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Mobile Mapping for Earthwork Monitoring: A Case Study on the Convergence of Photogrammetry with Advanced Positioning Techniques for Maximum Productivity and Accuracy

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ABSTRACT

Establishing a new standard and calibre of Geomatics in the real estate industry utilizing state-of-the-art technologies defines an important application chosne by Limitless for earthwork monitoring for the “Arabian Canal project”. Two mobile mapping platforms were chosen, namely: a helicopter-based Applanix DSS integrated with an LMS-Q240 LIDAR, and a land-based Applanix LandMark. The Applanix DSS produces directly georeferenced high-resolution orthomosaic color maps and high-accuracy 3D terrain measurements in the form of laser point clouds and digital surface models. Similarly, the Applanix LandMark produces georeferenced oblique video imagery and high density laser point clouds. The two aforementioned data sets are combined to produce a high-accuracy, high-density 3D terrain model of the dig with built in redundancy. A dedicated GNSS reference station network including five GPS stations and Leica GNSS Spider software provide the necessary RTK correction data for the entire area.

This paper demonstrates the various techniques utilized to use such technologies efficiently. The quality control procedure used to assure quality mapping products including a 10 cm precision in timely fashion (within a week) is presented. The results of the deliverables using the Airborne- and the land-based Mobile Mapping Systems in the Arabian Canal project are presented for vast and fast earthwork monitoring method that proved to be a very efficient for cost-reduction and time-saving.

1. INTRODUCTION

Limitless, a Dubai World business unit, is a global integrated real estate developer, specialized in master-planning of large scale mixed-use projects and conceptualization and execution of waterfront developments. The Arabian Canal, one of its current projects, is one of the largest developments of its kind in the world.

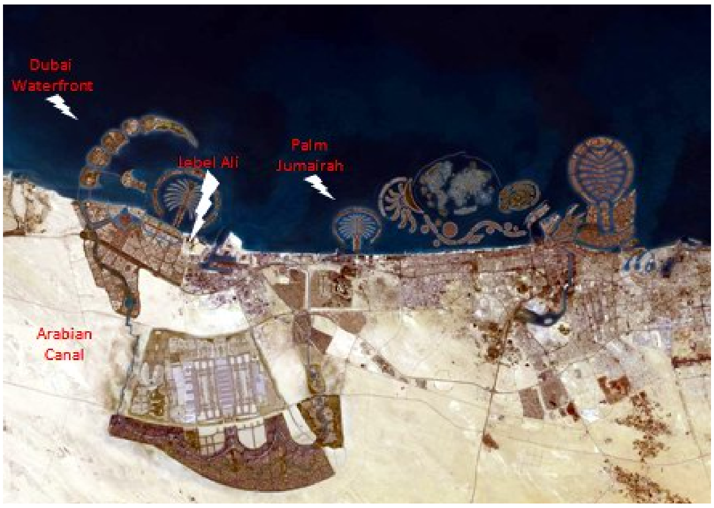


Fig. 1: The Arabian Canal in Dubai (www.arabiancanal.com).

The Arabian Canal is perhaps the most complex civil engineering project in the Middle East. It will become a globally recognized landmark destination for Dubai’s visitors and residents. The manmade waterway will flow inland from the north, near Palm Jumairah, to Dubai Waterfront at Jebel Ali. It will feature a range of mixed-use developments by some of the region's top developers. Limitless manages the design and construction of the canal to develop an area in excess of 10,000 hectares through which the canal will flow. Figure 1 shows the Arabian Canal project footprint in Dubai. Figure 2 depicts the 3D view of the Arabian Canal.

Construction of such a large project involves several challenges, including the need to accurately measuring the amount of earthwork moved each day. A total of one million cubic meters of earthworks will be moved every day. This corresponds to about 5,000 to 10,000 trucks moving earthworks every day. Therefore, it is essential to use an efficient technology to monitor such activity. The basic concept is to remotely monitor the terrain changes daily to compute the amount of earthworks done every day.

