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Banknote crease detection and banknote fitness classification

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Abstract

We present an approach for the detection of crease in banknotes using 3D image processing. A line-scan camera equipped with two lenses implements a stereo vision system acquiring images of banknotes transported perpendicular to the stereo baseline. Depth data is obtained from stereo matching and local curvature features are calculated from the estimated 3D banknote surface model. Mean and Gaussian curvature measures are calculated for each banknote pixel and median values are used to characterize whole banknotes with respect to their fitness for circulation. The scale at which the curvature description provides most meaningful information with respect to the banknote fitness grade is identified by pyramidal decomposition of the depth map. The approach is validated based on banknotes with varying crease which were labeled by experts into several fitness grades.

Introduction

The use of currency remains predominant in retail payment systems in most countries. Banknotes are deteriorating over their life-time, e.g. they become soiled, creased, or even destroyed at all. Together with soiling the creasing is one of the main reasons why banknotes become unfit for recirculation. Central banks are recirculating banknotes based on their so called fitness level, this means deteriorated banknotes are withdrawn from the cash cycle and replaced with newly printed banknotes. Longer lifetimes of banknotes results in lower printing costs and reduced environmental pollution. Furthermore, the acceptance of paper money by the public is typically increased by maintaining high quality appearance. It was shown that polymer banknotes have increased durability when compared to paper banknotes [1]. On the other hand, the problem of soiling becomes less important for polymer banknotes, instead, creasing becomes a more serious reason for turning banknotes to unfit.

The life-length of banknotes was studied in case studies [2] and recently the reasons for banknote soiling were investigated [3] as well as machine learning for banknote fitness sorting based on optical 2D images [4]. Usually, when unfit banknotes are removed from circulation, a large number of fit banknotes are destroyed in this process as well, as currently no reliable method for precise determination of the banknote fitness is at disposal. Fitness assessment based on 2D images is an established procedure, both in banknote printing quality assessment as well as in cash recycling. Dedicated banknote sorting machines use a plurality of sensors to sort out banknotes at high speed. Creasing, also referred to as crumbling or multiple random folds, is typically identified by reduced level of reflectance or stiffness [5]. For reliable discrimination between creasing and other defect classes such as soiling, staining, de-inking etc. a 3D description of the banknote surface offers a new source of information.

A more precise approach to banknote fitness sorting using 3D information together with concepts from differential geometry [6], should reduce the number of false fit or false unfit banknotes. This becomes especially important for polymer banknotes where creasing dominates soiling as a reason for turning banknotes to unfit. Therefore, we suggest an approach for automatic banknote fitness determination induced by creasing. Due to the industrial setting of cash recycling workflows, a line-scan camera acquisition is suggested and efficient algorithms for inline assessment are to be investigated. Identification of folding and creasing of banknotes from 2D images, e.g. by making use of shading effects [7], is unreliable in our application as this is often not distinguishable from printed patterns and soiling. On the other hand, an approach based on 3D image acquisition and analysis is able to separate texture-like elements on the surface from the 3D properties of the deformed banknote surface. Apart from image acquisition design and the algorithmic solution, the technical challenge is to propose a system applicable in a typical banknote fitness sorting setup.

This paper is organized as follows. After discussing banknote inspection we concentrate on 3D information extraction from images and surface analysis, where we motivate our 3D approach. The results section discusses the performance surface curvature measures and image resolution issues. Finally, we draw some conclusions.

