Document Title: Software Tool and Methodology for Enhancement of Unidentified Decedent Systems with Postmortem Automatic Iris Recognition

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Table of Contents

1. Summary of the project ... ***3***

1.1 Major goals and objectives ... **3**

1.2 Research questions ... **3**

1.3 Research design, methods, analytical and data analysis techniques ... **3**

1.4 Expected applicability of the research ... **4**

2. Participants ... ***5***

3. Outcomes ... ***6***

3.1. Activities and accomplishments ... **6**

3.2. Results and findings ... **7**

3.3. Limitations ... **15**

3.4. Artifacts ... **15**

3.4.1 List of products ... 15

3.4.2 Data sets generated ... 16

3.4.3 Dissemination activities ... 16

References ... ***19***

1. Summary of the project

1.1 Major goals and objectives

The purpose of this project is to deliver a complete methodology and the software that enhance unidentified decedent systems with a capability for comparisons of perimortem and postmortem iris images. The final products should include (1) a methodology and its implementation as a software tool returning a ranked list of "best matches" between a postmortem sample and a gallery of antemortem and postmortem samples, with visualization of features that support computer's judgement, and (2) a human examination methodology, which together with computer-added analysis of the returned candidate images, may deliver the final judgement about the identity of a decedent.

1.2 Research questions

The main research problem concerns novel methods, both related to computer vision and human examination, that allow for identification of deceased subjects based on their iris patterns. Iris recognition for live subjects exist for at least two decades. The main research question in this project was, however, how to establish a possibility of performing post-mortem (forensic) iris automatic recognition, and how to assist human examiners in their efforts.

1.3 Research design, methods, analytical and data analysis techniques

We have applied various computer vision techniques for performing post-mortem iris image processing (segmentation, encoding and matching). Among the methods developed, the benefits of purely deep learning-based solutions (e.g., a multi-channel CNN, patch-based feature extraction, and triplet loss-based models) as well as those incorporating human intelligence in the method design (e.g., human-driven BSIF) for matching PM images with AM or perimortem images was established. Additionally, the ACE-V [McRoberts-2002, VanderKolk-2011] -- the established method of examination of fingerprints – was a backbone for designing our methodology of human-machine pairing for human examination of forensic iris samples. Three datasets of post-mortem iris samples (some with corresponding pre-mortem images) collected from 482 deceased subjects were used in training and validation of all proposed methods. This project was the most comprehensive study of post-mortem iris recognition, both in terms of application of Artificial Intelligence methods, as well as involvement of human subjects analyzing the iris samples.

1.4 Expected applicability of the research

With increasing interest of iris recognition, USG services addressing these needs (e.g., the FBI Next Generation Identification (NGI) Iris Service[1]), and iris image datasets being enlarged, there may be a need quite soon to have a legally binding decision about the identity of the deceased subject based solely on their iris patterns. This project made an important step toward such a possibility by offering a software-based system for automatic post-mortem iris recognition, methodology supporting human examiners, and a new dataset of peri-mortem and post-mortem iris samples collected from 269 subjects for future research use.

The designed software was delivered to Dutchess County Medical Examiner's office and installed at their premises. Also, it was deposited at the National Archive of Criminal Justice Data repository. This software may thus serve as an element of forensic toolkit right away, or after necessary adaptations by the interested entities eligible to use resources deposited with the NACJD.

The designed methodology could be also useful in case of mass fatalities or traumatic injuries, where only part of the face is present, or where limbs are separated from torso and head; or in morgues that are temporarily above their normal capacity (i.e., where large numbers of remains

[1] https://www.fbibiospecs.cjis.gov/Iris

are temporarily being refrigerated in a truck/conex) and identification could be confirmed by another method prior to release of the remains; or in cases where there are no fingerprints, dental records, premortem radiologic or prior surgical records available; or in remains that are only partially damaged by burns with relative sparing of the globes.