2. AN OVERVIEW OF THE ARABIAN CANAL PROJECT

Limitless LLC, a business unit of Dubai World, is based in Dubai, UAE. It is a leader in integrated real estate development across all market segments, delivering distinctive and sustainable developments. Limitless established a Geomatics Information System (GIS) Department to manage its various Geomatics activities across its worldwide projects. The GIS department has identified the necessity to utilize the state of the art technologies in order to monitor the Arabian Canal earthworks. The Arabian Canal will stretch 75 km in the form of a horseshoe from Palm Jumeirah to the west to the new Dubai World Central International Airport, and back to the harbor area. The Canal will be of up to 150 m width and 6 m depth (under the Mean Sea Level).

The banks of the Arabian Canal will be built to emphasise hills and valleys, through which a modern city including all sorts of amenitieswill be built to provide space for around 2.0 million people. Supplied with water from the Gulf, in the middle of the desert in Dubai there will be marinas, promenades, beaches, and public transport on the canal, supplemented by a dedicated subway. The construction costs are estimated to be US$ 11 billion, while the complete project is to cost around US$ 50 billion and cover an area of 12,750 hectares. See Figure 1 and Figure 2.

Fig. 2: 3D View of the Arabian Canal (www.arabiancanal.com).

Progress reports on the number of cubic meters of earth moved allow project managers to accurately track the project and to quickly identify any variances that need addressing to meet three critical requirements, namely:

1. Progress against plan,
2. As-build against plan and
3. Invoice Approvals

Methods used for these measurements must be very fast and effective. For example, we need to accurately measure the topography of 100 hectares within hours. An accurate 3D map of the excavation provides a fast and efficient means for continuously monitoring the dig against the plans and for making adjustments as necessary. The volume of earth moved is used to validate the invoices submitted by the subcontractors working on the project.

For smaller construction projects, earthwork monitoring is often carried out using traditional survey equipment such as total stations or GPS, or more recently with 3D static laser scanners that produce highly accurate point clouds from which geometric measurements can be made. However for such a large area, and given the constraint that measurements could only be made between shift changes (approx 1.5 hours every 12 hours), it was quickly determined that traditional static survey methods would require large number of crews and static survey equipment, all at great expense. Even more troublesome was the risk that the area might not be able to be surveyed within the time constraint. Based upon this the decision was made to use two mobile mapping platforms were chosen instead of static surveying techniques. Mobile mapping represents an optimal convergence of Digital Photogrammetry with other positioning technologies such as laser scanning, GNSS and inertial. Mobile mapping reduces both the cost and the schedule risk by increasing the efficiency of the collection process.

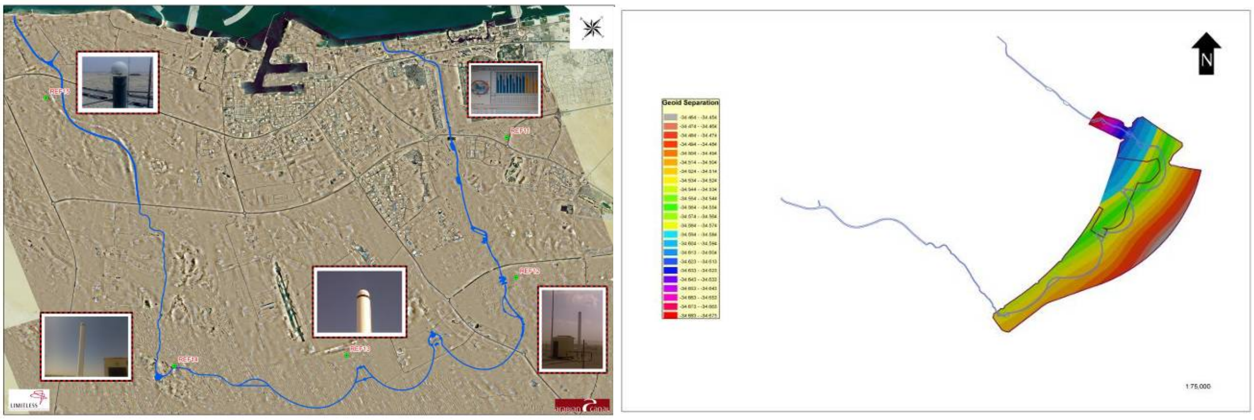
An important practice that Limitless requires is to acquire the best available practices and technologies to monitor, Audit, and provide topographic Services and perform earthwork monitoring for all of its projects. The mobile mapping technology has been identified to have the an efficient implementation of the required mapping in terms of time and cost due to:

- Know-how and expertise,
- State of the art technologies,
- Efficient implementation of in-house or outsourcing production processes.
- No construction-risks due to datum shift because of improper establishment-implementation of control field and topographic surveys,
- Provision of one standard for all Geospatial related operations,
- Better management tool for following up projects progress,
- Efficient automation of many GIS related processes.

