A Virtual Try-on System for Prescription Eyeglasses

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***Abstract*—We present a system for virtual try-on of prescription eyeglasses. This augmented reality system acts as a "virtual mirror", allowing users to try on a variety of eyeglasses with corrective lenses according to their prescription. An image sequence of the user without eyeglasses is used as input, along with the user's eyeglasses prescription and a 3D model of the desired eyeglasses frame. Our system generates a 3D representation of the corrective lenses mounted into the eyeglasses frame, and modifies the video sequence to virtually insert the eyeglasses through image-based rendering. Compared to existing virtual try-on systems, our approach simulates the refraction effects due to the corrective lens and takes into account reflections and shading. We present a user study assessing the perceived realism of virtual try-on videos generated with our approach and study the effects of refraction and reflection on the perceived realism.**

***Index Terms*—virtual try-on, eyeglasses, refraction, augmented reality.**

Fig. 1. The refraction effects introduced by prescription eyeglasses changes a wearer's appearance. As illustrated in the photographs above, the eyes of a person wearing corrective lenses for nearsightedness (a) appear smaller compared to wearing non-prescription lenses (b), whereas the eyes of a person wearing lenses for farsightedness (c) appear larger. The numbers below each image correspond to the optical power of lenses in Diopters, where "OD" and "OS" represent the right and left eye, respectively.

I. Introduction

Vision-correcting eyeglasses have improved the life of millions. A small transparent lens, with a carefully designed shape, can correct for most aberrations in the human eye. The correction in eyeglasses lenses is specific to each patient and depends on their eyeglasses prescription, which is specified by an ophthalmologist or optometrist following an eye exam.

Eyeglasses significantly affect the appearance of their wearer, and the decision to buy new eyeglasses is largely based on how pleasant the wearer finds them on her face when she tries them on. However, an often overlooked fact is that corrective lenses introduce distortion, which is due to the effect of refraction. As illustrated in Fig. 1, the eyes of a person wearing corrective lenses for nearsightedness appear smaller compared to wearing non-prescription lenses, whereas the eyes of a person wearing lenses for farsightedness appear larger.

The traditional process of trying on and picking new eyeglasses frames in a brick-and-mortar shop has a significant shortcoming: eyeglasses on the display are equipped with demo lenses that have zero corrective power, and thus do not deform the eyes due to refraction. Customers cannot see how they will look like until the sale is closed and their custom prescription lenses are fitted in. Their final appearance is different compared to the in-store trial; this can cause disappointment and buyer's remorse, especially for customers with strong eyeglasses prescriptions. A similar issue occurs with online stores which propose to "virtually try-on" eyeglasses frames by blending them with an input image.

We present a system for virtual try-on of prescription eyeglasses. Our system acts as a "virtual mirror", allowing users to try on a variety of eyeglasses with corrective lenses according to their prescription (Fig. 2). An image sequence of the user without eyeglasses is used as input, along with the user's eyeglasses prescription and a 3D model of the desired eyeglasses frame. Our system generates a 3D representation of the corrective lenses mounted into the eyeglasses frame, and modifies the video sequence to virtually insert the eyeglasses through image-based rendering. This approach simulates the distortion introduced by the prescription lenses and gives users a better idea of how they would look when wearing a new pair of eyeglasses.

To the best of our knowledge, the proposed system for virtual try-on of prescription eyeglasses is the first to account for the refraction effects. In addition to the overall system, we make the following contributions:

1) Inspired by the traditional eyeglasses manufacturing pipeline followed by opticians, we generate a 3D representation of the corrective lenses that fit the user's eyeglasses prescription and the chosen eyeglasses frame.
2) We describe an image-based rendering technique for virtually inserting prescription eyeglasses into the input video, while taking into account the effects of refraction, reflection, and shading.
3) We perform a user study which highlights the importance of refraction and reflection in the perceived realism of virtual try-on results.

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(a) Input video (b) Synthesized video with prescription eyeglasses inserted

Fig. 2. Our virtual try-on system for prescription eyeglasses modifies an input video (a) and virtually inserts prescription eyeglasses, producing an output (b) similar to a virtual mirror. Our approach handles reflection and shadows, and simulates the effects of refraction according to the user's eyeglasses prescription. A variety of eyeglasses frames are available for selection.

II. Related work

Augmented reality technologies [1] allow integrating virtual objects into real-world video sequences, enabling computer-generated objects to be inserted into an input image or video as if they were part of the observed scene. These technologies enhance people's perception of reality and enable a variety of applications in fields such as education, maintenance, design as well as e-shopping. Virtual try-on systems make the pre-visualization of products possible and enable a more credible try-on experience for users from the comfort of their home. Virtual try-on systems have been proposed for objects such as clothes [2], [3], [4] and eyeglasses [5], [6].

An eyeglasses virtual try-on application inserts virtual eyewear, such as vision-correcting eyeglasses frames or sunglasses, onto a user's face captured by a color camera. Many online eyeglasses stores [7], [8] allow users to upload a frontal face image and insert glasses on it; Other commercial applications [9], [10] allow inserting eyewear directly into a live video stream captured by webcam. Research literature on virtual eyeglasses try-on, such as [11], [12], proposes image-based blending techniques to insert eyeglasses onto the user's face. Those existing systems, either using still image or video, act as a virtual mirror allowing users to try on eyeglasses virtually. However, to the best of our knowledge, all available virtual try-on solutions ignore the effects of refraction caused by eyeglasses lenses.