Finally, there is a potential impact on biometric recognition discipline. For a long time, post-mortem iris recognition has been assumed as an impossible task due to hypothesized fast decomposition of the eye structures. This project shows, however, that these decomposition processes are slower than we assumed, and the iris recognition methods developed in this project allow for obtaining correct matches with high confidence for short low PMIs.

2. Participants

This project was led by the University of Notre Dame (UND), which developed a software tool supporting human examination of postmortem iris images. Dutchess County Medical Examiner's Office (DCMEO) collected new postmortem and perimortem iris images and verified the usefulness of the created software from the standpoint of medical examination requirements. Michigan State University (MSU) worked with UND on new computer vision methods for postmortem iris processing and matching. The developed methods were verified with data acquired from new 269 cadavers, including perimortem samples from one subject. The experiments with 283 human examiners analyzing perimortem and postmortem iris image pairs with different levels of difficulty were conducted by UND. Based on these results, the methodology for human expert-based analysis of the best-matching candidates was developed, based on the ACE-V protocol used for comparison of fingerprints. The project generated the first known to us complete system, including methodology and supporting software (with source codes) for forensic analysis of post-mortem iris images.

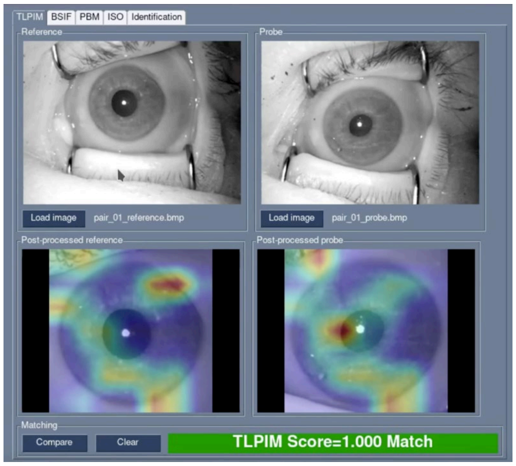
3. Outcomes

3.1. Activities and accomplishments

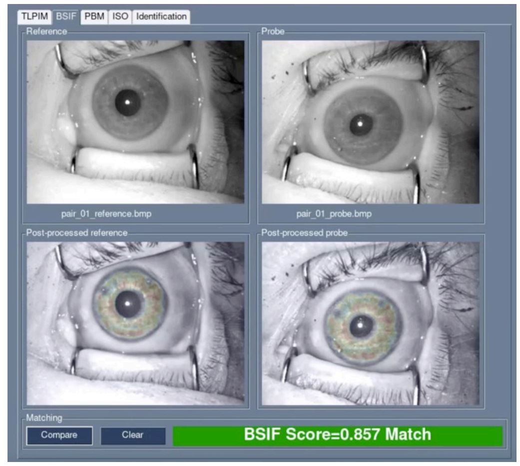
The research outcomes of this project offer several novel and important solutions to post-mortem iris recognition. First, a neural network-based multi-class iris segmentation algorithm was designed, which identifies never-considered-before in automatic iris recognition post-mortem deformations of the cornea and iris tissue. Second, the human intelligence was applied to create a human-driven and neural network-based algorithm that detects iris features (in a form of small image patches) and matches them in a way similar to how humans are doing that. Third, a methodology of visual explanations of the automatic post-mortem iris recognition process was designed and proposed for each of the three iris recognition methods. Finally, inspired by the ACE-V [McRoberts-2002, VanderKolk-2011] -- the established method of examination of fingerprints to determine or exclude the source of the print -- we proposed the first known to us human-machine pairing approach to support human examiners in matching post-mortem irises. The goal was to primarily minimize the number of false matches. Summarizing, the final accomplishments of the project include:

a) a **methodology and its implementation as a software tool** returning a ranked list of "best matches" between a postmortem sample and a gallery of antemortem and postmortem samples, with visualization of features that support computer's judgement, and
b) a **human examination methodology**, which together with computer-added analysis of the returned candidate images, may deliver the final judgement about the identity of a decedent.

