



MASK SPOOFING IN FACE RECOGNITION AND COUNTERMEASURES

Neslihan Kose, Jean-Luc Dugelay

► To cite this version:

Neslihan Kose, Jean-Luc Dugelay. MASK SPOOFING IN FACE RECOGNITION AND COUNTERMEASURES. Image and Vision Computing, 2014, 32 (10), pp.779-789. 10.1016/j.imavis.2014.06.003 . hal-03906926

HAL Id: hal-03906926

<https://hal.science/hal-03906926>

Submitted on 19 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

MASK SPOOFING IN FACE RECOGNITION AND COUNTERMEASURES

Neslihan Kose, *Student Member, IEEE*, Jean-Luc Dugelay, *Fellow, IEEE*
Multimedia Department EURECOM Sophia-Antipolis France

Abstract

In this paper, initially, the impact of mask spoofing on face recognition is analyzed. For this purpose, one baseline technique is selected for both 2D and 3D face recognition. Next, novel countermeasures, which are based on the analysis of different shape, texture and reflectance characteristics of real faces and mask faces, are proposed to detect mask spoofing. In this paper, countermeasures are developed using both 2D data (texture images) and 3D data (3D scans) available in the mask database. The results show that each of the proposed countermeasures is successful in detecting mask spoofing, and the fusion of these countermeasures further improves the results compared to using a single countermeasure. Since there is no publicly available mask database, studies on mask spoofing are limited. This paper provides significant results by proposing novel countermeasures to protect face recognition systems against mask spoofing.

Keywords: spoofing, mask attacks, countermeasure, face recognition

Email address: neslihan.kose@eurecom.fr, jean-luc.dugelay@eurecom.fr
(Neslihan Kose, *Student Member, IEEE*, Jean-Luc Dugelay, *Fellow, IEEE*)

1. INTRODUCTION

In a spoofing attempt, a person tries to masquerade as another person and thereby, tries to gain access to recognition system. Face recognition is used in domains such as surveillance and access control. Since face data can be acquired easily in a contactless manner, spoofing is a real threat for face recognition systems.

The most common spoofing attacks are photograph and video attacks due to their convenience and low cost. Based on the observations that 2D face recognition (FR) systems are vulnerable to these attacks, researchers started to work on countermeasures to reduce their impact on recognition performances.

Proposed countermeasures against photo and video attacks are mainly based on liveness detection, motion analysis and texture analysis. Countermeasures based on liveness detection examine movements such as eye blinking [24] or lip movements [9]. In the literature, there are several countermeasures based on motion analysis [4, 22]. These countermeasures rely on the fact that the movement of a 2D plane is different compared to the movement of a 3D object. In [4], under the assumption that the test region is a 2D plane, the authors obtain a reference field from the actual optical flow field data. Then the degree of differences between the two fields is used to distinguish between a 3D face and a 2D photograph. In [22], a set of facial points are located automatically and their geometric invariants are used to detect attacks. The last

23 group is countermeasures based on texture analysis. In [3] and [19], images
 24 are examined to find printing artifacts and blurring, respectively. In [14], dif-
 25 ferent contrast and texture characteristics of photographs and real faces are
 26 analyzed to detect spoofing. Furthermore in [20, 21], micro-texture analysis
 27 is proposed to detect 2D attacks. The study [7] includes brief information
 28 about different types of 2D face countermeasures, which were developed for
 29 a competition on countermeasures against 2D facial spoofing attacks. Six
 30 teams participated to this competition. These teams are AMILAB, CASIA,
 31 IDIAP, SIANI, UNICAMP and UOULU. All teams used one or multiple
 32 clues obtained clearly from motion analysis, texture analysis and liveness
 33 detection. The CASIA team presented a method with the combination of
 34 motion and texture analysis techniques, and the method also allows switch-
 35 ing between detection schemes based on the scene context. The AMILAB
 36 and the UNICAMP teams used all motion analysis, texture analysis and live-
 37 ness detection in deriving the detection scheme. IDIAP and UOULU used
 38 texture analysis method and obtained zero percent Equal Error Rate (EER)
 39 on development set and zero percent Half Total Error Rate (HTER) on test
 40 set. This leads to the conclusion that, the attack videos in the database used
 41 for this competition (i.e. PRINT-ATTACK Database [26]) mainly consist of
 42 detectable texture patterns.

43 When 3D masks are introduced as attacks, some of the countermeasures
 44 proposed for the detection of 2D attacks are no longer applicable. The study
 45 of Kollreider et al. [13] shows that a face recognition system relying on eye

46 blinking and lip movements can be defeated by using photographic masks
47 wrapped over face with eyes and mouth regions cut out. Also, since motion
48 based countermeasures depend on different movements of 2D and 3D surfaces,
49 they are not applicable when masks are used instead of photos or videos. It
50 appears that the detection of 3D mask attacks is more challenging compared
51 to the detection of 2D facial attacks.

52 3D mask attacks to FR systems is a considerably new subject. The main
53 reason for the delay in mask spoofing studies is due to the unavailability of
54 public mask databases. To our knowledge, in the literature, there are two
55 countermeasure studies against 3D mask attacks [11, 29] excluding our stud-
56 ies. These two studies are based on reflectance analysis. They utilize 2D data
57 (texture images) in their approach to detect 3D mask attacks. Kim et al.
58 [11] exploit the reflectance disparity based on albedo between real faces and
59 mask materials (silicon, latex or skinjell). The feature vector, which is used
60 in their approach for mask detection, consists of radiance measurements of
61 the forehead region under 850 and 685 nm illuminations. They report 97.78%
62 accuracy for mask detection. In [11], the experiments are done directly on
63 the mask materials not on the real facial masks. Thus, it is not possible to
64 report spoofing performances of the masks used. The measurements are done
65 at exactly 30 cm and on the forehead region for mask detection. The require-
66 ment for an exact distance and occlusion possibility in the forehead during
67 the measurements are the limitations of this method. In [29], multi-spectral
68 reflectance analysis is proposed. After measuring the albedo curves of facial

69 skin and mask materials with varying distances, two discriminative wave-
 70 lengths (850 and 1450 nm) are selected. Finally, a Support Vector Machine
 71 (SVM) [8] classifier is used to discriminate between real and fake samples.
 72 Experiments are conducted on a database of 20 masks from different materi-
 73 als (4 plastic, 6 silica gel, 4 paper pulp, 4 plaster and 2 sponge). The results
 74 show that this method can achieve 89.18% accuracy. The superiorities of
 75 [29] compared to [11] are the elimination of range limitation and the usage
 76 of real facial masks. However, spoofing performances of the masks are still
 77 not reported. In order to contribute to this compelling research problem and
 78 fill the missing portions of the existing studies, we have proposed several
 79 countermeasure techniques against 3D mask attacks in [15], [18] and [17].

80 The spoofing performances of the masks used and the countermeasure
 81 which uses 3D data (3D scan) instead of 2D data (texture image) as input
 82 to detect mask spoofing were first analyzed in our previous studies [16, 15],
 83 respectively, using the mask database which was prepared within the context
 84 of the European Union (EU) research project TABULA RASA [28]. The
 85 mask database used in the present study and our previous studies [15, 16,
 86 18, 17] was created by MORPHO [23]. This database includes many high-
 87 quality mask samples. It consists of 3D masks of 16 real subjects. The scans
 88 of subjects were acquired by a 3D scanner, and the masks were manufactured
 89 using a 3D printer. In addition to texture images, it includes 3D scans for
 90 both real and mask samples. Thanks to the nature of this database, we
 91 were able to evaluate the impact of mask spoofing on both 2D and 3D face

92 recognition, and to develop our countermeasures using both 2D and 3D data.
 93 If a 3D mask is not able to spoof a recognition system, it is not a suc-
 94 cessful attack, and there is no need to develop a countermeasure against it.
 95 Therefore, in [16], we analyzed how well the spoofing performances of the
 96 masks used in our studies are. The results of this study show that the masks
 97 used have very similar texture and especially 3D face shape characteristics to
 98 their target faces. They are very successful to spoof face recognition systems.
 99 To the best of our knowledge, spoofing performances of the masks used were
 100 the first to be analyzed in this study. In [15], we proposed to apply micro-
 101 texture analysis on both texture and depth images, and obtained 88.12%
 102 and 86% accuracy, respectively, for the classification of mask and real faces.
 103 The novelty of this work is that it was the first time 3D data was utilized
 104 to discriminate mask and real samples. In our next study [18], which is the
 105 continuation of [15], we studied fusing the information extracted from both
 106 the texture and depth images, and obtained a higher classification accuracy
 107 of 93.5%. In addition to the increase in performance, it was the first time the
 108 performances of face recognition systems were analyzed with/without mask
 109 attacks and with/without the proposed countermeasure integrated to the
 110 recognition systems in [18]. By this way, it is possible to observe the positive
 111 impact of countermeasure on recognition performances in presence of mask
 112 attacks. Finally, in [17], we proposed a countermeasure based on reflectance
 113 analysis using the texture images in the same database. We obtained 94%
 114 classification accuracy in [17], which was the best score we had obtained so

115 far.

