



Research paper

Fieldwork in Geosciences assisted by ARGeo: A mobile Augmented Reality system[☆]Nicolás F. Gazcón^{a,b,*}, Juan M. Trippel Nagel^{a,b}, Ernesto A. Bjerg^{c,d}, Silvia M. Castro^{a,b}^a Instituto de Ciencias e Ingeniería de la Computación (CONICET-UNS), Bahía Blanca, Argentina^b VyGLab, Departamento de Ciencias e Ingeniería de la Computación, Universidad Nacional del Sur, Bahía Blanca, Argentina^c Instituto Geológico del Sur (CONICET-UNS), Bahía Blanca, Argentina^d Departamento de Geología, Universidad Nacional del Sur, Bahía Blanca, Argentina

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ABSTRACT

Gathering data on the field is a crucial task in many disciplines. Moreover, in the Geosciences the GPS positioning is relevant to the data acquisition as well as to the planning of the fieldwork. Nowadays, mobile devices are widespread, constituting an accessible platform consisting of single devices coupled with different sensors for data acquisition, such as GPS, compass, magnetometer, etc. Emerging technologies such as Augmented Reality (AR) enable the use of these devices as a software platform to complement the perception of our surrounding environment. Despite the fact that there are several AR applications focused on different aspects of Geosciences, a comprehensive fieldwork oriented system, which can be easily adapted to the community needs, is still missing. Based on a multidisciplinary work between professionals from Geosciences and Computer Sciences, we designed and developed a framework based AR system named ARGeo. The proposed system constitutes a complementing tool for the geologist's fieldwork carefully designed to be used in remote sites, using only the mobile device hardware and without the need of an internet connection for data acquisition.

ARGeo complements the fieldwork observation and the precise recording of geological data needed, e.g., for the interpretation of folded structures. It allows the user to register geo-tagged information such as points of interests (i.e. references on the field or the fold itself) using natural interactions. In addition, it provides two novel features: an interactive dipping plane measurement from distant points of view and a back-in-time visualization of previous recorded positions, in order to help understanding the spatial relations among the recorded samples. Pilot studies were conducted with domain experts of geology and they agree on the potential of the system. Results point out that ARGeo naturally integrates mobile devices and AR to the geologists' fieldwork. Its possible extension with new features to the Geosciences as well as to other application fields is detailed.

1. Introduction

For most professionals of the Earth Sciences, fieldwork plays a relevant role. Since outdoor activities require to construct accurate and precise records, fieldwork demands the use of specialized equipment. Moreover, when it comes to complex processes involving observation and interpretation such as geological folds analysis, on-site activities requires a careful study, persistence and experience. Field sketches are commonly used to assist during the thinking process. Nevertheless, folds analysis and interpretation of features become a really challenging activity even for experienced professionals (Coe, 2010).

This scenario becomes an excellent opportunity to incorporate immersive technologies. Thanks to the tremendous increase of availability to mobile hardware, it is possible to use technologies such as Augmented Reality (AR) in the field. Nowadays it is usual that professionals carry smart phones or tablets in addition to their work specific devices. AR opens up the possibility to complement fieldwork performed by geologists complementing the real environment with virtual or digital information (Milgram et al., 1994; Azuma, 1997). This technology allows to visualize information in the actual context where it is needed. For instance, pointing the device to the desired location could trigger contextual information. In fact, AR not only provides

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passive data exploration, but it also allows to generate new on-site information (e.g. storing or recording geo-tagged field data). Connecting the real world to a virtual representation allows to provide digital information seamlessly integrated to the environment, and it also helps to intuitively interpret and analyze the spatial relationships among data (Schall et al., 2009).

AR has been applied to the Geosciences in terms of geological visualization of data in the field (Lee et al., 2015; Pierdicca et al., 2016). Examples of it are its use for interactive geological maps visualization (Westhead et al., 2012) or geological subsurface structures (Mathiesen et al., 2012). It also has been used to provide specialized software to visualize and interact with borehole data (Lee et al., 2015). Nevertheless, this context is still in lack of a comprehensive framework shaped from scratch to be extensible and adaptable to different fieldwork applications. An AR application that could be used to complement the geologist fieldwork should exhibit enough flexibility to be adapted to the current needs. For instance, constraints such as no internet access or GSM coverage must be taken into account.

Based on a multidisciplinary work between professionals of Geosciences and Computer Sciences, an AR system named ARGeo¹ was designed and developed. The system is aimed to operate in mobile Android devices and its design allows to easily extend its functionality tailored to the needs of the community. Moreover, we developed the system according to a case study focused on fieldwork observation and analysis of geological folds (i.e. planar orientation data collection). In addition to the basic virtual elements such as Points of Interest (PoI), we showed how it can be specialized to provide dedicated features to this context. We proposed an interactive dipping plane measurement from distant points of view and a back-in-time visualization of previous recorded positions, to help to understand the spatial relationships among the recorded samples.

ARGeo was evaluated under a pilot study with geologists, using a Samsung Galaxy Tab S with a 8.4" display. These studies reflect the potential of ARGeo and also provide useful information for possible upgrades, as well as the future research lines which the proposed system enables. The main contributions of the manuscript can be summarized as follows. (1) An extensible framework-based system for AR applications oriented to geological fieldwork. (2) The specialized features to assist the geologist in the interpretation and analysis of fold structures.

