**Highlights**

- point 1
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# Digital 3D Geosciences on Mobile Devices - Concepts, Challenges and Applications

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## Abstract

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## 1. Introduction

- computing equipment continuously elevates the analytical capabilities for solving geoscientific problems
- large drawback on computing equipment: the more powerful it is, the more stationary it is
- geoscience disciplines such as hydrology, geology or glaciology are driven by outdoor experiments that prohibit bulky equipment
- the advent of mobile computing equipment, such as smartphones and tablets, provides a possible solution to the equipment problem

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- form factor of mobile devices is small enough to allow every field-related geoscientist to carry one in the field
- as seen is popular articles, the range of available devices increases, which allows to find a devices fit-for-purpose to each situation
- range of devices also comes with a range of capabilities that influence their usability for specific field tasks
- availability of small form factor devices is only on part contribution to making digital geosciences more "mobile"
- availability and easy access to geoscience data (e.g. domain-specific maps, digital elevation models (DEMs), surface models in 3D) is equally important to perform combined digital- and field analysis
- while basemap access on mobile devices is trivial, surface-scanned data in form of point clouds and (textured) triangulated meshes is becoming increasingly available with novice-operable structure from motion (SfM) software and drones
- crowdsourced data and Volunteered Geographic Information (VGI) provides numerous data for domain-specific analysis, which is facilitated by easier data capture from amateur scientists using mobile devices
- In order to connect data and devices in the field, domain-specific mobile software is required
- the difficulties in mobile software development stem from the specific demands and challenges for mobile software, such as energy efficiency, multi-manufacturer support, smart sensor utilisation [add and expand]
- with the emergence of new application cases, which are demonstrated and discussed in this article, and an increasing interest from geoscience- and computer technology industry, a significant rise in the mobile software

availability for geoscience problem solving is expected for the near-term future

- Even considering the fast technological development, some challenges around mobile device development exists that are rooted in the technology itself
- several techniques and methods - such as SfM, virtual reality (VR) or augmented reality (AR) - have been demonstrated to work on small-scale lab studies in computer science itself
- translation and adaptation of these techniques to specific geoscience case studies and domain-specific issues is prohibited by scale and reliability
- Other challenges influencing mobile digital geosciences are short-comings in geo-localization accuracy, object matching- and registration accuracy, geometric- and photometric data processing, data volumes and the availability of off-the-shelf program codes to common problems in computing
- these problems are already familiar to disciplines such as software engineering, photogrammetry and data science for established computing platforms (e.g. PCs, workstations, laptops)
- there are also problems specific or exclusive to mobile device processes, which are discussed in detail in this article
- they contain issues such as device variability, power consumption and computing efficiency (i.e. fast calculations with drastically limited computing capabilities)
- For the next sections, the article adheres to following structure:
- First, use cases are presented as opening statements to introduce task that are exclusively addressed by mobile devices in the digital geosciences

- Secondly, the basics for 3D digital processing for our cases are presented. The overview is limited to the applied concepts to mobile devices and the extensions necessary to make the mapping to such devices.
- Then, algorithms that are key to the digital geosciences outdoors are presented. The overview is also meant to highlight that alternative methods are available to achieve the target tasks
- Fourth, the algorithms are mapped to the specific mobile technologies and components. The technologies and major parameters that impact geoscience problem applicability are highlighted.
- Finally, we showcase and discuss how available mobile systems are used in application scenarios from hydrology and petroleum geology to improve analysis processes, help disseminating acquired knowledge and integrate outdoor measurements in digital workflows
- Then, the article is finalized with some concluding remarks and a discussion for future developments in this research trajectory

## 2. Target case studies

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## 3. Representation basis – Geometry and Radiometry

Various representation forms for 3D terrain data are available. While early digital systems used DEMs for their simplicity and compact storage [**? ? ?** ], digital surface models (DSMs) and triangulated irregular networks (TINs) are dominating most terrain-based systems for application-specific analysis. Examples can be seen at ... for glaciology, where the authors use ... for the terrain representation. The same application of ... can be observed for climate studies, as in ... . In this context, it is important to distinguish geometrically valid TINs from polygon soup surfaces. While the latter is often employed in early stages of mesh-based software systems due to its simplicity and ease of implementation, valid TINs are employed in mature stages of the analysis. This is because some automated analysis (e.g. auto-interpretation, volume derivation) require clean surfaces with coherently outward-oriented surface normals.

In geoscience domains such as petroleum geology, texture- and color information are vital for interpretation- and analysis tasks. In these cases, as demonstrated by Buckley et. al [**?** ] and Caumon et. al, the TIN is supplemented with photographic information that is projected on the surface as textures. As it is also possible to project textures from outside the visible spectrum as supplementary information on the surface [**?** ], we generalize for the remainder of the article that the model in question consists of its geometric and radiometric information.