116 In this paper, after showing the impact of attacks on the selected recog-
117 nition systems; we provide an overview on our spoofing detection approaches
118 which were introduced in the studies [15], [18] and [17]. We extend the
119 works explained in these studies with some improvements, additional analy-
120 sis, comparisons of performances of diverse countermeasures using the same
121 protocol, and with a detailed analysis of the fusion scenarios. Additionally, a
122 novel countermeasure is proposed in the present paper. In [15], micro-texture
123 analysis is applied on texture images, whereas in this paper, we apply micro-
124 texture analysis on reflectance components of texture images as a new coun-
125 termeasure. We observe that higher accuracy is obtained using reflectance
126 component instead of texture image (original image) itself. This proves that
127 reflectance image provides more appropriate information than original im-
128 age to discriminate mask and real samples. In the present study, we obtain
129 98.99% classification accuracy, which is the best accuracy that have been re-
130 ported in the literature for mask spoofing detection up to now. Also, in the
131 present paper, we integrate the countermeasure with the best performance
132 to the selected 3D FR system in order to show the positive impact of the
133 countermeasure on the system under mask attacks, directly.

134 The paper is organized as follows: Section 2 gives brief information on the
135 mask database which is used in this study. Section 3 presents the selected 2D
136 and 3D FR systems, and then evaluates the impact of mask spoofing on these
137 systems. Section 4 gives brief information about the techniques that were

138 used to develop the proposed countermeasures. Section 5 explains each of
139 the proposed countermeasures. Section 6 shows the experiments and results
140 of all the proposed countermeasures together with the fusion scenarios for
141 comparison purposes. Finally, conclusions are provided in Section 7.

142 2. THE MASK DATABASE

143 A mask used for 3D face spoofing purposes has to show very similar
144 3D shape characteristics to the target face to be considered as a successful
145 attack. The mask database used in this study was prepared to fulfill this
146 objective. Initially, scans of the subjects in the mask database were taken
147 by a 3D scanner which uses a structured light technology in order to obtain
148 similar face shape characteristics to the target person. Then the 3D model
149 (3D mesh) of each subject was sent to a 3D printer and the masks were
150 manufactured by Sculpteo 3D Printing [27]. The material used for the masks
151 is polychrome mineral powder, which is a 3D printing standard.

152 The mask database is 2D+3D. For the sake of clarity, the database of real
153 faces in 2D and 3D will be referred as DB-r2 and DB-r3, while the database
154 of mask attacks will be referred as DB-m2 and DB-m3 in the rest of this
155 paper.

156 In the mask database, 20 subjects appear in total. The masks were
157 manufactured for 16 of these subjects. For DB-r, an average of 10 scans
158 of each subject were acquired. For DB-m, an average of 10 scans of each
159 subject wearing either his/her own mask or masks of the other subjects that



Figure 1: Example from the mask database which is created by [23]. From left to right (upper row) The real face, the cropped texture image, the 3D scan after preprocessing, the cropped depth map estimated from the raw 3D scan (lower row) same images for the corresponding mask attack.

160 appear in the same database were acquired. Finally, 200 real face acquisitions
 161 from 20 subjects and 198 mask acquisitions from 16 masks are used for the
 162 evaluations of this study. Figure 1 shows one example from this database for
 163 a real face access and the corresponding mask attack access.

164 In the mask database, DB-r and DB-m are partitioned in train and test
 165 sets. 8 subjects out of 16 subjects whose masks are manufactured, and 2
 166 subjects out of 4 subjects whose masks are not manufactured are selected
 167 for DB-r. The samples of the selected subjects are assigned to the test set of
 168 DB-r, while the rest is used for the train set of DB-r. For DB-m, the mask
 169 attack accesses to the corresponding identities in the test set of DB-r are
 170 involved in the test set of DB-m, while the rest is used for the train set of
 171 DB-m. There is no overlap between the train and test sets, which makes the
 172 spoofing detection more challenging. Finally, there are 100 samples in each
 173 of the client (real accesses) test and train sets, and 99 samples in each of the

174 impostor (mask attack accesses) test and train sets.

175 **3. IMPACT ANALYSIS OF MASK SPOOFING ON FACE RECOG-** 176 **NITION**

177 In this section, initially, we explain the pre-processing applied for the
178 selected 3D and 2D FR techniques. Next, we give the details about these
179 recognition techniques. Finally, we evaluate the impact of spoofing mask
180 attacks on both 3D and 2D face recognition.

181 *3.1. Pre-Processing for the Selected Face Recognition Systems*

182 The pre-processing for the selected 3D FR system is based on the method
183 given in [10]. In order to crop the face region, the tip of the nose is detected,
184 and the facial surface is cropped by a sphere with radius 80 mm, centered 10
185 mm away from the nose tip in +z direction. Note that the face looks towards
186 +z direction. Next, the spikes are removed by thresholding, and then a hole
187 filling procedure is applied. Finally, a bilateral smoothing filter is used to
188 remove white noise while preserving edges. These pre-processed 3D scans
189 (only shape, without texture) are used as input for 3D face recognition.

190 For 2D face recognition, the texture images in the mask database are
191 cropped as shown in Figure 1, and resized into 64×64 images. In this study,
192 we aim to show first how vulnerable the systems are to spoofing mask attacks
193 by evaluating the performances of the selected systems with/without attacks,
194 and then how a countermeasure improves the performance in presence of

mask attacks by evaluating the performances of these systems with/without countermeasure. For micro-texture analysis applied inside the proposed countermeasures, which is explained in Section 4, images are resized into 64×64 as proposed in [20]. Thus, although this resizing parameter may reduce the baseline performance in 2D, since our aim in this study is not to report high baseline performance, we preferred to use the same images as input for both the 2D baseline evaluation and proposed countermeasures.

Figure 1 shows an example for the texture images and 3D scans which are used in 2D and 3D evaluations, respectively.

3.2. Selected Face Recognition Systems

The 3D FR system selected as baseline for this study is introduced in [10]. It is also selected as baseline system in TABULA RASA project [28]. It uses the pre-processed 3D mesh of the face as input. Three landmark points are previously annotated at the nose tip and outer eye corners for each sample in the database. Initially, a linear transformation is computed in a least squares sense (LSS), based on two sets of landmarks (landmarks of generic model and subject’s face). Least squares means that the overall solution minimizes the sum of the squares of the errors made in the results of every single equation. The best fit in the LSS here is calculated by minimizing the squared distance between the point sets of generic model and subject’s face. For this purpose, the obtained transformation that includes rotation, translation and isotropic scaling is applied onto the generic model, aligning it

217 with the subject's face. Next, the alignment is further improved by Iterative
 218 Closest Point (ICP) method [5]. Afterwards, 140 previously selected points
 219 on the generic model are coupled with the closest vertices on the face under
 220 analysis, and Thin Plate Spline (TPS) [6] warping is applied on the generic
 221 model resulting in warping parameters (WP) of size 140×3 . WPs that
 222 represent the deviations from the common structure are given to the classifier
 223 for recognition. Finally, the distance between two face models is computed
 224 by taking the median of cosine distances between the corresponding feature
 225 vectors (WP), and recognition rates are computed. Figure 2 shows the feature
 226 extraction scheme on a sample model using this method, which is named WP.

