POSSIBILITIES OF SOFTWARE RECOGNITION OF SMALL IRREGULAR PATTERNS IN BIOMETRICS FOR PURPOSES OF FINGERPRINT ANALYSIS

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Resumé: When performing an in-depth analysis of biometric features we often encounter a problem of automated software recognition of biometric trait details. These are mostly small patterns with unstable dimensions and undefined spatial distribution. At higher variation of their spatial distribution they exhibit only some degree of shape similarity. This is why their software recognition is not a trivial task. In our work we deal with methods allowing to solve this kind of problem. Our procedures and examples are primarily focused on gray-scale fingerprint image analysis. After modifications they can be used for different areas of biometrics. Basically, in our approach we solved this problem using a digital bitmap analysis focusing on regions containing patterns of our interest (in our case these were Level-2 fingerprint features). We determine their shape directly according to the typical image attributes or using neural network based classification. Our collection of software tools is primarily intended for use in fingerprint analysis. A mobile application and recently finished development of web-based server version of the system allow their widespread use. We can use these tools during expert training, in specialized institutions or at schools where biometrics courses are taught.

Key words: fingerprint image analysis, small irregular patterns, mobile and server application, expert training

1 Introduction

Software solutions are convenient way for doing things in case of tasks that repeat quite often and during their existence, it is necessary to adapt them for new technologies, knowledge development in a particular field and adjustments to legislation. Biometrics and dactyloscopy is such area. One may expect that software in-depth analysis of biometric trait attributes has been a routine solution for a long time. Although technology advancement shows unprecedented progress, in professional world and education of experts, biometric trait analysis has no adequate software support. For purposes of authentication we generally do not need to find and know the properties of all biometric features that moreover have no associated description of their shape. This also applies to the fingerprint minutiae. Hence it is not a trivial task to propose an algorithm for their automated recognition even today. Manual analysis by experts aims at a limited number of fingerprints. These are just a fraction of all registered images in databases today. However we use fingerprints daily for a variety of purposes, without knowing their properties indeed. We can change the present condition only if we ensure a regular, high quality training of experts and develop algorithms and systems for recognition of unsolved complex patterns. In this process, current software solutions become irreplaceable support for expert training. Analysis of state of the art shows that dactyloscopy expert training takes place in the form with capacity and content constraints, practically only as a part of forensic education. More detailed fingerprint analysis is not a subject of education process. It is rarely performed and only in manual form on expert level. It commonly lacks specialized software support and is limited just to forensic applications. Based on the percentage of processed available databases we may conclude that in-depth analysis of fingerprints is missing. Drawn conclusions based on limited knowledge might have a very limited validity.

After adoption of new accreditation, conditions for expert training were created even at our university. Within the scope of such training, accent is put on possibilities of algorithm design and development of software support for fingerprint analysis. Besides full-time study we plan to organize teaching in form of distance learning and in case of interest, education in form of courses. We have been dealing with this problem for a longer time at our institution. We develop components of network version of modular and unique expert system. Unlike AFIS (Automated Fingerprint Identification System) that searches only for ridge ending and bifurcation patterns, our solution is intended for in-depth fingerprint analysis with the possibility of parameter adjustment. It is predetermined for direct deployment in research and expert education with visualization of algorithms for fingerprint processing during laboratory lessons. By presenting our experience in this work, we would like help those who deal with similar problems.

2 Concepts of education in the field of dactyloscopy

From the available resources we analyzed situation in Slovakia, neighboring countries of European Union and other countries of the world. Based on this we may say that we found no country where suitable and comprehensive expert training for this field is in effect. Moreover we can say there is also no necessary software support. Therefore our proposals emerged as original material with no possibility to compare them with similar solutions. To make it clear, we need to add that all of our proposals were based on the following conditions:

- In continual form of the study, laboratory lessons will be held every week in total duration of 12 weeks.
- Other forms of the training will be planned to have adapted course contents and duration according to valid curriculum and training objectives at the time.
- All training forms will be supported by adequate computer applications for mobile devices (online/offline process), server applications and standard standalone computer programs during the entire teaching process.
- All applications will be open-source.
- Computer applications are required to recognize basic and complex Level-2 features defined by classification in Fig. 6 and perform in-depth fingerprint analysis.

