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3-D wavelet-based fusion approach for comprehensively analyzing multiple physical-property voxel models inverted from potential-field data

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ABSTRACT

The fusion technique is a simple and fast but useful tool for integrated interpretation of various types of geophysical data. Based on the routine 2-D wavelet-based image fusion approach, we presented a 3-D wavelet-based fusion approach for comprehensively analyzing various physical-property voxel models inverted from gravity and magnetic data. The approach decomposes the models via the 3-D discrete wavelet transformation, and then fuses them according to the separated fusion rules of the approximated and detailed components in the wavelet domain, and then reconstructs the fused model via the inverse 3-D discrete wavelet transformation. The related parameters of the approach include the wavelet basis, the layer number of decomposition, the weighted coefficients for fusing the approximated components, and the window size for fusing the detailed components. Tests on the synthetic data and the real data from a metallic deposit area in Northwest China verified feasibility of the 3-D fusion approach.

1. Introduction

Potential-field (gravity and magnetic) methods have been playing an important role in resource exploration and engineering investigation. Currently, besides of the routine measurement of gravity and magnetic fields, the measurement of their gradients is becoming popular in resource exploration for obtaining high resolution structure in the subsurface. This results in accumulating multiple types of potential-field data with the same or different resolution level, such as gravity anomalies, magnetic three components, magnetic total field anomalies, and their gradients. Generally, the gradients own a higher resolution than the original anomalies. 3-D inversion is one important step in quantitative interpretation of these data, each of which derives one 3-D physical-property (density or magnetization or susceptibility) distribution underground, usually in a style of 3-D voxel model. Quite a few approaches were presented for such inversion, including Zeyen and Pous (1991), Bear et al. (1995), Li and Oldenburg (1996, 1998), Pilkington (1997), Zhdanov et al. (2004), Uieda and Barbosa (2012), Lu and Qian (2015) and so on.

However, 3-D inversion of each single data contains inherent ambiguity, and each single inversion usually only presents partial information about the subsurface. For decreasing ambiguity and obtaining comprehensive interpretation, one strategy is to perform joint or constrained inversion on gravity and magnetic data, which includes approaches such as Zeyen and Pous (1993), Pilkington (2006), Bosch et al. (2006), Fregoso and Gallardo (2009), Kamm et al. (2015), and Zhou et al. (2015). The joint inversion usually requires a deterministic relationship between density and magnetization or susceptibility, which is unable to express in formula and thus hampers its application in the real world. Another strategy is to interpret the results of several single inversions comprehensively, without the requirement of the deterministic relationship between density and magnetization or susceptibility. Fusion is one technique to combine information from multi-source data, making them supplement each other and thus producing a new data containing more abundant or precise information than any single-source data. Thus, fusion could be an alternative useful tool for the second strategy.

The techniques for data fusion are in general divided into two main categories: spatial-domain fusion (such as principal component analysis, PCA) and transform-based fusion (such as discrete wavelet transform, DWT). Currently, these techniques are applied widely in the fields of computer science, engineering and medicine (Li, 2006; Gökberk et al., 2008; Liu et al., 2016). However, most of the applications of fusion in the geophysical literature are based on the 2-D fusion techniques which were used only on 2-D data, such as gravity and magnetic anomalies, rather than on 3-D dataset. For instance, Hassan and Peirce (2008) combined airborne gravity and magnetic images into one single image by using 2D wavelet-based image fusion approach for improved

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detection of structural control. Erkan et al. (2012) fused gravity gradient and magnetic field data for discrimination of anomalies using deformation analysis.

The comprehensive interpretation of multiple 3-D physical-property voxel models inverted from potential-field data requires a 3-D fusion technique. Gökberk et al. (2008) presented a comprehensive scheme of representation plurality and fusion for 3-D face recognition, in which they examined the benefits of various score-, rank-, and decision-level fusion rules. Pop et al. (2008) presented a PDE-based approach to 3-D multiazimuth seismic data fusion, which combines low-level fusion and diffusion processes through the use of a unique model based on partial differential equations. Ker et al. (2013) presented a wavelet-based fusion approach to merge multiresolution seismic data based on generalized Lévy-alpha stable functions. Liu et al. (2016) proposed an automatic and precise approach to fuse 3-D models in geographic information systems (GIS), with the basic steps of pose adjustment, silhouette extraction, size adjustment and position matching. But, these three approaches are unsuitable for fusing multiple 3-D voxel models inverted from gravity and magnetic data.

The 2-D imaging fusion approach based on the DWT (Li et al., 1995; Pajares and Cruz, 2004; Li, 2006) is one simple and fast approach. Its basic principle is decomposed multiple images by using the 2-D DWT, and then fuse the decomposed images based on specific rules, and then perform the inverse wavelet transform to obtain the fused image. In this paper, we expands the 2-D wavelet-based fusion approach to the 3-D case, and thus present a 3-D wavelet-based fusion approach for comprehensively interpreting multiple 3-D voxel models inverted from potential-field data. The principle and procedure of the approach are provided in details. We verify feasibility of the presented approach on both the synthetic data and the real data from a metallic deposit area in Northwest China.

