Ground Control Point Localization Criterion

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Kriterij lokalizacije kontrolnih točk na satelitskih posnetkih

V članku predlagamo kriterijsko funkcijo za določanje lokacije izbranih kontrolnih točk satelitskega posnetka na podlagi primerjave vzorcev cest v okolici izbrane točke z digitalnimi vektorskimi podatki cestnega omrežja. Predlagana kriterijska funkcija omogoča robustno iskanje optimalne lokacije kontrolne točke, ter je odporna na nepravilnosti pri detekciji cest na satelitskem posnetku.

1 Introduction

In remote sensing, the automatic registration of satellite imagery [2] is more and more important due to increasing volumes of remote sensing data and because manual or semi-automatic registration is tedious, costly and error-prone. The task is to automatically detect accurate Ground Control Points (GCPs) which are then used for orthorectification of the entire image. The main principle of registration methods is to find a set of transformation parameters which optimize a selected similarity measure. Traditional methods are either point-based or area based, where local similarity in image intensities (SIFT, SURF) or area statistics (mutual information methods) is computed. This requires that the satellite image is compared to already registered reference image, and is called image-to-image registration. The drawback is that multi-temporal and multi-sensor registration is difficult as same real-world objects might exhibit very different intensity and statistics at different times or in different spectral bands.

In this work we propose to use object-level processing instead of general image intensity-based features for registration. This means that image segmentation is performed first, and then segmented objects are directly matched to the digital topographic data. The advantages of image-to-map registration are in the elimination of reference image preparation step, there are no errors coming from different appearances of reference and unregistered image, and the position of located map features is more stable and accurate.

The road network is a natural selection for image-to-map matching, as it is large-scale and stable structure which is visible in most circumstances. The idea is to segment visible roads from unregistered satellite image and map it directly to the road vector map, which is available from Geographical Information Systems. Although several similar experiments have been done [3], [4], [5], [6], this approach has not yet been extensively studied or utilized in practical applications.

This paper proposes a criterion for accurate Ground Control Point localization, which is based on template matching of road patterns instead of intensity-based features. In Chapter 2 we propose an algorithm and a criterion to compute accurate location of the selected GCP within earth coordinate system. In Chapter 3 we simulate effects of criterion parameters on the location error, and in Chapter 4 we analyse reliability of finding correct location of the manually selected GCPs.

2 Ground Control Point Localization

The goal of the GCP localization algorithm is to find an optimal ground coordinate $g_k = (x_k, y_k)$ for a given satellite image pixel coordinate $s_k = (i_k, j_k)$ within a predefined search area. A k-th Ground Control Point translates satellite image pixel coordinates s_k into local ground (Earth) coordinate system coordinate g_k.

The GCP localization algorithm is shown in the Figure 1. The algorithm requires that road detection algorithm is performed on the input satellite image, producing binary mask of detected roads M showing all visible roads.

Any satellite image pixel can be selected as a control point, however we always select road or crossroad pixel as a GCP. Image patch centered at a GCP location is shown in Figure 2 (left) with corresponding road mask patch (right), which is used as a template for GCP localization. For each selected GCP pixel we prepare a rotated and rescaled version of a road mask, because satellite image is rotated with respect to earth coordinate system.

This *road patch image* $P_{i,j}$ contains a resized and rotated neighborhood of the selected GCP pixel of the satellite road mask image M, an example is shown in Fig. 4 (left). The scaling is determined according

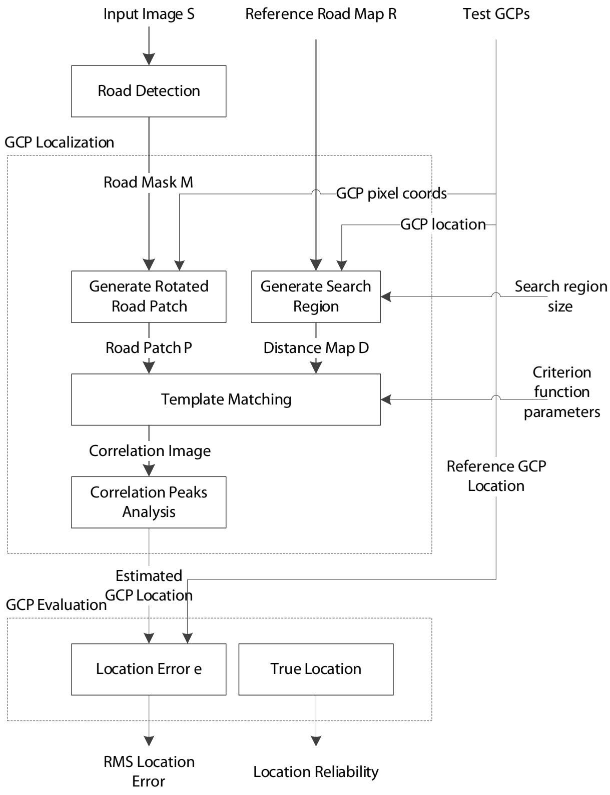

Figure 1: GCP extraction and evaluation algorithm.