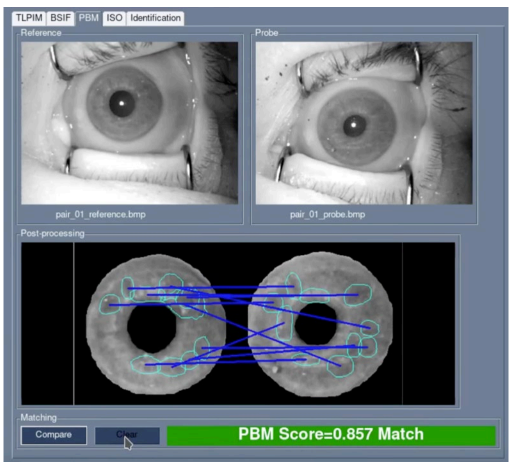
Figure 1 illustrates the designed software tool in operation (example results for three recognition methods and ISO/IEC quality metrics).



Method 1: TLPIM



Method 2: Human-driven BSIF



Methods 3: PBM

ISO/IEC 29794-6 quality metrics

Figure 1: Illustration of the designed software tool in operation.

3.2. Results and findings

In this Subsection, we briefly characterize results associated with two accomplishments listed in Sec. 3.1.

The designed new methodology of post-mortem iris recognition and the tool (accomplishment (a) in Sec. 3.1) incorporate:

- A post-mortem automatic iris segmentation tool pointing the human examiner and automatic iris image matching algorithms to potentially useful areas within the forensic iris samples; the segmentation tool locates iris annulus, irregular specular highlights (mostly from the cornea) and irregular post-mortem wrinkles within the iris and cornea. To accomplish this, we trained the Mask-RCNN [He-2017] deep learning model on hand-annotated post-mortem iris samples. Fig. 2 presents an example output of our segmenter.

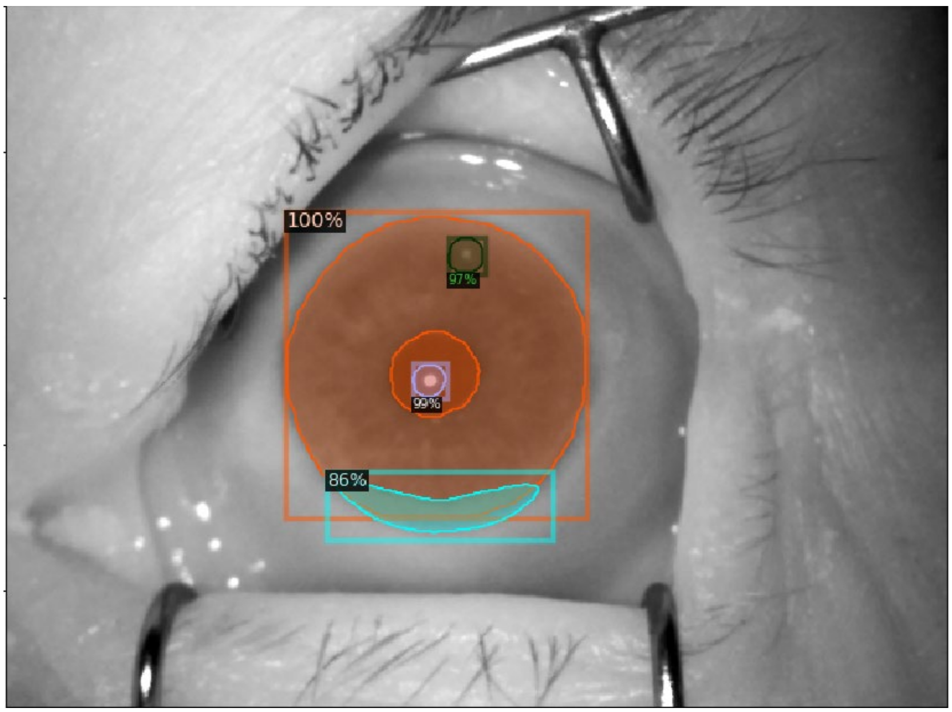


Figure 2. Mask-RCNN-based individual detection of iris annulus, wrinkles and regions with specular highlights

- Three Artificial Intelligence-based methods, implementing different approaches to encoding and matching deformed and degraded iris images of deceased subjects.