Using the available sources and our experience from several years of work on the design of algorithms for fingerprint content processing and recognition for purposes of in-depth analysis we had opportunity to work with the following methods:

1. In first, a monochromatic 2D fingerprint image is examined using known pixel formations (e.g. Crossing Number technique). It is quite fast and generally accepted method, but it has limited usage due to its difficulties with recognition of slight pattern modifications.
2. In second, image is analyzed by means of neural networks which after being trained are able to recognize patterns and their modifications with certain level of tolerance. At present, neural networks are used for identification by matching using the entire fingerprint image. This approach is not directly suitable for in-depth analysis of fingerprints as the image is processed globally, not in block-wise manner.

After considering possibilities of mentioned methods we needed to develop new way of incorporating neural networks where after all, we can employ desired in-depth fingerprint analysis. In our novel, hybrid method we firstly determine location of smaller region in fingerprint image containing minutia point. Afterwards, using neural network we classify specific type of the minutia point.

For reliable and accurate minutiae detection we always need to preprocess fingerprint images using proper enhancement methods. During this process, the image is changed what besides prevailing positive effects necessarily introduces new defects into the processing. In the following sections we deal with chosen key problems that needed to be addressed while achieving our goals.

3 Sensing and preprocessing of fingerprints

To secure high quality and full-fledged expert training in the field of fingerprint recognition it is necessary to respect modern-day trends in the area of interest the same as long established rules in biometric system design. Software solutions for in-depth fingerprint pattern analysis that are to be presented in this contribution, are somewhat reflecting the concept of general biometric system that could be understood as a sequence of consecutive processes. Biometric system flowchart can be seen in Fig. 1.

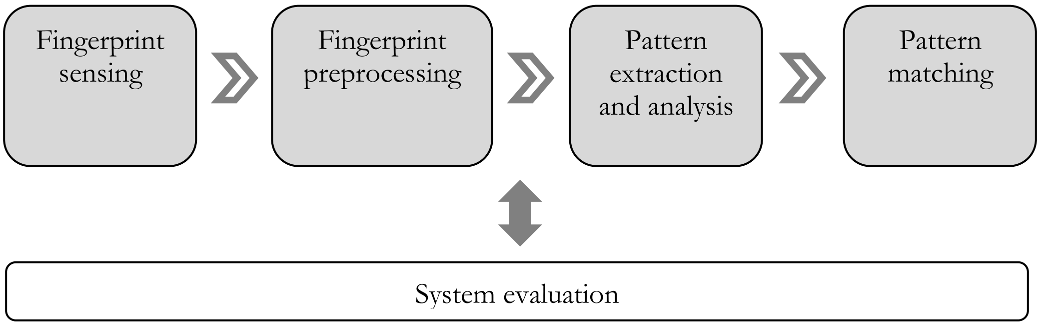

Fig. 1: Flowchart of key operations of general fingerprint recognition system

3.1 Fingerprint sensing

The first step is always fingerprint image sensing. In our case, the design was based on the fact that fingerprint preprocessing input will be 2D monochromatic fingerprint image acquired and digitized by appropriate sensor (new fingerprints) or taken from paper cards or tenprint cards maintained by law enforcement agencies. During training, we will also use publicly available and anonymous fingerprint databases. They contain thousands of fingerprint images, e.g. NIST databases. There is a wide range of sensing technologies. For our needs we used optical sensors, specifically the following devices:

- Futronic FS80 USB 2.0 with CMOS sensor (image resolution of 500 PPI at image size of 480x320)
- Biometrika HiScan-PRO professional optical sensor meeting the quality criteria given by FBI IAFIS Image Quality Specifications Appendix F (image resolution of 1000 PPI at 1x1 inch scanning area)

Some of our software applications we developed can use these sensors as image data source. This allows to classify software from applications with the least demanding requirements to the strictest, requiring high quality image without distortion in order to clearly see the smallest details. Futronic FS80 sensor was also tested on mobile Android device. For needs of laboratory lessons, HiScan-PRO is available in a number of 4 pieces and Futronic FS80 in a number of 4 pieces as well.

Our work was significantly encouraged and supported by long-term cooperation with the expert group at the Institute of Forensic Science of Slovak Police Force. Except expert advice they provided us with very useful and needed fingerprint images examined by human experts. We used these as reference while testing our own software.

3.2 Fingerprint pattern preprocessing

Preprocessing is indispensable part of in-depth fingerprint analysis due to the nature of these very complex patterns. Low quality may degrade fingerprint image to such degree that we are not able to identify basic ridge formations and therefore analysis of features becomes difficult.

