Trial Somaliland Voting Register De-Duplication Using Iris Recognition

Kevin W. Bowyer, Estefan Ortiz, and Amanda Sgroi
Department of Computer Science & Engineering, University of Notre Dame, Notre Dame, IN 46566 USA

***Abstract*— Face and fingerprint were used in de-duplication of the voter registration list for the 2010 Somaliland presidential election. Iris recognition was evaluated as a possible more powerful means of de-duplication of the voting register for the planned 2015 elections. On a trial dataset of 1,062 registration records, all instances of duplicate registration were detected and zero non-duplicates were falsely classified as duplicates, indicating the power of iris recognition for voting register de-duplication. All but a tiny fraction of the cases were classified by automatic matching, and the remaining cases were classified by forensic iris matching. Images in this dataset reveal the existence of unusual eye conditions that consistently cause false-non-match results. Examples are shown and discussed.**

I. INTRODUCTION

The Republic of Somaliland is a country of about 3.5 million people, located on the horn of Africa. The Somaliland government has executive, legislative (House of Representatives and House of Elders) and judicial branches, operating under a Constitution. The government web site currently includes the slogan: "Recognition – The number one priority for the Somaliland government" [1]. Part of the Somaliland government's effort to achieve international recognition includes holding elections that are respected as fair and that enable peaceful political transitions.

A report [2] done by Electoral Reform International Services for the Somaliland National Electoral Commission (NEC) discusses the voter registration process used in the 2010 Somaliland presidential election. Registration information collected in late 2008 and early 2009 included face and fingerprint images. Face and fingerprint were used in weeding out "duplicate" registrations. (A "duplicate" registration is an attempt by one person to register under multiple identities.) However, the report [2] describes that – "… problems arose during registration, when the registration officers were unable to resist pressure from local elders, and fraudulent registrations were permitted. Procedures and technical controls were not strong enough to prevent these, *and the fingerprint and photograph data were not good enough to allow the duplicates to be detected at the centre*." (emphasis added) One of the conclusions of the report is that even "after delays and extensive cleaning *the voter register still contains around 30% of fraudulent and duplicate records*" (emphasis added) and that "this problem must be resolved if the next election is to be credible" [2]. It is in this context that the Somaliland NEC contacted us to arrange an evaluation of iris recognition for voting register de-duplication.

Somaliland is not alone in experiencing difficulties with the introduction of biometric technology into the creation of a voting register. Gelb and Clark survey a number of such efforts and the problems that they encountered, as part of a larger survey titled "Identification for Development" [3].

In the current Somaliland voting context, iris recognition is not envisioned to be used to verify a person's identity in "real time" at the polling place on election day. This is due in part to the expense of a real-time system and to the critical nature of a possible computer failure during the election. Voter registration is performed in advance of the election, the voting register is de-duplicated and publicized, and persons are issued an identification card that qualifies them to vote at a specific polling place during the election.

Several factors combine to make voting register de-duplication a "biometrics in the wild" application. One factor is that voter registration data is acquired in real-world conditions for an entire population. There are no "laboratory conditions" and there is no selection or screening of persons. Another factor is that the people whose data is being acquired are not regular users of the technology, and so there is no familiarity with the technology that might lead to more standard or "cleaner" data. Still another factor is the stringent requirements for the application. The use of biometrics should not unfairly disadvantage any citizen, should provide strong protection against fraud, and the time and cost of using the system should be low.

II. EVALUATION OF IRIS RECOGNITION FOR SOMALILAND NEC

The Somaliland NEC contacted the Notre Dame research group in May of 2014 to discuss support of an evaluation of iris recognition for creating a new voter registration list. It was agreed that the NEC would collect a small, trial voter registration dataset that included iris as the biometric. A registration record (as seen by the Notre Dame researchers) would include a registration number and a left-right pair of iris images. The NEC would seed the dataset with a number of "duplicate" records, and this number would be unknown to the Notre Dame researchers. A "duplicate" is an second left-right pair of iris images for a person, taken at a different time and/or place, and given a different registration number. A copy of the dataset would be sent to the Notre Dame research group, who would use iris recognition analysis to produce a list of pairs of voter registration numbers determined to represent duplicates.

A total of 1,062 trial voter registration records were acquired over a five-day period in June 2014 in the Somaliland cities of Hargeisa and Baki. A commercial, "binoculars-style" dual-iris sensor was used to acquire the iris images. Notre Dame researchers were not involved in the data acquisition effort. A copy of the image dataset was transferred to Notre Dame for analysis.

Before running any automated matching experiments, we first reviewed the dataset for image quality. Out of the 2,124 iris images, there was one image in which no iris was visible. There also was a small number of images in which an iris was only partially in view, was highly occluded by eyelids, or appeared heavily blurred.