3. MOBILE MAPPING SYSTEMS

Two mobile mapping platforms were chosen. A helicopter based Applanix DSS integrated with LMS-Q240 LIDAR. The second system is a Land Mark system. Both systems produce directly georeferenced high-resolution 3D terrain model in the form of laser point clouds and finally filtered digital surface models. In addition, the airborne system produces orthomosaic color image maps, while the Land Mark system provides oblique imagery.

To ensure seamless integration and Georeferencing to the same datum system, a dedicated GNSS reference station network with five GPS/GNSS Leica reference stations and Leica GNSS Spider software provide the necessary RTK correction data for the entire area were installed to operate 24 hours a day to provide the necessary GPS data corrections for the navigation systems. In addition, the geoids model of the area is also built based on Dubai datum and is integrated into the software to provide directly Orthometric DTM measurements. See Figure 3.



(a) (b)

Fig. 3: Vertical Datum modeling and Distribution of five GPS/GNSS reference stations around the Canal and development area. (a) Location of the GPS/GNSS reference stations (b) Geoids' Model to model of the development area.

Both systems produce directly georeferenced high-resolution 3D terrain model in the form of laser point clouds and finally filtered digital surface models. The land and airborne data sets are complementing each other to produce full coverage and a high-accuracy, high-density 3D terrain model of the dig with built in redundancy.

3.1. What is the right Choice of needed Sensors?

As in static surveying, there are many different options that were available to do the required job. Some are very expensive and the challenge is to understand the requirements and thus choose the suitable sensors that meet the requirements while minimizing capital cost and maximize efficiency. The following sections discuss the details of both systems.

3.2. Airborn Mobile Mapping System Specifications

An airborne helicopter based Applanix DSS 439 system is used in the Arabian Canal Project. The system includes a rugged medium-format of 39 mega pixel aerial camera, a flight management system, a GNSS-Aided INS Direct Georeferencing system and a full suite of processing software. These components are custom-designed and engineered to be tightly integrated with the Riegal LMS-Q240 LIDAR system. The Applanix DSS produces directly georeferenced high-resolution orthomosaic color image maps and high-accuracy 3D terrain measurements in the form of laser point clouds and digital surface models. In terms of production process, flying the helicopter at 450 meters above ground, Limitless GIS Department is able to deliver within one week from the flight mission an Orthophoto and a DSM/DEM with 10cm precision along the X, Y, and Z axes.

Fig. 4: The airborne System mounted in Bell 206.

The system has the following components:

- Special POD mounted in a Bell 206 helicopter pod.
- Complete workflow software to generate orthomosaic maps, DEM, filtered point clouds ready for volume calculations.
- DSS turn-key, low-cost fully integrated with camera, GNSS, IMU, Flight Management system and ortho mapping software.
- Q240i meets point cloud density, range and accuracy requirements at relatively low cost.

The following are needed requirements for conducting the earth work monitoring:

- Orthophoto Maps of construction area for planning and visualization
    - Ground Sample Distance: 10 cm (max), Ortho accuracy 12 cm RMS.
- Point measurements for volume calculations of cut/fill areas
    - Points every 1-1.5 m, 10-12 cm RMS (max)
    - Based on flying height from 200 m up to 450 m
    - Point density ranges from 25 cm to 150 cm interval.

3.3. LandMark Mobile Mapping System Specefications

A land vehicle based Applanix LandMark, consisting of a high accuracy GNSS-Aided INS Direct Georeferencing with the Riegal LMS-Q240 LIDAR system. A digital rugged camera is also built into this integration. The Land Mark system is custom-designed to deliver 5 to 10 cm positional accuracy, which put this prototype as the first of its kind in the world. The Applanix LandMark produces georeferenced oblique video imagery and high density laser point clouds.

Fig. 5: The Land Mark System mounted on Land cruiser car.