2. Background

Mobile GIS combines GIS applications with mobile devices allowing to port, in some extent, desktop applications to the field. In this way, commonly used software solutions offer their mobile extensions. An example of this is the ArcGIS system (ArcGis, 1999) and its corresponding ArcPad mobile system (ArcPad, 2013). Besides the usefulness of traditional 2D representations and visualizations of 2D and 3D data, complex data such as spatial data or even on-site data analysis and interactive exploration remain challenging (Veas et al., 2013). To cope with this, immersive visualization techniques such as Virtual Reality (VR) and AR have also been explored in the GIS context (Kreylos et al., 2006; Billen et al., 2008; Martínez-Graña et al., 2013; Westerteiger, 2014).

Kreylos et al. (2006), for instance, showed how VR techniques can be applied to scientific problems of the Earth Sciences, to take advantage of the skills, and to train geologists in the exploration of their data in a VR environment. Billen et al. (2008) presented the Visualizer, a software for visualization of 3D gridded data sets in Geosciences, which has been designed for immersive 3D VR environments. They

outlined how the Visualizer can enable discoveries or insight related to complex 3D gridded data sets.

The increasing power of mobile devices and their massive adoption, allow the development of immersive mobile applications focused on outdoor experiences. Technologies such as GPS, compass, accelerometer, or gyroscope are integrated in smartphones or tablets, allowing to extend these applications to the GIS context. AR technology is becoming increasingly popular thanks to its capabilities to complement the perception and interpretation of our surrounding real world (Schmalstieg and Hollerer, 2016). AR browsers such as Wikitude (2009) or Layar (2009) grant access to standard AR features like adding or querying PoIs. In fact, AR applied to on-site exploration or remote monitoring has proved its true potential (Veas et al., 2013). The potential for learning purposes was also explored by Wang et al. (2017). They describe the design of a mobile application for geography fieldwork learning.

Schall et al. (2009) considered a first approach of AR for subsurface infrastructure visualization. Later on, Schall et al. (2013) also introduced a first approach demonstrating the potential for improving workflows such as on-site planning, data capture and surveying through interactive, on-site visualizations. Veas et al. (2013) presented a system that displays hydrological information in the Swiss Alps based on a sensor network. More sophisticated visualization techniques were explored to overcome the problem of data visualization over large areas (Veas et al., 2012). Natural interaction patterns such as pointing the device to certain locations were also explored (Meek et al., 2013). In their work, the authors presented an interactive mobile application to capture remote points of interest resulting from the intersection of the line of sight between the device and a digital surface model.

In recent times, AR has begun to be applied in the Geosciences to provide interactive visualization in the field. Perhaps, one of the first ideas of using AR and tablet computers to visualize geological data, was the concept video made in 2012 at the Norwegian University of Science and Technology.² Lee et al. (2015) proposed an AR application to visualize borehole information on iPad devices. They presented the combination of 3D information of borehole data on the real world view and the corresponding positioning on a 2D map layer.

Supplementary video related to this article can be found at <https://doi.org/10.1016/j.cageo.2018.09.004>

Based on an AR browser (Layar, 2009), Pierdicca et al. (2016) presented a virtual overlay showing the nearest buffer strips. Their AR cloud-based application enhances the performance of on-site inspections over large territories by dynamically superimposing geographic features, comments, and other related content. Authors reported that thanks to a quick access to relevant information, domain experts could carry out their work in less time.

In fact, ESRI Labs has recently presented AuGeo (2017). This is an AR mobile application to explore the possibilities of using ArcGis data on an AR environment. AuGeo development is in an early stage, and at the moment it can only provide PoIs visualization. However, it clearly shows the importance and the future relevance of AR in the field.

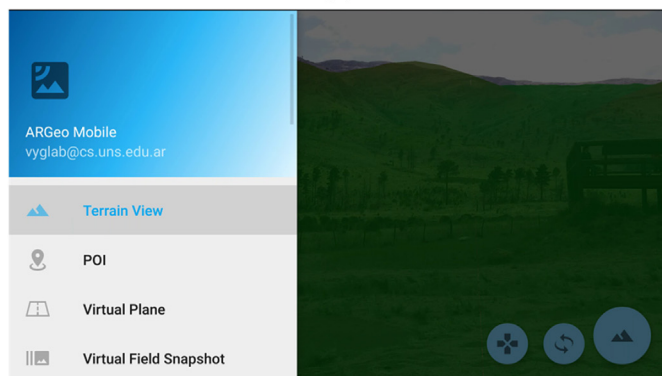
Despite the fact that AR has been explored in outdoor environments, there is still missing a comprehensive system that can be used for applications focused on fieldwork. ARGeo system provides a basic and extensible AR environment necessary to be incorporated into the performed workflow during fieldwork. The proposed system was designed to operate in remote zones without an internet connection (e.g. wireless network or GSM coverage), fieldwork characteristic that results mandatory in the general workflow performed. Moreover, a fully virtual 3D terrain of the surrounding environment can be superimposed onto the real world to give the user an important frame of reference. This terrain visualization can be used to interactively explore and incorporate geo-tagged data.

¹ ARGeo can be obtained freely upon request. The system and the source code can also be accessed from the public repository <https://github.com/nicolasVvGLab/ARGeo.git>.