The first step in our de-duplication analysis was an "all-versus-all" matching. We used the Neurotechnology VeriEye matcher version 2.7 [4] for this. This matcher reports a match score that is different from the fractional Hamming distance used in a Daugman-style matcher. For VeriEye, a score of 0 represents "no match" between a pair of images, and a larger positive value represents a stronger degree of match. (In the version of VeriEye that we used for this analysis, the max match score value is 1,557. This would be achieved only for matching two copies of the same image).

The dataset contained 1,062 records. This means that there are 1,062 x 1,061 / 2 = 563,391 pairs of records to classify for de-duplication. The goal is to classify each pair of records as being either Non-Duplicate, meaning from different persons, or Duplicate, meaning from the same person. We take a "dual-iris-agreed" approach to automatically classify pairs of records. A pair is categorized as Non-Duplicate if both the left irises and the right irises generate a match score of zero. A pair is categorized as Duplicate if both the left irises and the right irises generate a match score that is positive. A pair is categorized as Contradictory if the match score is zero for the left irises but positive for the right irises, or vice-versa. Such a result is Contradictory because the result for one eye indicates that the records are from the same person, while the result from the other eye indicates that the records are from different persons.

Following this dual-iris-agreed approach, 562,901 of the 563,391 pairs of records were classified as Non-Duplicate, 450 were classified as Duplicate, and 40 were classified as Contradictory. An example of one Non-Duplicate instance is shown in Figure 1. (For the one record that had an iris visible in only one of the two images, that record's match to the other 1,061 records was made on the basis of the one iris image.)

TABLE I. SUMMARY OF RESULTS OF CLASSIFYING PAIRS OF TRIAL VOTER REGISTRATION RECORDS AS NON-DUPLICATE / DUPLICATE

Number of pairs of records compared	**How classified as Non-Duplicate / Duplicate**
562,901	Automatically classified as Non-Dup by left + right both having match score = 0
450	Automatically classified as Dup by left + right both having match score > 0
33	Contradictory left-right automatic results; classified as Non-Dup by forensic exam
7	Contradictory left-right automatic results; classified as Dup by forensic exam

The Contradictory instances should be resolved in some manner. For the results that we reported to the Somaliland NEC, the Contradictory instances were resolved though manual "forensic" review. Each of the 40 Contradictory instances was independently reviewed by two of the authors to make a determination of Duplicate / Non-Duplicate. The two forensic determinations agreed for all 40 pairs of images. 33 were determined to be Non-Duplicates and 7 to be Duplicates. These results are summarized in Table I.

In the end, 457 pairs of registration numbers were reported to the Somaliland NEC as the Duplicates found in the trial voter registration dataset. The Somaliland NEC compared this list to their independent recording of the Duplicates seeded into the dataset, and confirmed that the analysis had classified the trial dataset into Duplicates / Non-duplicates with zero errors. That is, all instances classified as Duplicates were in fact Duplicates, and all instances classified as Non-Duplicates were in fact Non-Duplicates.

Before reporting results to the Somaliland NEC, we performed a forensic review of a small number of the pairs of records that were automatically classified as Non-Duplicate and Duplicate using the dual-iris-agreed rule. In all these cases, the forensic review supported with the automatic classification.

The automated matching was done at the image level rather than at the registration record level. That is, an image that was labeled left (right) in one registration record was still matched against images labeled as right (left) in other records. This was done to allow a check for possible left-right labeling errors of images. We found no instances of left-right labeling errors. There were 37 instances in which a left iris of one record matched to a right iris of another record, but the other images of the pair of records did not match. However, forensic examination of these instances determined that all 37 instances were in fact images from different eyes.

Forensic examination of pairs of iris images to determine if they are of the same iris is not yet a commonly accepted practice. However, previous work from our research group has shown that even novice iris image examiners can match iris images with relatively high accuracy [5]. In instances where automated matching of the left and right irises produces conflicting results, forensic examination by a human image interpreter is a viable option.

III. IDEALIZED PROJECTED ERROR RATES AND SCALING

Iris recognition accuracy is excellent on the modest-sized trial dataset. Even more important is that the results seem to be in broad agreement with a conceptual model that predicts high accuracy even for much larger datasets.

In the context of iris recognition, the idealized "Daugman performance point" combines a false-match rate of about 1-in-1-million with a false-non-match rate of about 1-in-100. The false non-match rate in actual experience is likely to be slightly higher than this idealized projection. But if we assume that an iris matcher is tuned to achieve this pair of error rates, and also assume that matching of the left and right irises is independent, then we can compute projected accuracy for our Dual-Iris-Agreed matching scenario, as tabulated in Table II.

A true Duplicate instance is a pair of voter registration records from the same person. With our assumed error rates, a true Duplicate pair will generate a Duplicate result over 98% of the time, a Contradictory result just under 2% of the time, and incorrectly generate a Non-Duplicate result 1-in-10,000 times.