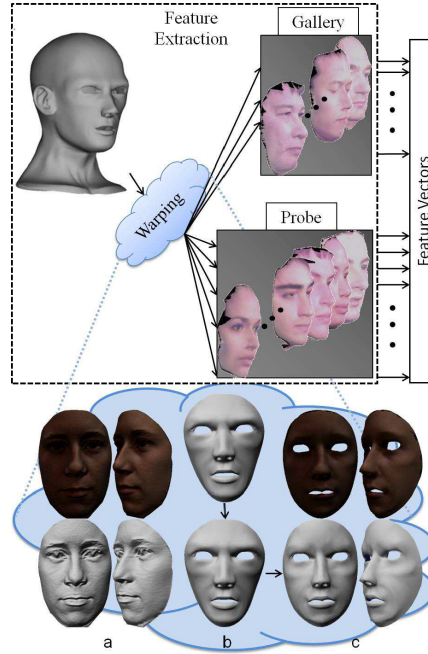


Figure 2: The feature extraction scheme and an illustration on a sample model: (a) The subject's face with and without texture (b) generic model before and after alignment (c) generic model after warping with and without texture. This figure is taken from [10].

227 For 2D face recognition, Local Binary Patterns (LBP) [1] is selected as
 228 baseline. The success of LBP in face description is due to the discriminative
 229 power, computational simplicity of the operator, and its robustness to mono-
 230 tonic gray scale changes caused by, for example, illumination variations. The
 231 use of histograms as features also makes the LBP approach robust to face
 232 misalignment and pose variations to some extent. For 2D FR, we use the
 233 operator $LBP_{8,2}^{u2}$ on 8×8 blocks. The similarity between each image pair is
 234 computed with chi-square distance metric. Performances are evaluated using
 235 the similarity scores between image pairs.

236 3.2.1. *Evaluation on 2D and 3D Face Recognition*

237 In this part, the evaluations are done for 2 modes. The first mode is
 238 the baseline mode: a standard biometric system with no spoofing and no
 239 countermeasure. The baseline performance is evaluated using DB-r. Perfor-
 240 mance is evaluated by verification all vs. all. Access from every identity in
 241 DB-r is tested against all other models in DB-r. The performance is mea-
 242 sured by observing the rate of users rejected when authenticating against
 243 their own template (False Rejection Rate - FRR) and by the rate of users
 244 accepted when authenticating against someone else's template (False Accep-
 245 tance Rate - FAR). The second mode is the evaluation of FR systems under
 246 mask attacks (baseline under attacks in Figure 3). Both DB-r and DB-m
 247 are used. When spoofing attacks are applied, performance is expected to
 248 degrade. In this mode, the FAR corresponds to the rate of attacks that are

249 accepted by the system when spoofed. The FRR corresponds to the rate of
 250 real-access attempts that are incorrectly dismissed by the system as attacks.

251 For the evaluations regarding 2D and 3D FR systems here, only test set
 252 is used. Train set is used for classifier training inside the proposed counter-
 253 measures. Figure 3 shows the behavior of the 3D and 2D baseline systems
 254 with/without attacks. All results are presented in terms of detection error
 255 trade-of (DET) profiles which illustrate the behavior of a system as the de-
 256 cision threshold is changed, i.e. how the false rejection rate varies according
 257 to the false acceptance rate.

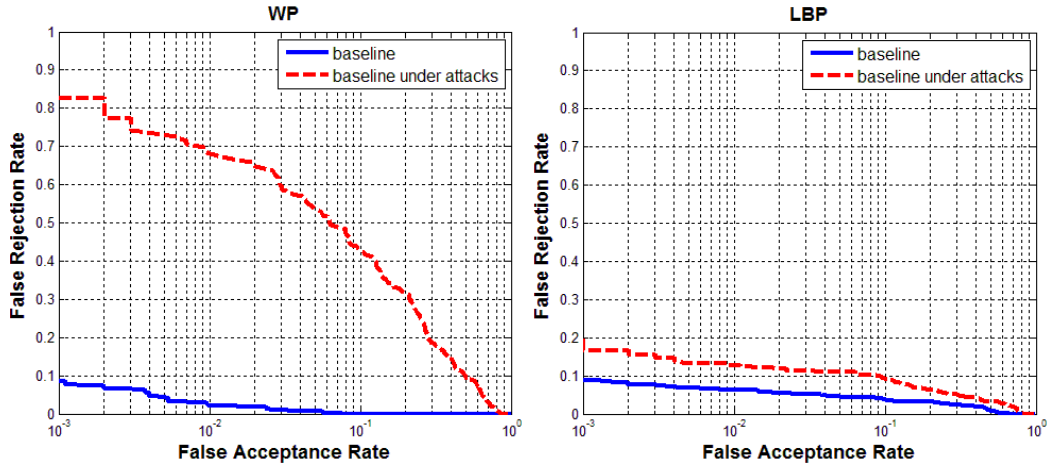


Figure 3: The DET Curves of the 3D and 2D face baseline biometric system with/without mask attacks, respectively.

258 Figure 3 shows that:

- 259 • Although the mask attacks are successful to spoof both 2D and 3D
 260 FR systems, the 3D FR system is more vulnerable to mask attacks
 261 compared to the 2D FR system (area between red and blue curves is

- 262 much more for 3D compared to 2D FR system).
- 263 • Equal Error Rate (EER) at the baseline mode increases from 1.8% to
264 25.1% for 3D and from 4.7% to 9.9% for 2D FR system under attacks.
 - 265 • 3D shape characteristics of a real face and corresponding mask at-
266 tack are more similar compared to their texture characteristics. Hence,
267 analysis on texture may reveal more information to detect mask attacks
268 compared to analysis on 3D shape characteristic.
 - 269 • Robustness against mask spoofing is observed to be both method and
270 modality dependent as also concluded in [16].
 - 271 • FR systems are vulnerable to spoofing mask attacks hence, counter-
272 measures are necessary to reduce their impact on face recognition.

273 For the baseline mode evaluations, we used the test set of DB-r, which
274 contains 100 real samples from 10 subjects. In this study, we also report
275 the baseline performances of the selected systems on the Face Recognition
276 Grand Challenge Database (FRGC) v1.0 [25] database in order to check
277 if the selected systems still provide satisfactory baseline performances with
278 more number of subjects. The scans of the subjects in the mask database
279 were acquired with a high quality laser scanner (technology of MORPHO).
280 The FRGC database was also prepared using the high quality laser scanner
281 Minolta. Therefore, the scan quality in the FRGC is quite similar to the scan
282 quality in our mask database. Furthermore, FRGC v1.0 includes 943 samples

from 275 subjects and more challenging compared to the DB-r of the mask database. Table 1 shows the EER, verification rate at 0.001 FAR and rank-1 identification rates computed with the selected systems using both the mask database (the DB-r of the mask database) and the FRGC database.

Table 1: EER, Verification Rate at 0.001 FAR and Rank-1 Identification Rate (IR) for the 3D and 2D baseline systems using the Mask Database (MD) and the FRGC Database.

Techniques	WP		LBP	
	(MD)	(FRGC)	(MD)	(FRGC)
EER (%)	1.79	2.41	4.68	2.96
VR at 0.001 FAR (%)	91.33	87.70	90.89	90.03
IR (%)	100	94.01	98.89	94.50

Table 1 shows that slightly better performances are obtained in terms of identification and verification using the mask database compared to the ones obtained using the FRGC. For each FR technique, EER computed for the two databases are quite similar. Although there is a high increase in the number of subjects/samples when the FRGC is used for the evaluation, the performances of the selected baseline systems on the FRGC are still satisfactory, even quite similar to the results obtained using the mask database. These results show that the selected systems provide significant performances hence they are appropriate for this study, and the number of subjects/samples in the mask database is sufficient enough to obtain consistent results in this study.

298 4. TECHNIQUES USED INSIDE THE PROPOSED COUNTER- 299 MEASURES

300 Mask attack is a 3D attack that can be used to spoof both 2D and 3D
301 FR systems. Most of the existing 3D scanners do not provide only 3D scan,
302 they also capture texture image. Figure 1 shows an example for the two
303 outputs of a scanner. Thus, when there is only one camera for 2D and one
304 scanner for 3D FR system, a countermeasure which uses texture images as
305 input can be used to protect both 2D and 3D FR systems if texture images
306 are provided as default output of a scanner. In the present study, we propose
307 four countermeasures against 3D mask attacks, which use either the depth
308 maps or texture images as input (Figure 5).

309 In this section, we first explain the pre-processing applied for the proposed
310 countermeasures. Then, we give a detailed information about the techniques
311 that were used to develop the proposed countermeasures.

