Synthesising Radiance Maps from Legacy Outdoor Photographs for Real-time IBL on HMDs

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***Abstract*—This paper presents a novel method to synthesise a high dynamic range (HDR) spherical radiance map (RM) from a single low dynamic range (LDR) legacy photograph of an outdoor scene. The synthesised HDR RM is then used for real-time image based lighting (IBL) to render 3D virtual objects with plausible illumination matching with the background outdoor scene. Seam Carving (SC) is utilised to extend the legacy photograph to a panoramic image having a wider field of view for both backdrop and RM. Since SC is a content-aware image resizing technique, it effectively preserves important details such as shape and location of the sun in the outdoor scene and minimises distortion while expanding. The boundary of the 360-degree panoramic image used as RM is refined to minimise the seam. The extended LDR RM is then converted into a HDR RM using our novel inverse tone mapping (ITM) that provides fine tuning to simulate sunlight fall-off for sunny outdoor scenes. The synthesised HDR RM provides believable real-world lighting for IBL. With the combination of extended backdrop and real-time IBL, our pipeline can provide a potential solution for augmented reality (AR) rendering via head mounted displays (HMDs), only from a single legacy photograph.**

I. Introduction

Due to the recent growth of consumer level head mounted displays (HMDs) such as the Oculus Rift [1], demand for suitable content for these devices is increasing. One of the important contents for HMDs is virtual reality (VR) and augmented reality (AR). In order to maximise the immersive experience of AR content on HMDs, the seamless composition of the 3D virtual object and the real-world environment is important. Image based lighting (IBL) [2], [3] has been used to emulate illumination of 3D virtual objects from the surrounding real-world scene captured by a 360-degree panoramic photograph. Ideally, the panoramic photograph can also provide an intuitive real-world backdrop for HMDs to cover the wide range of viewpoints arising from motion of the viewers head.

However, creation of such a panoramic image requires either a special-purpose camera, or a set of photographs captured from multiple cameras or angles followed by the post-processing to combine them. Especially, the image used for IBL is captured at various exposure levels to obtain the high dynamic range (HDR) output. Therefore, legacy photographs captured by a conventional camera setup cannot be used directly as a radiance map (RM) nor as a backdrop for HMDs due to their limitation in both field of view (FOV) and dynamic range.

The most commonly used RMs in IBL are panoramic outdoor scenes which emulate directional lighting from a long-distance surrounding environment such as a skybox. Synthesising HDR 360-degree panoramic RMs of the outdoor scene from conventional legacy photographs is highly demanding but estimating the uncaptured surrounding irradiance from a photograph of limited sight and dynamic range is challenging. Especially for sunny outdoor scenes, the synthesised HDR RM should preserve the location and shape of the dominant light source, the sun. Therefore, simple image resizing or inverse tone mapping operators have limitations to providing a proper solution.

Recently Karsch et al. [4] provide a novel solution for finding a believable RM of the given limited scene from an already captured HDR RM database. Although it provides plausible IBL effects, the selected RM is unlikely to precisely match the scene depicted in the photograph for highly specular illumination. Also, it requires a huge amount of extra HDR RMs in the database.

In this paper, we present a novel solution to overcome the above challenges. Our pipeline is mostly automatic and does not rely on a database. We adapt seam carving (SC) [5] to expand a legacy outdoor low dynamic range (LDR) photo to a panoramic image having a wide FOV for both backdrop and RM. Our novel approach can improve the SC algorithm to effectively preserve important details such as shape and location of the sun in the outdoor scene, and minimises distortion and seams to create a fluid 360-degree panoramic image. The extended LDR RM is then converted into a HDR RM using our novel inverse tone mapping (ITM) that provides fine tuning to simulate sunlight fall-off in a sunny outdoor scene.

Finally, the synthesised image provides a full HDR spherical RM which provides believable surround lighting to fit in with the original outdoor scene captured in limited view and dynamic range. By precomputing surface reflectance properties, virtual objects with many realistic material types can be simulated efficiently in real-time, making this application suitable for use on various platforms. The resulting IBL rendering reliably provides framerates of over 75Hz, as required for comfortable viewing on stereo HMDs. The final result is the IBL rendering of augmented 3D virtual objects providing believable surrounding illumination from a conventional legacy outdoor photograph. Correct application of the detailed additional steps will be explained in each section and the overall pipeline is shown in Fig 1.