2. Methodology

We expand the 2-D wavelet-based image fusion approach (Li, 2006) to the 3-D case. In the following, we use two arbitrary 3-D voxel models inverted from gravity and magnetic data as an example, but this principle can be easily expanded to fuse three and more models.

Firstly, the two voxel models are normalized to be dimensionless models, *m1* and *m2* respectively.

Secondly, each of the *m1* and *m2* models is decomposed level-by-level in the wavelet domain by using the 3-D DWT. In the first level, the model is decomposed along *x* direction into two components a_1 and d_1, and then both two components are further decomposed along *y* direction into four components aa_1, ad_1, da_1 and dd_1, and then all the four components are further decomposed along *z* direction into eight components aaa_1, aad_1, ada_1, add_1, daa_1, dad_1, dda_1 and ddd_1 (see Fig. 1). Wherein, aaa_1 is the approximation reflecting the smooth or trending feature of the model, while all the other seven components are the details reflecting the detailed or diversity features of the model along three different directions. Hence, we can obtain one approximation and seven details per level in decomposing. In the second level, the approximation in the first level is considered as an original signal and is decomposed into new eight components (one new approximation and seven new details). The rest levels can be done in the same way. The decomposition of *n* levels will finally produce one approximation and 7*n details.

The formula for decomposing the *m1* and *m2* voxel models by the 3-D DWT can be expressed as below

$$S_{m1} = \left\{ \begin{array}{l} A_{aaa_n}(m1), D_{daa_n}(m1), D_{aad_n}(m1), D_{dad_n}(m1), D_{dda_n}(m1), D_{add_n}(m1), D_{ada_n}(m1), D_{ddd_n}(m1), \\ \cdots, D_{daa_1}(m1), D_{aad_1}(m1), D_{dad_1}(m1), D_{dda_1}(m1), D_{add_1}(m1), D_{ada_1}(m1), D_{ddd_1}(m1) \end{array} \right\}$$
$$S_{m2} = \left\{ \begin{array}{l} A_{aaa_n}(m2), D_{daa_n}(m2), D_{aad_n}(m2), D_{dad_n}(m2), D_{dda_n}(m2), D_{add_n}(m2), D_{ada_n}(m2), D_{ddd_n}(m2), \\ \cdots, D_{daa_1}(m2), D_{aad_1}(m2), D_{dad_1}(m2), D_{dda_1}(m2), D_{add_1}(m2), D_{ada_1}(m2), D_{ddd_1}(m2) \end{array} \right\} \tag{1}$$

where, subscript *a* or *d* represents the approximation or detail process of the component and its subscript number represents decomposition level, and *A* represents approximations and *D* represents detail.

Thirdly, the fusion rules of the approximation and details in the wavelet domain in the 2-D case (Li, 2006) are adopted and expanded to the 3-D case with some modifications. Wherein, for the approximation, we can directly obtain the fusion result from the weighted summation of the two models,

$$A_{aaa_n}(m) = \alpha * A_{aaa_n}(m1) + \beta * A_{aaa_n}(m2), \tag{2}$$

where, the subscripts are the same as Eq. (1), α, β are the positive weighted coefficients, and $\alpha + \beta = 1$.

For the details, we utilized a sophisticated rule (Li, 2006) for fusion. The detailed features of the voxel model are usually represented by these details and their variations. In the wavelet domain, they are represented by the absolute of transformation coefficients of these details and their variations. In general, the maximum of the absolute coefficients contains the most important information of the features, and this maximum is suggested to be found statistically in a local 3-D space. Hence, we analyze statistically the absolute coefficients covered in a certain-size 3-D window centered at an arbitrary point to be fused from the two voxel models. The transformation coefficient at the point from the one, who have more of high absolute coefficients, is chosen as the fusion result.

The procedure of the fusion rule for an arbitrary *p*-th ($p \in [ddd_1, ada_1, \ldots, aaa_n]$) detailed component at an arbitrary point

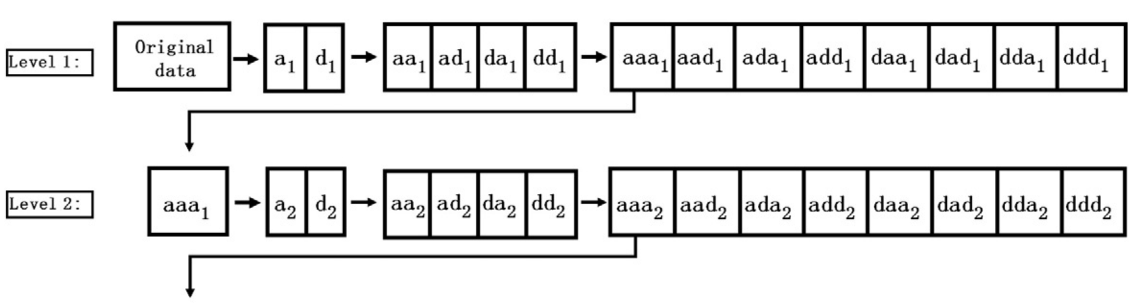

Fig. 1. Schematic diagram of 3-D wavelet decomposition.