312 4.1. *Pre-Processing for the Countermeasures*

313 There are slight alignment differences between faces in the mask database.
314 For the countermeasures, initially, all 3D faces in DB-r3 and DB-m3 are
315 aligned to a generic face using LSS alignment, which makes the alignment of
316 all faces identical.

317 In this study, we want to benefit from the information that the mask
318 surface is smoother than the real face surface to detect mask attacks. There-
319 fore, the depth maps are estimated from the raw aligned 3D scans. Next, 2D

cropping is applied to extract face region from both the texture images and depth maps. Then all images are resized into 64×64 grayscale image.

In our previous studies [15, 17], we used normalized images. We notice that normalization has a positive impact in performances when the countermeasure is applied on depth maps, whereas it reduces performances slightly when applied on texture images. In the present paper, we did not apply normalization, and we improved our cropping code compared to the ones used in our previous studies. The final version of the texture images and depth maps used for the proposed countermeasures are shown in the second and fourth columns of Figure 1, respectively.

4.2. The Variational Retinex Algorithm

In the present paper, the image is decomposed into reflectance and illumination components using the variational retinex algorithm explained in the studies [2, 12].

In this subsection, we first give information about minimizing energy functions. Then, we explain the variational retinex algorithm [2, 12].

4.2.1. Minimizing Energy Functions

The concept of minimizing the energy of a given system is used in image processing. Minimizing energy functions often includes solving partial differential equations, more specifically, Euler-Lagrange differential equations.

In the Euler-Lagrange problem, we usually have a continuous real-valued function $y = f(x)$ with continuous derivative $y' = df/dx$. Considering x, y ,

342 and y' as three independent variables, a new function $g(x, y, y')$ is defined.
 343 Using this function, the energy function is defined as: $E = \int g(x, y, y')dx$.
 344 The energy function E has a minimal value if Euler-Lagrange equation:

$$\frac{\partial g}{\partial y} - \frac{\partial}{\partial x} \left(\frac{\partial g}{\partial y'} \right) = 0 \quad (1)$$

345 is satisfied. The left hand side of this equation is denoted as ∇E . Here f is
 346 introduced as a function of one independent variable x , the same concept is
 347 applied when f is a function of n independent variables: $x_1, x_2, \dots, x_n$. In
 348 particular, when $u = f(x, y)$, function of two independent variables x and y ,
 349 Euler- Lagrange equation becomes:

$$\nabla E = \frac{\partial g}{\partial u} - \frac{\partial}{\partial x} \left(\frac{\partial g}{\partial u_x} \right) - \frac{\partial}{\partial y} \left(\frac{\partial g}{\partial u_y} \right) = 0 \quad (2)$$

350 The variational retinex algorithm is developed by defining and minimizing
 351 an energy function.

352 4.2.2. The Variational Retinex Algorithm

353 An image can be considered as a two dimensional function $S(x, y)$, where
 354 (x, y) denotes a pixel on the image. The value of the function $S = S(x, y)$
 355 represents the intensity of the light at the pixel (x, y) . As stated in [2], the
 356 intensity S may be characterized by two components which are;

- 357 • the amount of source illumination falling on the object, the illumination
 358 component $L(x, y)$.

359 • the amount of illumination reflected by the object, the reflectance com-
 360 ponent $R(x, y)$.

361 $S(x, y)$ is computed using the illumination and reflectance components as
 362 shown in Eq. (3).

$$S(x, y) = L(x, y) \times R(x, y) \quad (3)$$

363 In [2], it is stated that if images are assumed to be composed of illumina-
 364 tion and reflectance components, generating the retinex effect means being
 365 able to separate one component from another. A first step taken by most
 366 algorithms in such sort of problems is the conversion to the logarithmic do-
 367 main by $s = \log(S)$, $l = \log(L)$, and $r = \log(R)$. In the logarithmic domain
 368 the relation between these three images becomes: $s = l + r$.

369 In [12], Kimmel et al. make the following assumptions:

- 370 1. The logarithmic illumination l varies spatially smoothly.
- 371 2. The logarithmic reflectance r consists of constant or smooth parts and
 372 discontinuous jump parts.
- 373 3. l is greater than or equal to the logarithmic intensity s ($l \geq s$).
- 374 4. l is close to s (i.e. l does not deviate far away from s).

375 Based on the assumptions listed above, in the studies [2, 12], the energy
 376 function is defined as follows:

$$E(l) = \int (|\nabla l|^2 + \alpha(l - s)^2 + \beta|\nabla(l - s)|^2) dx dy \quad (4)$$

377 where α and β are positive constants. Since S is the given image, s here is
 378 constant. In this equation;

- 379 • The first penalty term ($|\nabla l|^2$) forces spatial smoothness on l .
- 380 • The second penalty term $(l - s)^2$ forces a proximity between l and s .
 381 The difference between these images is exactly r , which means that the
 382 norm of r should be small. Simultaneously, it forces the solution l to
 383 be $l \geq s$. In [12], it is stated that in practice this term should be weak
 384 enough not to attract l down too much towards s . This is why the
 385 parameter α should be very small.
- 386 • The third term forces r to be spatially smooth. In [12], it is stated
 387 that the parameter β should be a very small value to preserve the
 388 discontinuous jumps of r . Note that spatially smooth r contradicts
 389 spatially smooth l since $r + l = s$. However in practice adding this
 390 penalty term kicks in mainly on sharp edges and handles situations
 391 where the illumination is not smooth (as well as cases of direct light
 392 sources and specularities).

393 The integrand of this energy function is:

$$\begin{aligned}
 g(l, l_x, l_y) &= |\nabla l|^2 + \alpha(l - s)^2 + \beta|\nabla(l - s)|^2 \\
 &= (l_x^2 + l_y^2) + \alpha(l - s)^2 + \beta((l_x - s_x)^2 + (l_y - s_y)^2)
 \end{aligned}
 \tag{5}$$

394 Euler-Lagrange equation becomes:

$$\begin{aligned}
\nabla E &= \frac{\partial g}{\partial l} - \frac{\partial}{\partial x} \left(\frac{\partial g}{\partial l_x} \right) - \frac{\partial g}{\partial y} \left(\frac{\partial g}{\partial l_y} \right) \\
&= 2\alpha(l - s) - \frac{\partial}{\partial x} (2l_x + 2\beta(l_x - s_x)) - \frac{\partial}{\partial y} (2l_y + 2\beta(l_y - s_y)) \\
&= 2\alpha(l - s) - 2l_{xx} - 2\beta(l_{xx} - s_{xx}) - 2l_{yy} - 2\beta(l_{yy} - s_{yy}) \\
&= 2[\alpha(l - s) - \Delta l - \beta\Delta(l - s)] \\
&= 0
\end{aligned} \tag{6}$$

395 which means $\alpha(l - s) - \Delta l - \beta\Delta(l - s) = 0$. In [2], to solve this equation, the
396 idea of the steepest descent is applied with an auxiliary variable t :

$$\frac{dl}{dt} = -\nabla E = \Delta l + \beta\Delta(l - s) - \alpha(l - s) \tag{7}$$

397 To find a local minimum of a function using steepest descent, one takes
398 steps proportional to the negative of the gradient of the function at the
399 current point. In our evaluation, l is computed via steepest descent as follows:

$$l_n = l_{n-1} - dt \cdot \nabla E \tag{8}$$

400 Finally, projecting onto the constraint $l \geq s$ is done by $l_n = \max(l_n, s)$.

401 In our experiments, the values 0.0001 and 0.1 are used for α and β ,
402 respectively, as suggested in [2, 12]. The initial value of l (l_0) is taken as
403 s . The step size dt and the total number of iterations are selected as 0.05
404 and 5000, respectively. After the iterations, optimum l is obtained, and

405 r is computed from $r = s - l$. Finally, the reflectance and illumination
 406 components are evaluated from $R = e^r$ and $L = e^l$, respectively.



Figure 4: Example from the mask database which is created by [23] (a) The real face with texture, the reflectance image and the illumination image of the real face (b) Same images associated with the mask of the same person.

407 Figure 4 shows an example from the mask database for a real face and
 408 corresponding mask attack. First column shows the original images, sec-
 409 ond column and third column show the reflectance and illumination images,
 410 respectively, which are computed using the variational retinex algorithm.