In general, all preprocessing techniques are divided into two typologically different approaches:

- Image preprocessing as a whole (contrast adjustments, noise removal, image rotations or size changes)
- Contextual preprocessing respecting ridge structure (orientation and frequency estimation, ridge pattern filtering, ridge thinning and other morphological modifications)

The idea of preprocessing is to prepare an input image into the form where pattern analysis is the most reliable. In other words, we try to emphasize the real structure of fingerprint as much as possible and reduce noisy and redundant data [1]. With regard to diversity of input images (origin, size, resolution and quality) it is necessary to make sure these techniques are tested on huge fingerprint databases to find optimal parameters of chosen preprocessing algorithms. In order to make such time-consuming and intellectually challenging task feasible, it is necessary to automate the whole process by using latest information technologies. By adding suitable user interface, such computer software becomes a very good education tool assisting in teaching or serving as a mechanism for obtaining scientific results.

During the period of our own research in this area we managed to create several software solutions representing the building blocks of our modular network system. They perform fingerprint preprocessing and visualize its fundamental processes. In all these solutions, there was one primary requirement to allow an operator to interact with the software in most effective way to verify results of experiments and to gain new expertise. One of the most important advantages of our expert system is visualization of individual preprocessing steps using specific parameters. This way we can visually inspect achieved results. It is very necessary property for training process and research activity. All presented software solutions were created as a result of bachelor and master theses of students under our supervision or as a result of own research.

An example is the software developed by one of our students, Martin Dický [12], who integrated more preprocessing methods in one solution. This software allows to set parameters for the following techniques: contrast normalization, fingerprint segmentation, ridge orientation estimation, image filtering using Gabor filter and ridge thinning.

The output of preprocessing is a skeleton image, described as the most suitable fingerprint representation in literature as it can be easily processed by software and it contains all necessary patterns of fingerprint. The integral part of this software are two display windows where user can switch between intermediate outputs and compare how sequential application of techniques transforms fingerprint or what effect do individual settings have on the result of preprocessing. In Fig. 2 we can see the example of original fingerprint (left window) and Gabor filtering output (right window) along with associated settings grouped in section titled "Gabor filter". The software was developed using C++ programming language with use of Qt library. It is standard desktop application allowing processing individual images or it can run in batch mode defined by user.

Fig. 2: Fingerprint preprocessing software with possibility of parameter adjustment [12]

This software allows users to become familiar with the basics of fingerprint preprocessing as described in relevant literature the same as to learn the necessary habits to ensure high quality of preprocessing offering true basis for pattern analysis. Software solutions of this kind allow avoiding frequent mistakes that lead to image corruption. The software itself points out how inevitable some techniques are and how important it is to know what are their best settings at different image types.

Different approach to extraction is presented by the software developed by Miroslav Taraj [14] who in his final thesis dealt with the problem in slightly different manner, extending the whole issue by new findings.

The author of the system depicted in Fig. 3 extended preprocessing concept in use by adding new functions such as inverting colors (ridge and background color interchange), visualization of Gabor filter kernels at different settings, detection of fingerprint core in order to rotate fingerprint pattern with respect to its natural origin and simulate skin distortion. Although the most important contribution of this system is possibility to adapt all preprocessing parameters to specific image resolution. In the current version, system works with resolutions of 500, 750 and 1000 PPI.

Preprocessing not only eliminates defects but it also introduces additional image deficiencies. Their number depends mainly on type and particular setting of used filters where settings are linked to image content. In practice the most common type of filter is

Gabor, Wiener filter or filtering in Fourier domain. In OpenCV library environment we also can make use of Laplacian operator. During testing we found out that Laplacian operator is faster, however applicable just for images of resolution lower than 500 PPI. At higher resolutions it introduces disproportionate number of defects (e.g. sweat pores create artificial holes along ridges).

Fig. 3: Alternative solution for fingerprint preprocessing [14]

Besides aforementioned solutions, there are other software programs for fingerprint preprocessing and they are equally appropriate teaching aids offering graphical or text interfaces [6], [9] and [20]. A worth mentioning work in [18] deals with investigation of inaccuracies produced in preprocessing of fingerprints and some recommendations were formulated for their elimination. This way many frequent implementation errors were identified the same as incorrect settings of algorithms.

4 Feature extraction and in-depth analysis

As we said at the beginning, we divide fingerprint analysis into two different approaches: the ones based on pixel formation examination and the ones based on neural networks. Before we introduce selected software solutions for fingerprint detail analysis, let us remind standard classification of fingerprint patterns [1].