[EXAMPLE PHOTO FROM LIME]

~~In other geoscience domains, such as hydrology and free surface flow management, colored point data streams are used as models, which are provided by drones and SfM. In general, applications that rely on data throughput and large-scale analysis more commonly employ colored ”point cloud“ models because of their rapid procvessing and the skip of surface triangulation. Presentation techniques (i.e. rendering) are in these cases adapted versions of Point-based Rendering (PBR) [**? ?** ]. Examples of point-based surface analysis in hydrology can be found in Leskens et. al [**?** ], whereas Virtual Reality Geological Studio (VRGS) is an example software for petroleum geology that employs similar techniques (see Rarity et. al [**?** ]).~~

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The stated base concepts of geometric and radiometric model information and their representations are also valid for mobile device software. Because of the limited processing speed of mobile chipsets, a tendency for employing point cloud models on mobile devices (as Pintus et. al [**?** ] and Garcia et. al [**?** ]) can be observed. A drawback of point cloud models is their sparse nature, which prohibits continuous analysis of field data. Therefore, DEMs have seen a revival in the mobile computing domain because they provide dense, closed geometric models that can be rendered and processed very effectively. Furthermore, with the inferior memory capacity of mobile devices in comparison to laptops and workstations, it is advantageous to be able to aggressively compress the data for mobile use, which is facilitated both by point clouds and DEMs. Base mapping applications such as Open Street Maps [1] and Google Maps [2] use ... as their main 3D data representation. Other systems within the geosciences processing 3D data on mobile devices, such as "Outcrop" and Geological Registration and Interpretation Toolset (GRIT), employ genuine textured triangulated DSM.

The form of model representation chosen significantly impacts the algorithms and analytical capabilities employed on the mobile device. Although all algorithms presented in this article work on either form of representation, some of the algorithms favor the treatment of triangulated surfaces (e.g. image-to-geometry registration, guided interpretation), while others clearly favor point-based representations (e.g. SfM and rendering).

## 4. Algorithms

This section demonstrates novel- as well as existing algorithms and methods on mobile devices that are used for solving analysis tasks in the geoscience use cases laid out in section ??. As mentioned before, the effectiveness of each algorithm depends on the applied model representation.

### *4.1. Structure-from-Motion (SfM) and Visual Simultaneous Localization and Mapping (Visual SLAM)*

- ~~short description what it does~~
- ~~how is it generally employed~~
- ~~relation to mobile devices~~
- ~~approaches and implementation known on mobile devices~~

[1] asdas
[2] asdas

- integration to the above-mentioned use cases

SfM and visual simultaneous localisation and mapping (SLAM) aim at automatically reconstructing a 3D environment from a stream of images [**?** ]. The output of these 3D reconstruction methods are colored point sets (i.e. point clouds). The technique is employed in the geosciences to acquire and measure 3D surfaces and terrain either via a manually collected photo set, or by using drones [**?** ]. The large potential for these algorithms on mobile devices being used directly in the field is that no other equipment was needed the generation of the digital 3D data used for analysis. A powerful mobile devices, such as the Project Tango[3] or NVIDIA Shield[4], is capable of 3D terrain data collection in realtime directly in the field.

Because of the large potential to all branches in the geosciences to deliver on-spot data acquisition, several research groups have conducted research into that topic. **FILL IN PARTS FROM THE THESIS HERE!**

A problem with the listed approaches is their lack of maintenance. There is no readily-available software to this date in the mobile app stores that allows real-time SLAM or SfM. Reasons for the disappearance on previous prototypes can vary, but a major problem is the speed of development for mobile devices. As new operation system versions are published on a half-year to yearly basis, it means that software gets deprecated very rapidly. If no industrial partner cares to maintain and market a given research prototype, then that is vanishing from the mobile software market quickly.

### *4.2. Image-to-geometry registration*

- ~~short description what it does~~
- ~~how is it generally employed~~
- ~~relation to mobile devices~~

3

4

- ~~approaches and implementation known on mobile devices~~
- integration to the above-mentioned use cases

Image-to-geometry algorithms aim at registering a 2D image to a given 3D surface, providing a transformation from 2D coordinate system to 3D coordinate system as follows:

$$P' = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = [R_{3,3}|T_{1,3}] \cdot P \tag{1}$$

$$P = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{2}$$

$$P' \in \mathbb{R}^2 = \frac{P'}{w} \tag{3}$$

Using this coordinate system transformation on combination with a known interior camera orientation, it is possible to projectively map entire images on the surface just as surface texturing does. It is also possible to map specific objects on the image, such as image-based interpretations, on the surface. In the geosciences, these algorithms are employed to create a direct correlation between 3D model and the screen- or image space on which annotations and interpretations are based on [**?** ]. The technique is also employed to provide texture mappings for multi-layer images, such as hyperspectral data or domain-specific thematic maps.

