Virtual Reality Interfaces Applied to Correct Elevation Errors in Digital Elevation Models

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Abstract. In this paper we introduce a new methodology to correct elevation errors in remote sensing data, namely digital elevation models, enhancing their accuracy and precision. This methodology proposes the use of desktop virtual reality interfaces by specialized remote sensing data users to visualize, explore, analyze and edit digital elevation models, in order to identify and remove any type of errors contained in the models. A system called DEMEditor has been implemented, validating the proposed methodology. Both, the methodology and the DEMEditor are described in detail. An insight into relevant implementation issues taken into account for the development of the virtual reality system is also given. This system has been used with real datasets to verify its applicability to solve the proposed problem.

Keywords: virtual reality, digital elevation models, editing, elevation errors.

1. Introduction

Two facts make up the motivation for this research work: (1) DEMs present elevation errors produced by different kinds of problems, which should be corrected in an intuitive and efficient way relieving the need for specific detection and removing algorithms that specialize in detecting errors with particular characteristics, and (2) the remote sensing community, as far as we know, has not got an efficient and complete tool for this purpose. Such a tool should combine a realistic visualization and intuitive manipulation of the data, as well as a qualitative analysis, together with a toolkit composed of editing functionalities for correction of different types of errors found in the DEM.

2. Related Work

Many researchers have used three-dimensional (3D) virtual reality (VR) interfaces to visualize large amounts of data [Lum and Ma 2002], such as DEMs. Desktop VR environments offer an intuitive, efficient and cost-effective way to explore terrain data, including through the Web [Koller et al. 1995; Reddy et al. 1999]. Projects related to the use of immersive VR have also applied terrain models as an application area for their experiments, and have constructed realistic and powerful virtual environments for the visualization and exploration of large datasets [Watson et al. 2000; Piper et al. 2002].

Interaction techniques in VR systems have largely been studied, for categorization of interactions that take place in virtual environments [Bowman et al. 2001], for interface design [Wingrave et al. 2002; Hann et al. 2002], and for construction of interactive content [Fuhrmann et al. 2001; Rekimoto 2002], to name only a few.

Some research works have developed methodologies to quantify uncertainty in DEMs, since the models are commonly used as data sources without quantifying the effects of its inherent errors [Ehlschlaeger 1998; Wechsler 2000]. Beyond, tools that implement algorithms to identify specific types of errors in DEMs, and offer functionality to edit them have also been implemented [Ehlschlaeger 1998]. The DM4DEM is one of the most complete
examples [Durañona 2001].

3. Methodology
The approach proposed by the authors in order to correct elevation errors in DEMs is based on VR interfaces. These interfaces are used to perform visualization and exploration of the data, as well as statistical analysis in order to identify errors, and to edit the errors found in the models. Once adjusted, these models become more accurate and precise, as well as reliable.

According to our methodology, users have to perform three basic activities:

- visualize the DEM and explore it, in order to obtain knowledge about the data that can be used to make a visual interpretation and verification of the model;
- analyze the DEM using specialized analysis tools, so that precise statistical values can be used to find error areas;
- edit error areas identified visually and/or through statistical analysis, enhancing accuracy and precision of the DEM.

It is important to say that users that exploit the methodology described here should own knowledge about the data to be corrected (e.g., interferometric synthetic aperture radar (InSAR) data), in order to produce as good as possible results. This requirement is due to the fact that visual interpretation plays an important role in this methodology.

3.1. Visualization of DEMs
How the user chooses to portray a dataset can have a significant effect on how accurately and efficiently visualization communicates the information the user seeks to reveal. It is the authors’ belief that when visualization is made in three dimensions and in an interactive manner, the user is able to more quickly derive expressive visualizations. Such visualization may be accomplished using VR technology. Following the methodology, the DEM should be presented as a 3D precise surface to perform visualization, analysis and editing tasks.

Another way to present DEM data is the use of contour levels. A functionality to enhance visualization in the VR environment is to present data as a compound view, composed by the 3D surface, overlapped by its contour levels. This form of visualization is commonly used to enhance comprehension of elevation data in two dimensions, what is also true in three dimensions.

Color can be manipulated based on height to improve height perception. Often warmer hues are used for the lower values and become cooler in the higher values. Each vertex of the surface is mapped with height-based predefined colors, so that terrain’s shape can be easily observed.

Wrap 3D objects with textures is a sophisticated way to enhance the realism of content presented in VR. Specialized research groups have given special effort to produce textures of high-resolution and at the same time usable, so that the objects can be loaded in a low time consuming manner. In the DEM context, the amplitude image generated from the same raw data as the DEM is an adequate texture to be used. The virtual terrain, wrapped with its corresponding amplitude image, allows the reproduction of the surface appearance of the terrain (vegetation coverage, for example) in the real world, when imaged by the sensor.