  The first solution, *Triplet Loss Postmortem Iris Model* (TLPIM), uses a triplet-based approach like what was proposed in [Schroff-2015]: during training, the network is presented with triplets of images, containing an "anchor", a "positive" image (another sample from the same subject), and a "negative" image (a sample from another subject). The model extracts a vector of features from each image and calculates the distance between them to guide the learning process. Ideally, the distance between the anchor and the positive samples should be smaller than the distance between the anchor and the negative sample. If not, the neural network weights should be adjusted, and the process is repeated. Additionally, Class Activation Mechanism was designed and implemented to present salient feature to the human examiner.

The second solution, *Patch-Based Matching* (PBM), deploys again the Mask-RCNN model to detect patches of usable iris texture in an image. The model was trained on features previously judged as salient by humans solving post-mortem iris recognition task, making this method more "human-like" and more human interpretable.

The third method, *Human-Driven Binary Statistical Image Features* (HD-BSIF), incorporates designed in this project Mask-RCNN-based segmentation, and previously designed image filtering based on human-sourced filters trained on a mixture of post-mortem and live iris images [Czajka-2019].

- Methods of automatic visualizations of Artificial Intelligence decisions, highlighting the regions deemed by a computer as the most important to commit to a given identification decision.

- Iris image quality metrics, based on ISO/IEC 29794-6 international standard, additionally assisting human examiners in assessing the biometric usability of the processed sample.

All methods were trained on post-mortem iris samples previously collected from 213 deceased subjects (before this funded research: WARSAW and DCMEOv1 datasets), and available to this research team. All evaluations were made on subject-disjoint dataset, collected in this project from 269 subjects (DCMEOv2 dataset; submitted to the National Archive of Criminal Justice Data -- NACJD). The obtained recognition accuracies for selected methods very favorably compare to those observed for a commercial VeriEye method, highly ranked in the NIST's IREX X program (see Figs 3 and 4).