411 4.3. *Micro-Texture Analysis Technique*

412 The micro-texture analysis, which was first proposed in [20] to detect 2D
 413 face attacks, is used to detect 3D mask attacks here. In [20], it is applied
 414 on texture images, whereas in this paper, we apply this technique not only
 415 on texture images but also on depth maps estimated from 3D scans and on
 416 reflectance components of texture images.

417 This LBP based micro-texture analysis technique emphasizes the micro-
 418 texture differences in the feature space. It aims at learning the differences
 419 between real and fake face, and designs a feature space which emphasizes
 420 those differences. The original LBP forms labels for the image pixels by
 421 thresholding the 3×3 neighborhood of each pixel with the center value and
 422 considering the result as a binary number. The LBP operator has been
 423 extended to use neighborhoods of different sizes. $LBP_{P,R}$ is computed such
 424 that for a given central pixel in an image, a pattern number is computed by
 425 comparing its value with those of its neighbors. In Eq. (9), g_c is the gray
 426 value of the central pixel, g_p is the value of its neighbors, P is the number of
 427 neighbors around a circle of radius R . $LBP_{P,R}$ calculation is shown in Eq.
 428 (9) and (10):

$$LBP_{P,R} = \sum_{p=0}^{P-1} s(g_p - g_c) 2^p \quad (9)$$

$$s(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (10)$$

430 Uniform patterns are verified to be the fundamental patterns of local
 431 image texture. A local binary pattern is called uniform if the binary pattern
 432 contains at most two bitwise transitions from 0 to 1 or vice versa when the
 433 bit pattern is traversed circularly. The notation is $LBP_{P,R}^{u2}$. $u2$ stands for
 434 using only uniform patterns and labeling all remaining patterns with a single

435 label.

436 In [20], authors claim that micro-texture details that are needed to dis-
437 criminate a real face from face print can best be detected using combination
438 of different LBP operators. Thus, they derive an enhanced facial repre-
439 sentation using multi-scale LBP operators. Their proposed representation
440 computes LBP features from 3×3 overlapping regions to capture the spatial
441 information and enhances the holistic description by including global LBP
442 histograms computed over the whole image. This is done as follows: the face
443 is cropped and resized into a 64×64 pixel image. Then, $LBP_{8,1}^{u2}$ operator is
444 applied on the face image and the resulting LBP image is divided into 3×3
445 overlapping regions (with an overlapping size of 14 pixels). The local 59-bin
446 histograms from each region are computed and collected into a single 531-bin
447 histogram. Then, two other histograms are computed from the whole face
448 image using $LBP_{8,2}^{u2}$ and $LBP_{16,2}^{u2}$ operators, yielding 59-bin and 243-bin his-
449 tograms that are added to the 531-bin histogram previously computed. In
450 [20], the length of the final enhanced feature histogram is reported as 833
451 (i.e. $531 + 59 + 243$).

452 4.4. Classification Technique

453 Mask face detection is a two-class classification problem. Since SVM [8]
454 are proven to be a powerful tool for discriminating two classes of data, we
455 adopted an SVM classifier for this purpose. SVM finds the maximum margin
456 hyper-plane to separate the training data in feature space and a decision for

457 a new test data x is classified. In our experiments, we adopted linear kernel
 458 since our feature vectors are high-dimensional and are hence likely to be
 459 linear separable.

460 5. THE PROPOSED COUNTERMEASURES

461 Four countermeasures are proposed in this study to discriminate mask
 462 and real samples. Three of them use the 2D data (texture images), and the
 463 remaining one uses the 3D data (depth maps estimated from the raw 3D
 464 scans) available in the mask database as input.

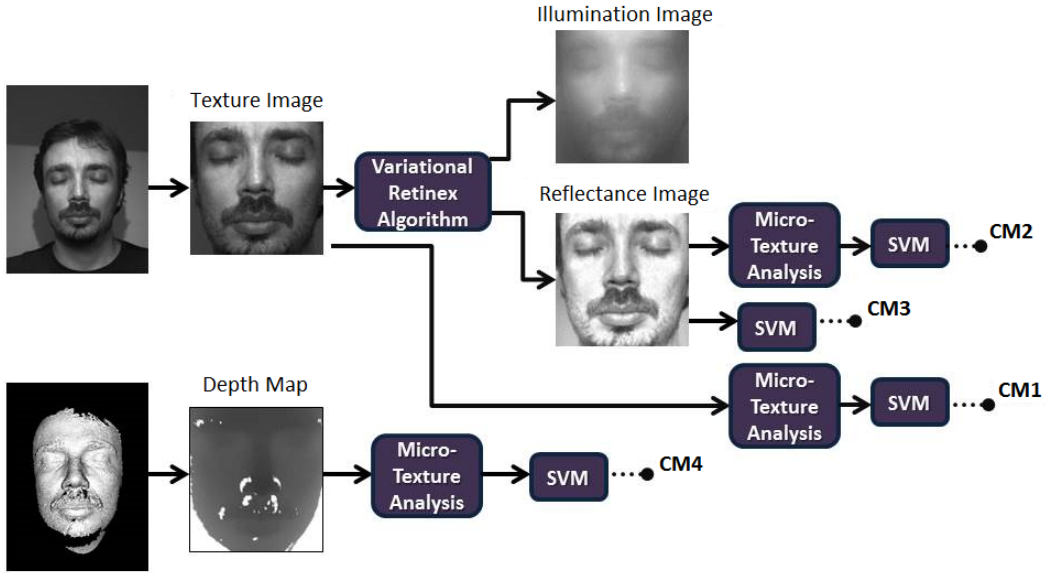


Figure 5: The flowchart of the proposed countermeasures.

465 The flowchart of the countermeasures proposed in this paper are shown in
 466 Figure 5. In this figure, the micro-texture analysis (explained in Subsection
 467 4.3) applied on texture images is called CM1, applied on reflectance images

468 is called CM2, applied on depth maps is called CM4, and finally the counter-
469 measure for which the pixel intensity values on reflectance images are used
470 directly by the classifier is called CM3 (CM denotes countermeasure).

471 CM1 and CM4 are first introduced in our study [15], and CM3 is first
472 introduced in our study [17]. In the present paper, we provide an overview on
473 our spoofing detection approaches introduced in the studies [15, 17]. We ex-
474 tend the works explained in these studies with some improvements (e.g. bet-
475 ter cropping, usage of non-normalized images instead of normalized images),
476 additional analysis, comparisons of performances of diverse countermeasures
477 using the same protocol, and with a detailed analysis of the fusion scenarios.
478 Also, CM2 is first introduced in the present paper. It is a new counter-
479 measure providing very satisfactory accuracy to classify mask and real faces.
480 The results of CM2 show that reflectance component of an image provides
481 more appropriate information than original image itself for mask detection.
482 From the fusion results, we also observed that it provides complementary
483 information on mask detection.

484 5.1. CM1: Micro-Texture Analysis on Texture Images

485 Captured image from mask may visually look very similar to the image
486 captured from live face (e.g. the texture images in the first column of Fig-
487 ure 4). A close look at the differences between faces in DB-r2 and DB-m2
488 reveals that their surface properties are different. For mask manufacturing
489 3D printers are used, hence they may contain printing quality defects that

490 can be detected with micro-texture patterns. For CM1, micro-texture anal-
491 ysis is applied on texture images, and the feature histogram of length 833 is
492 obtained. Finally, linear SVM classifier is applied to detect mask and real
493 faces.

494 5.2. CM2: Micro-Texture Analysis on Reflectance Images

495 For CM2, initially, the illumination and reflectance components (Figure
496 5) of the texture images are obtained using the variational retinex algorithm
497 introduced in Subsection 4.2. Then, micro-texture analysis is applied on
498 reflectance components of texture images rather than texture images itself.
499 The reason of this analysis on reflectance images is that a close look at the
500 differences between the reflectance images of the real and mask faces reveals
501 that the texture characteristics on their reflectance components are also dif-
502 ferent. The feature vectors of length 833, which are obtained by applying
503 micro-texture analysis on reflectance images, are used as input by linear SVM
504 classifier. This feature vector gives information from the reflectance image
505 in the image texture level.