3.2. Interaction in the Virtual Environment
The variety of reported interaction techniques can be overwhelming for the developer. However, some
general principles regarding the choice of manipulation techniques can be stated. None of the
techniques can be identified as the best: their performance is task and environment dependent. Often,
nonrealistic techniques have better performance than those based on the real world.

Navigation, manipulation and system control are the three types of interaction activities that
normally take place in a virtual environment [Bowman et al. 2001; Wingrave et al. 2002]. The
presented methodology uses techniques that make possible to the user perform these interaction
activities to explore virtual DEMs and edit errors on them.

3.2.1. Two-Dimensional Interaction

A common misconception of 3D user interface design is that, because the applications usually contain
3D worlds in which users can create, select, and manipulate 3D objects, the interaction design space
should utilize only 3D interaction. In reality, 2D interaction offers a number of distinct advantages over
3D interaction techniques for certain tasks. If haptic or tactile displays are not present, 2D interaction
on a physical surface provides a sense of feedback that is especially useful for drawing and annotating.
By taking advantage of the benefits of both 2D and 3D interaction techniques, it can be created
interfaces for 3D applications that are easier to use and more intuitive for the user. The methodology
described here intends to apply both, 2D and 3D interaction techniques.

The methodology suggests the use of widget-based interfaces, with menus and command-line
input, to control the system.

3.2.2. Navigation

The methodology uses different metaphors to travel through the virtual environment (move the
viewpoint of the user from one location to another, considering its orientation as well):

- steering: the user specifies continuously the direction of motion, using a pointing technique. The
  user’s hand orientation determines the direction of travel, moving forward with the mouse;

- target-based travel: the user specifies the destination, and the system handles the actual movement.
  This may take the form of “teleportation”, in which the user jumps immediately to the new location,
  or, preferably, the system may perform some transitional movement between the starting point and
  the destination;

- route planning: the user specifies the path that should be taken through the environment, and the
  system handles the actual movement. These techniques allow the user to control travel while he/she
  retains the ability to perform other tasks during motion.

3.2.3. Object Manipulation

Interaction techniques for 3D manipulation in virtual environments should provide means to
accomplish at least one of three basic tasks: object selection, object positioning, and object rotation.
Direct hand manipulation is a major interaction modality in physical environments, so that the design
of interaction techniques in virtual environments using this metaphor has a profound effect on the
environment user interface.

The methodology uses the approach of touching an object with the mouse and then rotating it.
This approach simulates a real-world interaction with objects. Some objects in the virtual environment,
in order to perform predefined actions, are associated to touch sensors. The user may select and
manipulate them to, for example, change their position in the world.
3.2.4. *System Control*

System control refers to a task in which a command is applied to change either the state of the system or the mode of interaction.

The use of tools, that is to say, virtual objects with an implicit function or mode, is a technique used for virtual environments and adopted by our methodology.

3.3. *Analysis of DEMs*

Remote sensing data users perform analysis on data using some well-established methods. The proposed methodology approaches analysis through the use of a histogram tool, a tool to draw profiles, and a position-height pick up tool, as well as through the verification of statistical information about the DEM, such as mean, variance, skewness and kurtosis.

3.3.1. *Histogram*

A histogram is a statistical representation of a dataset, such as an image, that shows how many pixels there are at each of the possible values, what is to say the distribution of the data.

The histogram affords a global description of the appearance of an image; in other words, the overall darkness or brightness of an image. For example, given a digital image with gray levels in the interval $[0, L-1]$, if the gray levels are concentrated near the darkest extreme of the gray levels interval, the histogram corresponds to an image with predominantly dark features, and if the gray levels are concentrated near the brightest extreme of the gray levels interval, the histogram corresponds to an image with mainly bright features. If the histogram presents a strait shape, indicating a small dynamic scale, it corresponds to an image with low contrast, and, finally, if the histogram presents a more even distribution of pixels over the entire intensity range, it corresponds to an image with high contrast.

In despite of these properties be global descriptions that do not tell something specific about the content of the image, the shape of the histogram provides useful information about how to enhance its contrast. Contrast enhancement may help users to comprehend terrain’s height variations, since bright and dark areas can be highlighted.

3.3.2. *Profile*

A profile represents the height of a set of points along a line, drawn by the user. These elevation information may be compared to height data collected from the real-world corresponding terrain, in order to verify its precision. The points from which height values are compared to true values are commonly located at areas of the terrain for which it is difficult for the sensor to collect data. Consequently, the inaccuracy level presented by these points represents the worst case for the whole DEM. If this level remains low for all verified points, the DEM can be considered reliable.