- feature-based registration: detect prominent points or edges in the input 2D images and a rendered representation of the 3D model
- different concept for registration:
  - for mesh models, 2D feature locations are raycasted using camera projection and the 3D model in background; 3D feature location determined upon ray-plane intersection

  - for point-based models, raycasting doesn't directly work as point cannot be intersected; prominent solution is employing a smart rendering technique that expands the point into an area, and generate a depth map; after depth map generation, the 3D coordinate of a 2D feature map can be read directly from the depth map; drawback of the method / offset for speed: accuracy limitation of depth maps; high-resolution depthmaps (above $512^2$) cost a lot of performance

- registration then has source- and target 2D-3D point pairs (in a normalized manner) that are put into a least-squares optimization system (give math here)

- optimization system usually non-linear, usually employing Levenberg-Marquardt optimization schemes [**?** ]

- largest challenges for feature-based registration: (a) reliable feature correlation and (b) optimization stability; useful constraints can employed in both cases – such as horizon information, building edges, object outlines – to increase the registration reliability and accuracy

- employing constraints is highly application-dependent

- feature-based registration techniques most prevalent on mobile devices due to execution speed, implementation ease and so forth

- examples of mobile implementation: [**? ? ? ?** ]

- drawback of feature-based methods: reliability and instability to imaging variances (discussed later in this article)

- a contrasting technique commonly achieving more accurate results: mutual information

- idea: pixel-wise comparison between 2D input image and 2D rendering of 3D scene; if both images match (meaning: $argmin\delta(I_{2D}, I'_{3D})$), then registration is completed

- mutual information [? ] use notion of self-information and entropy to measure $\delta(I_{2D}, I'_{3D})$

- challenge: optimization of 7 degree-of-freedom system over such overdetermined system (i.e. each image pixel results in 2 equations for the optimization scheme) unstable and prone to local minima

- only optimization known to provide stable results is NEWUOA (i.e. Powell's method) [? ];

- has recently been employed in an earth science case for light detection and range (lidar) registration [? ]

- not available for mobile devices until now

- in terms of usability on mobile devices (why should we want to have that on mobile devices), projection of image-based information is vital on mobile devices

- because of interaction difficulty, image-based interpretations on 3D surface data is preferable

- it is potentially advantageous, in terms of power consumption, to implement data interaction in 2D rather than 3D; a hypothesis proven by experiment in this article

- as it directly relates to the interactive component of the geoscience app, it has to be executed in real-time on the device instead of an offline process

### *4.3. Data presentation and rendering*

- ~~short description what it does~~

- ~~how is it generally employed~~

- ~~relation to mobile devices~~

- ~~approaches and implementation known on mobile devices~~

- integration to the above-mentioned use cases
- rendering the 3D model in this context refers to generation of image generation of 3D model by projective rasterization of model data to 2D imaging plane of a virtual camera
- rendering is performed to view the 3D model on the mobile device
- also employed to generate a reference image used in the image-to-geometry registration and the annotation and interpretation of the data
- major concepts: mesh-based rendering and PBR
- technical details on how this is done covered in the technology section **??**

### *4.3.1. Mesh-based rendering*

- well-known concept
- mesh is transferred as vertex set and primitive set (i.e. triangles or polygons, depending on employing TIN or polygonal soup geometry) to graphics processor
- virtual camera is set up as projective view matrix
- primitives are positions in 3D scene via model transformation matrix
- rasterizer projects information to camera plane and transforms continuous data into discrete pixel-based representation
- in-time decompression can be optionally employed (see [**?** ])
- texturing is employed to map image information on the surface; correlation between surface patches and texture images established explicitly beforehand or implicitly defined by geographic coordinate systems (e.g. WGS84 or UTM) for georeferenced surface

## *4.4. A novel approach to mobile point-based rendering*

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### *4.5. Interpretation and annotation*

- short description what it does
- how is it generally employed
- relation to mobile devices
- approaches and implementation known on mobile devices
- integration to the above-mentioned use cases

## 5. Technology

### *5.1. Sensors*

#### *5.1.1. Localization*

#### *5.1.2. Orientation*

- stability IMU (see 3D-NO)
- precision IMU

#### *5.1.3. Parameter sensitivity*

### *5.2. Graphics*

- software- vs hardware renderer
- web-rendering
- rendering-on-device
- hardware differences: speed, capability, CUDA

### *5.3. Power consumption*

## 6. Applications and Requirements

### *6.1. Waterline detection*

- recap: task to be solved

- main requirements for (location- and orientation) sensor accuracy and geometric accuracy
- specific requirements to this use case: data availability; illumination; device range to cover
- available approach to address the task

*6.2. Field Geology*

- recap: task to be solved
- main requirements for (location- and orientation) sensor accuracy and geometric accuracy
- specific requirements to this use case: data availability; illumination; network inavailability
- available approach to address the task

*6.3. Virtual Field Trips*

- recap: task to be solved
- main requirements for (location- and orientation) sensor accuracy and geometric accuracy
- specific requirements to this use case: data availability; illumination; network inavailability
- available approach to address the task

*6.4. The digital fieldbook*

- recap: task to be solved
- main requirements for (location- and orientation) sensor accuracy and geometric accuracy

- specific requirements to this use case: device range to cover; data integration; no network
- available approach to address the task

## 7. Conclusions

which problems are sufficiently solved ? which challenges remain that have already been discussed

## 8. Discussion

- porting existing desktop algorithms on mobile devices [quick and fast]
- vegetation in scans
- pre-processing of geodata for mobile use

## References