Level-1 features

These are global shape characteristics of fingerprint visible by naked eye. They are characterized by overall ridge flow and their curvature creating three basic arrangements: loop, whorl and arch. These shapes are however not unique. Using software for their recognition we can accelerate person identification by narrowing the entire search space to just wanted Level-1 type. On the other hand, by classifying these shapes we can carry out so-called negative identification, refusing identity (Fig. 4 and Fig. 5).

Level-2 features

Key features of every single fingerprint formed by various ridge formations in very small scale. These patterns tend to be called minutiae in the professional community. There are more minutiae types while our own classification consulted with forensic experts includes types depicted in Fig. 6. Generally we can divide Level-2 features by type into basic or complex ones. In casual authentication software solutions available online only basic types are used as their extraction does not pose such nontrivial problem as it is in case of complex Level-2 features.

Fig. 4: HiScan-PRO and FS80 scanners

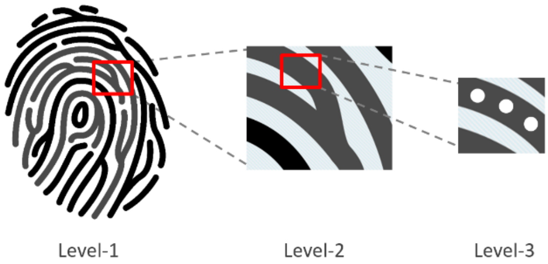

Fig. 5: Taxonomy of fingerprint pattern levels

Complex minutiae extraction techniques are very rarely published mostly totally missing and that is why we decided to pay them due attention. We developed several solutions offering unconventional ways of complex minutiae recognition and analysis. Based on our experience we can say that these features represent very useful information mainly when working with incomplete fingerprints or in situations where number of basic minutiae is limited.

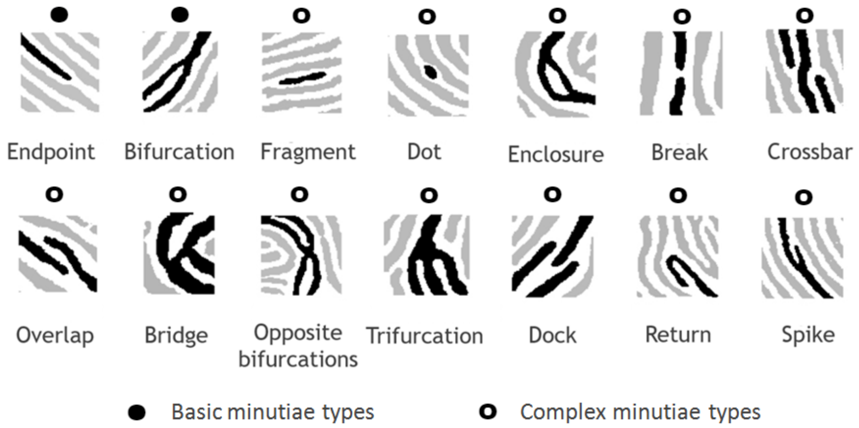

Fig. 6: Classification of Level-2 features

There are also Level-3 features that represent microscopic details at pore level. These patterns are respected in manual fingerprint examination however we are not dealing with them in this paper. In the following overview we present computer applications that may serve as adequate software support in training and education in the field of dactyloscopy thanks to their features and innovative algorithms of extraction and analysis of fingerprint patterns.

4.1 Methods based on examination of pixel properties

In bachelor thesis of Martin Dický [12] we successfully implemented a complex system for fingerprint analysis. Its preprocessing part was already stated in section 3.2. This system detects basic minutiae with attributes like location, orientation, shape type and distance of selected minutia points from the fingerprint core. Except this the software can detect Level-1 features such as core position and Level-1 pattern type (global pattern) using SVM approach.

The goal of the software is to provide data obtained from detailed analysis of fingerprint and merge them into unified representation constituting identifier of each fingerprint. Advantage of basic minutiae and their attributes is their distinctiveness. Their disadvantage is a necessity to work with high quality pattern in order to make their extraction reliable. Sometimes, preprocessing is not enough to recover them and sometimes we do not even have sufficient number of minutiae ensuring an indisputable match of two prints. In these situations we need to distinguish more types of fingerprint patterns whose detection is feasible also in low quality conditions. We are talking about Level-1 features. Except fusion of these two fingerprint feature types, a fingerprint matching algorithm was introduced and person recognition performance was evaluated using standard error indicators such as FMR, FNMR and ROC curves. The results showed this system delivers performance comparable to state-of-the-art solutions in literature, moreover fusion of both feature types brings higher recognition rates than system based only on one feature type.