The system has the following components:

- Applanix LANDMark mobile mapping system configured with single video camera and Q240i laser scanner, highest accuracy RLG IMU
- Complete workflow software for georeferencing video, *same workflow* as airborne system for generating filtered point clouds
- Only needed single camera and scanner since always driving in and out of or around dig
- Q240 meets point cloud density requirements and accuracy at relatively low cost
- Highest accuracy IMU could maintain position accuracy during outages

The following are the requirements for efficient earthwork monitoring:

- Collection and data acquisition within few hour
- Georeferenced video log of scanned area for planning, quality control and visualization
    - 2MP camvideo, the Ground Sample Distance varies with scanning distance.
- Point measurements for volume calculations of cut/fill areas
    - Points every 1-1.5 m, 10cm RMS (max): Actual collection is about 25 to 50 cm.
    - Ranges from 300 m

4. MOBILE MAPPING VS. TRADITIONAL SURVEYS

The following are important aspects that we need to take into consideration utilizing the mobile mapping technology to deliver needed measurements.

1. Earthworks monitoring:
    - Monitor and measure dig and filling on 24 hour cycle for
    - Progress
    - Visualization (quality control, marketing)
    - Invoicing
2. Data Requirements:
    - Measurement from 25 to 150 cm, 10 cm RMS absolute accuracy (minimum)
    - Depths up to 55 m
    - Widths of canal excavation is greater than 300 m, depending upon slope
    - Dimensions of filling areas vary but need to monitor about 1-5 square km on daily bases.
3. Challenges:
    - Better to be able to collect data between shift changes
    - Manage to filter LIDAR data of machinery either if it is on idle or working mode and still provide the required accuracy
    - Access to excavation site areas during working hours
    - No guaranteed access to edge of canal
    - Huge area to collect: 100 hectares within hours

On the other hand, if traditional methods and/or Static surveys are used such as Total Stations/GPS/3D static Scanners, they are considered as proven technology that deliver high accuracy and relatively low capital costs, however it has the following problems:

- Many crews and equipment to cover large area and therefore result in high personnel costs, many data sets to merge, logistical nightmare for quality control
- Can't get the exact DTM of a large area in one day, while in mobile mapping we can cover almost 5 to 10 square km per day.
- Access required to edge of canal, in canal among large earth moving equipment and therefore there is a serious safety issue which endanger the crew members.
- Manual equipment setup and collection which very much make the operation more slow.

On the other hand, although using the mobile mapping technologies is relatively requires high capital cost and need logistically complex and expensive operation. However, it justifiable when looking at the advantages for such huge project as it:

- Doesn't need certain set up and very fast in data acquisition and area coverage
- Need to only merge 1 or 2 data sets to perform quality control and delivered very high reliability in terms of data accuracy and precision
- Requires only one single pilot or driver and thus has low personnel costs
- Requires one set of equipment can cover large area and thus it is efficient
- Does not need staff presence in the field and all measurements are done in remote acquisition mode and thus more safe.

In addition, the advantages of using both the airborne and landmark systems have the following advantages:

- Have the same laser scanner and thus both have the same built-in back up and same error characteristics for data integration.
- Have the same Georeferencing workflow (Differential GNSS-Inertial processing) and same workflow used to generate/filter point clouds, generate DEM and do volume calculations.
- While the airborne can cover much larger areas however, in many circumstances, data gaps are found and thus the Land Mark system cover these gaps and thus have complete DTM model of our areas
- Land Mark system has less operation logistics and thus can be used alone to update DTM without the need to do aerial mapping.
- One complement the other for which makes is easier to check DEM accuracy against each other and merge data sets as well as guarantee complete coverage.