A true Non-Duplicate instance is a pair of voter registration records from two different persons. With our assumed single-iris error rates, a true Non-Duplicate pair will generate a Non-Duplicate result over 99.9997% of the time, a Contradictory result 2-in-1-million times, and incorrectly generate a Duplicate result about 1-in-1-trillion times.

TABLE II. PROJECTED DUAL-IRIS-AGREED RESULTS BASED ON "DAUGMAN PERFORMANCE POINT" FOR SINGLE IRIS

True state of pair	Left iris	Right iris	Dual-iris-agreed result	Probability
Duplicate	match	match	Duplicate (true)	0.99 x 0.99
Duplicate	non-match	non-match	Non-Dup (false)	0.01 x 0.01
Duplicate	match	non-match	Contradictory	0.99 x 0.01
Duplicate	non-match	match	Contradictory	0.01 x 0.99
Non-Dup	non-match	non-match	Non-Dup (true)	0.999999 x 0.999999
Non-Dup	match	match	Duplicate (false)	0.000001 x 0.000001
Non-Dup	non-match	match	Contradictory	0.999999 x 0.000001
Non-Dup	match	non-match	Contradictory	0.000001 x 0.999999

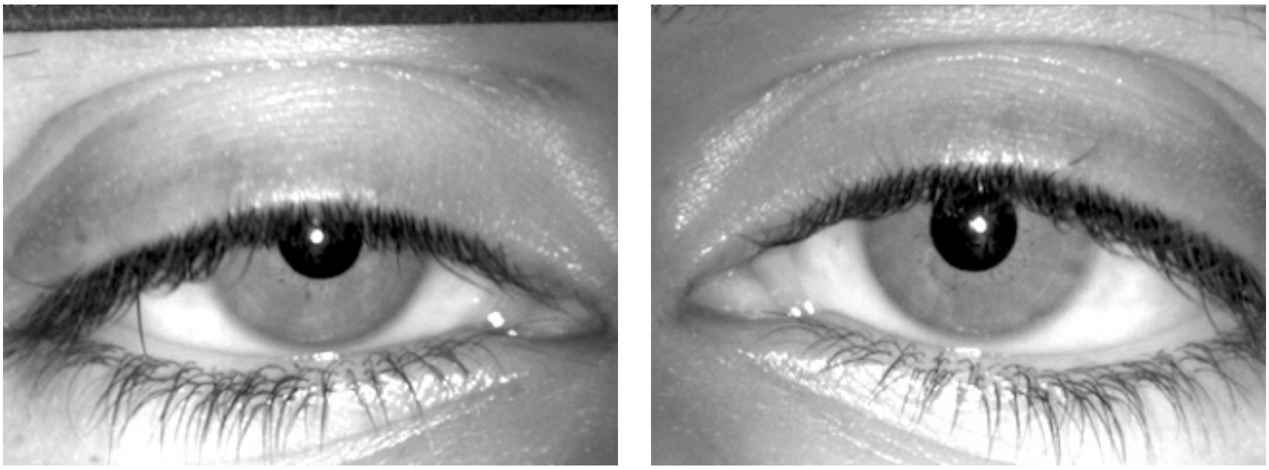
This analysis assumes the idealized "Daugman performance point" error rates. With attention to image quality at time of acquisition, and assuming that attempts at fraud are "zero-effort" attempts, error rates close to the Daugman performance point are likely achievable for a large fraction of the population. However, as discussed in a later section, there may be some persons whose iris cannot be handled successfully by current iris recognition algorithms, and those persons will experience a higher error rate. Also, if persons desiring to commit fraud use a spoof technique that is not undetected, the actual error rate will of course be higher.

Checking our experimental results against the predictions made using the idealized model in Table II reveals some differences. With 457 true Duplicate pairs in the dataset, if the idealized Daugman performance point held in our analysis, we would expect 0.99 x 0.01 x 2 x 457 = about 9 of the Duplicate pairs to end up as Contradictory results, whereas we saw 7 Duplicate pairs end up as Contradictory results. Also, some of those Contradictory results are due to special iris conditions that are discussed later. We would also expect 0.000001 x 0.999999 x 2 x 562,934 = about 1 of the true Non-Duplicate pairs to be classified as Contradictory results, whereas we saw 33. Thus we saw fewer true Duplicate pairs than expected, and more true non-Duplicate pairs than expected, classified as Contradictory. This suggests that the matcher is effectively operating at a decision point slightly different than the classic Daugman performance point.