506 5.3. CM3: Pixel Intensity Analysis on Reflectance Images

507 Our observations on the reflectance components of mask and real faces
508 reveal that reflectance characteristics of mask and real face samples are dif-
509 ferent especially at some specific regions of the face (eyelashes, eyebrows and
510 moustache). Based on these observations, in this study, we use the intensity

511 values on reflectance component of each image as input for linear SVM clas-
 512 sifier. Since the intensity values on reflectance images are between 0 and 1
 513 ($R(x, y) \in [0, 1]$), we stretched it to the interval $[0, 255]$ by multiplying R
 514 with 255. The reflectance component, which is in the size of 64×64 pixel
 515 image, is reshaped as $[1 \ 4096]$ ($64 \times 64 = 4096$). The resultant vector is
 516 the feature vector providing information in the pixel intensity level. Finally,
 517 linear SVM classifier is applied to detect real and mask faces.

518 5.4. CM4: Micro-Texture Analysis on Depth Maps

519 The 3D shape of high quality mask is also very similar to the 3D shape
 520 of corresponding real face (e.g. the 3D scans in the second column of Figure
 521 1). Our analysis on DB-r3 and DB-m3 show that the mask scan is smoother
 522 than the real face scan. Especially the parts of the face with facial hair are
 523 quite different. Since there is no real facial hair (e.g. mustache, eyebrow) on
 524 the masks, the 3D scan of mask is smoother in these parts compared to the
 525 real face scan. When high quality scanners are used for acquisition, although
 526 there is a decrease in the number of holes, it is still possible to observe some
 527 holes on the scan especially at the parts of the face with facial hair. Thus, in
 528 our study, micro-texture analysis is also applied on the depth maps which are
 529 estimated from the raw 3D scans, and the other feature histogram of length
 530 833 is obtained. Finally, linear SVM classifier is applied to detect real and
 531 mask faces.

532 6. EXPERIMENTS AND RESULTS

533 In this section, we first show the stand-alone classification performances
534 of the proposed countermeasures together with the fusion scenarios. Then,
535 we integrate the countermeasure providing the best performance to the se-
536 lected 3D FR system in order to observe the improvement in the recognition
537 performance of the system in presence of mask attacks.

538 6.1. Stand-Alone Classification Performances of the Countermeasures

539 In the present study, we apply the proposed countermeasures (CM1, CM2,
540 CM3, CM4) using the same database with the same train-test sets, hence an
541 exact comparison between these countermeasures is possible. Train set is
542 used for classifier training. This classifier is subject to two kind of errors:

- 543 • FLR (False Living Rate), that represents the percentage of fake data
544 misclassified as real. (similar to FAR)
- 545 • FFR (False Fake Rate), which computes the percentage of real data
546 assigned to the fake class. (similar to FRR)

547 The lower these two errors, the better the performance of the counter-
548 measures. In this section, we first evaluate the performances of the single
549 countermeasures, and then evaluate the performances for the fusion scenar-
550 ios. The Region of Convergence (ROC) curves in Figure 6 shows the stand-
551 alone classification performances of the four countermeasures together with
552 the fusion based countermeasure providing the best performance in Table 3.

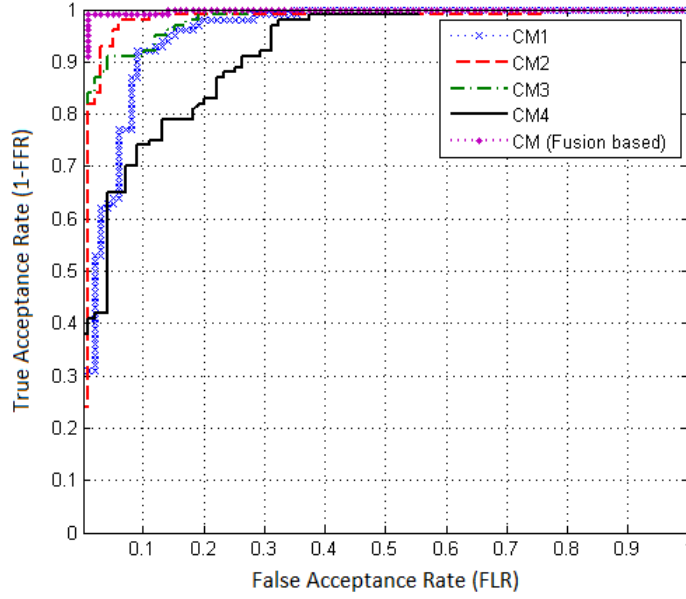


Figure 6: The Classification Performances of the Countermeasures.

Area Under Curve (AUC), EER and best accuracy results using CM1,
CM2, CM3, and CM4 are shown in Table 2.

Table 2: AUC, EER and Accuracy Results Using the Four Countermeasures

Countermeasures	AUC	EER(%)	Accuracy(%)
CM1	0.956	9.04	91.46
CM2	0.980	5.02	95.98
CM3	0.984	9.04	93.47
CM4	0.919	18.59	82.91

Table 2 and Figure 6 show that;

- The best performances in terms of EER and accuracy are obtained using CM2, and the best performance in terms of AUC is obtained using CM3.

- 559 • The best performances are obtained with the countermeasures based
560 on reflectance analysis (CM2 and CM3) compared to the performances
561 obtained with CM1 and CM4. This shows that reflectance character-
562 istics of the real and mask faces in the mask database provide more
563 appropriate information than their texture and smoothness character-
564 istics.
- 565 • CM4, which is based on smoothness analysis, provides worse results
566 compared to the other countermeasures. However, the performance of
567 CM4 can be still considered as satisfactory.
- 568 • 2D data (texture images) provide more information than 3D data (depth
569 maps) to detect mask spoofing.

570 After evaluating the performances of the single countermeasures, we an-
571alyze the performances for the fusion scenarios.

572 For feature level fusion, the feature histograms computed from different
573 types of images (texture, reflectance and depth) are concatenated and the
574 classifier is applied on the resultant feature histogram. In Table 3, the fea-
575 ture level fusion of 2 countermeasures, 3 countermeasures and finally all the
576 4 countermeasures are reported for which the length of the final feature his-
577 tograms are 1666, 2499 and 3332, respectively. Once the enhanced histogram
578 is computed, a linear SVM classifier is used to determine whether the image
579 corresponds to a live face or not.

For score level fusion, linear SVM classifier is applied using the features computed from each type of images (texture, reflectance and depth) separately, and then Z-score normalization is applied for each score group. Finally, the weighted score level fusion is used for combining the outputs of the individual SVMs to determine whether the image corresponds to a live face or not.

AUC, EER and best accuracy results are shown in Table 3 for the fusion scenarios.

Table 3: AUC, EER and Accuracy Results for the Fusion Scenarios of the Proposed Countermeasures

Countermeasures Involved in Fusion	Feature Level Fusion			Score Level Fusion		
	AUC	EER (%)	Acc. (%)	AUC	EER (%)	Acc. (%)
CM1, CM2	0.994	3.01	97.49	0.988	3.01	97.49
CM1, CM3	0.985	9.04	93.97	0.993	5.02	96.48
CM1, CM4	0.972	9.04	92.96	0.976	8.04	94.47
CM2, CM3	0.984	9.04	93.47	0.993	5.02	96.48
CM2, CM4	0.994	3.01	97.49	0.992	4.02	96.98
CM3, CM4	0.986	8.04	92.96	0.994	5.02	95.98
CM1, CM2, CM3	0.985	9.04	93.47	0.998	2.01	98.99
CM1, CM2, CM4	0.998	2.01	97.99	0.993	5.02	96.48
CM1, CM3, CM4	0.987	8.04	93.47	0.997	2.01	97.99
CM2, CM3, CM4	0.986	8.04	93.47	0.997	2.00	98.49
CM1, CM2, CM3, CM4	0.987	8.04	93.47	0.997	2.01	98.49

From the reported results in Table 3, we can remark the followings:

- Both score and feature level fusion of the countermeasures improve the performance compared to using single countermeasure. For instance, CM4 provides a detection accuracy of 82.9% whereas when CM4 and

CM1 are fused, the accuracy is improved to 92.96% for feature and 94.47% for score level fusion. This proves that when both the texture images and depth maps are provided by 3D scanners, more robust countermeasures can be obtained by fusion.