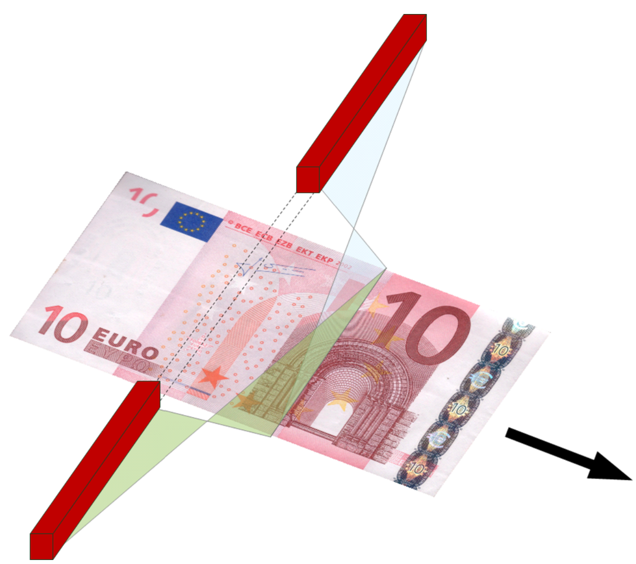

Figure 1: Line-scan stereo image acquisition principle

Banknote Inspection and Fitness

Automatic banknote inspection by optical means takes place in production quality control as well as to assess to suitability of used banknotes for recirculation. Several such inspection systems consisting of transportation, decision and sorting units are on the

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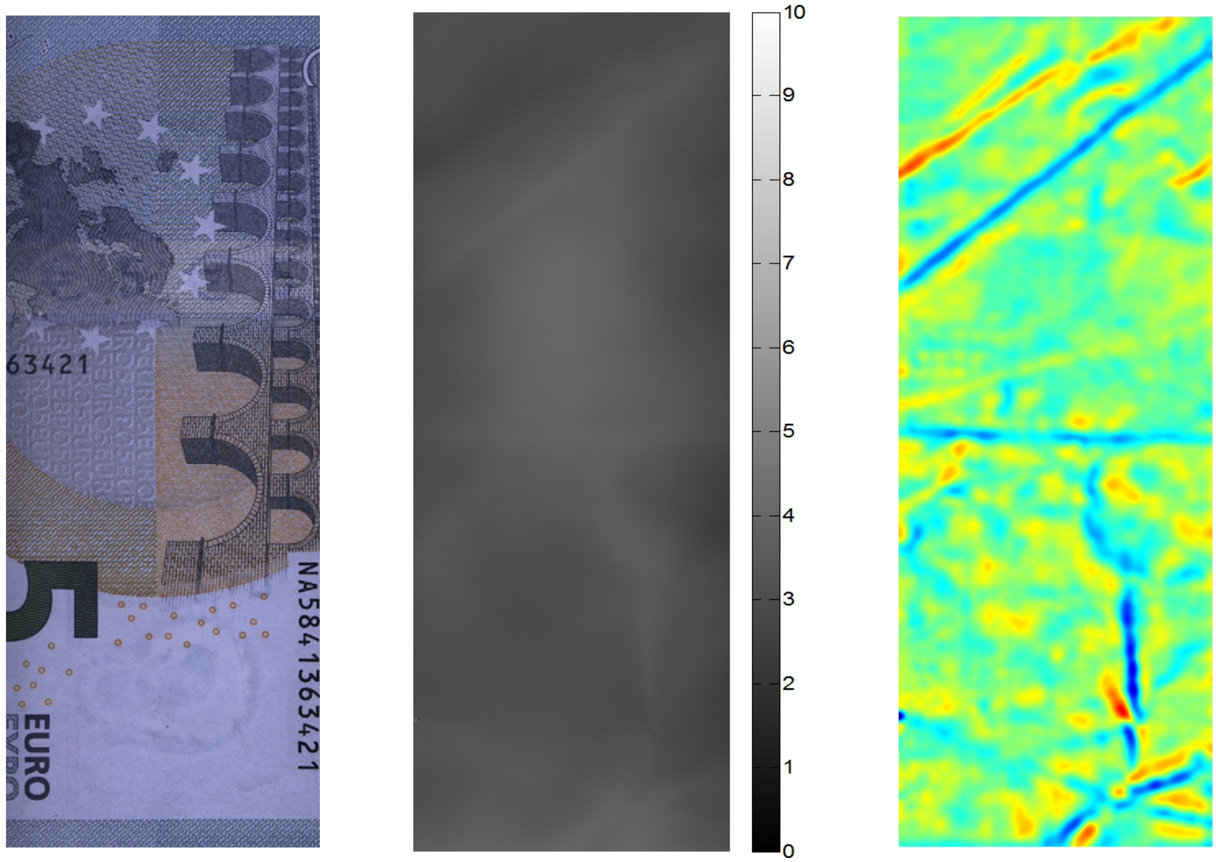

(a) Color image (b) Depth variation in millimeters (c) Mean curvature of depth image

Figure 2: Fit Euro 5 banknote, 3D information and surface description.

market. Up to our knowledge, there exists no system extracting 3D information from the banknote surface.