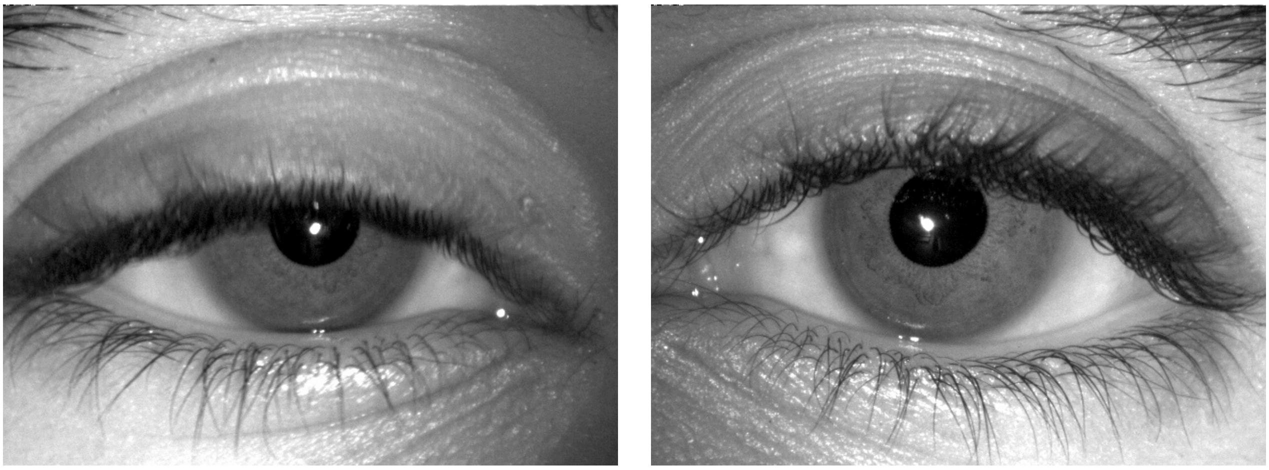
The population of Somaliland for purposes of the new voting register is likely on the order of 2 million. The number of pairs to be considered for de-duplication is then on the order of 2 trillion. If 2 trillion Non-Duplicate pairs are considered, it should be expected that about 2 Non-Duplicate pairs will get falsely labeled as Duplicate. Provision should be made to be able to correct these expected errors by some means. Fortunately, the expected number is small enough that the administrative burden to resolve them should be small.

IV. RESOLUTION OF CONTRADICTORY MATCH RESULTS

Various approaches can be taken to resolve Contradictory results from automatic matching. The approach taken in our report to the Somaliland NEC was to use forensic analysis to attempt to correctly classify each of the Contradictory results as either Non-Duplicate or Duplicate. Forensic iris image matching can be understood by analogy to fingerprint examination. Features of the iris images are considered as iris-based or non-iris-based. An example of an iris-based feature is a crypt, which appears as a darker spot on the iris. An example of a non-iris-based feature is a bright region appearing on the nasal side of the iris image, which would be a specular reflection caused by the near-IR illumination reflecting off the nose. Complications can be introduced by differences in dilation between two images. Allowances must be made for small crypts that appear in a constricted-pupil image but not in a dilated-pupil image, or dilation creases that appear in a dilated-pupil image but not in a constricted-pupil image. If (1) a number of clearly-visible, iris-based features appear in corresponding locations in two iris images, and (2) there is no instance of a clearly-visible, iris-based feature that appears in one image but not the other image, then the two images are classified as being of the same iris. If there is any significant iris-based feature that is clearly present in one image but clearly not present in the other image, then the two images are classified as being of different irises. This approach allowed us to correctly classify all 40 of the Contradictory results as either Non-Duplicate or Duplicate.



a) Iris Images R_a6f6e206-fab0-4857-b7cd-18a21df20b8e_R1 (on left) and _L1 (on right)



b) Iris Images R_25e21fce-0789-4937-88b3-b41f231e8cae_R1 (on left) and _L1 (on right)

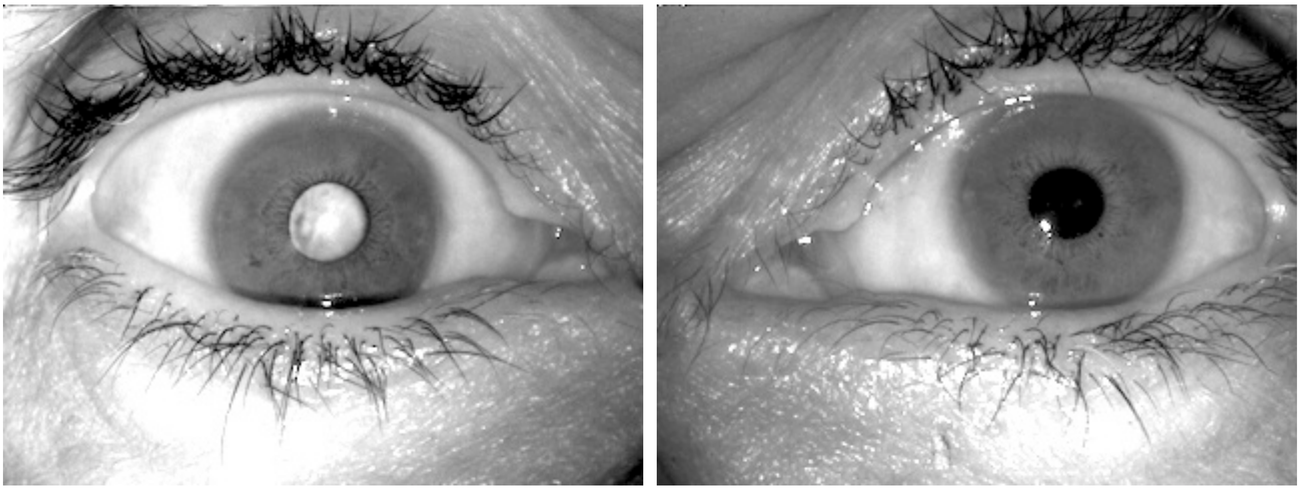
Figure 1. Example Non-Duplicate Instance With Contradictory Left and Right Iris Match Results.
The right iris images (appearing on the left) had a positive match score (62) and the left iris images (appearing on the right) had a zero score. Manual examination of image details correctly determined that the images in (a) and the images in (b) come from different persons. Images in this figure have been brightened for easier visualization.