- For feature level fusion, the best performances are obtained by the fusion of CM1, CM2 and CM4. In this part, we observed that when we concatenate the same type of features (micro-texture features of length 833 for each of CM1, CM2 and CM4), we observe a significant increase in the performance. In CM3, the features are pixel intensity values (features of length 4096). Therefore, when we apply feature level fusion using CM3 with the other countermeasures, the positive impact of CM3 in the performances was not observable as shown in Table 3.
- For score level fusion, the best performances are obtained by the fusion of CM1, CM2 and CM3. All these countermeasures (CM1, CM2 and CM3) uses texture images as input (reflectance image is computed from texture image). This proves that 2D data provides very beneficial information for mask spoofing detection.
- CM3 increases the performances when it is used in score level fusion, whereas the impact of it in feature level fusion is not remarkable.
- Although CM1, CM2 and CM3 provide very satisfactory results alone, the score level fusion of these countermeasures provides the best performance compared to all other scenarios in Table 2 and 3. Therefore, in

614 Figure 6, the ROC curve of this fusion based countermeasure is shown
615 as the best one.

- 616 • Since existing 3D scanners provide both 3D scan and corresponding
617 texture image, more robust countermeasures can be developed by fusion
618 of these two type of outputs (2D and 3D data).

619 6.2. *Integration of the Countermeasure to Face Recognition Systems*

620 In this subsection, we integrate the countermeasure with the best per-
621 formance (fusion of CM1, CM2 and CM3) to the 3D FR system selected as
622 baseline.

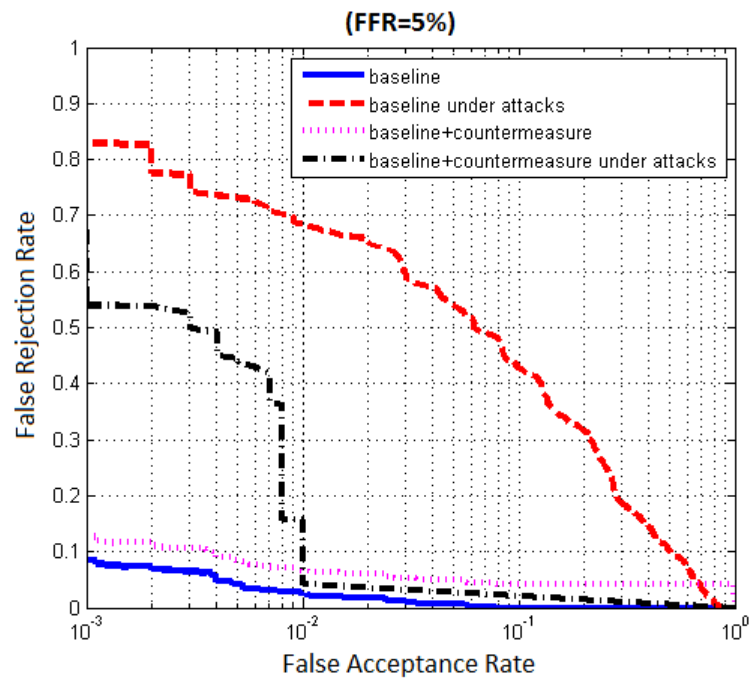
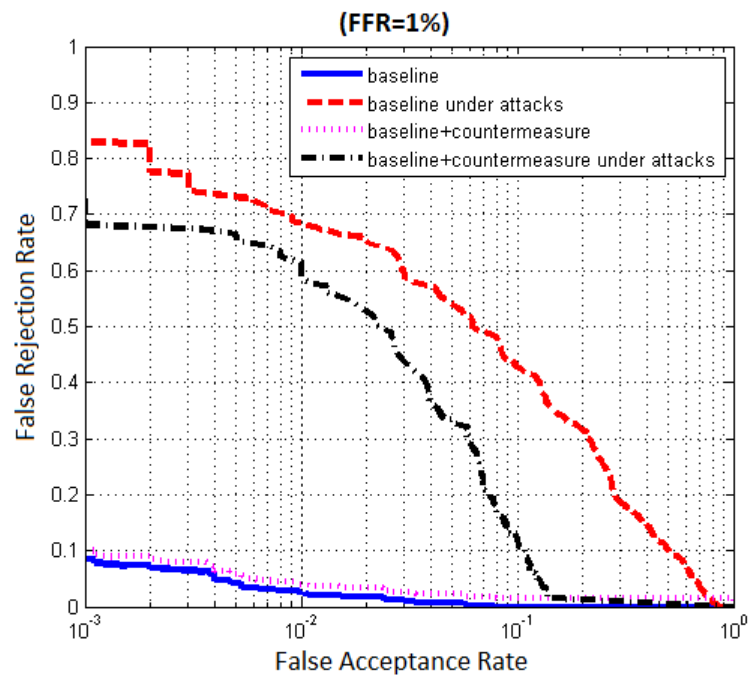
623 The evaluations are done for 4 modes. The first two modes are the base-
624 line mode and the mode under attacks, which are explained in Subsection
625 3.3. The third mode illustrates performance when the countermeasure is
626 applied against the attacks, that results in an improved performance with
627 respect to the second mode. For the samples which are detected as attack
628 by the countermeasure, a least similarity score, which is zero in this test,
629 is assigned to those samples in verification tests. Last mode evaluates the
630 performance of the baseline system together with the countermeasure in the
631 normal operation mode of system, i.e., without attacks. The inclusion of the
632 countermeasure may degrade the baseline performance when not confronted
633 to attack (e.g. the countermeasure may consider as fake some real users.).

634 For evaluations, we fix 3 different evaluation points at $\text{FFR} = 1\%$, 5% ,
635 and 10% (FFR and FLR were defined in the previous subsection). Once

fixed, we incorporate the countermeasure as a first step into the baseline biometric systems oriented to discard fake data, and generate the performance evaluations for the 4 modes explained above.

Figure 7 shows the behavior of the 3D face baseline system with/without attacks and with/without the countermeasure. The three figures represent the overall system performance under spoofing attacks when three different operating points ($\text{FFR} = 1\%$, 5% , and 10%) are used for adjusting the countermeasure.

It is clear from Figure 7 that the 3D FR system is vulnerable to mask attacks (more area between blue and red curves indicates more vulnerability to the attacks). Performance enhancement is obtained almost all regions of DET plots in Figure 7 when the countermeasure is introduced in presence of mask attacks (black curve compared to red curve). If we take an operating point where $\text{FFR} = 1\%$, then FRR of the 3D FR system under attacks drops from around 65% to around 50% at $\text{FAR} = 2\%$. For both of the two other plots (at $\text{FFR} = 5\%$ and 10%), the introduction of the countermeasure lowers FRR from around 65% to 4% and 7% , respectively, at $\text{FAR} = 2\%$. The performance of the countermeasure is observed to be better at $\text{FFR} = 5\%$ compared to the cases at $\text{FFR} = 1\%$ and 10% . Finally, the inclusion of the countermeasure improves the results of 3D FR system under attacks, whereas it degrades baseline performances of the system when not confronted to attack (pink curve compared to blue curve).



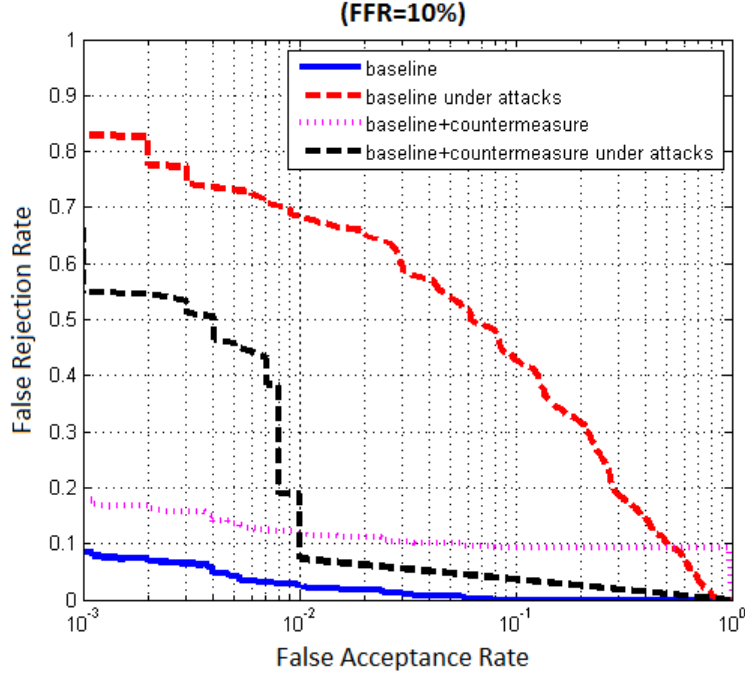


Figure 7: The DET Curves of the 3D face baseline biometric system when integrating the countermeasure.