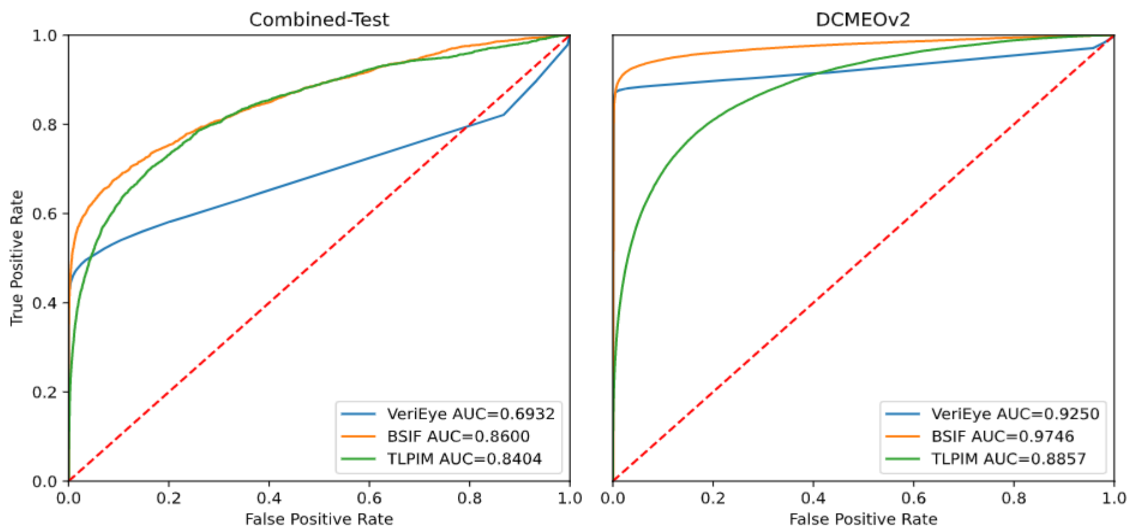


Figure 3. ROC curves comparing our proposed deep learning-based post-mortem iris matching method (**TLPIM**), commercial **VeriEye** method and our past method adapted to post-mortem setting (**BSIF**) on both the test partition of the combined set (WARSAW+DCMEOv1), and newly collected DCMEOv2 set.

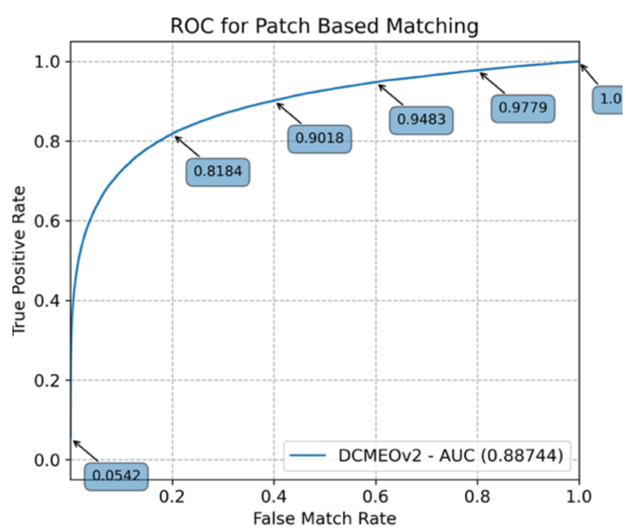


Figure 4. ROC demonstrating performance of the **patch-based human-interpretable post-mortem iris recognition method (PBM)** on DCMEOv2 dataset.

To find the optimal human-machine pairing (accomplishment (b) in Sec. 3.1), we designed a series of experiments in which two human subjects and our best-performing method (human-driven BSIF) were deciding on the same pair of iris images. The procedure is inspired by the ACE-V, which consists of four phases: Analysis, Comparison, and Evaluation, followed by Verification. Adapted to the realm of post-mortem iris recognition, these steps could be characterized as follows:

- *Analysis* is the assessment of the quality of the iris image to judge whether a given sample can be processed. Based on previous training, experience and understanding of the problem, the examiner decides whether the iris sample is sufficient for comparison with another sample.

If the machine is used to support the process, the ISO quality metrics added to the created software, can serve as a cue. The ISO/IEC 29794-6 provides thresholds indicating a "good quality" iris sample for each metric, which may be further used in the Analysis step. This process is, however, subjective as there are no agreed thresholds or quality metrics designed for post-mortem iris images.

- *Comparison* is direct feature-by-feature comparison of iris details to determine whether these details in two irises are in agreement based upon similarity and spatial location.

It is noteworthy that there are no definitions of "iris features", which could be globally accepted as universal and stable "minutiae" of the iris. There are a few identified anatomical features of the iris, such as Fuchs' crypts and "anti-crypts" (Kruckmann-Wolfflin bodies or Brushfield spots). These features, however, do not describe a full richness of iris texture and its entropy, hence basing the human identification solely on these elements could end up with a system with lower discrimination power than systems making a better use of huge iris texture entropy [Daugman-2021].

- *Evaluation* is the formulation of a conclusion based on analysis and comparison of post-mortem iris features.

This process is highly dependent on the experience of the examiner. Given no formal curricula and/or training programs that would educate iris image examiners, and the fact that forensic iris recognition is an emerging area, the evaluation results may significantly vary from examiner to examiner.

- *Verification* is the independent examination by another qualified examiner resulting in the same conclusion.