In this paper we demonstrate that refraction artifacts, which occur on real prescription lenses, drastically change the appearance of their wearer, thus affecting how customers perceive their potential new pair of eyeglasses. The system proposed in this paper acts as a virtual mirror, but in contrast to previous methods, it leverages 3D geometry to simulate refraction, reflection, and shadows, yielding virtual try-on results with increased perceived realism.

III. Overview

We describe an eyeglasses virtual try-on system which inserts prescription eyeglasses onto the user's face and simulates important changes to the appearance due to refraction, reflection, or shadows cast on the face.

TABLE I
Example of an eyeglasses prescription.

	Sphere	Cylinder	Axis	PD
OD	-4.25	-0.75	160	64
OS	-4.50	-	-	

"OD" and "OS" represent lens prescription of the right and left eye (from the wearer's point of view), respectively. "Sphere" and "Cylinder" are the spherical and cylindrical correction, while "Axis" means the cylinder axis in the case of astigmatism-correcting lenses. "PD", an abbreviation for Pupillary Distance, is the distance between the pupil centers.

Our method takes as input:

1) Image sequence. An image sequence of the user without eyeglasses is captured with a color camera.
2) User's eyeglasses prescription. An eyeglasses prescription, usually provided by an optometrist, specifies the value of all parameters necessary to correct blurred vision due to refractive errors, including myopia, hyperopia, presbyopia, and astigmatism. Table I shows a typical eyeglasses prescription.
3) Eyeglasses frame. The user chooses her desired eyeglasses frame. The eyeglasses geometry is typically accessible from online stores, as they scan and digitize the eyeglasses frames. In this work, we purchased 3D models of six different eyeglasses from [13], which were modeled according to commercially available eyeglasses frames.

Fig. 3 gives an overview of the pipeline of our approach, which consists of two main stages:

Virtual eyeglasses generation. In this stage, we aim to generate a 3D representation of the prescription eyeglasses (i.e., frame and corrective lenses), with appropriate position relative to the user's face geometry. Inspired by the traditional eyeglasses manufacturing pipeline, this stage has three steps:

- Positioning of eyeglasses on the user's face. After an initial manual positioning step for the first frame, we use

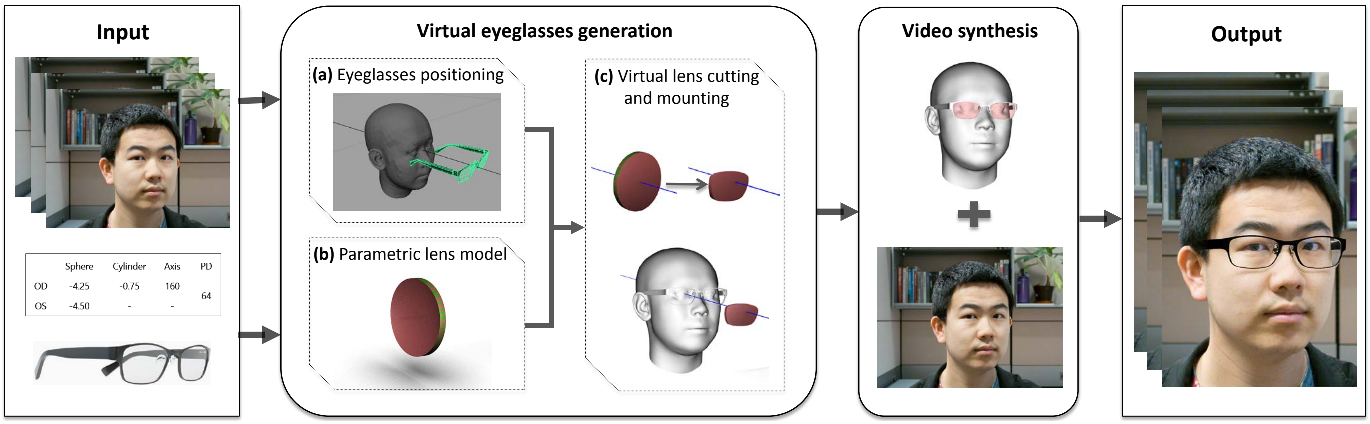

Fig. 3. Overview of the pipeline for virtual try-on of prescription eyeglasses. Our system takes as input a video of the user, the user's eyeglasses prescription, and a 3D model of the desired eyeglasses frame. In the virtual eyeglasses generation stage, we first create a virtual 3D representation of the desired prescription eyeglasses, by (a) positioning the eyeglasses frame with respect to the user's face, (b) building a parametric lens model based on the user's eyeglasses prescription, and (c) cutting the corrective lenses before mounting them into the eyeglasses frame. In the second stage, video synthesis, we use image-based rendering to generate a synthetic image sequence where the prescription eyeglasses are virtually inserted, taking into account the effects of refraction, reflection, and shadows due to the inserted eyeglasses.

face tracking to automatically align the eyeglasses with the user's face in the following frames. (Section IV-A).