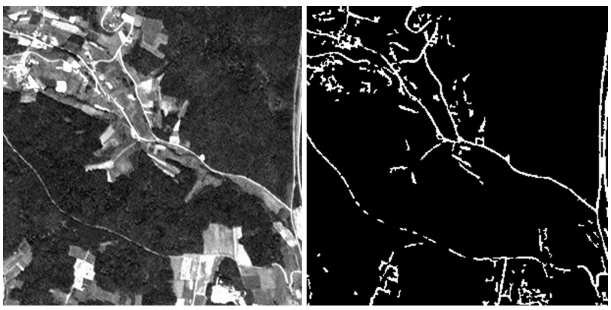

Figure 2: Satellite image patch (left) and corresponding detected road mask M (right).

to the resolution of the reference map, and the rotation is given by initial predicted satellite image angle $\tilde{\alpha}$.

2.1 Reference roads

We use digital road map vectors as a reference for road-based image registration. In order to simplify processing, digital road maps were rasterized and stored as image tiles, where road pixel value indicates road width, and each tile is precisely located in the local ground coordinate system. Resolution of road map images is 1m per pixel.

A *reference road map image* $R_{i,j} \in \{0, 1\}$ is compiled from road map tiles, covering the maximum possible satellite patch search region. The ground coordinates of all pixels of a reference road map image are known. In order to optimize location of the detected roads with respect to reference roads, the

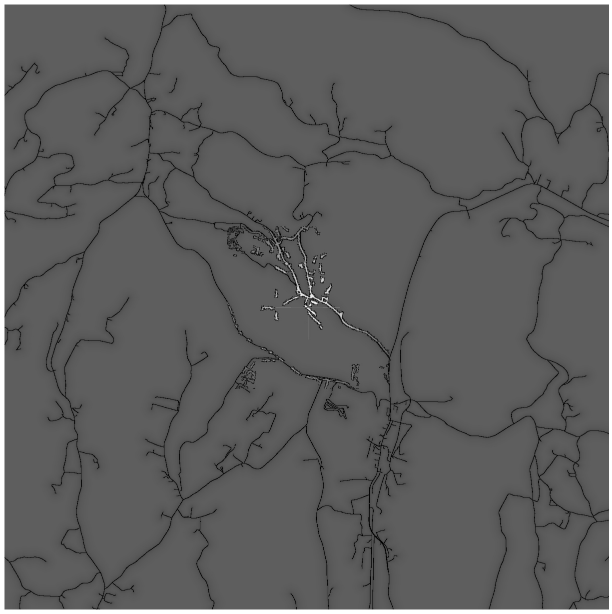

Figure 3: Reference roads within a search area. Pixel values correspond to the reference road feature map values $G_{i,j}$. Estimated location of the GCP is shown as bright cross, and white pixels represent rotated road patch P at its estimated location.

Euclidean distance $dist(i, j)$ of each pixel to the closest reference road pixel is computed, which results in a *road distance map image* $D_{i,j}$.

A template matching between road patch $P_{i,j}$ and distance map $D_{i,j}$ results in an average Euclidean distance of the detected road pixels to the closest reference road, which is minimized at some location of the patch. However minimization of average distance does not work well because misclassified road pixels which are far from reference roads tend to bias the location of the road patch. In order to eliminate their influence we introduce a maximum road distance parameter $D_{\max}$ so that more distant pixels have constant contribution to the location error regardless of their distance to the reference roads. Further we weight the contribution of each detected road pixel nonlinearly. We define a nonlinear function of the distance $g(d)$ as

$$g(d) = 1 - e^{-\left(\frac{d}{D_m}\right)^{\gamma}}, \qquad (1)$$

where $D_m = 0.6 \cdot D_{\max}$ is a maximum distance related constant, and γ allows us to select appropriate shape of the function.