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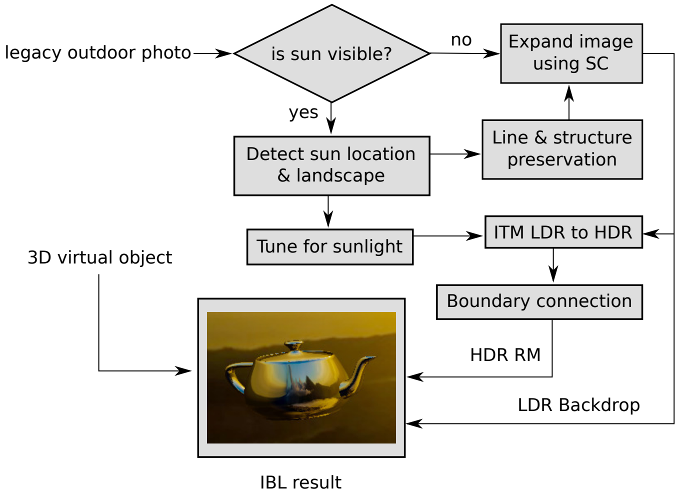


Fig. 1. Our system pipeline

II. Background and Related Work

For lighting the augmented 3D virtual objects into the real-world environment, one of the most realistic techniques is to use an HDR image as the RM. This technique, described early on by Miller and Hoffman [2], is called IBL. Debevec [6] used the technique to insert virtual objects seamlessly into real-world photographs [3]. This requires an HDR 360 panoramic image captured in the real-world scene where the virtual objects will be inserted. To photograph the 360 image, a light probe or fish-eye camera lens can be used. This technique usually requires multiple camera angles to be captured, which are then stitched together in special-purpose software to create the full 360 image. Multiple photographs are taken using differing exposure levels, which are then combined into a single HDR image. Once the HDR image is obtained, it can be used directly as a RM.

Estimating scene radiance from photographs is a long standing issue. Khan et al. [7] generate a RM from a standard LDR image by morphing it into a hemispherical image, which they show to be perceptually plausible. This method does not consider seam matching or image warping, both of which are particularly important features in highly specular objects. Karsch et al. [8] demonstrate seamless composition of 3D virtual objects into a single 2D image, with correct object alignment and lighting. A limitation of this method is that it requires user interaction to annotate the light sources in the image. Our system is fully automatic and produces a full 360 panoramic HDR RM from a single image. The result preserves the detail in the RM, allowing for a seamless composition of virtual objects with varying material types.

Karsch et al. [4] estimated RMs from legacy photographs by selecting from a large database of already-captured radiance maps. This removes the need to obtain a HDR radiance map directly from the original scene, which may be impossible for the legacy photograph. This allows lighting to match a much wider range of already existing photographs. The main drawback to this approach is that the selected radiance map is unlikely to precisely match the scene depicted in the photograph. Specular material types such as shiny metal will likely reflect an obviously incorrect scene, and as bright light sources are unlikely to match positions precisely they must be accounted for separately.

(a) Original Image

(b) SC

(c) SCLP

Fig. 2. Seam Carving (middle, bottom) applied to expand the original image (top). The bottom image also utilises line preservation (SCLP) for a smoother result.

The primary technique we will be using to create a radiance map from an input photograph is Seam Carving, which was first described by Avidan et al. [5]. It is a content-aware technique for resizing images by expanding or contracting the areas that have less effect on human visual perception of the scene. The version we use has been improved by Kiess et al. [9] and Ma et al. [10] to preserve macroscopic line structure in the image. The key idea is to avoid passing seams through a certain area repeatedly by accounting for the placement of previous seams when determining the next optimal seam.

For maintaining accurate sky lighting we detect and model the brightness of the sky from the input photograph. The sky model we use is the Hosek-Wilkie model [11] which produces realistic daytime skies by using interpolated values based on real-world captured data. We also use the modeled brightness values for inverse tonemapping [12] of the input to create the eventual HDR radiance map.