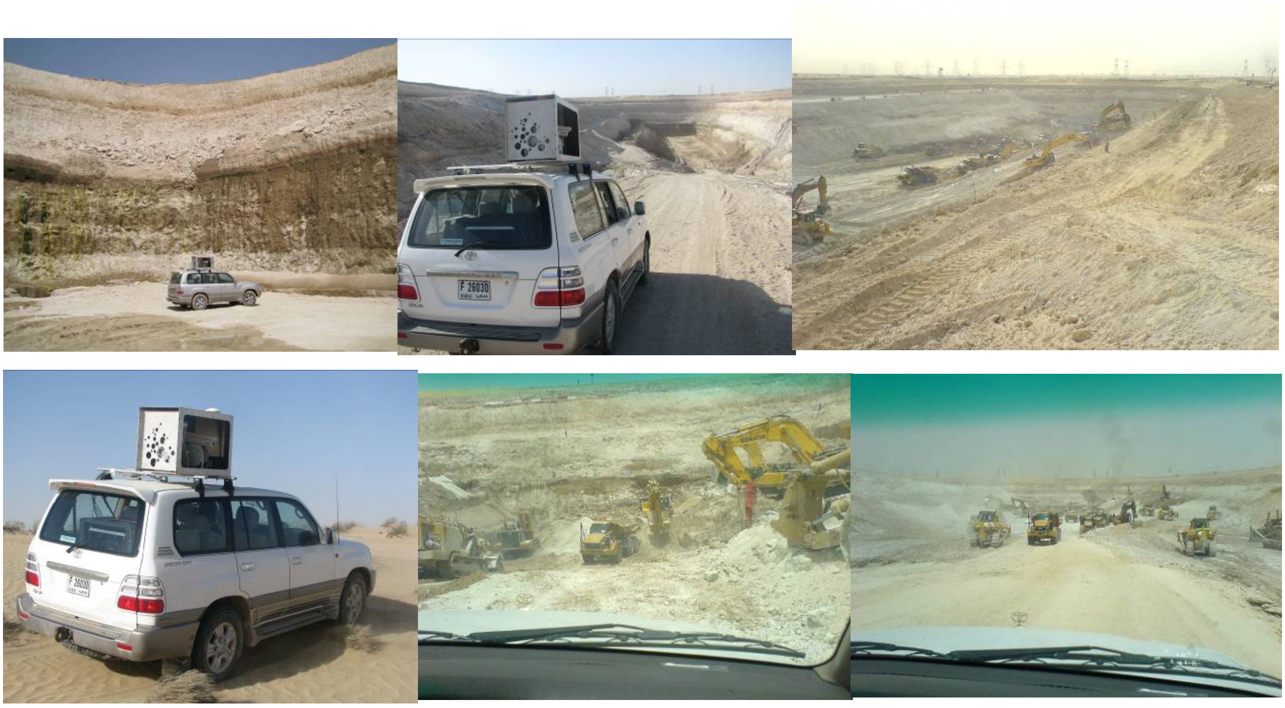
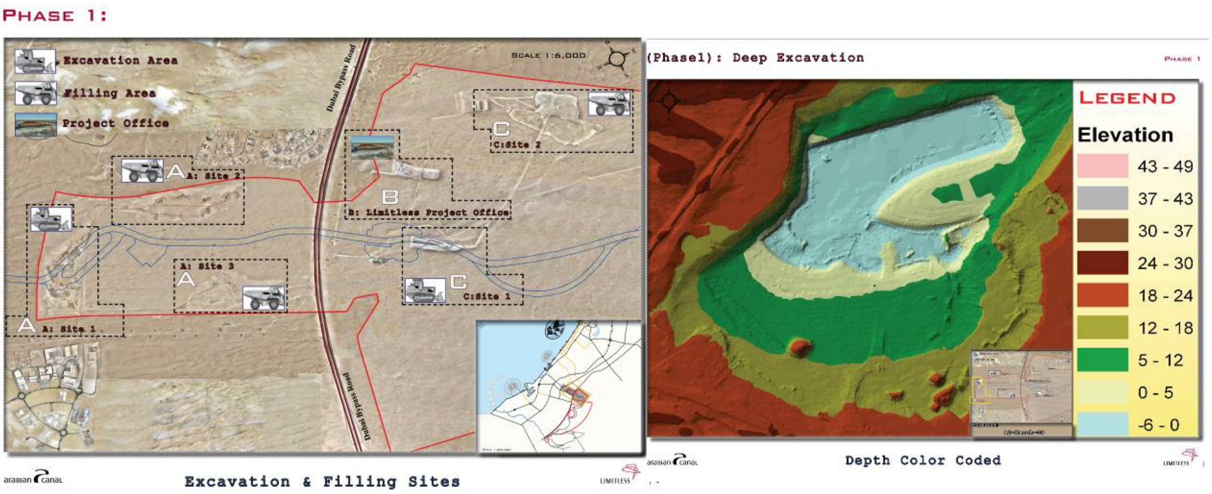


Fig. 6: Illustrates the harsh working condition of the Land Mark System scanner and the danger/accessibility problems.

