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Abstract

Image registration is a central task in many image processing applications. We focus on multispectral or hyperspectral remote sensing images that are used, for example, to analyze changes in land use, or to monitor the environmental effect of natural disasters. In all these examples, different images of the same area are required. The registration objective is to calculate the geometric transformation that aligns the different captures of the same scene.

The images to be registered are obtained at different times and, in many cases, also by different sensors. And it is common that they present differences as a consequence of being obtained from different points of view, differences in the number of spectral bands captured by the sensors, in illumination and intensity, and also changes in the objects present in the images, among others. Dealing with this situation, feature-based methods try to detect interest points in the images at high level, extracting significant regions, lines or points. Knowing the correspondence between several points in two images, a geometrical transformation is then determined to map the target image to the reference image.

Feature-based methods are more efficient at registering than area-based methods when the images are very rich in geometrical details, as it is the case for remote sensing images. But they present, nevertheless, the problem of being computationally more costly because the number of distinctive points to be calculated for these images is high.

The standard algorithms use a single band of the images to solve the registration problem. The authors proposed HSI-KAZE, a version of A-KAZE using the M-SURF descriptor that is especially adapted to hyperspectral images, as the spectral information is taken into account. The spectral information is considered when a set of representative bands of the image are selected based on their entropy and spectral distance and the spectral signature is incoporated to the keypoint descriptor. The HSI-KAZE method presents high computational requirements, so it is a good candidate to be projected in high performance computing architectures such as GPUs.

In this paper the implementation of the HSI-KAZE registration algorithm on programmable GPUs is explored as an attempt to reduce its computational cost. The GPU implementation focuses on reducing the cost of the two most costly steps of the algorithm, keypoint detection and keypoint matching. The CUDA code runs on a Pascal NVIDIA GeForce GTX 1070 with 15 SMs and 128 CUDA cores each. A detailed analysis of the implementation issues as well as its cost is carried out, showing that commodity GPUs are an adequate platform to perform efficient registration even for large images.

Exploring the Registration of Remote Sensing Images using HSI–KAZE in Graphical Units

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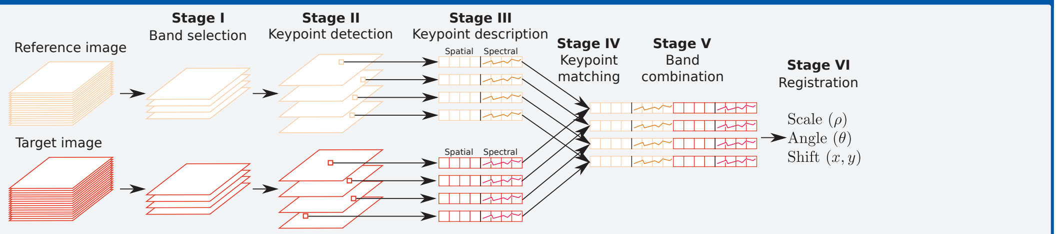
Registration of hyperspectral remote sensing images is a common task in many image processing applications such as land use classification, environmental monitoring and change detection. The images to be registered present differences as a consequence of being obtained from different points of view, differences in the number of spectral bands captured by the sensors, in illumination and intensity, and also changes in the objects present in the images, among others. Feature–based methods as HSI–KAZE are more efficient at registering than area-based methods when the images are very rich in geometrical details, as it is the case for remote sensing images. But they present, nevertheless, the problem of being computationally more costly because the number of distinctive points to be calculated for these images is high. HSI–KAZE is a method to register hyperspectral remote sensing images based on KAZE features but considering the spectral information. In this work, a robust and efficient implementation of this method on programmable GPUs is presented.

HSI–KAZE on GPU



Algorithm 1 HSI–KAZE pseudocode.