It is noteworthy that the ACE-V phases do not always happen in the order as listed in the method's name. For instance, the examiner may reconsider starting from the beginning when the Comparison is finished with initially inconclusive result, and they feel that more in-depth Analysis is needed. Also, the phases may partially overlap. For instance, during the Comparison the examiner may simultaneously developing a decision, hence mentally starting the Evaluation phase. Moreover, the thresholds applied in all phases of the ACE-V (such as a well-known 12 matching minutiae points proposed by Loccard to judge that two prints match) have not been globally standardized, hence leaving them to examiners' decision [VanderKolk-2011].

We verified multiple scenarios of human-machine pairing, in particular:

a) humans – group 1 only (ACE)
b) humans – group 1 (ACE) then group 2 (V)
c) humans – group 1 only (ACE) + machine (AND or OR fusion of their decisions)
d) humans – group 1 (ACE) then group 2 (V) + machine (AND or OR fusion of their decisions)

The logical "OR" strategy fusion ended up with results that were inferior to the performance observed for other pairing strategies, so it was ignored in further analysis.

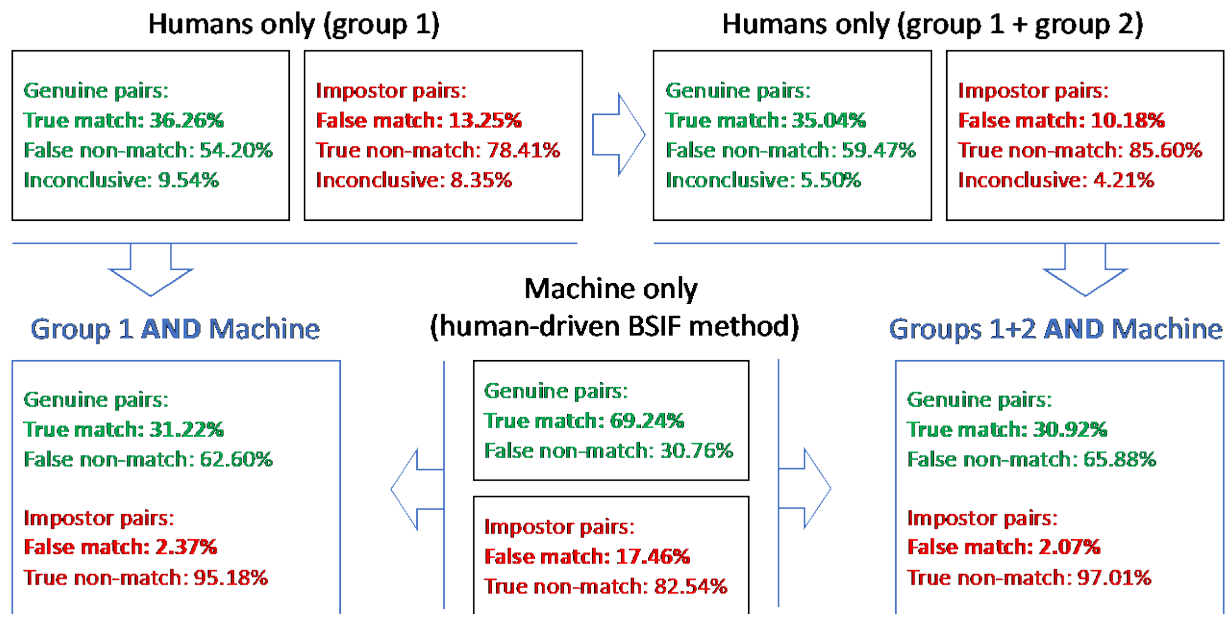


Figure 5. Results of human examination and matching of post-mortem iris image pairs combined in various ways with an Artificial Intelligence.

Matching results for all considered combinations of human-machine pairing are shown in Fig. 5. The machine accuracy on the post-mortem iris image pairs selected for this experiment is mediocre (due to challenging samples being processed): only 69% of pairs correctly matched, and 17% falsely matched. Note that these results represent the best-possible accuracy of automatic post-mortem iris recognition for a given set. However, there are several very interesting observations from this experiment.