3D Information Extraction

Range information from images is typically obtained using time-of-flight sensors [8], configurations based on pattern projection [9], illumination variation by photometric stereo [10], focus variation [11], multi-camera systems [12] or light field cameras [13]. Line-scanning is a popular method to acquire images of moving objects. Mechanical transport of banknotes and acquisition of corresponding sensor data inside banknote sorting systems is a common approach. With respect to involved object motion and time constraints we decided to employ a binocular line-scan stereo system.

In stereo imaging the range for each pixel is obtained from the estimated disparity, i.e. the displacement between corresponding points observed in two (or more) images. The epipolar constraint in a stereo vision system states that a point in one image is found along the corresponding epipolar line in the other image. Epipolar rectification in area-scan stereo pairs aligns epipolar lines to images lines, thus reducing the correspondence estimation to a search oriented along an expected disparity range in image lines. In a line-scan stereo system one adjusts this geometrical constraints such that epipolar lines correspond to sensor lines. Estimation of disparities is then performed along sensor lines.

We used a line-scan stereo camera sensitive in the visible spectrum for one-sided acquisition of the banknote surface while the banknote is transported. Banknotes are acquired using either one long image sensor line shared by two lenses or two collinearly arranged line-scan image sensors observing the same surface line patch. Fig. 1 shows the setup using two colinearly arranged line-scan sensors observing the banknote from two different viewpoints.

Stereo correspondence is obtained by block matching on local 2D surface patches oriented along sensor lines. This results in depth information for each pixel position. The employed camera is a 3DPIXMA manufactured by Chromasens GmbH. Germany, capable of lateral pixel resolutions of 15 μm, a line rate of 20 kHz and a nominal height resolution of 3 μm [14].

3D Analysis

The reconstructed banknote surface is analyzed using concepts borrowed from differential geometry, particularly we extracted local curvature features. The curvature features eventually are related to three classes of banknote fitness.