- Creation of a parametric lens model based on the user's prescription and desired lens properties. This model describes the geometry of the uncut lens before mounting. (Section IV-B).
- Lens cutting and mounting. We trim the lens geometry according to the shape of the eyeglasses frame, and insert the virtual lenses into the eyeglasses frame. (Section IV-C).

Video synthesis. In this stage, we render the virtual eyeglasses and insert them into the input image sequences, taking into account eyeglasses frame, lenses and the surrounding lighting. In particular, we account for the effects of refraction, reflection, and shadows due to the inserted eyeglasses. (Section V).

IV. Virtual eyeglasses generation

In this first stage, we aim to generate a 3D representation of the scene with prescription eyeglasses inserted, where the eyeglasses frame and corrective lenses are appropriately positioned with respect to the user's face geometry.

Inspired by the traditional eyeglasses manufacturing pipeline followed by opticians, we develop an approach based on three steps: eyeglasses positioning, lens blank selection, lens cutting and mounting. In the following we briefly describe the traditional eyeglasses manufacturing process, before introducing our proposed system.

Eyeglasses positioning. Once the customer has chosen an eyeglasses frame for purchase, the optician measures the Pupillary Distance, or PD, which is the horizontal distance between the left and right pupils. This can be done by marking the position of the pupils on the demo lenses, while the customer has the glasses on. This step is essential to ensure that the prescription lenses will be appropriately positioned with respect to the eyes.

Lens blank selection. The next step is to choose lens blanks based on the strength of the correction needed and desired lens properties (e.g., lens material). Lens blanks are circular, uncut lenses that are usually stocked by the lens manufacturers, with a variety of front surface curvatures. If necessary, the back surface of the lens is ground and polished to produce a lens according to the desired prescription.

Lens cutting and mounting. The eyeglasses frame is inserted into a dedicated tracing machine in order to measure its inner contours, which will be used to cut the lens blanks to the appropriate shapes. Each lens blank is then placed into an instrument to locate and mark their "optical center"; these points will be positioned in front the customer's pupils to ensure optimal vision. Finally, an edging machine is used to trim the lens blanks into the proper lens shapes, according to the contours previously measured. The cut lenses are then inserted into the eyeglasses frame.

We create virtual eyeglasses with a similar process. First, we place the eyeglasses frame appropriately onto the user's face geometry (Section IV-A); we then build a parametric model representing the geometry of each lens according to the user's eyeglasses prescription (Section IV-B); finally, lenses are cut and mounted into the eyeglasses frame (Section IV-C).

A. *Eyeglasses positioning*

Similar to the optician pipeline, we first place the eyeglasses frame with respect to the user's face geometry. Manually positioning the eyeglasses frame model with respect to the face geometry is performed in the first image. For the subsequent images, face tracking is used to automatically position the eyeglasses frame model.

User's face geometry. We obtain the geometry and pose of the user's face for each frame by tracking the face using software Faceshift [14] and a Primesense Carmine 1.09 RGBD sensor. Calibration between the RGBD sensor and the color camera, which is used to capture the user's input image sequence, was performed via camera calibration toolbox [15].

The camera intrinsic and extrinsic parameters allow us to align the face geometry with the input color images.

Eyeglasses positioning. We manually position the eyeglasses onto the face mesh for the first frame. It takes less than 5 minutes for all the examples tested. A fully-automatic option would be using affine transformation computed based on pre-selected feature points on face and eyeglasses 3d model [16], or with a physics-driven technique [17].

Face tracking. After the initial manual positioning of the eyeglasses for the first frame, we track the head pose to automatically align the eyeglasses with the user's face in the subsequent frames. This is achieved by calculating the relative pose change in each frame.

B. Parametric lens model

Given the user's eyeglasses prescription we generate the 3D lens geometry based on a parametric model, so that the optical power of the virtual lens corresponds to the user's prescription. A lens is a 3-dimensional transparent and closed object. It consists of two main surfaces: the front surface and the back surface. The lens thickness is defined as the distance between front and back surface along its optical axis. Physical lenses are made of a transparent material with a certain index of refraction, which affects lens thickness, weight and optical properties.

Optical power refers to the ability of a lens to bent light rays, specified by the eyeglasses prescription. The front and back surface curves determines the optical power of a lens. Spherical lenses, are rotationally symmetric and their front and back surfaces have a constant curvatures. In contrast, the surface curvature of toroidal lenses, which are used to correct astigmatism, varies with the direction; it is usually defined along two orthogonal directions called axis meridian and power meridian. Modern lenses generally takes a meniscus shape, with convex front curves and concave back curves. The optical power P of a lens in diopters, is given by:

$$P = F + B + (t/\eta) * F^2 \tag{1}$$

where F and B are the front and back power in diopters, t the lens center thickness in meters and η the index of refraction. The focal power P is specified by the user, in the form of an eyeglasses prescription (Table I). Multiple lenses can achieve the same correction, the user can choose among different materials (with different refractive index η), thickness t (which depends on the material), and price. Similar to the manufacturing process, we choose an appropriate base curve for the front lens surface based on the optical power P of the lens. The base curve of the lens is the surface curve that becomes the basis from which the remaining curves will be calculated. For modern ophthalmic lenses, the base curve is typically the front curve of the lens blank, which has a front power F. Manufacturers make base curve selection charts [18] available that provide the recommended ranges of final surfaced power for each base curve in the series. Knowing the optical power P, front power F, lens center thickness t and index of refraction η, we can calculate the back surface power B according to Equation 1. Once all the quantities are known, we can generate the 3D geometry of the lens.