Another approach is to resolve Contradictory results using a default fail-safe rule, as outlined previously. Given the power of automated dual-iris-agreed matching for the purpose of de-duplication, this can be a reasonable option. As explained previously, all Contradictory results could be automatically resolved as Non-Duplicates. This would minimize chances of falsely accusing someone of voter fraud. The idealized performance projection outlined in the previous section suggests that this would result in a false accusation of fraud for only about 1-in-1-trillion pairs of records considered. At the same time, an attempt at duplicate registration would have as high as a 98% chance to be detected. And because the Contradictory results are resolved automatically, there is essentially zero cost for this approach. This combination of very low rate of false accusation, low enough rate of success for attempted fraud to discourage the attempt, and low cost, may be judged to be a very practical solution for some applications.

A third approach is to "hide" the separate left and right results through some type of biometric fusion that will let one outweigh the other in an overall result. For example, at the feature level, the separate iris codes for the two eyes could be merged into a longer person-level code. A disadvantage of this approach is that many failure modes in iris recognition are specific to one of the two eyes, and this fact is hidden in the merged representation.

A fourth approach is to use an additional biometric to resolve the Contradictory results. For example, if fingerprint or face is acquired in addition to iris, then Contradictory results from iris can potentially be resolved by fingerprint or face. A disadvantage of this approach is that it incurs the cost of collecting and storing the additional biometric for all persons when it may be used for only a small fraction of the match instances.

(a) Iris images R_5875f425-9241-4454-ae9f-43a265f60c35_R1 (on left) and _L1 (on right)



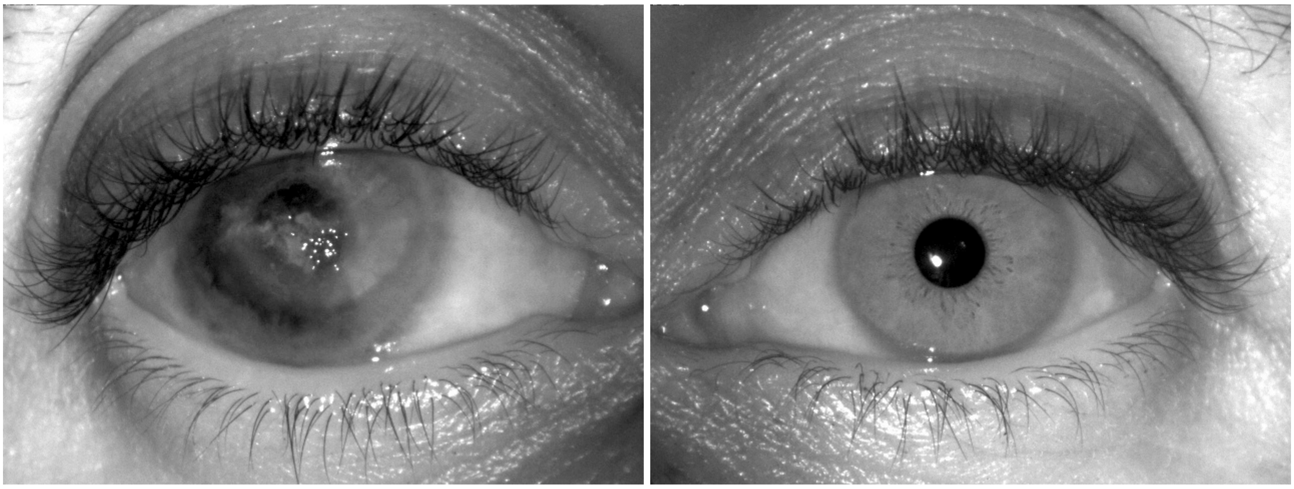
(b) Iris images R_080a5041-7446-4c62-b89c-00876f5f1da6_R1 (on left) and _L1 (on right)

Figure 2. Example of Initial "Contradictory" Result Resolved as "Duplicate" By Forensic Examination.
Automatic matching scored the left irises (appearing on the right) as a match (303) and scored the right iris images (appearing on the left) as a non-match. Note the condition in the pupil region on the right eyes; this is believed to be due to a cataract. There were three enrollments in the trial dataset corresponding to this same person. The images in this figure have been brightened to allow easier visualization in printed form.