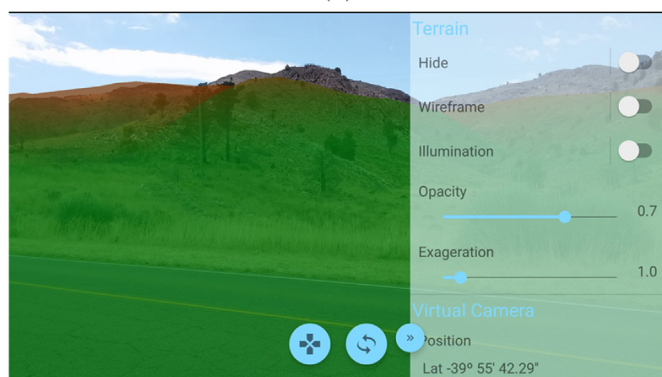
² <https://www.youtube.com/watch?v=gWrDaYP5w58>.



(a)



(b)



(c)

Fig. 1. The UI of ARGeo. (a) The three main zones of the UI. (b) Left panel menu to select the operation mode of ARGeo (Terrain mode is selected in the image). (c) Example of Terrain operation mode, showing the secondary buttons and the right panel menu with the properties of the current operation mode. To increase the immersion of the UI, this panel is translucent allowing to maintain the visibility of the background view. Both opacity and width values can be modified from the UI.

3. ARGeo system

In the following sections we provide the details of the main features of the System, as well as its implementation details.

3.1. ARGeo User Interface

The User Interface (UI) was carefully designed to be both intuitive and immersive (see Fig. 1). The UI was also arranged in three main zones, namely: the background zone, left menu zone and right menu zone. The background zone always provides the augmented

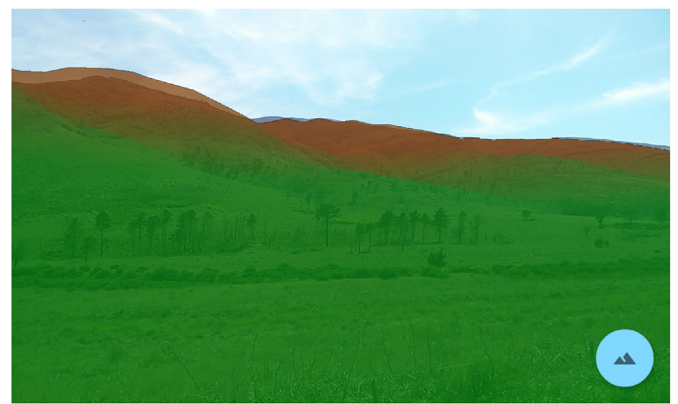


Fig. 2. Example of the virtual terrain superimposed onto the real world. A 3D mesh, constructed using the DEM file corresponding to the current location, is projected onto the captured camera frame. The location of this image is from the mountain area in Sierra de la Ventana, Buenos Aires, Argentina (site location latitude 38°04'22.7"S and longitude 62°00'55.2"W).

environment in full screen. In fact, the device must be used in landscape orientation, offering a UI as immersive as possible.

The left menu zone provides the left panel that can be accessed using a swipe gesture, according to the Android Material Design metaphor. The System provides four main operation modes which correspond to its main features and can be selected from this panel. The four operation modes are: Terrain Mode, PoI Mode, Virtual Plane Mode, and Virtual Field Snapshot Mode, and these are described in the following sections. The right menu zone presents the corresponding UI elements to the current operation mode.

3.2. Virtual terrain

The basic functionality of the ARGeo system is to provide virtual geo-data integrated into the real environment. In order to achieve this goal, a virtual terrain corresponding to the current field of view is shown. Thus, ARGeo provides the visualization of a mesh based terrain as an overlay onto the real world. Fig. 2 shows an example of the virtual terrain visualization.

To model the terrain we used the heightmaps provided by the Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEM) (Farr et al., 2007). We used the 3 arc-second per tile SRTM resolution, appropriate for the available hardware. Depending on the memory hardware of the mobile device, DEM files of 1 arc-second per tile SRTM resolution could also be used. DEM files corresponding to the desired fieldwork session must be previously uploaded to the device (DEM files are provided in the WGS84 coordinate system). This makes the ARGeo System not dependant on any wireless internet connection to operate.

During fieldwork ARGeo uses the GPS unit to obtain the current coordinates of the user and to load the actual DEM file, in order to provide the terrain visualization. ARGeo reacts in real-time to changes in the orientation of the mobile device. The orientation change is directly mapped to the terrain visualization using the built-in sensors (i.e. giroscope and compass). It is important to note that all the data representation and its processing are carried out on the mobile device.

3.3. PoI

The PoI operation mode offers the basic interaction with the augmented terrain which consists of adding virtual geo-tagged information. ARGeo allows to simply tap the screen of the device to add a PoI with its corresponding information. The detected touched position on the screen is projected to the 3D terrain, allowing to retrieve the latitude and longitude coordinates. Thus, adding references on top of the terrain



(a)



(b)

Fig. 3. POIs can be added simply tapping the virtual terrain. (a) Two POIs over the virtual terrain and the list of POIs on the right panel. (b) Properties of each POI can be accessed swiping the right panel after the POI is selected.

or information from measured data is as simple as tapping the desired location on the screen. POIs are listed on the right menu (see Fig. 3a). They can be selected to access their related information swiping the right menu panel (see Fig. 3b).