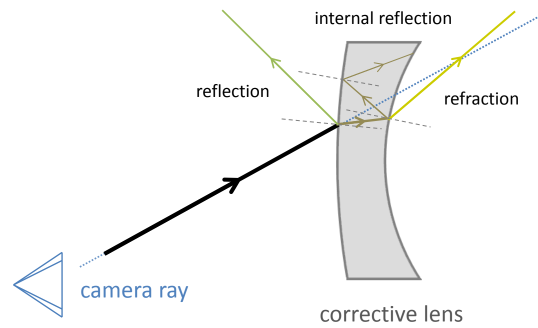

Fig. 4. Illustration of ray tracing for simulation of the refraction and reflection effects. As camera rays (blue) enter the first surface of a corrective lens, each ray is refracted or reflected, either into the lens or back into the scene. For some of the rays entering the lens, total internal reflection occurs.

For the purpose of simplicity, we only describe the lens model for spherical lenses. However, we can also generate lenses for astigmatism and presbyopia as well as bifocal lenses and progressive lenses, given the user's prescription.

C. Virtual lens cutting and mounting

Inspired by real lens cutting machines, we detect the 2D inner contour of the eyeglasses frame from a front-facing view, and extrude that contour to cut the lens. In the process, the uncut lens is aligned with the optical axis of the eye, making sure that the lens optical center lies in front of the pupil. The cut lens is represented using a triangle mesh with a fine tessellation. After the lens cutting, we insert each corrective lens into the eyeglasses frame by translating it along its optical axis.

V. Video synthesis

In this section, we will insert the virtual eyeglasses into the input sequence using image-based rendering, where the eyeglasses are rendered using ray tracing. From the previous sections, we have obtained a parametric lens model, the well-positioned eyeglasses and the user's face geometry for each image frame. We address the rendering process by first describing the objects in the virtual scene and the materials associated with them (Section V-A). Then we describe the ray tracing rendering of lenses, with the refraction and reflection effects, and the shading cast on face (Section V-B).

A. Scene description

We prepare a virtual scene for the rendering process, where the user is wearing the prescription eyeglasses. Obtained from the previous sections, there are four objects in the scene: two corrective lenses, the eyeglasses frame, the user's face mesh and the background. In ray tracing, each primary ray traced from the camera and intersecting the scene geometry is assigned a color, which depends on the local material and shading (i.e., the quantity of light received at the intersection point). Primary rays that do not intersect any of the scene objects are assigned the same color as in the input image. We now describe the materials of all objects in the scene.

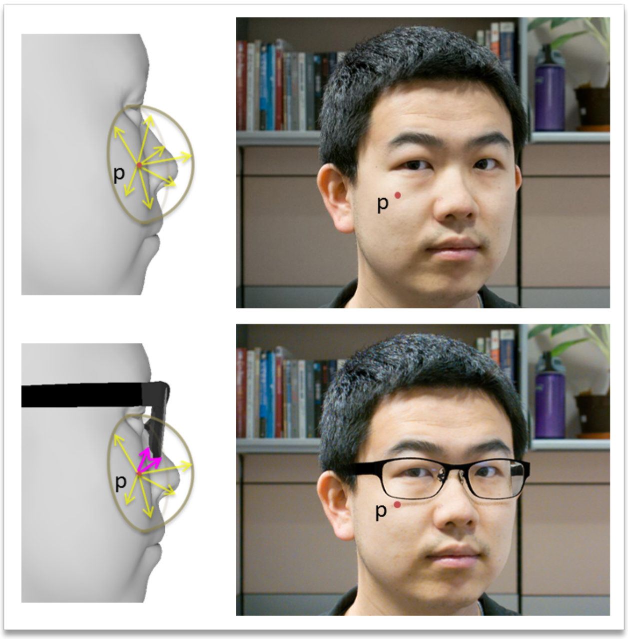

Fig. 5. Illustration of the Monte Carlo integration process, for shading computation. In order to estimate the shading at a point $\mathbf{p}$, rays are traced from $\mathbf{p}$ to several directions of the viewing hemisphere (top). Once virtual eyeglasses are inserted (bottom), the eyeglasses frame blocks some of these rays (rays in magenta). This results in shadows cast on the user's face, which our approach is able to simulate.

Incident lighting representation. In order to produce plausible shading, we first build a representation of the incident lighting that surrounds the scene. A simple way to capture this is to place a chrome sphere in the scene, before capturing the input video; a photograph of the sphere is then unwrapped into an environment map [19], which represents the amount of incident light coming from every direction. Other approaches for estimating the incident lighting include automatic methods such as shape-from-shading [20], [21], [22], or the real-time method [23]. In this system, we utilize the chrome sphere. Alternatively, a pre-captured default environment map can be used.