By using Eq. 1 we compute a road distance-based normalized value $G_{i,j}$ for each reference image pixel $R_{i,j}$

$$G_{i,j} = \begin{cases} 1; & D_{i,j} > D_{\max} \\ \frac{g(D_{i,j})}{g(D_{\max})}; & D_{i,j} \leq D_{\max} \end{cases} . \qquad (2)$$

This *reference road feature map* $G_{i,j}$ is used as a cost function in template matching and defines a cost of a detected road pixel as 1 for pixels that lie more that

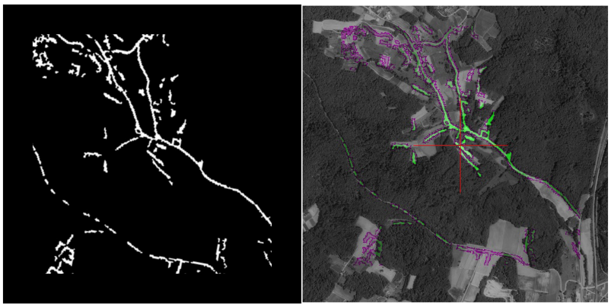

Figure 4: Satellite image patch (left) and corresponding detected road mask M (right).

$D_{\max}$ from the reference road, and 0 for pixels that lie on the reference road.

2.2 GCP matching criterion

The GCP matching criterion function $C(\Delta i, \Delta j)$ represents an error of positioning of a road patch P at the location $(\Delta i, \Delta j)$ within the search region in the reference road map $G_{i,j}$. The optimal road patch location should minimize this error, which means that it minimizes the distance to the reference roads. The proposed criterion $C(\Delta i, \Delta j)$ is given by Eq. 3, where reference road features are defined by Eq. 2.

$$C(\Delta i, \Delta j) = \frac{1}{N_i \cdot N_j} \sum_{i=0}^{2c_i} \sum_{j=0}^{2c_j} w_{i,j} \cdot P_{i,j} \cdot G_{s_i+\Delta i+i, s_j+\Delta j+j} \tag{3}$$

An additional weighting term $w_{i,j}$ is computed for each patch image pixel according to its distance from the central (GCP) pixel. The idea is that roads close to the GCP pixel should be aligned more accurately with the reference road map than distant roads, which might be already distorted due to scaling, rotation and perspective effects. The amount of distant road suppression is controlled by the parameters $\theta \in (0, 1)$ and D_r. The proposed weight depends on the pixel distance from the central pixel of the road patch,

$$w_{i,j} = \left(\frac{\sqrt{(c_i - i)^2 + (c_j - j)^2}}{D_r} \right)^{\theta} \tag{4}$$

3 Simulations in One Dimension

In order to test the proposed matching function and to estimate the influence of parameters we perform simulations of the patch localization in one dimension. Since road detection results in many erroneous pixels, the goal is to simulate several scenarios of distribution of true and error road pixels and measure their effect on the localization accuracy.

One dimensional patch signal P_i is compared against one-dimensional reference signal R_i, and the criterion $C(\Delta i)$ is computed. The patch signal includes one or more true road signals, which are defined by the location of their centers and the road width (selected as 9 meters in our simulations so that signal is symmetrical with respect to the road center), and one or more falsely detected roads, whose relative height represents relative amount of those pixels compared to true pixels. The reference signal $R_i \in \{0, 1\}$ defines the locations of reference roads, and is an input for computation of the road feature map G_i. True or desired location of the patch i' is known and after finding estimated location Δi as a minimum of criterion $C(\Delta i)$ we can compute location estimation error $e = \Delta i - i'$.

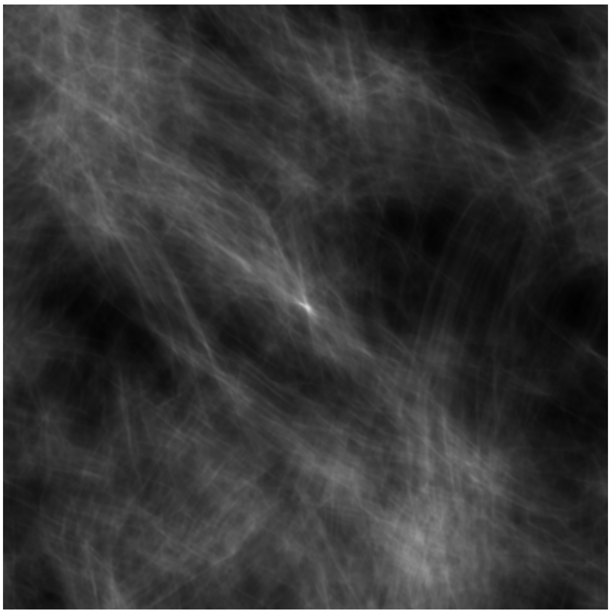

Figure 5: Location criterion function $C(\Delta i, \Delta j)$, whose values are shown normalized and inverted (white is smallest value, black is the largest). Bright peaks represent probable locations of the road patch within a search area.