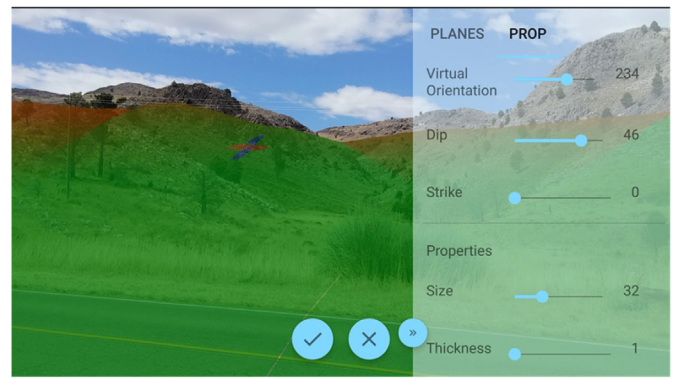
3.4. Virtual planes

As an example of a specialized feature, ARGeo provides the Virtual Plane operation mode. This feature allows to add planes on the augmented view to estimate the attitude of geological folds and fractures. These virtual planes are used to interactively approximate dipping planes. Using the same metaphor introduced to the POI placement, the user can add virtual objects similar to the planes used to describe geological folds. These planes are represented by the dip angle and a virtual orientation angle. The latter allows to orientate the plane on the virtual view. The plane also allows to record the estimated strike orientation. These values can be modified later, when the user conducts on-site measures of the geological structure.

The user can interactively change the orientation values. These changes are reflected on the augmented view in real-time. Fig. 4 shows how virtual planes can be added from ARGeo UI.

3.5. Virtual Field Snapshot

To assist the geologist during the inspection and interpretation of the environment, an important feature was incorporated to the design of ARGeo. Some geological features are easily detected from a distant point of view. However, when it is required to perform the actual measurement (i.e. dip and strike) or the interpretation of this data, the local perception obtained differs from that acquired from a distant



(a)



(b)

Fig. 4. Example of Virtual Planes over the virtual terrain. (a–b) Examples of two Virtual Planes and their properties.

point.

Thus, to easily keep track of these landscapes we embodied into what we called the Virtual Field Snapshot. ARGeo provides this operation mode which allows the user to take a snapshot of the desired field view. Besides the snapshots that are stored and that can be retrieved later on, they reflect the changes made to the virtual terrain in real-time. Therefore, changes introduced to the virtual entities are reflected on the snapshot like a back-in-time visualization of these locations (i.e. as the user was observing from the taken snapshot location). Fig. 5 shows how a Virtual Field Snapshot is presented in the UI, and how adding POIs and Virtual Planes to the terrain is reflected on the snapshot.

The Virtual Field Snapshot allows the geologist to keep record of the perception of the environment from the recorded points of view. Given that the changes to the terrain are reflected in real-time, the user can, for instance, modify the Virtual Planes as if he/she were in the previous location. This feature can be used to make a preliminary estimation of the folding angles, and later update this initial measurement with the actual on site gathered data. ARGeo allows to create and store multiple Virtual Field Snapshots. Nevertheless, the user must select the desired snapshot to be the active one. The active snapshot is presented in the lower left corner of the screen (see Fig. 5a).

3.6. Framework-based design

ARGeo was designed as an extensible framework oriented to assist fieldwork. It provides modules and components to be adapted to the current fieldwork needs. The framework was designed according to geologist's fieldwork activity, oriented to fieldwork planning and to the actual fieldwork (see Fig. 6).

Fieldwork planning is modeled by the Office Application Service. It



Fig. 5. The Virtual Field Snapshots are presented on the lower left corner of the screen. (a) Shows the initial Virtual Field Snapshot containing two POIs. (b) Adding a new POIs to the virtual terrain is automatically reflected on the current Virtual Field Snapshot.

provides the modules and components to store data into the mobile application, as well as to retrieve data from it. Thus, the data structure consists of ARGeo data and third party data. The latter can be imported using a standard representation (i.e. CSV files). The Format Parser is the component responsible of the translation from third party data into ARGeo data (e.g. POIs, Virtual Planes). The Database Manager handles the office database management. By default, it serves as the interface to a MySQL like database engine.

The Office Application Service was implemented as a desktop

Application, based on the .NET 4.5 framework. It provides the user a simple and intuitive interface to import and export data in CSV format (see Fig. 7). Therefore, the user can synchronize the data between the desktop application and the mobile application, as well as importing data from traditional office applications used by the geologists (e.g. QGIS (2018)).

The Mobile Application was designed to be operated without network communication during fieldwork. It provides a Communication Interface component to access data from the Office Database, that are stored in the Local Database. However, the Communication Interface can be extended to operate with access to online data providers.

The Local Database uses a SQLite database to store persistent data (e.g. POIs, Virtual Planes, Configuration Settings, etc.). In runtime the application uses data collections as structures to store data (e.g. list structures). To improve the memory management, it loads data on demand (e.g. accessing the nearest data to the user's location). The data visualization and AR tracking features are provided by the AR Visualization Engine component. This component provides the class hierarchy to model the data entities. At the moment, there is no automatic translation of the data entities to the database (e.g. Object-Relational mapping or XML based definition). However, we plan to extend the framework with this feature to make it easier to extend and to adapt with new data entities. Finally, the general structure and definition of the UI es provided by the User Interface component. It follows the Android standard, defining the UI using XML files.

3.7. System Architecture

The System Architecture consists of six main components arranged in layers (see Fig. 8). Details of each component are provided below.

User Interface. It provides the UI interactions and it groups the corresponding classes of the UI architecture (i.e. operation modes, right panels, and action buttons). All these components were designed following the Model View Controller pattern.