Materials in the scene. Each object of the scene has an associated material. For virtual objects, the material is set by default or pre-selected by users. The color on the eyeglasses frame is determined using Phong shading [24], whose properties (e.g., specularity) can be adjusted to change the eyeglasses color. The lenses are associated with a dielectric material which refracts or reflects light rays. For the user's face mesh and background, the materials come from the input image sequences. The user's face is considered a diffuse surface; in order to insert plausible shadows while still preserving the details from the input image sequence, we employ an image-based approach that described in the following.

B. Ray tracing

We render the scene using a ray-tracing based technique, which takes into account the refraction and reflection effects introduced by the corrective lenses and the shadow cast on face by the eyeglasses frames. Rays emanating from the camera position are cast through pixel centers of the images and intersected with the scene (Turner-Whitted style [25]). The following section describe the rendering process in more detail.

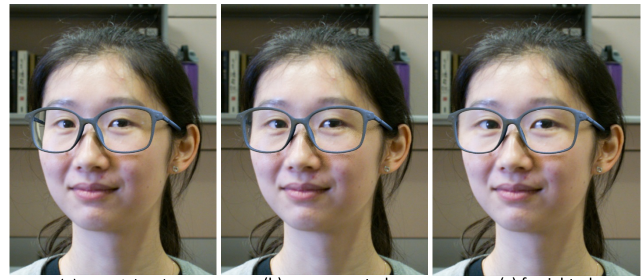

Fig. 6. Comparison of our synthetic results, where eyeglasses are mounted with different corrective lenses. Similar to real photographs in Fig. 1, eyes appear smaller behind minus lenses (for nearsightedness), while they are magnified by plus lenses (for farsightedness). This phenomenon becomes more obvious as the strength of the correction increases.

Refraction. Corrective lenses introduce refraction effects, and distort regions behind the lens. In our system, lenses are rendered using dielectric materials, which consist of a refraction part and an internal reflection part [26]. Rays are refracted using Snell-Descartes's law, which is a function of ray direction, surface normal at the intersection point, and lens index of refraction. As it enters the first lens surface (Fig. 4), each ray is refracted or reflected, either into the lens or back into the scene. Total internal reflection occurs for some of the rays entering the lens, where they keep bouncing "back and forth" within the lens.

Reflection. Reflection effects on the surface of the transparent lenses are simulated by leveraging the environment map. When a ray is reflected by the surface of the lens and does not further intersect any scene object, an environment map texture lookup is performed based on the ray's direction.

Shadows. In order to simulate the shadows cast by eyeglasses, we estimate the shading at each visible point on the face using Monte Carlo integration [27]. The procedure is described in the following algorithm.

For each point $\mathbf{p}$ at which we wish to estimate the shading, an integration over a hemisphere is performed. The hemisphere is centered on the local surface normal of point $\mathbf{p}$ and sampled using importance sampling [27] with weight $\mathbf{w}_i$. We cast rays originating from $\mathbf{p}$ towards sample points on the hemisphere (Fig. 5). Each ray is then tested for intersections with objects in the scene; rays that do not intersect with any object contribute to the local shading (we can look up their color in the environment map), while rays that are blocked by occluders do not. We perform the integration twice: once in a virtual scene containing solely the face geometry, yielding shading $S_{\text{noGlasses}}(\mathbf{p})$, and once with the added eyeglasses frame, yielding shading $S_{\text{withGlasses}}(\mathbf{p})$. The final color $I_{\text{withGlasses}}$ is obtained by multiplying the input color $I_{\text{noGlasses}}$ with the ratio of shading:

$$I_{\text{withGlasses}} = (S_{\text{withGlasses}}/S_{\text{noGlasses}}) * I_{\text{noGlasses}} \quad (2)$$