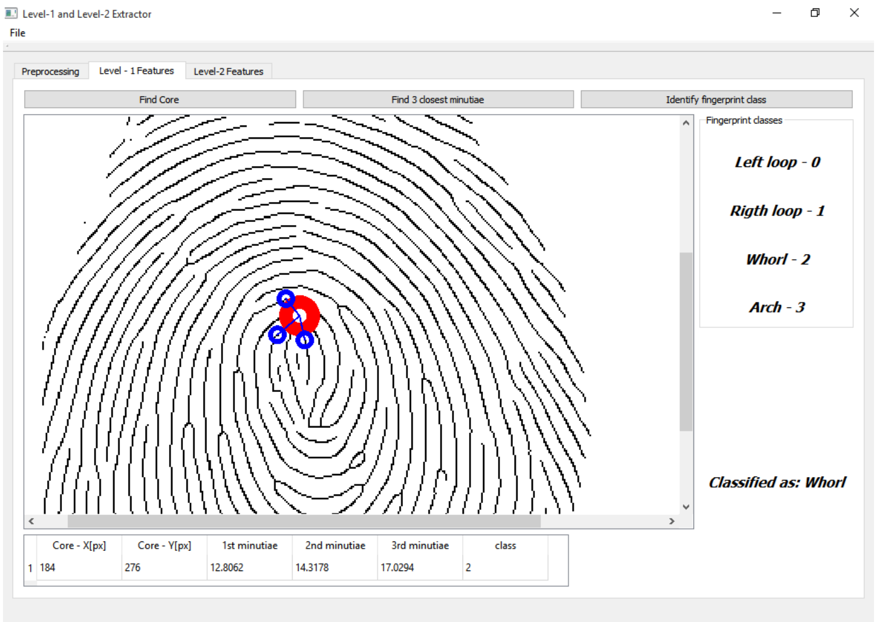

Fig. 7: Level-1 feature analysis interface [12]

In Fig. 7 we may see the application's environment for Level-1 feature recognition. User can arbitrarily move and zoom the image. Using buttons anyone can extract position of fingerprint core in automated way (depicted by red circle). After we found the core position we can continue with detection of 3 closest minutiae (blue circles). We worked with the assumption that distances of the triplet from the core are unique for each fingerprint. Subsequently, we can classify the image using SVM classifier into one of four classes: left loop, right loop, whorl and arch. The software visualizes all necessary outputs, displays core coordinates, distances of the three closest minutiae and class number.

In minutiae extraction we used well-known Crossing Number method which classifies minutiae into two types: ridge ending and bifurcation. It uses skeleton image as input. This method is based on examination of distribution of black and white pixels in the fingerprint skeleton. Black pixels are ridges whose 3x3 surroundings is investigated and three possible situations may arise as seen in Fig. 8. If there is a single black pixel in the surroundings of the central pixel, it is ridge ending. If there are two black pixels, we hit the intra-ridge pixel. In case of three black pixels, ridge bifurcation was discovered.

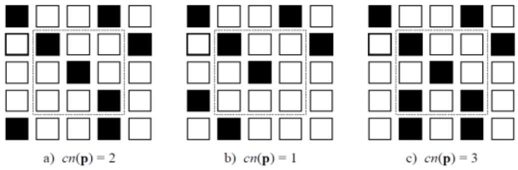

Fig. 8: Level-2 feature recognition in skeleton image using Crossing Number method

Image examination by Crossing Number method is followed by false ridge ending filtering from fingerprint edges. To do so we evaluated distance of ridge endings from the edge pixels of segmentation mask that defined usable fingerprint area. In Fig. 9 we see fingerprint skeleton created by our software (left), initial minutiae detection by Crossing Number (center) and minutiae set after filtering. Blue circles denote ridge bifurcations and red ones are ridge endings.

Fig. 9: Results of basic Level-2 features extraction [12]

On extraction results screen that is part of the software we may see the list of detected minutiae in table format after filtering false structures. Minutiae are given by their coordinates and orientation expressed by angle (Fig. 10).

To detect minutiae we can help ourselves by extracting other properties related to ridge geometry or texture properties. As example we present an application for basic minutiae extraction using ridge contour analysis of binarized images instead of skeletons [9].