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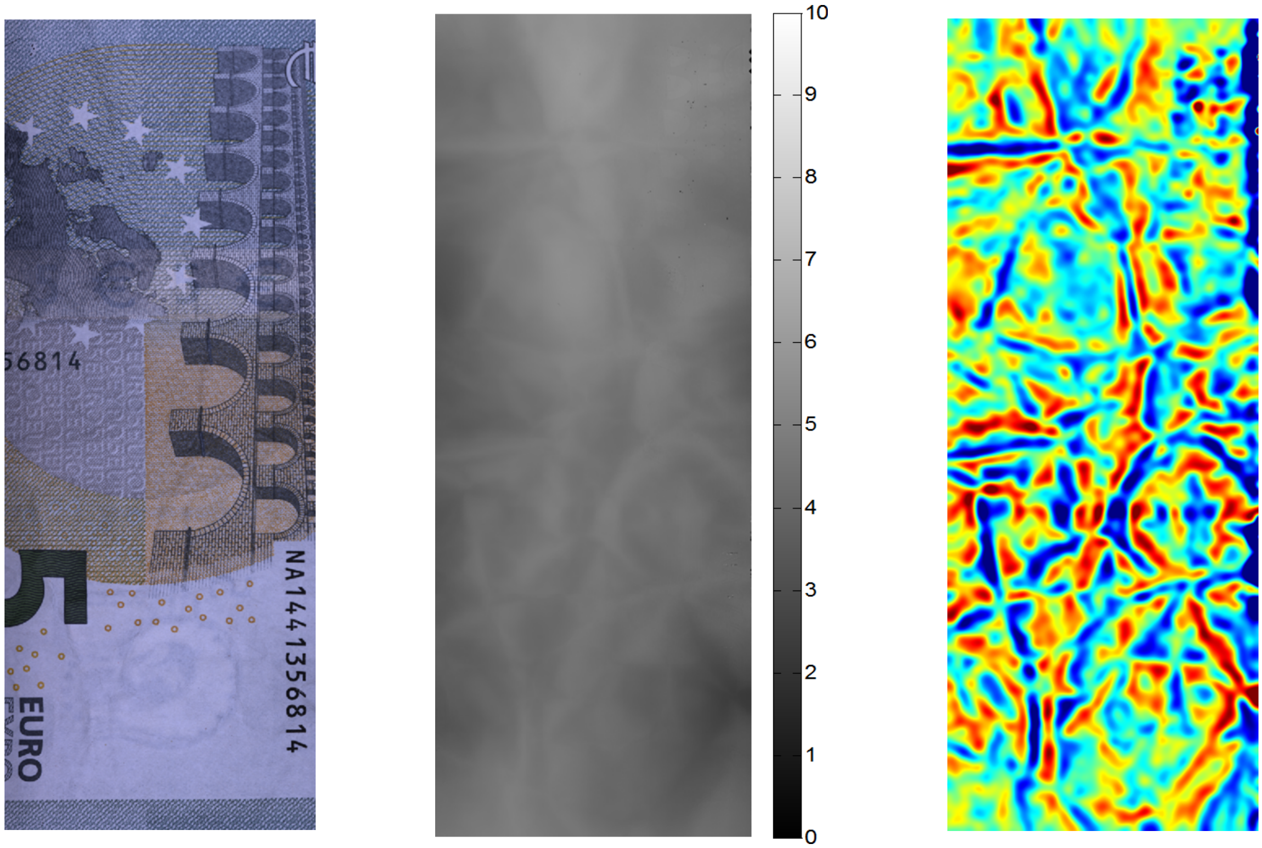

(a) Color image

(b) Depth variation in millimeters

(c) Mean curvature of depth image

Figure 3: Unfit Euro 5 banknote, 3D information and surface description.

In general, curvature features were reported being used to characterize 3D surfaces to obtain bending energy of paper fibers [15], to obtain the wrinkle structure in garment surface analysis [16] and ridge/valley extraction was demonstrated for several tasks in medical image registration, marble grain segmentation and drainage pattern delineation from digital elevation models [17].

We follow the original work by Besl and Jain [6] to describe 3D surfaces using elements from differential geometry. Surfaces are uniquely characterized by estimation of principal curvature or Gaussian or mean curvatures. We used mean curvature H and Gaussian curvatures K obtained from local surface properties as follows

$$H = \frac{(1+f_v^2)f_{uu} + (1+f_u^2)f_{vv} - 2f_u f_v f_{uv}}{2 \cdot \sqrt{(1+f_u^2+f_v^2)^3}}, \quad (1)$$

$$K = \frac{f_{uu}f_{vv} - f_{uv}^2}{(1+f_u^2+f_v^2)^2}, \quad (2)$$

where the $f_u, f_v, f_{uu}, f_{uv}, f_{vv}$ are partial derivatives with respect to image row u and column v directions. All derivatives were approximated by central differences and a Gaussian smoothing with parameter σ was applied beforehand. Principal curvatures $\kappa_{\max}, \kappa_{\min}$ are derived from H and K using

$$\kappa_{\max,\min} = H \pm \sqrt{H^2 - K}. \quad (3)$$

The combination of mean and Gaussian curvature as well as of prinicipal curvatures, could be used to categorize surface patches into surface types, e.g. peak, ridge, saddle, valley, etc., which is not further followed in this work. Instead, we used efficiently computable descriptors for global curvature statistics.

Results

We had a manually classified sample of 15 banknotes belonging to the classes fit (uncreased or slightly creased), moderate fit (creased, but suited for recirculation) and unfit (not suited for recirculation) at our disposal. Both sides of the banknotes were acquired at a resolution of 15 μm/pixel. We investigated the following questions:

- Which curvature measure is best suited for banknote fitness determination?
- Which is the best resolution for analysis?
- What is the best (coarsest) resolution for stereo matching?