3.3.3. *Statistical Information*

Mean and variance are useful statistical features of an image. Mean indicates the image’s average value. Variance, or $\mu^2$, is the square root of the standard deviation. The standard deviation is a measure of the frequency distribution, or range of pixel values, of an image. If an image is supposed to be even throughout, the standard deviation should be small, what indicates that the pixel intensities do not stray very far from the mean. A large value indicates a greater range. These values must be used with some caution when dealing with some applications, since more subjective analysis may be
required to determine the “goodness” or “badness” of an image. On the other hand, for another applications, such as machine vision, these statistical values can be very accurate indicators of image quality and can be used to make automated decisions.

Skewness, or $\mu_3$, indicates a lack of symmetry in a frequency distribution. Kurtosis, or $\mu_4 - 3$, represents the peakedness or flatness of the graph of a frequency distribution especially with respect to the concentration of values near the mean as compared with the normal distribution.

### 3.3.4. Position and Height

Each pair of coordinates $(x, y)$ has a $z$ value associated, which represents the height value at that point. The height value associated to each position on the DEM can be verified by the user.

### 3.4. Editing of DEMs

#### 3.4.1. Selecting Regions Of Interest

In order to correct errors found in the DEM, the user needs to select the regions identified as of interest before performing some editing task on the terrain. Once selected, the values of the coordinates held by the region of interest (ROI) may be removed and interpolated, and smoothed using a specific algorithm.

Functionalities to manipulate the ROIs are also needed. Therefore, tools to delete defined ROIs, and to select inactive ones should also be available to the user.

#### 3.4.2. Removing “Dummy Values”

DEM$s commonly present positions where there are no height data available. This happens because the sensor (e.g., a radar) could not collect data for these points. Normally, if no value for a specific position can be obtained, a so-called “dummy value” equal to −9999 is assigned to it.

Obviously these dummy values do not correspond to the correct height values of the terrain at that position, and have to be replaced. In order to achieve this, a method known as interpolation is used to compute a new value for the pixel. Our methodology foresees the use of linear and bilinear interpolation algorithms, in order to perform this editing task.

#### 3.4.3. Removing Error Values

Since an error value has been identified in the DEM, it has to be removed. A scissor tool can be used to cut out isolated error values or selected ROIs that hold the error areas.

#### 3.4.4. Interpolate Holes

The Earth surface does not contain holes (in this context, positions without height values), and similarly should not a reliable DEM. If the user cuts out a height value or set of height values (ROI), the leaved holes have to be closed. Interpolation techniques can satisfactory be used for this purpose.

#### 3.4.5. Smoothing

Another functionality associated to editing DEM$s is terrain smoothing. Different types of filters may be used to perform the smoothing of a surface. These include the median, mean and sigma filters. For example, the median filter is a filter classified as a statistical one. Statistical filters use statistical properties of an image to define its value at each pixel, and are used to remove noise on it.
Taubin [Taubin 2000] proposed a smoothing algorithm called $\lambda/\mu$ that intends to solve the problem of shrinkage presented by other smoothing algorithms, such as the box filter. This algorithm can be seen as an extension to the Laplacian smoothing, which is a well-established technique.

3.4.6. Modify Maximum and Minimum Values
The user can edit the minimum and maximum values of the DEM using a command-line widget or a height indication bar. The input of the new value through the 2D interface allows the user to define precisely what minimum and maximum height the terrain should have. The 3D icon allows the user to define the new height value interactively, moving the height indicator on the bar and visualizing the result on the virtual DEM, until the desired height is accomplished.

4. DEMEditor: a VR System to Visualize, Analyze and Edit DEMs
The DEMEditor, as the name already suggests, is a software for editing DEMs, in order to correct elevation errors. It is a desktop VR system, which reconstructs real-world terrain (or surface) in VR. The virtual environment is meant to be a place where specialized SAR data users explore and analyze their large amounts of data, validate them according to known quality parameters and make adjustments on the DEM, if needed.

The proposed system is implemented in IDL, version 5.x. IDL is largely used by remote sensing data users as it offers a number of built in functions for data analysis and visualization.

4.1. System Architecture
The proposed system is composed of a four-module architecture: 1) the presentation module, 2) the representation module, 3) the analysis module and 4) the editing module. These modules are interconnected and strongly depend on each other. Each module is responsible for specific functionalities offered by the DEMEditor.

The presentation module implements the interface of the system. A simple virtual environment is presented, composed basically of the 3D surface object that represents the DEM. Some additional icons are introduced into the environment to support user’s actions.