High Level Model. It holds the classes of the business model. It provides the model for the ARGeo features, such as the PoI, the Virtual Plane and the Virtual Field Snapshot elements.

Scene. It provides the classes to model the virtual scene and the virtual elements that are incorporated to it. All the scene is rendered by the Render Engine. The virtual elements are modeled as a hierarchy of elements. It can be extended with new classes, in order to easily add new elements to the hierarchy (see Fig. 8b).

Renderer. It consists of the render engine and its related classes. It handles the interface to the OpenGL API and its shader programs to render the virtual terrain, as well as the virtual elements.

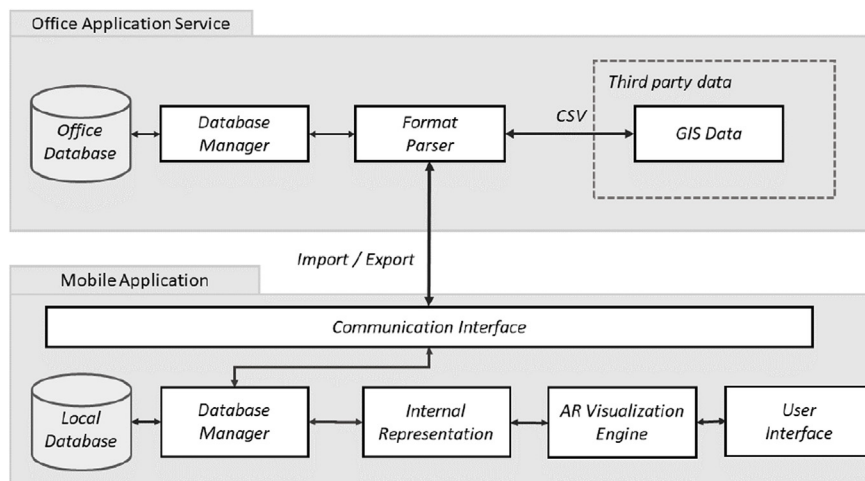


Fig. 6. Framework structure.

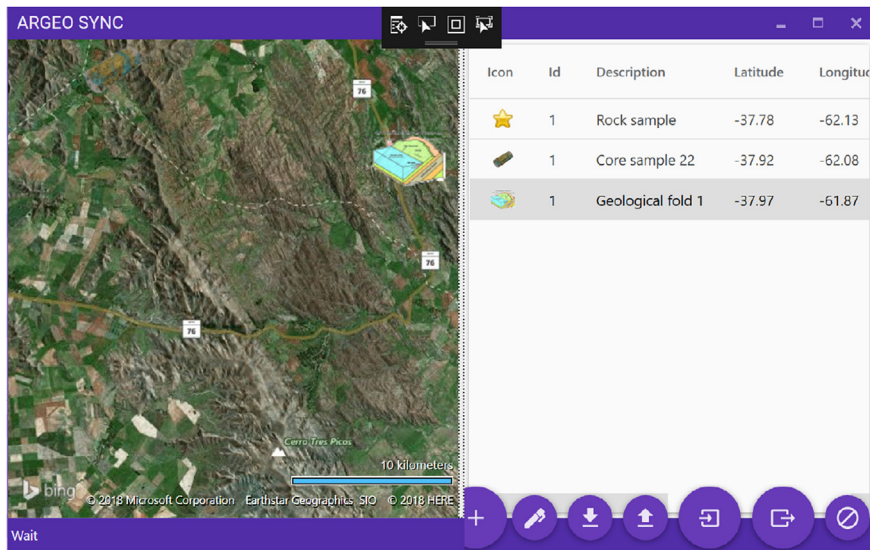


Fig. 7. Intuitive interface of the desktop application that allows the user to import and export data to the mobile application.

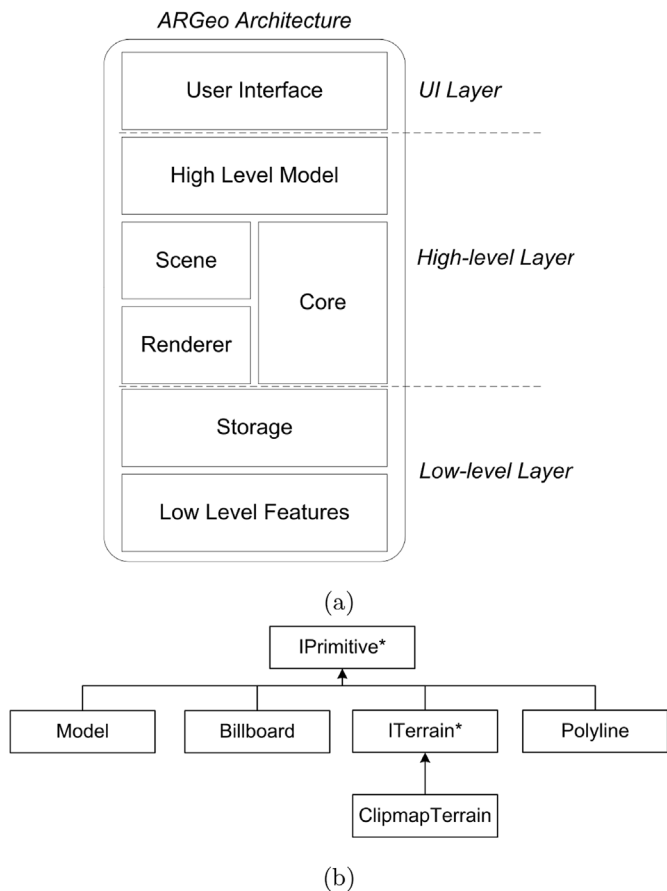


Fig. 8. ARGeo System Architecture. (a) The architecture is organized in three layers: the UI layer, the high-level layer, and the low-level layer. (b) Class diagram of virtual objects handled in the scene component (a class name with an ending * indicates an abstract class, it must be extended to be instantiated). This hierarchy can be extended to incorporate new virtual elements.