First, although including the second subject verifying of how the first subject examined the iris image improves (lowers) false match, this improvement is not significant (from 13% to 10%). There is even small decrease in correct match rate when the second examiner is added to the pipeline (from 36% to 35%).

Second, when the machine is combined (by performing a logical "AND" on machine's and human's decisions), the false match rate improves dramatically: from 13% and 17% for humans and machine alone, respectively, to only 2.37% for human-machine tandem. This is achieved for a relatively small decrease of true match rate (36% -> 31%).

Third, fusion of the decisions of the second examiner (who verifies the first examiner) with the machine does not bring drastic improvement in false match rate. Hence, the overall conclusion from this study is that **it may be beneficial to have only one expert cooperating with a machine, instead of two experts acting sequentially.**

Based on these findings, to minimize the false match rate, and keep the true match rate not severely impacted, the following procedure could be considered:

1. Assess the usability of both iris images, looking specifically at the amount of iris texture visible. Automatic segmentation offered in the PMExpert software tool may help in locating useful areas.
2. Run post-mortem iris matching using the most trusted automatic recognition method; that is, the method offering the highest performance on a validation set formed to simulate the target scenario (for instance, PMI). Note the machine’s decision.
3. Ask one expert to decide whether the iris image pair comes from the same eye, asking that person to annotate as many features supporting their decision as possible.
4. Take the logical AND operation from (2) and (3). In case of inconclusive expert’s decision, we suggest ending up with an inconclusive result of the entire examination.

We are not aware of any other strategies of human machine pairing for the purpose of post-mortem iris recognition, so this effort could be seen pioneering research in this area. The proposed procedure certainly serves as a starting point for future discussions and exploration of the ACE-V-like strategies of matching forensic iris images.

3.3. Limitations

There are two obvious limitations of this study. The first is related to relatively low PMI (estimated for a few weeks when a body is kept in favorable mortuary conditions, and for a few days when kept outside the mortuary) until which this methodology can be usable. The second limitation is a wide availability of iris scans taken from living individuals and easily accessible by agencies performing forensic iris analysis. The first limitation is biology-driven and potentially defines specific applications of this methodology, yet still very useful (like short-term, rapid cataloguing of the remains). The second limitation is going to be less and less severe as we observe iris recognition becoming an important element of the governmental automatic identity verification systems.

3.4. Artifacts

3.4.1 List of products

Peer-reviewed papers published:

A. Boyd et al., "Post-Mortem Iris Recognition—A Survey and Assessment of the State of the Art," in IEEE Access, vol. 8, pp. 136570-136593, 2020, doi: 10.1109/ACCESS.2020.3011364 (open access)
B. A. Kuehlkamp et al., "Interpretable Deep Learning-Based Forensic Iris Segmentation and Recognition," 2022 IEEE/CVF Winter Conference on Applications of Computer Vision Workshops (WACVW), 2022, pp. 359-368, doi: 10.1109/WACVW54805.2022.00042; pre-print: https://arxiv.org/abs/2112.00849

One of the products of this project is a software package implementing the methodology of automatic post-mortem iris recognition. The software has been deposited at the National Archive of Criminal Justice Data repository[2]. The software was prepared with the use of only open-source components, it's written in C++ and Python languages, and can be run on Windows, MacOS and Linux operating systems.

3.4.2 Data sets generated

An important outcome of this project is a newly acquired dataset of 5,770 near-infrared and 4,643 visible-light iris images captured from 269 deceased subjects in several sessions approximately 12 hours apart. Both left and right irises were photographed, where possible. Near-infrared iris images have been acquired by an iris recognition sensor compliant with ISO/IEC 19794-6. This database is unique in several ways: (a) it's the largest known to us, publicly-available dataset of post-mortem iris images; (b) the longest PMI (post-mortem interval) is 1,650h (approx. 68 days); (c) it includes one case (two eyes) with images acquired before death (peri-mortem samples) and the corresponding images acquired after demise (post-mortem samples); (d) it includes images of an iris photographed when the eye globe was completely dislocated posteriorly out of the bony eye socket. Fig. 6 shows a few samples from the newly collected DCMEOv2 dataset.