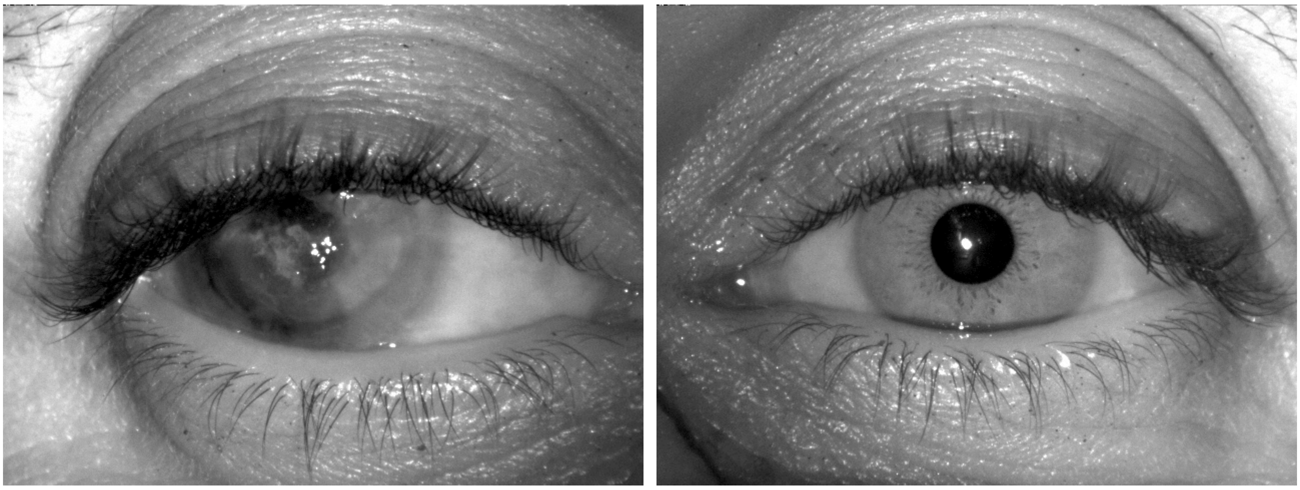
V. IRISES CAUSING CONSISTENT FALSE-NON-MATCH RESULT

The "Doddington zoo" [6] or "biometric zoo" [7,8] is a term used for the concept that individual persons fall into certain stereotypes in terms of the error rates of a biometric system. The stereotypes were originally given the names of animals such as wolf, sheep, lamb and goat. A "wolf" is a person who can impersonate other persons unusually well; that is, can pass as someone else through a false-match result. A "goat" is a person who has trouble being matched to their correct identity; that is, who often fails to verify as the correct identity due to a false-non-match result.

For any given biometric modality, a specific matcher for that modality, and a specific set of subjects whose data is acquired, there generally are individuals who can be identified as particular animals in a biometric zoo. However, a person's role in terms of the biometric zoo tends **not** to persist if the biometric modality is changed, or if the particular matcher for the modality is changed, or even if the other subjects in the dataset are changed [8]. A person who is labeled as a goat (wolf) in a face recognition study cannot be expected to also be a goat (wolf) for iris recognition. A person who is labeled as a goat in an iris recognition study cannot be expected to also be a goat if the study is repeated with the same image dataset but a different matcher. And a person who is a wolf in an iris recognition study cannot be expected to remain a wolf if another iris study is done with the same matcher but with the other subjects in the study exchanged for a different set of subjects. Thus, while the biometric zoo has been a popular



(a) Iris images R_fa609998-5890-4954-a854-f76226921693_R1 (on left) and _L1 (on right)



(b) R_45b73bb5-41de-4589-8ca2-11fa2d93c6aa_R1 (on left) and _L1 (on right)

Figure 3. Example of Initially "Contradictory" Result Resolved as "Duplicate" By Forensic Examination. Automatic matching scored the left irises (appearing on the right) as a match (320) and scored the right iris images (appearing on the left) as a non-match. Note the condition in the pupil region on the right eyes; this is believed to be due to a corneal condition. The images in this figure have been brightened to allow easier visualization in printed form.

concept in the research community, the roles have not proven persistent enough to have practical value.

However, in our forensic analysis of the Contradictory results trial voter registration dataset, we discovered that there are underlying bilogical conditions that can cause a person to almost always experience a false-non-match for their own iris images acquired at two different times. This is relevant to the voter registration problem because such a person could potentially enroll multiple times with a very low chance of this being detected.