Core. This component provides the general classes regarding to the Math and Coordinates handling. For instance, it includes the transformation between Geodetic and Geocentric coordinates.

Storage. It grants access to the storage operations on the mobile device.

Low Level Features. It provides specialized functionalities using the low level Android API. Access to device sensors and time-crucial processes required by the previous layers are provided by this component.

3.8. Implementation details

ARGeo was implemented for the Android platform due to its openness for development and moreover for its massive access along the different devices. It is important to depict how the 3D virtual terrain was implemented for mobile devices' hardware constraints. Large terrain height maps contain billions of samples, an excessive amount to render interactively by brute force (Losasso and Hoppe, 2004). In order to allow real-time rendering, we implemented Geometry Clipmaps using a Level of Detail (LOD) technique. The render engine design was based on the 3D virtual globe engine presented by Cozzi et al. (Cozzi and Ring, 2011).

The render engine and critic time tasks were fully implemented using the Native Development Kit (NDK) and Java Native Interface (JNI) allowing a smooth real-time performance experience. OpenGL ES 3.0³ was selected as the rendering environment due to its diverse toolkit and widespread adoption as the industry standard for 3D graphics. OpenGL enables control of all aspects of the rendering pipeline and allows the programmer to customize stylisation which is appropriate in this geological context (Mathiesen et al., 2012).

Several shading techniques were explored and tested to determine the best option for the terrain visualization while maintaining the visual cues (e.g. depth perception). After the feedback obtained from the experts, we concluded that a height mapped color ramp with added transparency was the best choice for the terrain. This eases the process to recognize regions of interest on the terrain.

The coordinates obtained by the GPS are taken as World Geodetic System of 1984 (WGS84) and then transformed to Earth Centered, Earth Fixed (ECEF) coordinates which are directly used by OpenGL for the camera positioning on the terrain (i.e. setting the rendering camera position on the virtual scene). To overcome the error prone measures of the altimeter, the altitude of the camera is calculated using bi-linear interpolation on the height-map's texels (i.e. accessing the fundamental unit of the height-map). Similarly, all virtual objects have WGS84 or ECEF coordinates which are used to build a translation matrix to set its position in the world. The virtual objects can also be clamped to the

³ <https://www.khronos.org/registry/OpenGL/>.

earth surface by applying the same technique employed to calculate the camera's altitude.

3.9. Tracking system

In order to visualize AR information a registration and tracking system is needed. It guarantees that the virtual objects are correctly aligned with the physical world. To achieve a reliable registration in unknown outdoor environments, we used a combination of location based tracking using the GPS receiver and the Inertial Measurement Unit (IMU) provided by the device. We also provided a manual registration process.

The registration process is carried out in two stages:

1. Coarse registration: The system assigns to the virtual camera the position obtained from the sensors of the device (GPS and Orientation).
2. Fine registration: The user interactively applies rotations and/or translations to the virtual camera when the virtual terrain does not match the real one. Rotations and translations are triggered by intuitive touch gestures on the device's screen.

All the virtual elements are geo-referenced, that is, they have a location on the Earth. To avoid *jittering* problems due to the precision limited by today's hardware (32-bit floating point in the GPU) the *Rendering Relative to Center* technique was used in combination with *double* precision emulation at GPU level.

The position of the virtual camera is encoded using the emulation algorithms of *double* precision. The *double* number is divided in two *floats*, which represent the lower and the upper part of the number respectively. Finally in the *shader program* the relative translation of the virtual element is performed using the emulated *double* sum.

3.10. Extending ARGeo

The careful framework based design used allows the designer to extend ARGeo with new features. The incorporation of a new fully operation mode supporting a 3D model feature, for instance, can be achieved following the next three steps. (1) The model hierarchy class, from the High Level model layer of the ARGeo architecture, can be extended with the desired new class that models the new feature. (2) The UI for this new feature can be incorporated following the right panel pattern from the UI module. (3) The corresponding 3D models can be incorporated extending the classes provided by the IPrimitive hierarchy.

4. Results and discussion

4.1. Case study and evaluation

ARGeo has been developed in close collaboration with geology experts. We carefully studied the workflow performed during fieldwork activities to incorporate the interactions described in the previous section. From this workflow we took into account two main tasks. The first one consists of the observational analysis and interpretation conducted to comprehend folded structures. The second main task is related to the sample gathering and the associated data storage in the actual observed location. Field tests of the application were carried out in the mountainous area of Sierra de la Ventana, Buenos Aires, Argentina because of the well exposed geological structures that can be measured in a relative accessible zone (1200 m.a.s.l.).

The tasks involved can be detailed as is shown in Fig. 9. Geologists fieldwork oriented to folded structures interpretation entails a careful iterative observation process. As usual, the prior fieldwork planning and preparation is an important task that can be done in the office. At this stage, data could be imported to ARGeo (e.g. PoIs data).