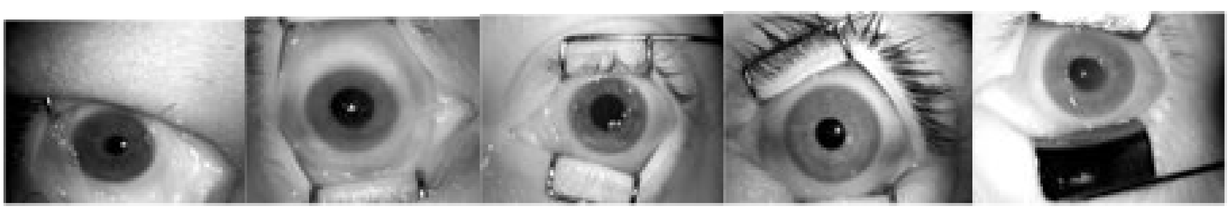


Figure 6: Sample images from the collected DCMEOv2 dataset.

3.4.3 Dissemination activities

The research results and accomplishments of this project were presented multiple times at research-oriented events. Dissemination activities during the award:

[2] https://www.icpsr.umich.edu/web/pages/NACJD/archiving/deposit-nij-data.html

1. Adam Czajka, "Post-mortem iris: going beyond using off-the-shelf iris recognition methods," **Iris Experts Group Meeting**, NIST, June 27, 2019 (slides attached to the RPPR final report as `slides_IEG_June_2019.pdf`)
2. Adam Czajka, "Update on Notre Dame Efforts on Post-mortem Iris Recognition," **Iris Experts Group Meeting**, NIST, June 25, 2020 (slides attached to the RPPR final report as `slides_IEG_June_2020.pdf`)
3. Adam Czajka, "Is That Eye Dead or Alive? Recognition of Presentation Attacks in Iris Biometrics," Lunch-time **EAB Online Seminar Series**, on-line event, January 12, 2021 (slides attached to the RPPR final report as `slides_EAB_January_2021.pdf`)
4. Adam Czajka, "Post-mortem Iris Recognition", **NIJ Forensic Science Research and Development Symposium**, on-line event, February, 2021 (slides attached to the RPPR final report as `slides_NIJ_Symposium_February_2021.pdf`)

Post-award activities:

5. Adam Czajka, Patrick J. Flynn, "Automatic Post-mortem Iris Recognition," **105th IAI International Educational Conference**, Nashville, TN, August 1-7, 2021 (slides attached to the RPPR final report as `slides_IAI_August_2021.pdf`)
6. Adam Czajka, "Software Tool and Methodology for Enhancement of Unidentified Decedent Systems with Postmortem Automatic Iris Recognition", **NIJ Forensic Science Research and Development Symposium**, on-line event, March, 2022
7. Adam Czajka, Patrick J. Flynn, "Human-Machine Pairing for Post-Mortem Iris Recognition," **106th IAI International Educational Conference**, Omaha, Nebraska, August 2022

Educational activities:

The topic of forensic iris recognition has been covered in multiple regular and guest lectures taught at the University of Notre Dame, including *Biometrics* (CSE 40537/60537), *Computer*

Vision I (CSE 40535/60535), *Computer Vision II* (CSE 40536/60536), and *Physics of the Brain* (PHYS 40435). The topic of post-mortem biometric recognition is now part of the *Biometrics* course (CSE 402; 0.5 lectures) taught at the Michigan State University. Additionally, this project gave an opportunity for mentoring graduate students post-doctoral fellows at the University of Notre Dame and at the Michigan State University.

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