This phenomenon was discovered in tracking down the causes for some of the Contradictory results. Examples are shown in Figures 2 and 3. In each of these, the Contradictory result coincidentally involved the left irises matching and the right irises not matching. From viewing the images, this is initially surprising, because in each example the right irises are visually highly similar. However, in both examples, the right irises also have a very unusual appearance. This turns out to be the common key to understanding these examples.

To better understand the matching results for the example irises shown in Figures 2 and 3, we used two different commercial matchers that are able to report the iris segmentation information in terms of the circular outline for the pupil-iris boundary and the iris-sclera boundary. This allows us to review how the irises in Figures 2 and 3 are segmented. We found that these irises had unusual properties that in essence caused the iris segmentation to fail in a different way on each image.

The trial dataset contains a total of three registration records for the person in Figure 2. The three different images of the same iris are shown in Figure 4 with the iris segmentation results from one commercial iris matcher shown on each image

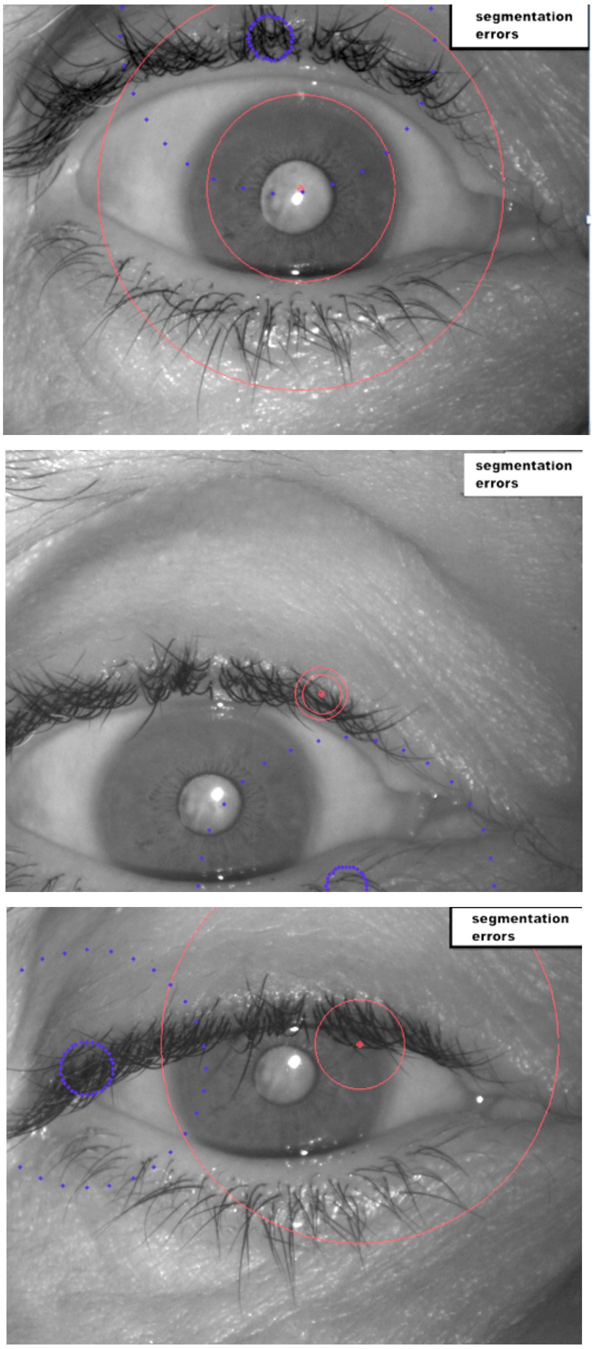


Figure 4. False Non-Match Caused By Segmentation. Images of the same iris from different registration records; Segmentation outlines from one iris matcher are shown in blue, and from a second matcher in red. Note that no two segmentations are similar.

in red, and the outlines for a different commercial matcher shown in blue. *Note that all six segmentations of the same iris are wrong, and that none of the segmentations are similar to each other!*

Consider that the pupil region in Figure 4 presents as a relatively uniform bright circular region. This runs counter to the typical assumption that the pupil region will be a darker region in a near-IR image of the iris. Thus a segmentation routine that is built on the standard assumption about the appearance of the pupil is very likely to fail. One can see suggestions in the segmentation results in Figure 4 that the algorithms were looking for relatively dark regions surrounded by relatively brighter regions.

The false non-match problem arises from the fact that commercial iris segmentation routines fail differently on each image of the iris that exhibits this condition. The segmentation failures doom the matching algorithm to produce a non-match result.

We were able to detect these unusual results because we were able to forensically review the segmentation results of the original images. But if a person had such unusual eye conditions in both eyes, they could give multiple pairs of iris images that would all be categorized as Non-Duplicate in the automated matching stage. And for some approaches to resolving Contradictory results, simply having one eye with such an unusual condition would be enough to create an eventual Non-Duplicate result.