III. Creating Panoramic Images using Seam Carving

A. Seam Carving

The principle aim of seam carving is to modify the size of an image in a way that doesn't disturb the main features as perceived by humans. To do this we first must determine which parts of the image are more or less visually important.

As human vision is particularly sensitive to edges, we begin by utilising the Sobel first-derivative operator to find the gradient map

$$G(i,j) = |\frac{\delta}{\delta x} I(i,j)| + |\frac{\delta}{\delta y} I(i,j)| \quad (1)$$

where I is the intensity and G is the intensity gradient at each pixel of the image. Given this gradient map, we find seams to add (or remove) based on an energy function produced from G, calculated as

$$E(i,j) = G(i,j) + min \begin{cases} E(i-1, j-1) \\ E(i-1, j) \\ E(i-1, j+1) \end{cases} \quad (2)$$

where E is the desired energy function, i is the pixel coordinate in the primary seam direction (x for horizontal seams, y for vertical seams), and j is the pixel coordinate in the other dimension. A seam is defined as an ordered collection of pixels, such that pixel position increases by exactly 1 in the seam direction, and either -1, 0, or $+1$ in the perpendicular direction. This allows us to calculate the seam with the lowest energy by choosing the bottom or rightmost (depending on seam direction) edge pixel with the lowest energy value E, and iteratively choosing the next seam pixel according to the lowest energy value among the three pixels that can be chosen to extend the seam. Because of the choice of our energy function E, this will minimise the total cost

$$C(s) = \sum_{p \in s} E(p) \quad (3)$$

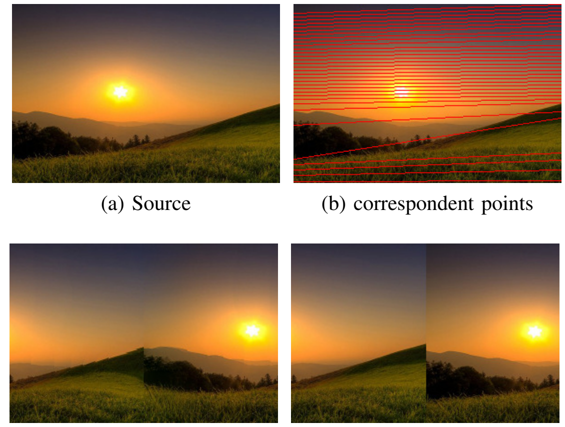
of pixels p in seam s, and our seam will thus tend to avoid areas containing high amounts of visual detail.

While this technique avoids high energy areas well, it can not guarantee that the contour of a specific object will not be distorted. To mitigate this, Kiess et al. [9] utilise Canny detection and a Hough Transform to detect lines in the image in order to preserve them. During each iteration of seam carving, if the seam goes through a detected line pixel, the energy of pixels adjacent to the seam-line intersection point is increased. Ma et al. [10] adjust the protection area based on the line slope for better line preservation, and this is the seam carving variant that we use in this paper.

Ma et al. use SC to shrink the image. Extending the image is more complex, and requires that all the desired optimal seams are found first. These are then duplicated simultaneously, taking into account the displacement of the seams as others are duplicated. Using this technique, we are able to extend a regular photo to a size applicable for use as a full 360°radiance map (see Fig 2).

B. *Synthesising a panoramic image for the radiance map*

Fig 1 shows the overview of our system. For sunny outdoor scenes, we need to preserve the location and shape of the sun, so if the sun is visible in the photograph, we estimate the field of view (FOV) to determine the how much we should extend in each direction. We then apply seam carving to find all of the optimal seams and rearrange the size. Shape preservation



(a) Source (b) correspondent points

(c) with boundary correction (d) without boundary correction

Fig. 3. The upper part shows the input source and the correspondent with left most and right most boundaries, marked with red line. The bottom shows the stitching two boundaries with and without the corrections respectively. After the operation of corrections, the result (c) shows less differences comparing with (d)

[10] [9] is considered in our system to maintain the line and shape structure in each iteration.