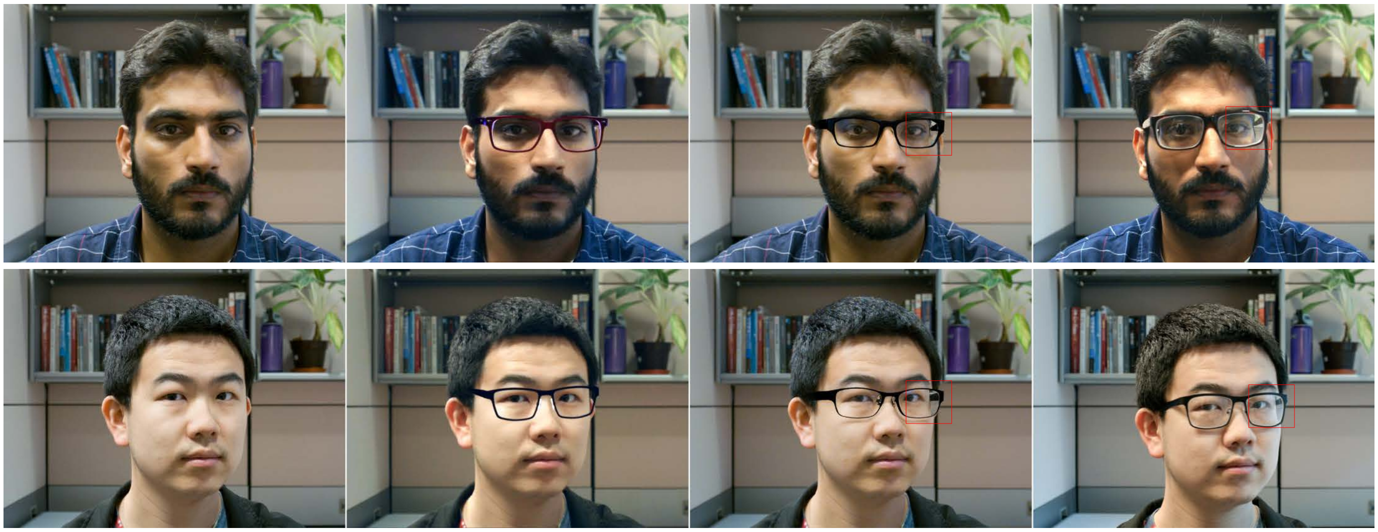

Fig. 7. Comparison of eyeglasses virtual try-on results. Given the input image (a), the virtual try-on solution from an online eyeglasses store (b) only inserts the eyeglasses frame, without considering the lenses. In contrast, our virtual try-on result (c) exhibits effects of refraction, reflection, and shadows. Our result appears more similar to the real reference image (d), captured with a similar pose, similar eyeglasses frame and the same prescription. In both (c) and (d), the eyes seem smaller due to prescription eyeglasses, and a discontinuity appears along the silhouette of the wearer's face (highlighted with red rectangles).

Algorithm 1 Shading Estimation

Input: intersection points $\mathbf{p}$ between camera rays and face geometry; color $I_{\text{noGlasses}}(\mathbf{p})$ from RGB image.
for each point $\mathbf{p}$ **do**
  $S_{\text{noGlasses}}$ = (0, 0, 0);
  $S_{\text{withGlasses}}$ = (0, 0, 0);
  Sample the hemisphere at $\mathbf{p}$ with weight $\mathbf{w}_i$;
  for each sample point $\mathbf{q}_i$ in the hemisphere **do**
    ray direction $\vec{\mathbf{d}}_i = (\overrightarrow{\mathbf{pq}_i}) \,/\, \|\overrightarrow{\mathbf{pq}_i}\|$;
    $\mathbf{S}_i = \mathbf{w}_i * \text{EnvMap}(\vec{\mathbf{d}}_i)$;
    $S_{\text{noGlasses}}$ += $\mathbf{S}_i$;
    if ray $\overrightarrow{\mathbf{pq}_i}$ does not hit eyeglasses frame **then**
      $S_{\text{withGlasses}}$ += $\mathbf{S}_i$;
    end if
  end for
  $I_{\text{withGlasses}} = (S_{\text{withGlasses}} \,/\, S_{\text{noGlasses}}) * I_{\text{noGlasses}}$;
end for
Output: color $I_{\text{withGlasses}}(\mathbf{p})$ at each intersection $\mathbf{p}$.

Note that this process ignores lens occlusion and lens effects such as caustics, which significantly speeds up rendering time.

Feathering of eyeglasses legs. In order to account for users with long hair and inaccuracies in the estimated face geometry, we smoothly fade out the eyeglasses frames near the ear region. We blend each pixel of the output image with the input through image compositing, based on the distance to the front of the face.

VI. Results

Our virtual try-on system for prescription eyeglasses modifies an input video and virtually inserts prescription eyeglasses, producing an output similar to a virtual mirror. Our approach handles reflection and shadows, and simulates refraction effects according to the user's eyeglasses prescription. A variety of eyeglasses frames are available for selection (Fig. 2 (b)).

The distortion introduced by prescription eyeglasses becomes more obvious as the strength of the prescription increases. Similar to the appearance changes when wearing real eyeglasses in Fig. 1, our synthesized images with virtual eyeglasses inserted demonstrate changes in eye size (Fig. 6). Eyes appear smaller behind minus lenses (for nearsightedness), while they are magnified by plus lenses (for farsightedness). This is an important phenomenon that makes people look different when they put on glasses, in addition to the eyeglasses frames.

Fig. 7 shows comparisons of eyeglasses virtual try-on results. Given the input image (a), the virtual try-on solution from an online eyeglasses store (b) only inserts the eyeglasses frame, without considering the lenses. In contrast, our virtual try-on result (c) takes into account refraction, reflection, and shadows, which appears more similar to the real reference image (d), captured with a similar pose and eyeglasses with the same prescription. Our simulation of the distortion due to corrective lens refraction gives the user more realistic experience.

The supplemental online video (see https://youtu.be/_fckwZCzCgc) provides results for several other virtual try-on sequences, including multiple users and eyeglasses frames.

User study. We performed a user study to assess the perceived realism of virtual try-on videos generated with our approach. Participants to the user study were shown multiple videos of virtual try-on results, and ranked them based on their perceived realism.