The questions concerning resolution are driven by the goal to use the coarsest possible resolution, i.e. the computationally less de-

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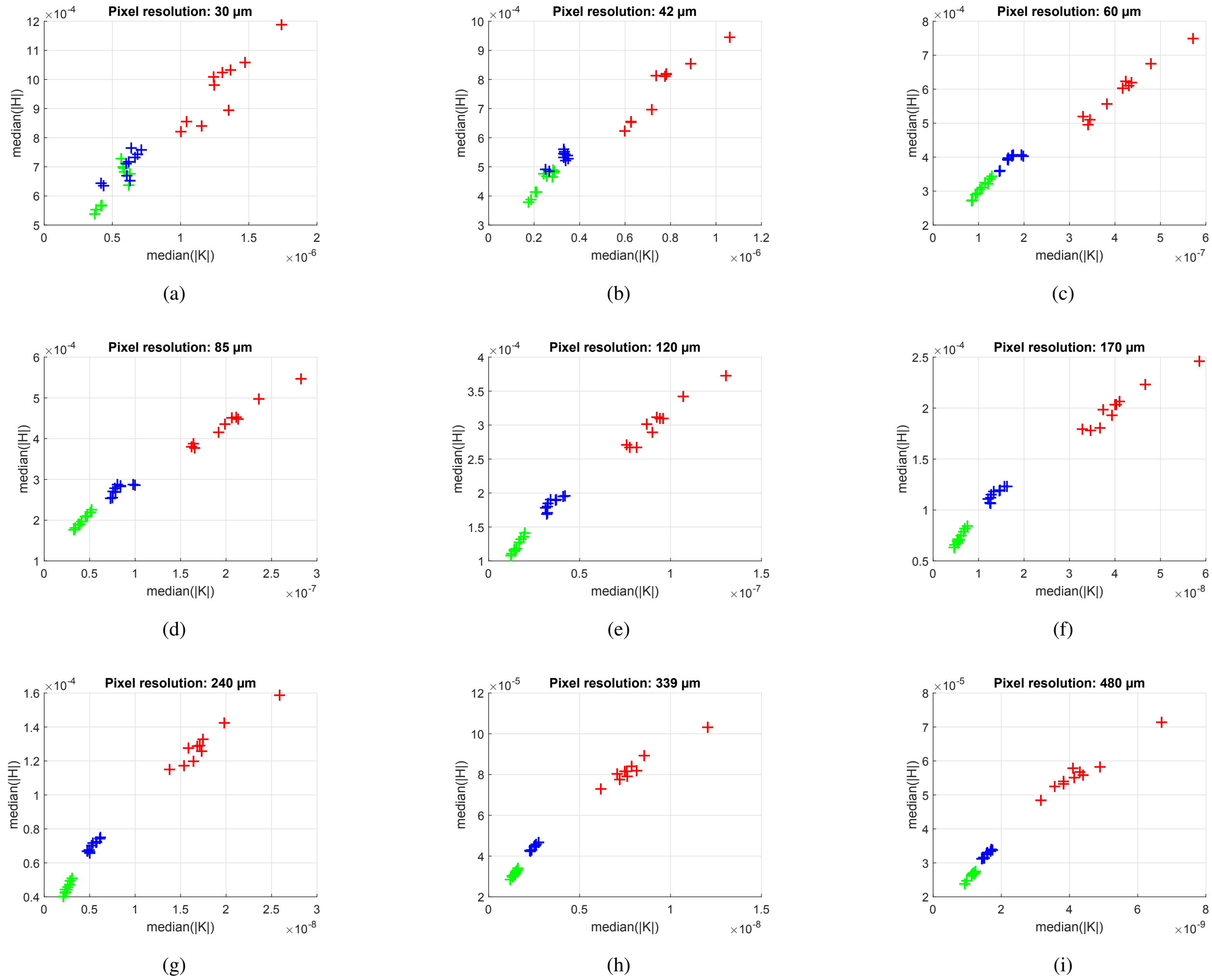

Figure 4: Median values of mean vs. Gaussian curvatures obtained for varying resolutions: green corresponds to fit, blue to moderately fit and red to unfit banknotes, respectively.

manding setup, for analysis and matching while still being discriminative in fitness determination.