The software analyzes sequences of ridge contour pixels and based on curvature it classifies the region as minutia region or region without minutiae. In Fig. 11 (left) we see the image with extracted contour pixels using Canny edge detector. Ridge contours marked in red constitute already processed image parts. This way the software visually informs users about analysis progress. The angle denotation explains how we measured ridge curvature. Extreme curvatures signalized minutia positions. The right of the picture shows fingerprint original with real minutiae marked by red semitransparent circles (bottom right) and image with basic minutiae positions marked by software by yellow circles (top right). Software is operated in text mode of command prompt.

In this method we compared achieved results with a database of manually extracted minutiae by forensic experts and we calculated location deviation along with false minutiae rate and missed minutiae rate. To calculate location deviation we used a tolerance 15x15 block at resolution of 1000 PPI. If minutia point extracted by software and the one extracted manually did not fall into this region we treated this situation as classification error. We used Goodness Index metric to evaluate false minutiae rate.

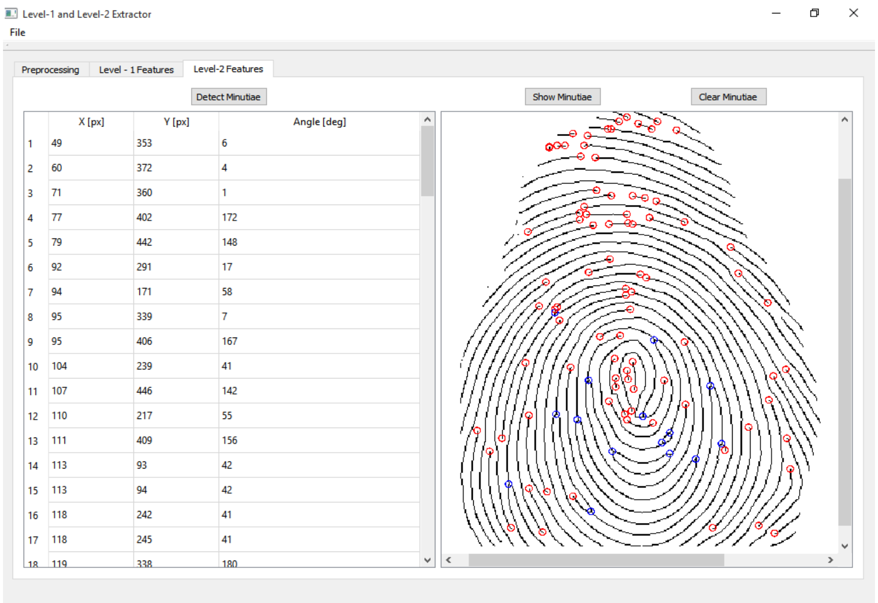

Fig. 10: Visualization of detected Level-2 features and their attributes [12]

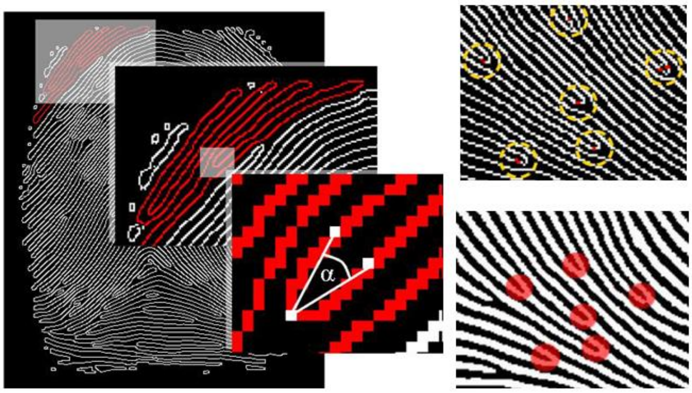

Fig. 11: Level-2 feature extraction using ridge curvature analysis [9]

Very interesting way of basic and two complex minutiae extraction is presented in [17]. The whole process resembles the radar operation that reveals object positions in a semicircle (Fig. 12). It is capable of detection of two minutiae: ridge overlap and dock.

Another method for fingerprint image content analysis is FingerCode. This method is based on fingerprint core detection and subsequent disk region extraction centered at the core point. This region is filtered by 8 differently oriented Gabor filters. After filtering, a characteristic vector containing all 8 filtered images is created. These are additionally split into sectors whose parameters are given by user. Grayscale variances are computed in these sectors and they are stored in the characteristic vector [14]. The method's idea is to create distinctive and rotation-invariant fingerprint representation. The rotation invariance is ensured by Gabor filters capturing features in 8 directions.