5. QUALITY CONTROL AND RESULTS

5.1. Workflow and Quality Control

The process of measuring excavation sites within the time frame highlights the strength of such a system. The Arabian canal development area is divided into four phases; each phase is about 25 to 35 squares Kilometre. Using the airborne mobile mapping system, four hours (flying time) are needed normally to cover phase I which is of about 25 km^2, see Figure 7. This operation is done bi-weekly. The LandMark system is used to cover the occluded area when using the airborne system or to get a higher density points in some areas of interest and also updates or some excavation area that are needed because of various reasons such as progress follow up, 3D visualization, invoicing slope monitoring, boundaries limitations. In a normal scenario, where accessibility is maintained, one can, in one hour, accurately measure about 200 hectares with the mobile mapping landmark system. Out of both systems, a DEM is created accurately with a 10 cm precision. Another important achievement is that within one week of conducting our image/LIDAR scans we are able to deliver the accurate topography as a final product. So far, this technology has highlighted the ability to produce accurate measuring in a short time, reinforcing our distinctive, innovative approach to development.



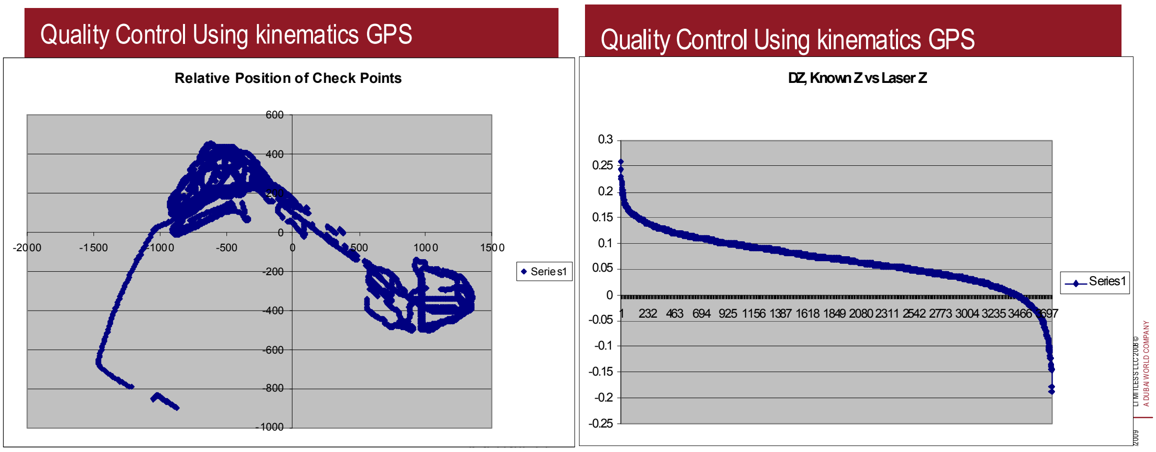
(a) (b)

Fig. 7: (a) Details of the Excavation and filling sites along the canal route within Phase I of the development area. (b) 3D color coded image of the excavation site 1 shown in (a).

To assure that the generated DTM model is accurate to the necessary precision, a quality control process is always conducted. One important aspect was covered in section 3, where a dedicated GPS/GNSS permanent reference station was constructed using the local Geoid model to eliminate any associated errors.

The quality control of the generated DTM involves three approaches. One is to use the distributed second order control points monuments distributed every 500 m along the canal route. The second is to the overlay clouds measurements to apply cross-checking between measurements. This will ensure reliability and repeatability of the acquired data sets. Third approach is measure during the acquisition process points. This is done via a car mounted GPS antenna to get very dense point clouds of chosen areas and rings around the site that are establish. In a typical situation 1000 to 4000 are taken. These points are used of validate map and point clouds products against each other to produce final product.

Figure 7 illustrates the working sites in areas I of Phase 1 and the resulting DTM illustrated in color-coded image. One can see the canal area and the created island within the canal. Figure 8 shows the navigation route of the car that took the Kinematics GPS measurements and the precision results of the vertical variances. The total numbers of GPS points taken were about 4000 measurements. The results of this exercise are an average height offset of 6.7 cm with a standard deviation of 5.0 cm and RMS value of 8.4 cm.