One main difficulty of this approach is that of matching up the boundaries of the image. When expanded to fill a full 360-degree horizontally, the image is likely to have a distinct and obvious seam where the two edges of the photo join. Consequently, we utilise thin-plate spline deformation [13] and Poisson image editing [14] to minimise the difference across the boundary transition.

Fig 3 illustrates the correction of the panorama boundary. We firstly use dynamic programming to find the correspondent points on two sides by matching pixels with similar value. Then we warp the image as in [13] so as to ensure that these points match up at the boundary. We add fixed correspondent points at the center of image and the top and bottom, avoiding any deformation there. Lastly, Poisson image editing [14] is applied to correct the color near the edge and make a seamless transition. We apply this over 10% of the image width to match smoothly without affecting central objects. The result Fig 3c shows the significant differences from Fig 3d. Seamless boundary stitching gives a display with minimal artifacts when parameterising on a sphere map for use as a radiance map, and display via HMD.

IV. Image based lighting in HMDs

Image based lighting is an effective technique for matching the appearance of virtual objects with a real-world backdrop [3], [6], [15]. Lighting a virtual object with the image of the scene itself will give the most natural composition between the scene and object. However, this usually requires a full 360-degree spherical or hemispherical capture of the environment. Furthermore, the image needs a higher dynamic range than that of standard photographs, especially for sunny scenes [12].

(a) LDR (b) tonemapped LDR (c) HDR

Fig. 4. Comparison of object lit with LDR image (left), with LDR-HDR tonemapped image (middle), and with HDR image (right)

Taking our panoramic LDR image produced via SC, we turn it into a radiance map with two primary steps. Firstly we create a HDR panoramic image from our LDR panoramic image by applying an inverse tonemapping operator. Secondly for photographs including the sun, we correct inaccurate illumination by matching a model for sky illumination to the original photograph, and apply this illumination model directly to our panoramic image. Once we have this resulting HDR image, we can use it for real-time image based lighting of 3D virtual objects for display via HMDs.

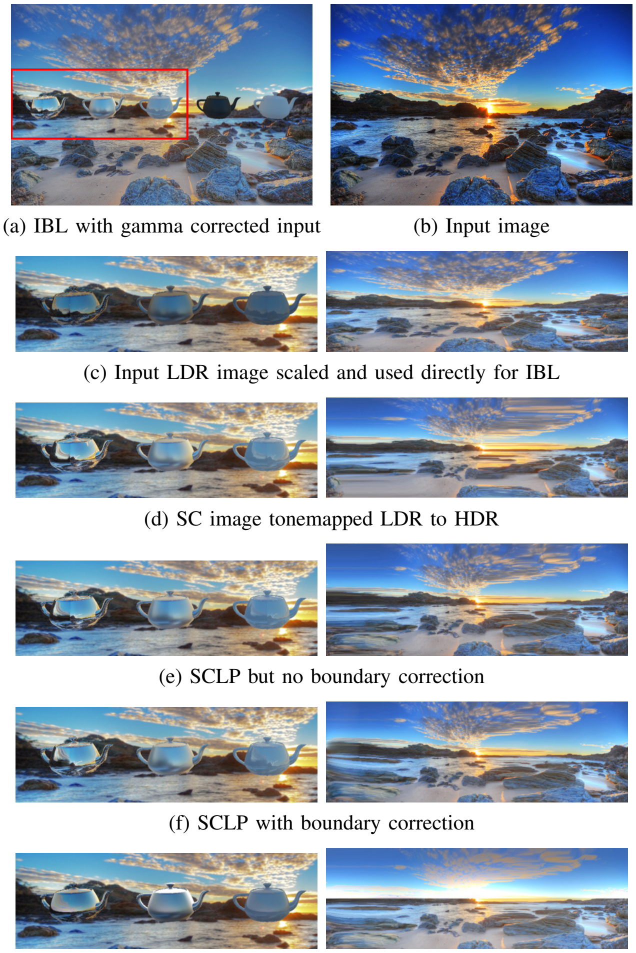
A. Inverse Tone Mapping LDR to HDR

Chalmers et al. [12] have shown that for virtual object illumination in AR, a LDR to HDR inverse tonemapping conversion can provide sufficient result that is not perceivable for human visual system compared with the IBL rendering using the original HDR RD. This gives believable lighting from our LDR input (see fig 4), which is necessary in order to match lighting to standard LDR photos. In our results we convert the input image to HDR by applying the tonemapping operator used by Chalmers et al., although we also found that other simple tonemapping operators produce similar results.