Input: Hyperspectral reference image $\mathbf{I}_1$ and hyperspectral target image $\mathbf{I}_2$ with N_T bands.
Output: Scale factor ρ, rotation angle θ, and translation (x, y).

```
Perform feature selection over both images → B_1 and B_2                        ▷ Band selection

for each band b in images B_1 and B_2 do
    Extract keypoints of B_1^b → P_1^b                                          ▷ Keypoint detection
    Extract keypoints of B_2^b → P_2^b                                          ▷ Keypoint detection
    Calculate the M–SURF descriptor of each keypoint in P_1^b                   ▷ Keypoint description
   and append the spectral signature → K_1^b
    Calculate the M–SURF descriptor of each keypoint in P_2^b                   ▷ Keypoint description
   and append the spectral signature → K_2^b
    Match keypoints in K_1^b and K_2^b → M_b                                    ▷ Keypoint matching
end for

Combine all the matched keypoints M_b → M                                       ▷ Band combination
Perform an exhaustive search to recover the registration                        ▷ Registration
parameters → ρ, θ, (x, y)
```

(a) (b) (c)

Figure: Example of registration considered in this work: a) Reference image (size 1096 × 715), b) Target image, and c) Result of the registration process showing the correctly registered superposition of the reference and target registered image (scale 23.0× and rotation angle 60°).

Keypoint detection and description on GPU

- Acronyms:
  - < >: Function executed in the GPU (kernel).
  - GM: Target function data is allocated in Global Memory.
  - SM: Target function data is allocated in Shared Memory.

Algorithm 2 Pseudocode for the keypoint detection and description stages.

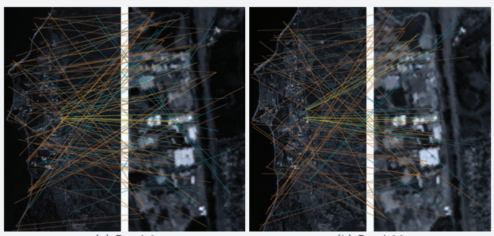
Input: Set of selected bands $\mathbf{B}_1$ and $\mathbf{B}_2$.
Output: A set of keypoints $\mathbf{K}$ for each selected band of both images.
Parameters: Number of sublevels N_{sub}.

```
Keypoint detection
Calculate the optimal number of octaves N_oct according to the spatial size of the images
< Upsample the images to obtain images whose size is divisible by the number of octaves N_oct >   ▷ GM
for each band b in images B_1 and B_2 do
    < Upsample the band by a factor of 2 using bilinear interpolation >                         ▷ GM
    stage Build the pyramidal scale space
        < Smooth the upsampled band using a Gaussian filter >                                   ▷ GM+SM
        < Compute the Scharr derivatives >                                                      ▷ GM+SM
        < Compute the contrast factor k from the gradient histogram of the smoothed band >      ▷ GM+SM
        sub-stage Build the pyramid using FED scheme
            for o ← 1, N_oct do
                < Subsample the last sublevel image by a factor of 2 >                          ▷ GM+SM
                for s ← 1, N_sub do
                    < Smooth using a Gaussian filter >                                          ▷ GM+SM
                    < Compute the Scharr derivatives >                                          ▷ GM+SM
                    < Compute the conductivity g >)                                             ▷ GM
                    < Discretized the nonlinear diffusion equation using the FED scheme >       ▷ GM+SM
                end for
            end for
        end sub-stage
    end stage

    stage Locate the keypoints in the scale space
        < Compute the determinant of the Hessian matrix >                                       ▷ GM+SM
        < Detect keypoints by searching for points that are the maxima of their neighbourhood → K_1^b, K_2^b >   ▷ GM
        < Refine the position and the scale of each keypoint >                                  ▷ GM+SM
    end stage

Keypoint description
    for each keypoint in K_1^b and K_2^b do
        < Calculate the main orientation >                                                      ▷ GM
        < Compute the M–SURF descriptor >                                                       ▷ GM
        Append the spectral signature
    end for
end for
```

Keypoint matching on GPU



(a) Band 6 (b) Band 26

Figure: Matched keypoints detected in two of the eight selected bands belonging to the Santa Barbara Front scene with scale 9.5×: matches discarded after considering spectral information (brown), incorrect matches (blue), correct matches (yellow), and correct matches used in registration (green).