In [19], a software solution for complex minutiae (ridge enclosure, fragment and dot) extraction using multi-core processors is proposed.

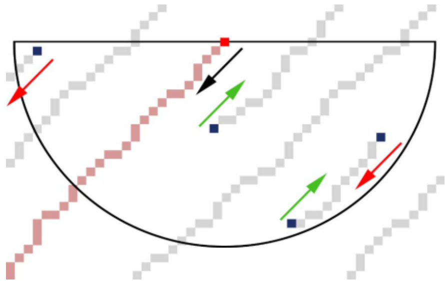

Fig. 12: Examined region of fingerprint for purposes of complex feature detection [17]

4.2 Methods based on neural networks

Another category of algorithms for in-depth fingerprint pattern analysis we developed are solutions based on neural networks. This choice was motivated mainly by advantageous properties of neural networks that can be employed to solve our problems. Neural networks are able to learn to distinguish various complex patterns and during training, they build knowledge allowing some degree of deviation tolerance. This way we do not need strict shape definitions as it was in case of algorithms in section 4.1. Recognition of ridge details seems to be appropriate task for multilayer perceptron networks with supervised learning.

Most advanced software solution so far based on neural networks is the work of group of students of Team Project course [20], who in 2016 developed and published a complete biometric system for person identification using fingerprints. It uses neural networks at two stages: Level-1 and Level-2 feature extraction. The solution was tested on number of databases and compared to other systems in literature.

By using Level-1 features user database is divided into 4 groups what makes identification process faster. Minutiae are used for fingerprint matching. Our system recognizes positions, orientations and shapes of these patterns and transforms them into the form compatible with well-known Bozorth3 fingerprint matching algorithm developed by NIST. The system was extended by adding false minutiae removal support. We can observe individual preprocessing steps, adjust parameters of network training and inspect the obtained minutiae. The entire system was tested on the database of more than 5800 fingerprint images acquired by more sensors.

Person recognition success rate was approximately 92 %. Level-1 extraction accuracy rate was 97 % and Level-2 accuracy rate was 98,64 %. The system is intended for 500 PPI images. The solution is depicted by the diagram in Fig. 13.

Our database size ensured the creation of sufficiently varied training sample for purposes of Level-1 training. These patterns are not classified in the original form but using properties of orientation map of fingerprint. Minutiae are classified by neural network in 11x11 image block. These blocks were extracted from the image obtained after Gabor filtering what is different from other methods that work with skeleton image. We verified the extracted minutiae and removed those which were flagged as false according to the abnormal density of occurrence. For training we need a sufficient number of these blocks containing minutiae. While databases of this kind are not publicly available and with high probability do not even exist, we used our own application for manual search and marking of minutiae with adjustable block size allowing future construction of different network configurations. This sample application under "Minutiae Marker" working title is shown in Fig. 14. OpenCV, Qt and FANN (neural networks support) libraries were used for development.