B. Fine tune for sky intensity distribution

Optionally, to correctly maintain sky brightness for images including the sun, we use the Hosek-Wilkie sky model [11] to estimate appropriate sky brightness. Parameters must be estimated from the original photograph, which we do semi-automatically with minimum manual adjustment. The horizon is automatically detected by searching for prominent horizontal lines in the image. The sun position in the sky is automatically detected by presuming the FOV of the original photograph. A brightness threshold is applied to the image, and the positions of the brightest pixels are averaged to give the detected sun position in the image. This is used in combination with the detected horizon to infer sun position in the sky. We then render a series of sky images using the Hosek-Wilkie model, with the sun position as detected, but other model parameters varying. The output which matches the input photograph most closely is selected. This can be selected manually or through an error minimisation process.

Once we have a sky model that matches the input photograph, we apply the intensity distribution from the model to the sky of the input image. This ensures that the brightness fall-off of the radiance map accurately matches that of real skies, otherwise the image would be too bright, containing large sections that were previously much closer to the sun than they now should be. We simply map the intensity of the sky model directly to the top half of the radiance map previously obtained by seam carving, but a possible improvement would be to manually or automatically create a mask so that it was only applied to the sky region.



(a) IBL with gamma corrected input (b) Input image

(c) Input LDR image scaled and used directly for IBL

(d) SC image tonemapped LDR to HDR

(e) SCLP but no boundary correction

(f) SCLP with boundary correction

(g) SCLP with boundary correction and sky model matching

Fig. 5. Comparison of IBL results using the indicated source as the radiance map. Virtual objects are displayed in front of a cropped region of the gamma corrected original image. Please focus to check illumination differences of the teapots.

C. Real-Time IBL in HMDs

Given the modified panorama constructed according to the LDR-HDR tone mapping and sunlight fall-off, we can calculate diffuse and glossy irradiance maps as in [15]. These can be used to efficiently render diffuse and glossy specular reflectance properties, which can be combined to believably emulate many real-world material types. Please refer the detail of the implementation from the reference paper [16].

Fig. 6. Radiance map displayed as panoramic backdrop for HMD. Left to right: image simply scaled; SC; SC with boundary correction.

V. Results

We tested our results with overcast, cloudy and clear sky input images, displaying on an Oculus Rift DK2 and via standard display. Results for our tested scenes can be seen in Fig 7, in which we display virtual teapots and bunnies in front of the original outdoor photograph, lit both with and without our pipeline. Illumination is noticeably more correct using SC than simple image scaling, and our boundary matching method makes the reflected seam much less noticeable.

We also tried using the radiance map as backdrop on the Oculus, and found that the images produced by SC were able to be used as a full panoramic backdrop for fully immersive display (see Fig 6). Simple scaling of the original image was also tested, but it appeared wrong with the backdrop scene appearing too large and distorted for comfortable viewing.

VI. Conclusion

We demonstrate an effective technique for converting real-life standard resolution LDR outdoor photos into a form suitable for use as radiance maps in image based lighting. Images expanded in this way are also suitable for display via HMD, making them applicable for creating immersive AR content using only a single standard definition photograph. 3D virtual objects lit by the radiance map created using this method are illuminated consistently with the original photographed scene.

Limitations: One of the limitations to this technique is that it cannot be used for indoor scenes, specifically scenes with multiple prominent light sources will likely be distorted and no longer illuminate properly; we may extend our sunlight refinement module to adapt this case in future work. Another limitation is that we cannot estimate illumination of sunny scenes without the sun in the photo, allowing the position to be known. Also photos with large starburts around the sun are not suitable using the current method, but a more sophisticated sun detection algorithm may be considered as future work.

Even acknowledging several limitations, and that more improvement at each stage of the pipeline is feasible, we claim that our method provides a novel approach and promising solution for converting existing static LDR content such as legacy outdoor photographs into a form suitable for use in IBL and backdrops in HMDs.