To generate the stimuli, we captured videos of five actors from different ethnicities and one mannequin. In each capture session, we asked the actor to try on prescription eyeglasses

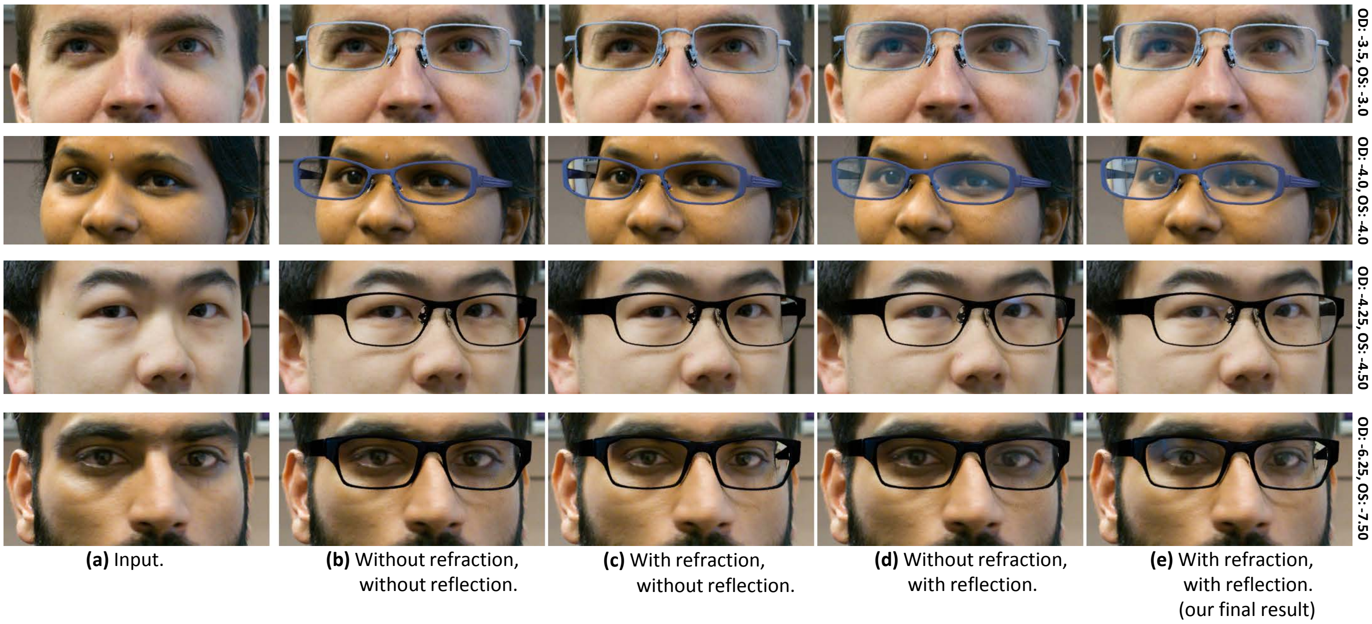

Fig. 8. Comparison between four variations of the virtual try-on results generated using our approach, with/without refraction and with/without reflections (b-e). (a) shows the input image. (e) is our final result. Prescription eyeglasses are inserted into the images with refraction and reflection effects. The optical power of prescription lenses are indicated on the right side of image (e), where "OD" and "OS" represents the right and left eyes, respectively.

that we provided, with sphere power ranging from -1 to -7.5 diopters; we recorded this as the reference video. We then recorded a second video of the actor without eyeglasses, and used this video as input to our virtual try-on. We generated four variations of virtual try-on results using our approach, with/without reflections and with/without refraction (Fig. 8), using lens model parameters corresponding to the prescription lenses in the reference video. We also record a live virtual try-on session on an online eyeglasses store [10] with similar eyeglasses frames. The five stimuli videos were cropped to less than 3 seconds for each actor.

In each trial of the study, a subject was first showed the reference video of an actor wearing real eyeglasses. The five stimuli corresponding to this actor were then shown simultaneously, playing in a loop; the subject was asked to rank the videos according to how they looked, from "most real" to "least real", by dragging them over the screen into ranking bins. Each trial corresponding to one actor was repeated twice and all trials were ordered randomly; two training trials were added at the beginning of the session but were not used in the analysis. In total, each participant completed 14 trials.

Twenty individuals (12 male, 8 female) participated in our study, with ages ranging from 23 to 49 (average 28). Nine participants reported to be familiar with computer graphics, and 17 of them wore eyeglasses. The average length of the study (including a short break) was 16 minutes.

