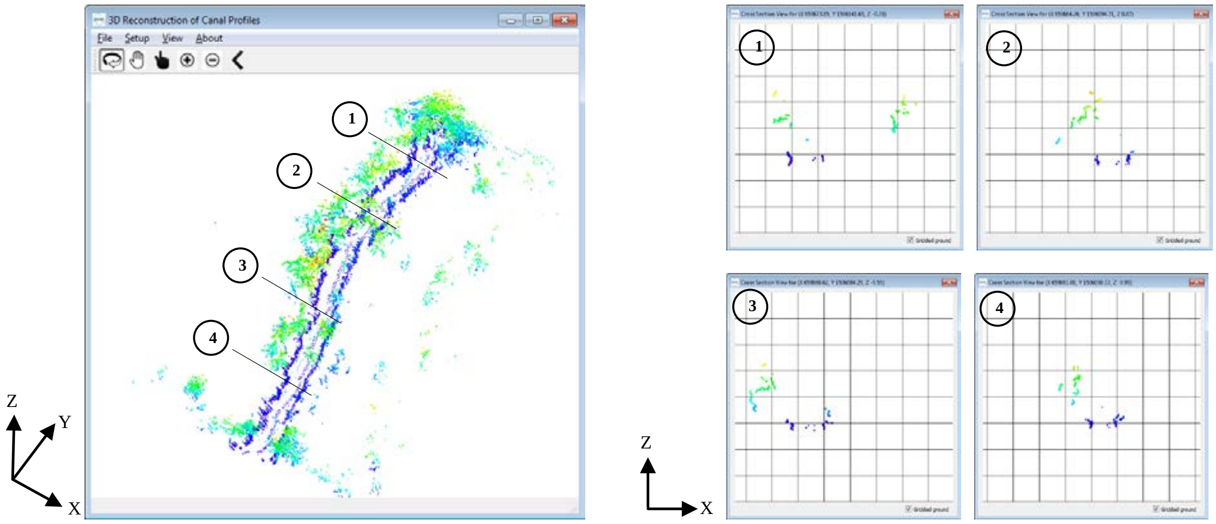


Figure 8. 3D image and its cross-sections.

5. DISCUSSIONS AND CONCLUSIONS

In this study, we present an application that enables the graphical visualization of canal profiles from the laser scanner, depth sounder, and geolocation data acquired using a teleoperated boat. We begin by introducing the mobile data acquisition system and explaining how to georeference these three sources of data into the absolute world coordinate system. We discuss the data structure and how to process input data as well as the method to create cross-section images. The experimental results tested with real data have been shown to be promising. In addition to presenting 3D canals which sufficiently well model the real ones, we show that the cross-section images can accurately produced. However, discarding the GPS’s elevation values, due to their unreliability, may incorrectly locate the canal bottom to be upper or lower than its true position. This may cause users to wrongly interpret the information about the surveyed canal. If exist, a method to improve the accuracy of the GPS’s Z values should be added to the hardware system. An alternative solution offered by the application is that the users may select to interpret the canal bottom by visualizing depth points with respect to the boat position. If we assume reliable input data from teleoperated boat, we believe that the application will be useful for flood management officers to understand canal profiles and assist them to develop an effective water diversion plans for flood preparedness.

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