7. CONCLUSIONS

In this study, a 2D+3D mask attack database is used to evaluate the performances of the proposed countermeasures for the protection of face recognition systems against mask attacks.

The novelty of this study is that it is still one of the few studies that proposes countermeasures against 3D mask attacks. The analysis are done on depth maps, texture images and reflectance components of texture images, and 4 different countermeasures are proposed. Three of the proposed countermeasures use 2D data (texture images), and the remaining one uses 3D data (depth images) as input. These countermeasures can be used to protect

668 both 2D and 3D FR systems against mask attacks. The results of this study
 669 show that analysis on reflectance images provide the best results compared
 670 to analysis on texture and depth images. All of the 4 countermeasures pro-
 671 vide satisfactory information hence can be used as independent sources to
 672 discriminate masks from real faces. However with the fusion of these coun-
 673 termeasures, we observe a significant improvement in the performances. For
 674 instance, in this paper, a classification accuracy of 99% (almost perfect ac-
 675 curacy) is achieved for real face vs. mask face by fusing the information
 676 extracted from the reflectance images and texture images.

677 Up to now, we have analyzed several characteristics of real and mask
 678 faces, and obtained almost perfect results on this mask database. The lim-
 679 itation of our study is that we were able to test the performances of the
 680 proposed countermeasures using the masks made from one type of material,
 681 which is polychrome mineral powder. When masks made from different ma-
 682 terials are used, we may obtain different performance accuracy. Our future
 683 works are first to test the performances of the proposed countermeasures us-
 684 ing masks made from different materials in order to observe if we can still
 685 obtain satisfactory results, and then to propose new countermeasures for
 686 more challenging mask databases with higher number of subjects as soon as
 687 available.

688 **Acknowledgment:** This work has been performed by the TABULA
 689 RASA project 7th Framework Research Programme of the European Union
 690 (EU), grant agreement number: 257289. The authors would like to thank

691 the EU for the financial support and the partners within the consortium for
692 a fruitful collaboration. For more information about the TABULA RASA
693 consortium please visit <http://www.tabularasa-euproject.org>.

694 References

- 695 [1] T. Ahonen, A. Hadid, M. Pietikainen, Face description with local bi-
696 nary patterns: Application to face recognition, IEEE Trans. on Pattern
697 Analysis and Machine Intelligence (2006) 2037–2041.
- 698 [2] N. Almoussa, Variational retinex and shadow removal, Technical Report,
699 The Mathematics Department, UCLA (2008).
- 700 [3] J. Bai, T.T. Ng, X. Gao, Y.Q. Shi, Is physics-based liveness detection
701 truly possible with a single image?, IEEE International Symposium on
702 Circuits and Systems (2010) 3425–3428.
- 703 [4] W. Bao, H. Li, N. Li, et al., A liveness detection method for face recogni-
704 tion based on optical flow field, Int. Conf. on Image Analysis and Signal
705 Processing (IASP) (2009) 233–236.
- 706 [5] P. Besl, N. McKay, A method for registration of 3-d shapes, IEEE Trans.
707 on Pattern Analysis and Machine Intelligence (1992) 239–256.
- 708 [6] F.L. Bookstein, Principal warps: Thin-plate splines and decomposition
709 of deformations, IEEE Trans. Pattern Analysis and Machine Intelligence
710 (1989) 567–585.

- 711 [7] M.M. Chakka, A. Anjos, S. Marcel, et al., Competition on counter mea-
712 sures to 2-d facial spoofing attacks, IEEE IAPR Int. Joint Conference
713 on Biometrics (IJCB) (2011) 1–6.
- 714 [8] C.C. Chang, C.J. Lin, Libsvm : a library for support vector machines,
715 ACM Transactions on Intelligent Systems and Technology (2011) 2:27:1–
716 27:27.
- 717 [9] G. Chetty, M. Wagner, Multi-level liveness verification for face-voice
718 biometric authentication, Biometrics Symposium: Special Session on
719 Research at the Biometric Consortium Conference (2006) 1–6.
- 720 [10] N. Erdogmus, J.L. Dugelay, On discriminative properties of tps warp-
721 ing parameters for 3d face recognition, IEEE Int. Conf. on Informatics,
722 Electronics and Vision (ICIEV) (2012) 225–230.
- 723 [11] Y. Kim, J. Na, S. Yoon, J. Yi, Masked fake face detection using radiance
724 measurements, Journal of the Optical Society of America A (2009) 760–
725 766.
- 726 [12] R. Kimmel, M. Elad, D. Shaked, R. Keshet, I. Sobel, A variational
727 framework for retinex, International Journal of Computer Vision (2003)
728 7–23.
- 729 [13] K. Kollreider, H. Fronthaler, J. Bigun, Verifying liveness by multiple
730 experts in face biometrics, IEEE Computer Society Conference on Com-
731 puter Vision and Pattern Recognition Workshops (2008) 1–6.

- 732 [14] N. Kose, J.L. Dugelay, Classification of captured and recaptured images
733 to detect photograph spoofing, IEEE Int. Conf. on Informatics, Elec-
734 tronics and Vision (ICIEV) (2012) 1027–1032.
- 735 [15] N. Kose, J.L. Dugelay, Countermeasure for the protection of face recog-
736 nition systems against mask attacks, IEEE Automatic Face and Gesture
737 Recognition (FG) (2013) 1–6.
- 738 [16] N. Kose, J.L. Dugelay, On the vulnerability of face recognition systems
739 to spoofing mask attacks, IEEE Int. Conf. on Acoustics, Speech, and
740 Signal Processing (ICASSP) (2013) 2357–2361.
- 741 [17] N. Kose, J.L. Dugelay, Reflectance analysis based countermeasure tech-
742 nique to detect face mask attacks, Int. Conf. on Digital Signal Processing
743 (DSP) (2013) 1–6.
- 744 [18] N. Kose, J.L. Dugelay, Shape and texture based countermeasure to pro-
745 tect face recognition systems against mask attacks, IEEE Computer
746 Vision and Pattern Recognition Workshop, on Biometrics (CVPRW)
747 (2013) 111–116.
- 748 [19] J. Li, Y. Wang, T. Tan, et al., Live face detection based on the analysis
749 of fourier spectra, Proceedings of the SPIE (2004) 296–303.
- 750 [20] J. Maatta, A. Hadid, M. Pietikainen, Face spoofing detection from single
751 images using micro-texture analysis, Proc. of IEEE Int. Joint Conf. on
752 Biometrics (IJCB) (2011) 1–7.

- 753 [21] J. Maatta, A. Hadid, M. Pietikainen, Face spoofing detection from single
754 images using texture and local shape analysis, IET Biometrics (2012)
755 3–10.
- 756 [22] M.D. Marsico, M. Nappi, D. Riccio, J.L. Dugelay, Moving face spoofing
757 detection via 3d projective invariants, IAPR Int. Conf. on Biometrics
758 (2012) 73–78.
- 759 [23] MORPHO, <http://www.morpho.com/>, 2010.
- 760 [24] G. Pan, L. Sun, Z. Wu, S. Lao, Eyeblick-based antispooing in face
761 recognition from a generic webcam, IEEE Int. Conf. on Computer
762 Vision (ICCV) (2007) 1–8.
- 763 [25] P.J. Phillips, P.J. Flynn, T. Scruggs, K. Bowyer, J. Chang, K. Hoff-
764 man, J. Marques, J. Min, W. Worek, Overview of the face recognition
765 grand challenge, IEEE Computer Society Conf. on Computer Vision and
766 Pattern Recognition (2005) 947–954.
- 767 [26] PRINT-ATTACK Database, <http://www.idiap.ch/dataset/printattack>,
768 2010.
- 769 [27] Sculpteo 3D Printing, <http://www.sculpteo.com/en/>, 2009.
- 770 [28] TABULA RASA Project, <http://www.tabularasa-euproject.org/>, 2010.
- 771 [29] Z. Zhang, D. Yi, et.al, Face liveness detection by learning multispectral

772 reflectance distributions, IEEE Automatic Face and Gesture Recogni-
773 tion (FG) (2011) 436–441.