Scenario A tests the influence of falsely detected road pixels on the location error e for different shapes of the reference function G_i given by parameters $D_{\max}$ and γ. The true road patch is given by two pixels separated by 50 units and with relative height of 1.0, and false pixels are positioned at 10 and 30 units after the first pixel, with relative height of 0.5. This simulation shows that in order to minimize the influence of falsely detected pixels, the reach of the reference road given by $D_{\max}$ should be small, and the nonlinearity should be high (γ is much smaller than 1).

Scenario B simulates the effects of road image rotation, perspective and scaling inaccuracies, which cause that the detected road pixels are not perfectly aligned to the reference roads across the whole road patch (see fig. 6). The second true pixel location is thus simulated to vary from ideal position, which causes location errors. The conclusion is that the reach of reference roads (given by $D_{\max}$) should be large enough to accommodate for second road location error, which is opposite to the Scenario A.

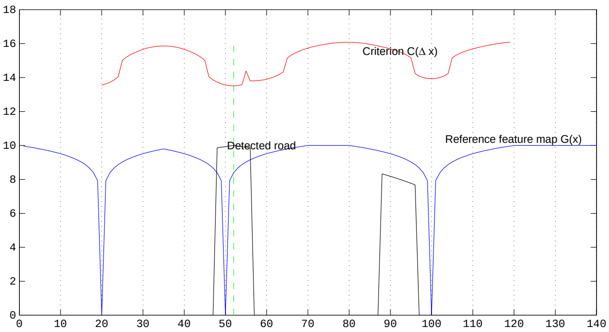

Figure 6: Simulation of the scaling and rotation errors (scenario B). The length between first and second detected road (right) is not the same as between reference roads, which leads to location estimation error.

Scenario C simulates an ambiguity in the reference data. For example, within city areas with large density of roads it is difficult to estimate true location of the road patch, as there are many competing equivalent locations. If $D_{\max}$ is more than half the distance between roads, then the average of the criterion is lower and in some cases a wrong patch location is selected within city area.

4 Evaluation on Satellite Images

In order to test the GCP localization algorithm on real images, we perform experiments on a set of 45 manually defined control points, where both satellite image and ground coordinates are defined manually. We use satellite GCP pixel coordinate to compute satellite road patch images, and we use ground coordinates to define search area and prepare reference masks which are centered exactly on a manually defined ground point, see Fig. 3.

The task of the localization algorithm is to perform template matching of a satellite road patch with reference mask, and the localization is successful if center of the search area is selected. As seen on Fig.1, we compute location reliability as a percentage of successfully located GCPs, and RMS location error of those GCPs in pixels. Results given in Table 1 correspond to road patch size of 1000 x 1000 m, while search area size is given by multiplier 1 to 8.

Search size	1x	2x	4x	6x	8x
Reliability	97.3	94.9	82.1	66.7	64.1
RMS Error	1.51	2.02	2.15	2.19	2.20

The analysis of falsely located GCPs have shown that the reason is the same as described within Scenario C. The city area with large density of roads matches better with the road patch than its original location, due to lower average distance. This low average error can be seen also in bottom right corner of the Figure 5. The misplacement is more common with larger search area. Further experiments with larger template sizes have shown better results.

5 Conclusion

We have presented an efficient GCP localization algorithm using road detection and matching with digital road map data. The road-based registration is robust with respect to the different brightness of image regions due to temporal and spectral variations of satellite images taken at different times, and does not require reference image.

Algorithm is robust with respect to errors of the road detection step, which includes buildings, fields and missing road segments. The usage of improved proposed criterion in template matching resulted in higher reliability of finding correct placement of an road patch. While conventional matching by minimizing average road distance results in reliability up to 50 percent, the new criterion achieves up to 100 percent. Further work is needed to improve reliability in the vicinity of city areas.

References

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