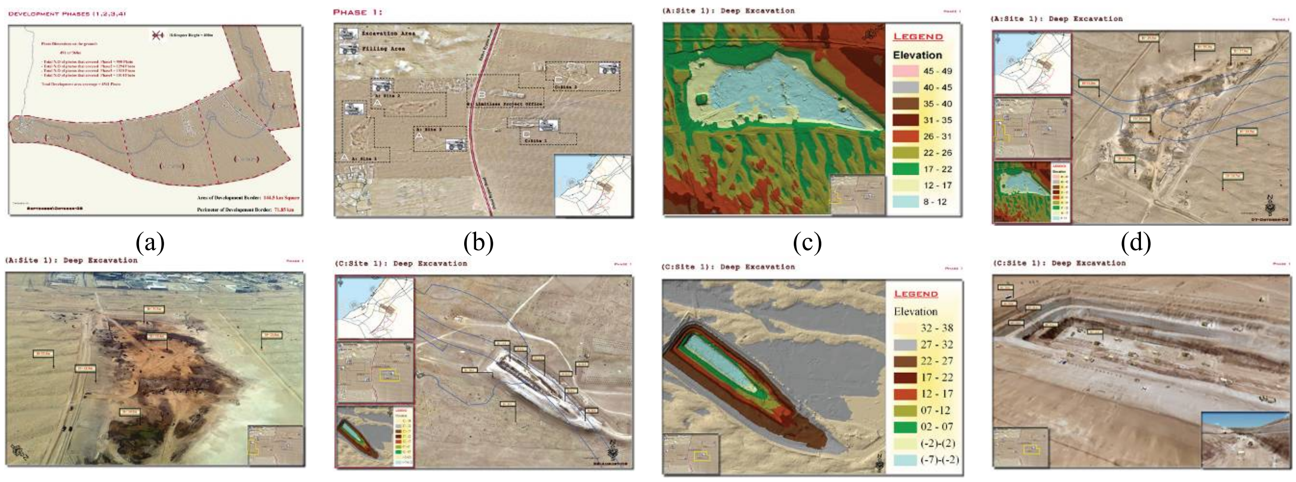
(a) (b)

Fig. 8: (a) the navigation route of the car with GPS antenna (b) vertical error variances of the generated DTM compared to GPS points.

The overall resultant quality checks on average values are as following:

- Average height offset: 6-8 cm
- Standard deviation: 3-6 cm
- RMS: 8-9 cm

5.2. Results



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 9: Arabian Canal Orthophoto and DTM modeling and illustrations of deliverables.

Figure 9 illustrates some of the system deliverables. Figure 9a shows the mapped area with our system (e.g. more than 4500 images), knowing that the produced pixel size precision is 10 cm. Figure 9b shows the active excavation and filling sites within phase one of our development. Figures 9c, 9d and 9e illustrate area 1 progress level with 3d model and color coded image. Figure 9f, 9g and 9h illustrate another active site that reached -6.5 meters below mean sea level with 9d model and color coded image. It is a 40 meter deep dig within the Canal rout, which illustrate the resultant excavation

6. CONCLUSIONS

Limitless Geomatics Information System Department has identified an integrated airborne and land mobile mapping systems as the necessary approach for earthwork monitoring for the Arabian Canal project due to the following reasons:

1. Traditional earthwork monitoring surveying techniques impose a significant risk as far as data acquisition completion during the allocated time.
2. Traditional techniques could have resulted in huge cost overruns if earthwork progress has been delayed and not detected on time.
3. Higher mobile mapping system cost is well absorbed due to its efficiency over traditional techniques, especially in large areas
4. Mobile Mapping systems provide high accuracy and short turn around compared to traditional techniques
5. Mobile Mapping systems eliminate schedule risk
6. Integrated Airborne/land mobile mapping systems reduce any accuracy risk due to their complementary nature.

During a daily data acquisition scenario, the airborne system covers an area of 25 km2 within four hours of flying, while the LandMark system covers 100 hectares mapped in an hour. The land-based data allows for providing higher density point clouds in some occluded areas from the airborne platform. Weekly 3D mapping products have been successfully delivered with the following accuracy consistently:

- Average height: 6-8 cm
- Standard deviation: 3-6 cm
- RMS: 8-9 cm

7. FUTURE WORK

We are now working on speeding up this process to be within three days exploring various filtering automation techniques, and are exploring ways to combine and integrate the datasets of both systems to assure a high-density 3D terrain model of the excavation or filling with built in redundancy.