The representation module assists the presentation module, taking care of the generation of a 3D surface based on predefined DEM data. It also constructs the virtual environment that contains the surface model. Predefined or in real-time defined navigation components are also made available to presentation by the representation module. Several interaction techniques are implemented in the virtual environment, which are managed through the representation module.

The analysis module implements tools responsible for studying, validating and reporting any problems in target data. For example, a histogram can be drawn from data presented in the virtual environment. A tool for drawing profile lines on the DEM is also available, which is an important one for accuracy validation. New analysis tools can be associated easily to this module, according to the tasks to be performed. In the DEMEditor, some main algorithms have been implemented with the support for initial quality control processes.

The editing module implements commonly used editing methods such as selection, cut and paste, interpolation and smoothing. These tools allow users to remove elevation errors from the virtual DEM, and to modify data to, for example, creating a terrain model from a surface one, removing the objects that appear over the terrain, such as trees, buildings, and so on.
4.2. Implementation Issues
Some relevant implementation issues have been taken into account during development of the VR system. An insight into them is given next.

4.2.1. A High-Resolution Virtual Environment
Precise representation of data was a fundamental requirement for the successful use of the DEMEditor, since without the adequate support for validation and editing procedures it has no legality. Each pair of coordinates \((x, y)\) and its corresponding \(z\) value had to be represented accurately in order to construct a reliable 3D model of the DEM. Since airborne InSAR-based data can be of very high-resolution (in the order of centimeters), the virtual DEM should also be a high-resolution model, with high level of details about the imaged terrain.

4.2.2. Performance
Traditionally, remote sensing users have to manipulate large amounts of data. A system that intends to present lots of data for manipulation has to achieve this in a way that allows the user to perform its tasks in a satisfactory manner.

Users of the DEMEditor should be able to explore DEMs stored in files with several megabytes, perform analysis and editing of the data. Consequently, performance was a critical point in the implementation of the system.

4.2.3. Realism
Realism or impression of reality leads the user into a state commonly referred to as immersion, or the suspension of disbelief. In the case presented here, representing precisely the DEM as a 3D surface object, and offering the user resources to enhance reliability of the virtual DEM made it possible to accomplish realism. In other words, the DEMEditor offers the following functionalities:

- to wrap the surface with an amplitude image of the terrain that matches precisely the region represented in 3D (Figure 1b);
- to present elevation differences in the terrain through different levels of colors, as illustrated in Figure 2a (for example, dark colors represent lower areas, and bright colors represent higher areas);
- to construct a compound representation through the presentation of contour lines mapped over the surface model (see Figure 2b);
- to populate the virtual DEM with 3D objects that are part of the region in the real world.

Figure 1 illustrates two ways to visualize DEM data: as a 2D image, and as a 3D surface presented in a virtual environment. Indeed, the VR interface brings realism to the presentation. Figure 1b shows the DEM wrapped with its corresponding grayscale amplitude image, so that the user obtains a realistic impression about the shape of the terrain, and also about the way it looks when visualized in the real world. The 3D surface has been positioned in the environment exactly in the same orientation as it appears in the 2D image; this allows observing that the bright points presented as a diagonal line in Figure 1a are spikes in the terrain, and that the dark area on the lower part of the image is the lowest region of the terrain, which also contains some spikes.
Figure 1: 2D and 3D interfaces to visualize a DEM. a) 2D view of an area of a DEM, presented as a grayscale image; b) The same area of a, viewed in the virtual environment as a 3D surface object.

Figure 2: The DEM presented with different aggregated information. a) Elevations highlighted through levels of colors; b) Contour levels and solid surface presented in a compound view.

Whether to use or not these resources can be seen as a function of the levels of detail (LOD) selected to present the virtual world, which increases or decreases the realism of the environment and supports data interpretation.

It is important to observe that a virtual environment, in order to be considered realistic, does not need to present real-world objects exactly as they are in real life. A realistic virtual environment is one where the user visualizes and interacts with its objects believing them, and becomes involved with the environment.

4.2.4. Interaction in the Virtual Environment

Interaction is one of the major advantages of VR interfaces, and a powerful tool for exploring large sets of data. The DEMEditor contains some interaction tools that can be used by expert SAR data users without knowledge of how exploring DEMs in the 3D space; this was a requirement in our system.