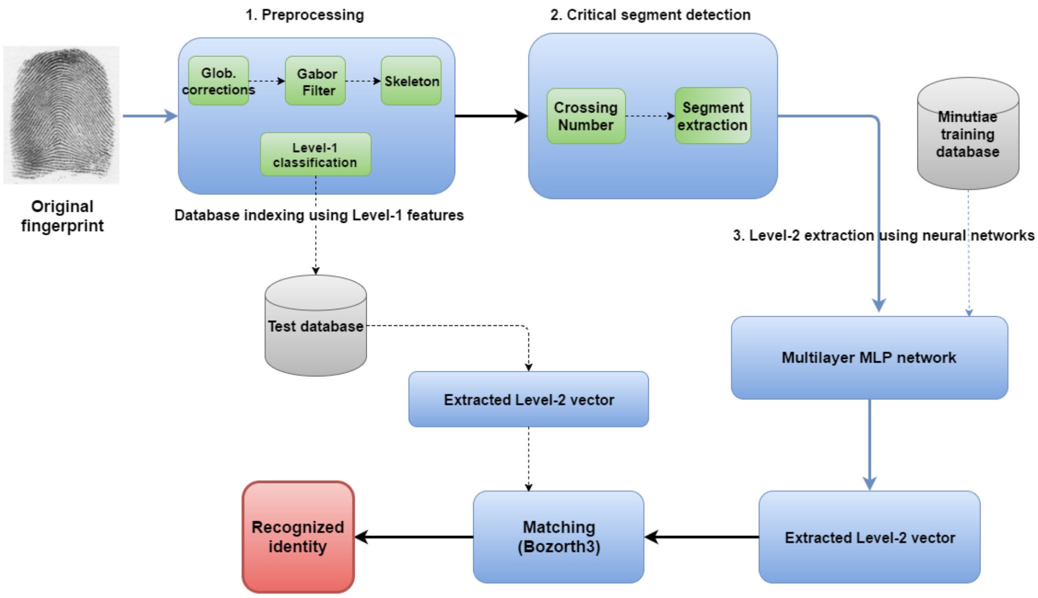

Fig. 13: Diagram of complete biometric system based on neural networks [20]

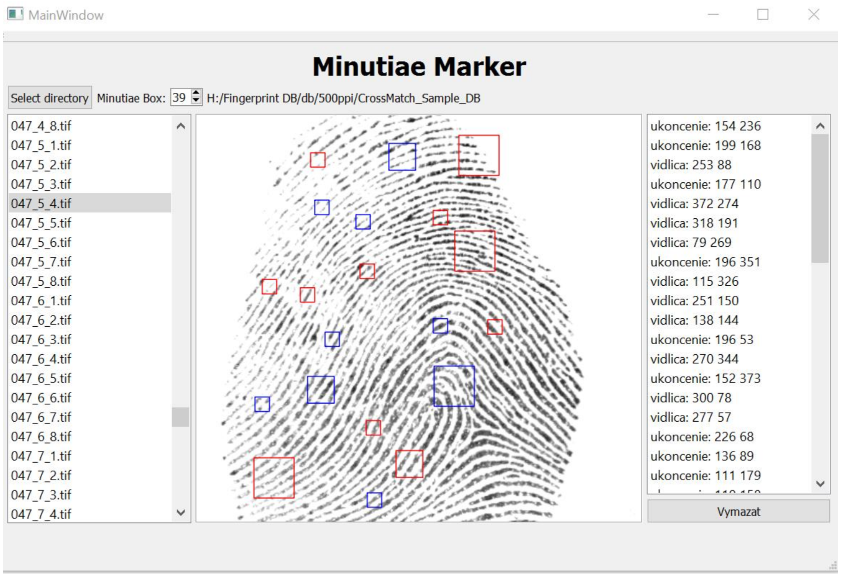

Fig. 14: Minutiae Marker widget for manual selection of image blocks containing Level-2 features [20]

Similar solution is presented in [16] where minutiae are recognized using neural network, but this time, they are detected directly in the original image. This way, we no longer need image preprocessing what might on the other significantly accelerate work of biometric system.

5 Computer network version of our expert system

Verified procedures, after additional modifications and possible flaw eliminations, will constitute another modules of network expert system in unified Linux environment to provide services of all developed components. The environment is easy-to-use and intuitive-to-operate and is sufficiently universal to integrate modules other than those from dactyloscopy area. For instance, we are currently working on modules for digital camera image analysis for purposes of their authenticity verification [5], [3] and [4].

Software operator uploads images he or she wants to analyze to server where new personalized directory is created to store the image. After that, we can selected the desired service of the desired module. Processing takes place on server side in batch mode with performance and memory optimization. Results are later stored in another folder for later download. Server version does not support fingerprint sensing at the moment. If necessary (during laboratory lessons or when in the field) fingerprints can be sensed by mobile Android device [8]. If we need images in higher quality we use notebook or desktop PC because of current drain and available drivers.

6 Conclusion

In this paper we presented some of our most important experience in design and implementation of expert system for educational and research purposes in the field of dactyloscopy. Considering specific requirements of research and expert training, our proposals and software support under development have no published and adequate alternative. Our primary goal was to share our obtained results with others solving similar problems and to show possible ways of solving problems of this kind. Software design itself is not enough to achieve expected results. We also need large and suitable fingerprint database that is hard to create using our own possibilities. In our case, except fingerprints obtained by our sensors, we used grayscale images from different sources. These are fingerprints acquired from other institutions using sensors or digitized paper cards from forensic area. Furthermore, we worked with public anonymous fingerprint databases. All we described is work in progress but intermediate results indicate that our design directions are correct in most cases. They intimate feasibility of our designs in reasonable time, promise interesting research outcomes and high-level expert training. We will be pleased to receive any comments or requirements by e-mail and we will consider their real world deployment. Moreover, we will try to find adequate solution for individual needs.

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