It should be possible to detect inherent false-non-match irises at acquisition time. The key is that, at the time of acquisition, a person acquires multiple images based on separate presentations of the iris. These images should match well for the iris to be accepted for enrollment. This should effectively detect persons wearing textured contact lenses as well as the sorts of iris conditions seen in Figures 2 and 3.

VI. Conclusions and Discussion

The results of the iris recognition analysis performed on the Somaliland trial voter registration dataset gave the Somaliland National Electoral Commission the confidence to begin the process of creating a new national ID and voter registration system. An official tender for purchase of the relevant biometric and computing technology was published on the Somaliland NEC web site [9].

Since the tender was first released in 2014, the terms of the NEC members expired and a new NEC was appointed. The new NEC may re-open the process of conducting a new voter registration.

Our work shows that forensic matching of iris images is a feasible step that can accurately resolve contradictory cases that result from automatic iris matching. Automatic iris recognition applied to the Somaliland trial voter registration dataset resulted in 40 instances of contradictory results. These 40 instances were then categorized by forensic examination as either Duplicate or Non-Duplicate with 100% accuracy.

Additionally, this work has documented the existence of two different eye conditions that effectively cause a random catastrophic failure in the iris segmentation stage of current commercial iris matchers. Such irises inherently produce a false non-match result with high frequency. We conjecture that such irises can be detected at the time of acquisition by using a multi-trial acquisition protocol. Given that two different novel cases were found in the relatively small trial dataset representing 663 different persons (373 having two records, 24 having three records, and 2 having 4 records), it is possible, even likely, that other novel cases will be encountered in the full new Somaliland voter registration.

The nature of the catastrophic segmentation failures also suggests the need for iris segmentation algorithms to be developed that perform a check on the reasonableness of the segmentation result. The general "hypothesize and verify" paradigm for detecting objects in images is an old approach in computer vision (e.g., [10]), and could lead to improved segmentation results and recognition of failed segmentations.

Cosmetic, or "textured", contact lenses are often thought of asa means to intentionally create a false-non-match result in iris recognition [11,12]. In our initial review of the Somaliland dataset for image quality, we also looked for instances of cosmetic contact lenses. We did not detect a single instance of a person wearing consmetic contact lenses.

ACKNOWLEDGMENT

The authors would like to thank Roy Dalle Vedove and the Somaliland National Electoral Commission for the opportunity to work on this project. Commercial products named in this paper are identified for purposes of providing more complete technical detail; no specific endorsement is intended. The authors have no commercial interest in any product or company mentioned in this paper.

REFERENCES

[1] Somaliland government web page. http://somalilandgov.com/

[2] D. Mathieson and R. Wager, Somaliland National Election Commission: Report on the Preparation of the Voter Register January to June, 2010 (Version 1.2), 10th Sept. 2010.

[3] A. Gelb and J. Clark, Identifcation for Development: The Biometrics Revolution, Center for Global Development Working Paper #315, January 2013. www.cgdev.org

[4] Neurotechnology VeriEye SDK, http://www.neurotechnology.com/verieye.html.

[5] K McGinn, S. Tarin and K. W. Bowyer, Identity Verification Using Iris Images: Performance of Human Examiners, *IEEE International Conference on Biometrics: Theory, Applications and Systems*, 2013.

[6] G. Doddington, W. Liggett, A. Martin, M. Przybocki and D. Reynolds, "Sheep, Goats, Lambs and Wolves: A Statistical Analysis of Speaker Performance in the NIST 1998 Speaker Recognition Evaluation," *Proc. of International Conference on Spoken Language Processing* (ICSLP), 1998, pp. 1351-1354.

[7] N. Yager and T. Dunstone, "The Biometric Menagerie", *IEEE Transactions on Pattern Analysis and Machine Intelligence* 32 (2), Feb. 2010, pp. 220-230.

[8] J. Paone and P.J. Flynn, "On the consistency of the biometric menagerie for irises and iris matchers", 2011 IEEE International Workshop on Information Forensics and Security (WIFS).

[9] Somaliland National Electoral Commission, Tender for the Supply of Voter Registration Equipment / Materials and Software, 5 August 2014. http://www.necsomaliland.com/

[10] Frederic Jurie, "Robust Hypothesis Verification: Application to Model-Based Object Recognition", Pattern Recognition 32 (6), June 1999, pp. 1069-1081.

[11] K. W. Bowyer and J. S. Doyle, Cosmetic Contact Lenses and Iris Recognition Spoofing, *IEEE Computer* 47 (5), 96-98, May 2014.

[12] D. Yadav, N. Kohli, J. S. Doyle, R. Singh, M. Vatsa and K. W. Bowyer, Unraveling the Effect of Textured Contact Lenses on Iris Recognition, *IEEE Transactions on Information Forensics and Security* 9 (5), 851-862, May 2014.