8. REFERENCES

Beyer, H. A. (1992), Geometric and Radiometric Analysis of a CCD-Camera Based Photogrammetric Close-Range System, Ph.D. Thesis, Institut für Geodäsie und Photogrammetrie, ETH-Hönggerberg, CH-8093 Zürich, Mitteilungen Nr. 51.

Eckl, M. C., R. Snay, T. Soler, M. W. Cline & G. L. Mader (2001), Accuracy of GPS-derived relative positions as a function of interstation distance and observing-session duration, Journal of Geodesy, 75(12), 633-640.

Fotopoulos, G. & M. E. Cannon (2001), An Overview of Multi-Reference Station Methods for Cm-Level Positioning, GPS Solutions, 4(3), 1-10.

Fortes, L. P., G. Lachapelle, M. E. Cannon, S. Ryan, G. Marceau, S. Wee, & J. Raquet (2000), Use of a Multi-Reference GPS Station Network for Precise 3D Positioning in Constricted Waterways, International Hydrographic Review, 1(1), 15-29.

Fraser, C. S. (1997), Digital Camera Self Calibration, ISPRS Journal of Photogrammetry & Remote Sensing, 52, 149-159.

Greening, T., W. Schickler & A. Thorpe (2000), The Proper Use of Directly Observed Orientation Data: Aerial Triangulation is not Obsolete. 2000 ASPRS Annual Conference, Washington, DC, May 22–26.

Hofmann, O., A. Kaltenecker & F. Müller (1993), Das flugzeuggestützte digitale Dreizeilenaufnahme- und Auswertesystem DPA - erste Erprobungsberichte. In: Photogrammetric Week '93, Eds. D. Fritsch/D. Hobbie, Wichmann, Karlsruhe, pp. 97-107.

Lachapelle, G., M. E. Cannon, L. P. Fortes & P. Alves (2000), Use of Multiple Reference GNSS Stations for RTK Positioning, Proceedings of the World Congress of the International Association of Institutes of Navigation, San Diego, June 26-28, pp. 803-809.

Mostafa, M. M. R., E. Roy & X. Zhang, (2007), SmartBase™ — An Efficient New Tool for Aircraft Positioning using Continuously Operated Reference Stations for Mapping Applications. Presented at the ASPRS Annual Fall Conference, Ottawa. Canada, October 28 – November 1, 2007.

Mostafa, M. M. R. (2003), Design and Performance of the DSS. Proceedings, 49th Photogrammetric Week, Stuttgart, Germany, September 1-5, 2003.

Mostafa, M. M. R. (2001), Boresight Calibration of Integrated Inertial/Camera Systems. Proceed. Int. Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation – KIS 2001, Banff, Canada, June 5-8.

Mostafa, M. M. R. & K. P. Schwarz (2000), A Multi-Sensor System for Airborne Image Capture and Georeferencing. PE&RS, 66 (12), 1417-1424.

Mostafa, M. M. R., K. P. Schwarz & P. Gong (1997), A Fully Digital System for Airborne Mapping, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada, pp 463-471.

Raquet, J., G. Lachapelle & L. Fortes (2001), Use of a Covariance Analysis Technique for Predicting Performance of Regional Area Differential Code and Carrier-Phase Networks. Navigation, The Institute of Navigation, Alexandria, VA, 48(1), 25-34.

Schwarz, K. P. (1995), Integrated Airborne Navigation Systems for Photogrammetry. In: Photogrammetric Week '95, Eds. D. Fritsch/D. Hobbie, Wichmann, Heidelberg, pp. 139-153.

Scherzinger, B. (1997), A Position and Orientation Post-Processing Software Package for Inertial/GPS Integration (POSProc). Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS 97), Banff, Canada, June 1997.

Škaloud, J., M. Cramer & K. P. Schwarz (1996), Exterior Orientation by Direct Measurement of Camera Position and Attitude, International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Part B3, pp. 125-130.

Snay, R. A., T. Soler & M. Eckl (2002), GPS precision with carrier phase observations: Does distance and/or time matter?, Professional Surveyor, 22(10), 20, 22, 24.