Fig. 2a shows a slightly creased banknote fit for recirculation. The image of a severely crumbled banknote unfit for recirculation is shown in Fig. 3a. From the 2D images in Fig. 2a and Fig. 3a one can observe that the difference is visually not that apparent. Depth variation in millimeters is shown for the example of a fit banknote in Fig. 2b and for the example of an unfit banknote in Fig. 3b, respectively. The surface description, which will further be numerically related to the fit/unfit decision, is shown in Fig. 2c for the fit banknote example and Fig. 3c or the unfit banknote example, respectively. The color blue corresponds to ridge-like structures and the color red to valley-like structures, green tones are uncreased or slightly creased regions.

We acquired image pairs at 15 μm/pixel resolution and performed stereo matching at this resolution. A series of coarser resolutions were obtained by reduction of the original image resolution of $r_1 = 15$ μm/pixel according to

$$r_i = r_1 \cdot \sqrt{2}, \quad i = 2, \ldots, 10, \tag{4}$$

which results in images of pixel resolutions of approximately $30, 42, 60, 85, 120, 170, 240, 339, 480$ μm. As we are not interested to differentiate creases with respect to ridge or valley shapes we used absolute values for H and K curvatures. We used the median of $|H|$ and $|K|$ as global statistical descriptors. Fig 4 shows median($|H|$) and median($|K|$) versus image resolution used in analysis, i.e. used in computation of the curvature measure. Even at a very coarse resolution of 480 μm/pixel it seems still possible to discriminate unfit from fit (uncreased or moderately creased) banknotes based either on H and/or K statistics. For resolution ranging from 30 to 170 μm/pixel a further discrimination between fit and moderately fit banknotes is also possible.

Fig. 5 and Fig. 6 address the question which measure to prefer and whether it is sufficient to use a single measure. At the appropriate image resolution of about $85 - 480$ μm/pixel the local curvature descriptors are both able to discriminate the three

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considered 3 classes of banknote fitness. Discrimination of unfit and fit (uncreased or moderately creased) classes is possible fore the whole range of resolution from 30 to 480 μm/pixel using the K measure. The H measure performs slightly worse, e.h. for the very fine resolutions of 30 and 42 μm/pixel it seems not possible to reliably discriminate all classes.

Interestingly, with very high resolution images in the range $30-60$ μm/pixel we are not able to characterize creasing well, which is probably due to the case that creasing takes place at coarser scales and what might be characterized at very fine scales is rather surface roughness and printing layers.

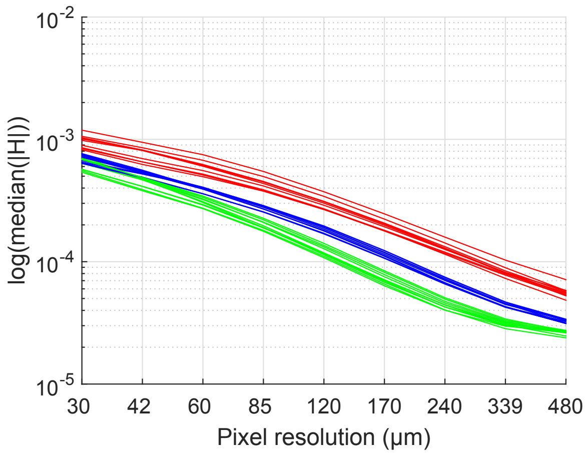

Figure 5: Median of mean curvature H vs. resolution used for analysis: green corresponds to fit, blue to moderately fit and red to unfit banknotes, respectively.