The DEMEditor implements simple, but sophisticated, interaction techniques that can be used intuitively for manipulation of the virtual 3D DEM and for navigation through the environment.
4.2.4.1. Navigation Strategies
Predefined walk-through tours to explore the virtual environment take the user to places of interest for comprehension of the world. For example, an overview tour may show the whole environment from a high position and help the user to obtain knowledge about the data (see Figure 2b). Another one would be a tour that takes the user to the four corners (south, north, east, west) of the virtual 3D DEM. These tours allow the user to investigate the environment in an easy way, since he/she is positioned and oriented during travel while obtaining always the best angular view from each position.

Viewpoint navigation is a technique that allows the user to jump from one position in the environment to another one, so that he/she obtains diverse impressions about the terrain from different perspectives; each viewpoint is composed of a position and an orientation. Figure 1b and Figure 2a illustrate the perspective point of view, staying in the south of the DEM and looking into the north, and staying in the southwest of the terrain and looking into the northeast, respectively. There are predefined viewpoints available for selection, and beyond these points of view, the user can define its own viewpoints by creating new ones.

Free navigation through the virtual environment (walk tool of VRML plug-ins), using the mouse, allows the user to explore the data without any help from the system, which is sometimes desirable.

4.2.4.2. Object Manipulation
The user can select the virtual 3D DEM by pointing the mouse to it (study tool of VRML plug-ins). This functionality is very important in order to manipulate the DEM object, since the user can deal with the surface as he/she is used to do with 3D objects in the real world. Once selected, the object may be rotated in space while it is examined.

During exploration or edition tasks, the user may switch on a light source, and direct it to a specific area of interest that he/she needs to visualize more carefully. This kind of interaction uses translation, scaling and rotation transformations to manipulate objects, as well as selection.

4.2.4.3. Interaction Icons
Some icons have been introduced into the environment to help the user to interact with the DEM data.

Figure 3a shows a DEM with elevations between 86,94 and 108,37 meters. The highest values appear as bright areas on the surface whereas the lowest areas appear dark. The user may modify these two values changing a height indicator, available on the bar on the left side of the virtual environment, to a new desired minimum and/or maximum value. This interactive way to edit the surface is especially useful if the user does not know exactly what should be the new minimum/maximum values for the terrain. In this case, he/she can move the height indicator until the DEM appears as desired. Figure 3b shows the same surface with a maximum value modified to 100,00 meters, obtained by moving the height indicator in the virtual environment.

A compass icon has been introduced in the environment to orient the user about what direction to follow when he/she wants, for example, to go to a given location. Remote sensing users commonly use support material, such as maps, when performing validation tasks on the data, so that an orientation tool may help them remain oriented (avoid being overwhelmed) between all information sources.
4.3. 2D Editing Methods Applied in 3D Environments

Figure 4 illustrates part of a terrain that contains error values known as dummy values. These values correspond to coordinates in the DEM for which the sensor could not collect the elevation value. Normally, they contain the number −9999. They can be identified in the figure by the little areas where the background (gray color) of the virtual environment can be seen in the area where the surface is plotted. These values have obligatory to be removed, since they do not correspond to actual elevation values. This can be achieved using interpolation techniques that make use of neighbor values to define approximate values for these points. Figure 4b shows the terrain once its dummy values have been removed.

The DEMEditor allows the user to edit the whole surface at once, similarly to the removal process of the dummy values presented in Figure 4, or to simply select a ROI to perform some task on a specific area. Figure 5a illustrates the selection of a ROI, which can be done by drawing a line around it with the mouse. After selection, the data contained inside the region can be edited by cutting it out
(Figure 5b), or by smoothing it in order to remove discrepant values etc.

Figure 5: Edition of a selected area on the surface. a) A ROI is selected on the terrain, defined by drawing with the mouse a polyline around the data to be edited; b) The data contained in the ROI are cut out.

In Figure 6 a virtual DEM has been generated and many areas with dummy values can be observed, specially in the middle part of the surface, which represents a region of the terrain where probably there is a forest that blocked the penetration of the electromagnetic radiation sent by the collection sensor. This DEM has been interpolated and smoothed, as shown in Figure 6b, so that dummy values were removed and very low elevation values, as well as very high values that originated spiked areas on the terrain disappeared.

Figure 6: Edition with the interpolation and smoothing tools, to remove dummy values and smooth the terrain. a) Surface with dummy values and discrepant areas that do not correspond to the true topography of the DEM; b) The same surface after interpolation and smoothing.

5. Conclusions

This research work brings two main contributions to the areas of remote sensing and VR interfaces. The first one is the reduction of precision problems in DEMs, since the proposed methodology allows the identification and removal of any kind of errors in the data.

The second one is the DEMEditor, a VR system that proves that desktop VR interfaces can effectively be used by expert remote sensing data users to visualize, manipulate, analyze and edit
DEM s, approaching a relevant problem of the remote sensing application area.

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7. References