Table: Number of matches obtained for Santa Barbara Front in the eight selected bands.

Number of matches	44550
Number of matches after spectral discarding	44490
Number of matches after removing repeated matches	43537
Number of correct matches	20741
Number of incorrect matches	22796

Registration results

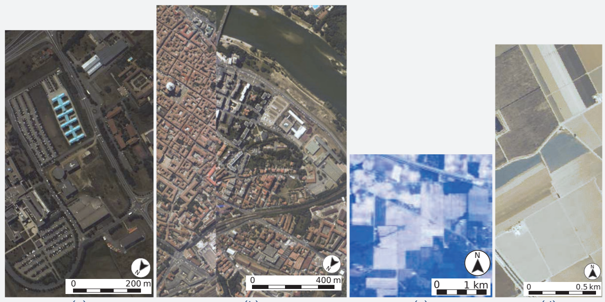
Table: Successfully registered cases for each scene and hyperspectral registration method. × means "scaling factor" and for each scaling 72 angles are considered. HYFM is not based on feature extraction.

Scene	HYFM	HSI–KAZE
Pavia University	1/4× to 5.5 × (13)	1/10× to 13.0 × (35)
Pavia Centre	1/5× to 7.5 × (18)	1/16× to 24.0 × (62)
Indian Pines	1/2× to 4.0 × (8)	1/4× to 5.5 × (13)
Salinas	1/2× to 4.5 × (9)	1/7× to 6.0 × (17)
Number of scalings	(11.43)	(30.71)

Experimental conditions

Table: Sensor, size, number of spectral bands, resolution (m/pixel), and location of the test hyperspectral images

Image	Sensor	Size	Bands	Spatial Resolution
Pavia University	ROSIS–03	610 × 340	103	1.3
Pavia Centre	ROSIS–03	1096 × 715	102	1.3
Indian Pines	AVIRIS	145 × 145	220	20.0
Salinas	AVIRIS	512 × 217	204	3.7



(a) (b) (c) (d)

Figure: Remote sensing hyperspectral images: a) Pavia University, b) Pavia Centre, c) Indian Pines, and d) Salinas.

GPU optimization strategies

- Memory hierarchy in the GP102 Tesla architecture:
  - 96 KB/SM of shared memory.
  - 48 KB/SM of L1/texture cache
  - 3072 KB of L2 cache.
- A set of strategies to reduce the computational time have been applied:
  1. Reduce data transfers among CPU and GPU memories
  2. Reuse data in shared memory.
  3. Search for the best kernel configuration to reduce the execution time and maximize the GPU occupancy.
  4. The use of atomic operations prevents the race conditions among threads.
  5. Efficient computation using optimized CUDA libraries.

Experimental results

- Intel Xeon E5–2623v4 CPU at 2.60 GHz.
- 128 GB of RAM
- Ubuntu 16.04.6 LTS.
- NVIDIA P40 (GP102).
  - 30 SMs, 128 CUDA cores/SM.
  - 24 GB of GM.
  - 1303 MHz of base clock.

Table: CPU and P40 GPU computation times for each scene.

	CPU	GPU	Speedup
Pavia University	71.75s	12.11s	5.92×
Pavia Centre	508.61s	45.30s	11.23×
Indian Pines	5.40s	1.90s	2.84×
Salinas	23.63s	5.23s	4.52×

Table: Detailed times for each stage projected onto GPU for Pavia Centre scene.

	CPU	GPU	Speedup
Band selection	10.87s	0.24s	45.29×
Keypoint detection	401.41s	12.75s	31.48×
Keypoint description	73.71s	13.83s	5.33×
Keypoint matching and band combination	22.37s	17.55s	1.27×

Conclusions

- An efficient CUDA GPU implementation of HSI–KAZE that registers hyperspectral images is presented.
- HSI–KAZE exploits the spectral information available in the images.
- The algorithm performs successful registration for scale factors of up to 24.0× for all the rotation angles and translations.
- Speedups of up to 11.3× for real remotes sensing images are achieved.
- Execution time reduction from around 9 minutes to less than 1 minute for the biggest test set image.

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