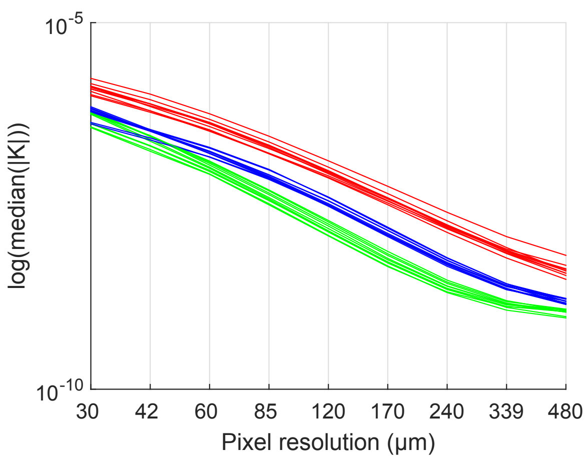

Figure 6: Median of Gaussian curvature K vs. resolution used for analysis: green corresponds to fit, blue to moderately fit and red to unfit banknotes, respectively.

As stereo matching at a very high resolution of 15 μm/pixel is computationally demanding the question of the required resolution for matching which, on the other hand, still preserves enough information for analysis based on curvature remains. Fig. 7 shows that stereo matching preserves surface information suitable for fit/unfit discrimination by curvature measures up to resolutions better than approximately 100 μm/pixel. Resolutions of approximately 75 μm/pixel also allows discrimination within the fit subclasses.

This finding is somehow in contradiction to the previous experiment, where we found that resolutions ranging from approximately 85 to 339 μm/pixel are well suited for the task at hand. Clearly, the reason for this contradiction is that stereo matching lacks structure when resolution gets coarser. As a consequence of both experiments we conclude that an image resolution of approximately 75 μm/pixel is appropriate to meet the requirements of coarsest possible resolution vs. reliable discrimination of fitness classes.

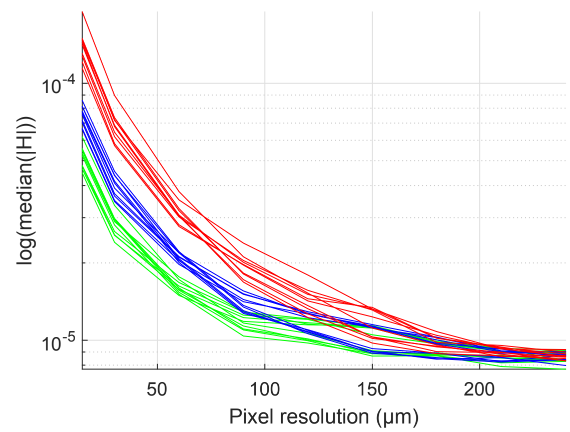

Figure 7: Median of mean curvature H vs. resolution used in stereo matching: green corresponds to fit, blue to moderately fit and red to unfit banknotes, respectively

Conclusion

An experimental acquisition setup base on line-scan stereo vision was build and an efficient and precise approach to fitness assessment based on creasing was developed. We identified the requirements with respect to image resolution and discriminative power of local curvature features. A global statistical measure of surface curvature was used. At the appropriate image resolution of approximately 75 μm/pixel it seems to be possible to preserve the creasing structure in stereo matching for the investigated set of banknotes. So far, we based our results on a limited data set of 30 examples of Euro 5 banknotes which were labeled by national bank experts. Further acquisitions of test banknotes should validate the approach and a machine learning approach will finally be used to obtain decision rules and thresholds for banknote fitness determination.

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Reinhold Huber-Mörk recieved his PhD in computer science from the University of Salzburg, Austria, in 1999. Since then he worked at the Aerosensing GmbH, Oberpfaffenhofen, Germany, in remote sensing image analysis, at the Advanced Computer Vision GmbH, Vienna, Austria, in computer vision and in 2006 he joined the AIT, Vienna, Austria, where he is currently senior scientist in the field of machine vision.

Johannes Ruisz received his MSc in Computer Science from the University of Technology, Vienna, Austria, in 1999. Since then he worked at Advanced Computer Vision GmbH and Kapsch TrafficCom in Vienna in the Research and Development department focused on medical image processing, quality inspection and traffic monitoring. He joined the AIT, Vienna, Austria in 2014 where he is currently engineer working in the field of image processing and computer vision in general.