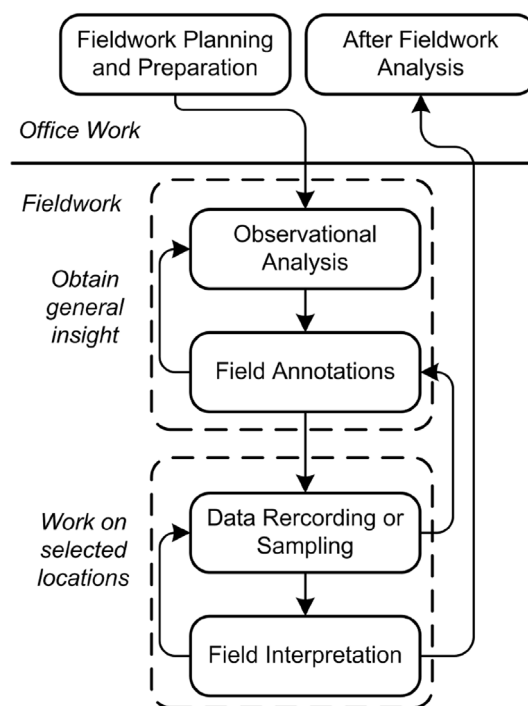


Fig. 9. Case study used in the ARGeo evaluation.

During fieldwork, the geologist can perform fold observation from distant points of view. He/She can observe the field attitude of folds, while using ARGeo to introduce new PoIs. During this stage the geologist obtains a general insight and takes notes of the relevant features to be measured. For instance, the geologist can estimate bearing and inclination angles using Virtual Planes. Before moving on to the relevant locations to be observed, the geologist can take a Virtual Snapshot of the observed area.

Later on, working on each selected location involves a complex constant association between recorded 2D information and the 3D information present in the real environment. The geologist can conduct the measures using the standard equipment and upload the measures to ARGeo. For instance, correcting a PoI coordinate from the output obtained of a differential GPS. However, in areas subjected to several episodes of folding it is really challenging to identify the location where the measurement must be taken and that has been previously defined from a distant viewpoint. At this point, the previously taken Virtual Snapshot could be really helpful. In addition to the information that can be observed from the acquired image, all the updates to be made to the virtual objects (i.e. PoIs and Virtual Planes) are going to be updated in the given Virtual Snapshot. This feature allows, for instance, to change a Virtual Plane orientation or inclination in-situ, and therefore, to see all these changes reflected in real time onto the Virtual Snapshot.

Finally, after the fieldwork and once in the office, the geologist can retrieve the data stored by ARGeo and export it in a standard format (e.g. CSV files). Nevertheless, the Virtual Snapshots taken over the fieldwork can also be retrieved. They could be still useful to link the gathered data to the outdoor environment.

We conducted a user centered design, with informal tests to evaluate the initial prototypes of the application. Early tests were useful to model the ARGeo UI and the interactions to complement the fieldwork workflow. ARGeo was not intended to replace the current fieldwork process, but to complement it by means of AR. ARGeo features were designed to complement fieldwork carried out by domain experts.

After the initial tests, we obtained a more robust prototype that we used to conduct an user test. We tested the ARGeo System with five domain experts, with 5–32 years of experience, mean 19.0 (ages from 30 to 57, mean 44.0, three males and two females). We proposed to

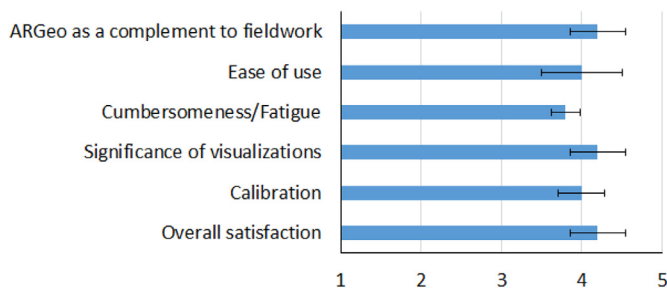


Fig. 10. Bar chart showing user feedback from questionnaire (mean and standard deviation). The used scale was from 1 (worst negative score) to 5 (best positive score). The overall result was positive towards the ARGeo system.

utilize the system during their standard activities while we took notes of the behaviour of the users with the system. We decided not to conduct a formal and structured test because we wanted to capture how the system was involved to complement their activities. Although the system is robust enough to be used in the field, additional tests should be conducted to generalize the results. The main focus was to capture usability issues and to record the user behaviour during the system operation. The device used was a Samsung Galaxy Tab S with a 8.4” display. The average time of each session was approximately 1 h.

At first, the users took a couple of minutes to familiarize with the system. They adjusted the opacity level of the virtual terrain to their personal preference. They also tested the system features adding some POIs to the terrain and taking a couple of field snapshots. Participants had no problem to perform the positioning of points of interest and virtual planes. All users agreed that the precision of the device was adequate. The mean satisfaction with the system and other relevant answers are present in Fig. 10.

4.2. Discussion

The general outcome of the ARGeo System evaluation was very positive. The system was easy to use and intuitive. All agreed that the system has a real potential to complement their usual fieldwork and several suggestions were provided. Much of the suggestions pointed to add new features or to modify the existing ones, such as modifying the color ramp of the terrain or providing access to a map feature.

Participants agreed that orientation sensors sensitivity was unstable. Although it is dependent on the employed device (e.g. the tablet used was more sensitive to orientation changes than the smartphone), sometimes the terrain visualization was too shaky. We plan to overcome this remark adding image processing assistance to stabilize the virtual terrain rendering.