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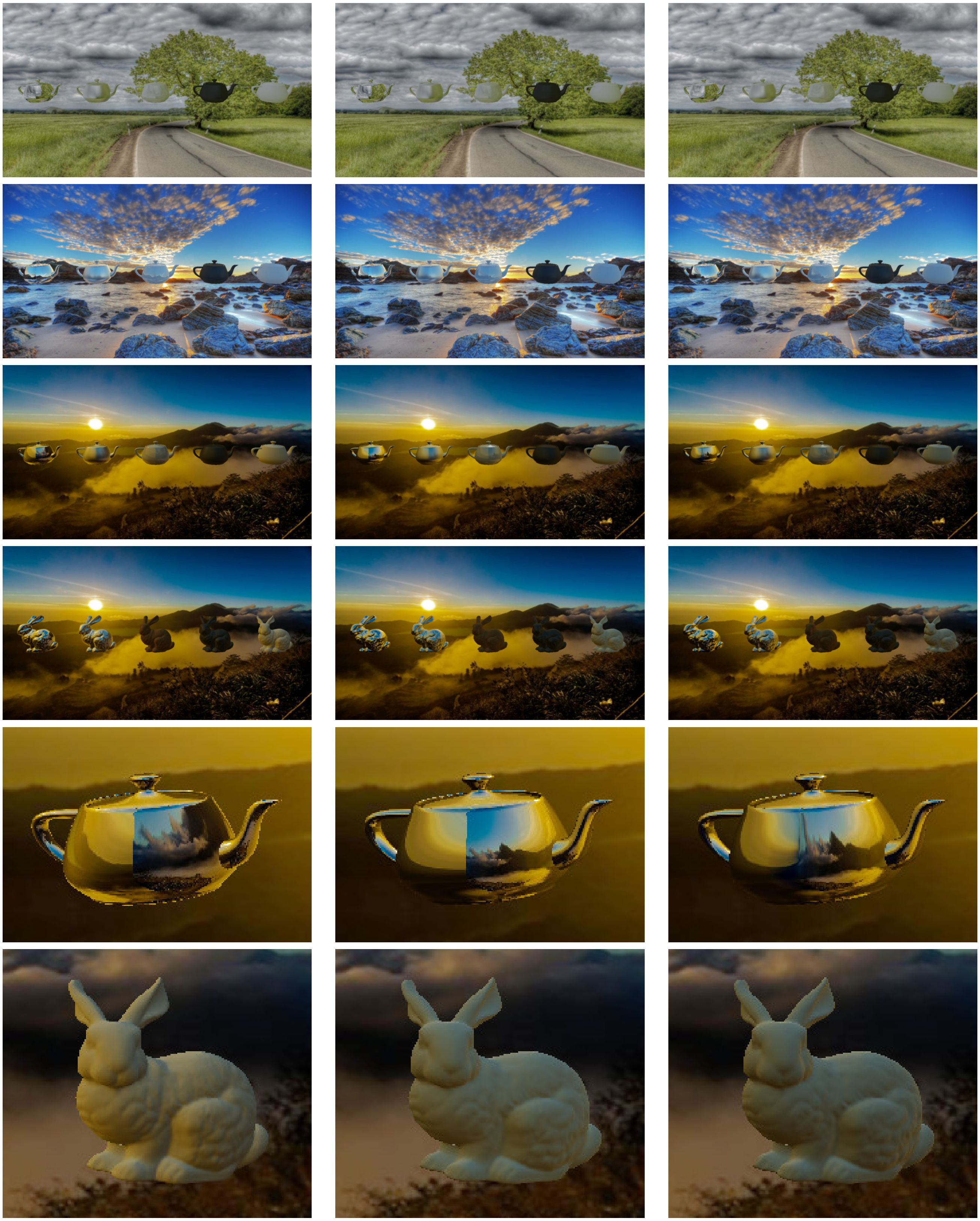

Fig. 7. Virtual objects illuminated with SC placed in front of the legacy photograph. The left column is illuminated with a scaled version of the original photograph. The middle is illuminated using only seam carving. The right column is illuminated with boundary correction.