Based on the ranking results, we assigned scores to all videos; in each trial, the best-rank video was assigned a score of 5, while the lowest-rank video was assigned a score of 1. Upon analyzing the scores from all trials and all participants, the overall opinion favored video sequences which exhibit refraction and reflections, which increased the perceived realism in our virtual try-on results (Fig. 9). Specifically:

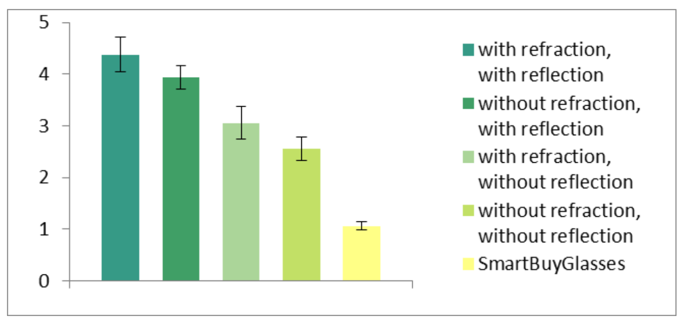

Fig. 9. User study results. Bar height indicates the average score for each type of video across all users. Error bars are between-subjects standard error of the mean. Five types of videos were displayed, including four variations of virtual try-on videos generated by our method and one screen capture from a commercial online eyeglasses store (SmartBuyGlasses). The highest-ranking video was assigned a score of 5, while the lowest-ranking video was assigned a score of 1.

- 62.50% of the votes favored our videos with refraction compared to our videos with no refraction (Table II), for sequences with reflections; paired t-test confirmed a statistically significant difference ($t = 7.09$, $p < 0.005$); a similar analysis can be made when reflections are disabled (66.67% of the votes, $t = 3.99$, $p < 0.005$);
- reflections were deemed significant in increasing perceived realism of the generated try-on sequences; videos with reflections were consistently favored over videos without reflections, both on the videos with and without refractions (86.67% of the votes, $t = 16.68$, $p < 0.005$; 89.17% of the votes, $t = 19.48$, $p < 0.005$).
- every of our results was systematically favored ($> 97\%$ of the votes) compared to those of the commercial online virtual try-on; this does not come as a surprise, since all

TABLE II
VOTING RESULTS FOR VIRTUAL TRY-ON VIDEOS.

Preferences	with refraction, with reflection	without refraction, with reflection	with refraction, without reflection	without refraction, without reflection	SmartBuy-Glasses
with refraction, with reflection	-	62.50%	86.67%	87.50%	99.17%
without refraction, with reflection	-	-	74.17%	89.17%	100.00%
with refraction, without reflection	-	-	-	66.67%	97.50%
without refraction, without reflection	-	-	-	-	98.33%
SmartBuyGlasses	-	-	-	-	-

In the user study, we presented four variations of virtual try-on videos generated by our method and one screen capture from a commercial online eyeglasses store. The percentage represents preference of the row video over the column video, e.g., 62.50% of the participants favor video "with refraction, with reflection" compared with video "without refraction, with reflection".

our renderings account for the surrounding lighting and exhibit convincing shadows on the face.

Further, comments provided by some participants indicate that once they understood what the differences (i.e. refraction and reflection) between stimuli were, they were able to rank them quickly and consistently.

The user study results support the observation that our eyeglasses virtual try-on system, which takes into account refraction, reflection and shadows, create more realistic experience in comparison with existing solutions.

Performance. We render the video on a per-frame basis. The input videos are resized to 720p, with 30 frames per second. We use a 3.6 GHz Intel Core i7 CPU in this paper, and our unoptimized program runs on a Linux virtual machine. It takes 5 minutes on average to render a frame with prescription eyeglasses inserted. Two key parameters that influence the running time are: samples per pixel for ray tracing and samples in hemisphere for Monte Carol integration. For results in this paper, we use 2×2 (i.e., 4) samples per pixel and 160 stratified samples in each hemisphere. Our current rendering of prescription eyeglasses are off-line, but the process could be greatly accelerated by multiprocessing or even real-time using GPU.

Discussion. We present a virtual try-on system for prescription eyeglasses. Although our pipeline involves some manual interaction, i.e., in the eyeglasses positioning and lens mounting step and incident lighting capturing step, which takes twelve minutes in total, it could be automated. Eyeglasses can be positioned using affine transformations computed based on pre-selected feature points on face and eyeglasses 3d model [16]. Lenses can be mounted automatically by aligning with optical axis of the eyeglasses frame and fitting the lens center into the lens plane of the frame. The incident lighting could be estimated in real-time using spherical harmonics [23]. We insert the eyeglasses based on face tracking. While individual frames are well rendered, errors in pose estimation may result in wobbling eyeglasses, especially when people turn head around quickly. This could be alleviated by smoothed head poses. Mapping the rendering to GPU would make the system real-time. Future work might employ those alternative techniques to develop a robust real-time system.

VII. Conclusion

In this paper we present a system for virtual try-on of prescription eyeglasses, acting as a "virtual mirror", allowing users to try on a variety of eyeglasses with corrective lenses according to their prescription. The proposed augmented reality system generates a 3D representation of the corrective lenses mounted in the eyeglasses frame, and modifies the video sequence to virtually insert the eyeglasses through image-based rendering. Compared to existing virtual try-on systems, our approach simulates the refraction effects due to the corrective lens and takes into account reflections and shading. We present a user study assessing the perceived realism of virtual try-on videos generated with our approach and study the effects of refraction and reflection on the perceived realism. This eyeglasses virtual try-on system generates realistic results and could apply to web-based applications, e.g., a solution for online eyeglasses stores. We leave it as our future work to develop a real-time system by employing alternative techniques.

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