With regard to the hardware used, there are some memory issues to take into account. If the resolution used to capture Virtual Field Snapshots was too high, the device memory was consumed really fast. We carefully implemented the memory management to maximize its use, however if the user constantly generated new snapshots the device ran out of memory. This issue did not interrupt the use of the application, but delayed the full use of it asking the user to free resources from the application (e.g. close open snapshots). Using devices with more memory can leverage this issue, however we plan to explore more sophisticated approaches to manage and reuse memory resources more efficiently.

The precision of the GPS Unit was in general accurate (3 m in average). If the accuracy of the GPS is poor, the system informs the user because it might be difficult to properly adjust the virtual terrain to the image captured by the camera (e.g. mountains silhouettes do not fit the virtual terrain silhouette). Nevertheless, the precision of the measurements can be approximated using the following equation:

$$\text{Precision} = \text{GPS acc.} + \text{DEM acc.} + R \text{ error}$$

The *GPS acc.* is 3 m in average. The *DEM acc.* refers to the DEM file sampling accuracy. We used 30 m accuracy files. However, if the device used grants access to better memory requirement, 1 m accuracy files can be handled by ARGeo. Finally, the *R error* represents the round/truncate error of the mobile device internal precision.

Regarding to the ARGeo UI, the general operation modes and the right panel menu were easy to use. Sometimes it became difficult to operate the system due to illumination conditions. Nevertheless, geologists are used to this kind of constraints and they did not point out this issue as a concern.

Although during the tests most participants reported that the terrain visualization with transparency and a height-mapped color ramp were adequate, later they suggested that the matching procedure between real and virtual terrain would be easier to achieve if the virtual terrain had a thicker outline. Therefore, matching the real and virtual world would be as easy as matching both silhouettes. Nevertheless, all the participants agreed they would like to continue using the ARGeo and proposed several improvements or new features. They also agreed that ARGeo could really assist them in their fieldwork and they were enthusiastic to use it in other locations.

5. Future work

We can detail two main future lines of work oriented toward the usability of ARGeo and the addition of novel interactions. The major usability drawback is related to the sensibility of the built-in sensors. We plan to enhance the experience obtained using ARGeo analyzing the implementation of a more robust prediction of the device movement. Beyond the well known Kalman filters, that in general are already implemented in the hardware of the device, we plan to incorporate intelligent methods (e.g. machine learning) to predict and to adapt to the orientation changes made by the user. We will also explore methods to automatically align the virtual terrain to the shape of the mountains. For instance, deep learning techniques can be used or combined to the current method, as it was recently presented by Rao et al. (2017). We also plan to evaluate the methods in terms of precision and performance.

Thanks to the framework based design, ARGeo can be easily extended taking into account the feedback provided in the evaluation. We can outline three main features that are currently under development, namely: new geographical entities, geological maps projections and automatic sketch visualization.

New geographical entities, in addition to PoIs and Virtual planes, are planned to be added. For instance, we are currently incorporating *polylines*. A *polyline* consists of a set of connected lines that can be useful to trace geo-referenced paths or to establish relationships among sampled data (see Fig. 11).

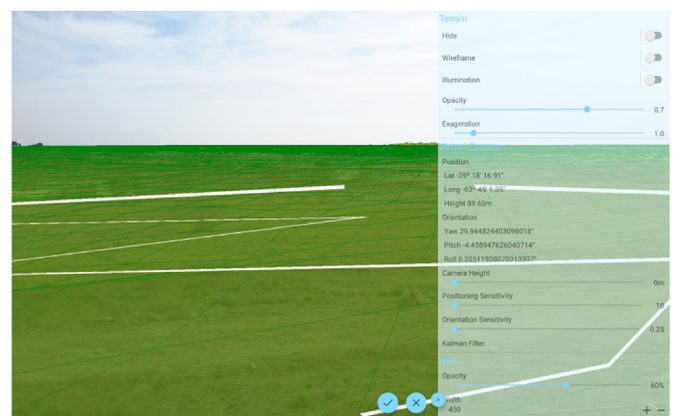


Fig. 11. Example of the polyline feature. Several geo-referenced positions can be linked to establish relationships among data.

The virtual terrain also allows the developer to explore new useful visualizations. Geological maps can be projected onto the virtual terrain, providing a richer visualization of the ground. This will also prevent the geologist from manipulating the map in the field.

Finally, we are currently exploring to incorporate *sketch like visualizations* to aid in the process of fault interpretation. Using intelligent features, for instance, faults can be detected and presented in a sketchy fashion, similar to the field sketches drawn by geologists.

These future lines are planned to be developed under an iterative process of the cycle *design - development - evaluation*. Each stage will be conducted as a collaborative work between professionals of Geology and Computer Science.

6. Conclusion

We presented the ARGeo system, an AR system to assist the geologist during fieldwork. It provides the visualization of a fully 3D virtual terrain, that can be used to incorporate geo-tagged virtual elements. Poles and Virtual Planes are examples of these virtual elements, which can be also interactively modified and visualized from different locations using the Virtual Field Snapshots. ARGeo was shaped using a framework design that enables further improvements incorporating new specialized features.

The conducted tests show the feasibility of ARGeo on the Geology field, and its potential to other Earth Sciences related fields. We identified future lines of work to enhance the usability of ARGeo, as well as to incorporate new dedicated features to the system.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cageo.2018.09.004>.

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