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High Dynamic Range Video for Cultural Heritage Documentation and Experimental Archaeology

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Abstract

Video recording and photography are frequently used to document Cultural Heritage (CH) objects and sites. High Dynamic Range (HDR) imaging is increasingly being used as it allows a wider range of light to be considered that most current technologies are unable to natively acquire and reproduce. HDR video content however has only recently become possible at desirable, high definition resolution and dynamic range. In this paper we explore the potential use of a 20 f-stop HDR video camera for CH documentation and experimental archaeology purposes. We discuss data acquisition of moving caustics, flames, distant light and in participating media. Comparisons of Low Dynamic Range (LDR) and HDR content are made to illustrate the additional data that this new technology is able to capture, and the benefits this is likely to bring to CH documentation and experimental archaeology.

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1. Introduction

The dynamic range of light available in the real world is vast, and the Human Visual System (HVS) is able to cope with this wide range by adapting to various lighting conditions. Current conventional capturing and display technologies do not support the full dynamic range our eyes are capable of seeing. The research field in computer graphics that deals with all aspects of acquiring, storing processing and displaying High Dynamic Range (HDR) content is known as High Dynamic Rage Imaging (HDRI). HDRI adds greater accuracy in lighting than Low Dynamic Range (LDR) content is able to provide.

Still photography and video recording are popular approaches to document Cultural Heritage (CH) environments and objects, however off-the-shelf technologies are unable to natively capture and deliver HDR content. Current consumer single-image and video cameras only support the light dynamic range of a single exposure. It is likely that HDR recording equipment and displays will play a larger role in the future because of current technologies' limitations.

In this paper we employ the HDR Video Camera prototype presented at Emerging Technologies at SIGGRAPH Asia 2009 [CBB*09] to illustrate uses of HDR video for CH documentation and experimental archaeology. We discuss site documentation, acquisition of moving caustics, flames, distant light and the interplay of light in participating media. A discussion on benefits and limitations of HDR video documentation compared an ordinary LDR video camera is also presented.

The paper is organised as follows: first, camera documentation is reviewed. This section covers the purpose of video documentation, limitations in existing cameras and related work. Section 3 details the various uses of HDR video and in particular for CH applications. We give examples of what can be investigated through HDR video in a CH site in section 4 and also present a discussion in section 5 before the conclusions in section 6.

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2. Background - Camera Documentation

Camera technologies play a key role in documenting CH as it allows for 2D documentation of shape, colour and light of objects at real world locations. In addition to a traditional photographic record, still images through Digital Single-Lens Reflex (D-SLR) photography can be edited to create texture maps for virtual 3D models. Environment maps can be used to represent the distant scene, and environment maps acquired in HDR can be used for Image-based Lighting (IBL) [Deb98] to relight these models. Reflectance Transformation Imaging (RTI) [MGW01] allows for image-space interactive relighting of objects. Other uses of camera technology include photogrammetry and image-based modelling [DTM96].

Visual documentation enables historians to refer to particular sections or entire objects in greater detail than words can often express. The advent of D-SLR photography has pushed cameras to reach greater image resolutions. Super resolution photography nevertheless, needs to be assembled manually. However, for general data acquisition, cameras have arguably reached a point in which manufacturers are starting to turn to improving other camera functions and abilities. Collecting HDR content through greater ranges of bracketed data acquisition is one such improvement. LDR photography can be merged to form HDR images [DM97], allowing for the possibility to document the visual impact of interplay of light in such environments at greater extents.

Camera body hardware determines image resolution and colour acquisition capabilities. However, from a user setup standpoint, the quality of data in an image (or sequence of images) captured by a stationary camera is dependent on four attributes set up prior to image acquisition. First, shutter speed/integration time determine the duration a camera spends to capture each image. The more time light has to pass through during that timespan, the more exposed the photograph becomes. Second, the aperture is a hole through which light passes through inside the lens. The bigger the opening, the less time it takes to obtain a satisfactory image. However aperture settings may cause depth-of-field problems, leaving unfocused objects blurry. Third, the ISO setting controls how sensitive the camera's image sensor/Charge-Coupled Device (CCD) is to physical world light. Greater sensitivity increases presence of grainy noise in a photograph. This is especially the case for low lighting conditions. The ISO setting should in practice be at the lowest possible value to decrease noise. Finally, the lens optics chosen determine how light enters the camera along with the amount of light. We can say that a larger lens with a smaller field of view allows less light to enter the camera. The benefit of using such lenses however include the ability to zoom great distances.

Clear/focused images at the mid-range exposure allow for best acquisition of LDR content. Most cameras today will have automatic light meters that adjusts the camera settings to best suit the needs of given lighting conditions. Video cameras allow for documentation of CH environments from consecutive frames of images, and a minimum of 24 Frames-Per-Second (FPS) is necessary for the human eye to seamlessly interpret the images as natural motion.

Video and single-image content both have advantages and disadvantages. Still photography allows for more control over the camera and its settings. Furthermore, planning needs to be an important part of the data acquisition pipeline. Most concepts from single image photography translate directly to video. The primary difference is the addition of temporal data. Motion blur due to fast motion can be interpreted correctly by the human eye in video. Temporal data makes video recording helpful in delivering a sense of spatial awareness of the environment, more so than single photograph often can provide, especially if the camera moves in physical space. Figure 1 shows example frames from a video taken inside Panagia Angeloktisti; a Byzantine church in Cyprus. The video starts at the western entrance and moves towards the altar inside Panagia Angeloktisti. By moving at a walking pace, the viewer obtains spatial awareness cues not available with single photographs.

One of the first attempts at HDR video was presented by Waese and Debevec [WD02] as data acquisition of sequential light probes for IBL purposes. This was done by altering a five point multi-image filter. A faceted lens was used to create a kaleidoscope effect and divide the image into five identical regions, four at other stop values (3, 6, 10 and 13). It was placed on a video camera that was mounted along with a mirrored ball on a span which ensured the distance between the camera and the ball never changed. Kang et al. demonstrated the acquisition of HDR video using a standard 8-bit sensor [KUWS03]. The approach consists of three main parts; automatic exposure control, HDR stitching across neighbouring frames and tone mapping (see section 3) for viewing. Another camera was presented later by Unger et al. [UGOJ04]. It acquired light probe images with a resolution of 512×512 pixels using a set of 10 exposures covering 15 f-stops at an HDR frame rate of up to 25 frames per second. Light probe acquisition along camera motion paths can render synthetic objects moving in complex lighting environments. HDR video can also be employed for photometric measurement of illumination [UG07].

3. Applications of HDR Video

Light is measured in several ways. Photometry is useful for measuring visible radiation as weighted by the photopic response of the human eye. It deals with the perception of brightness from light at various wavelengths, and not perception of colour itself [AMHH08]. Luminance is a photometric measure given in candela (power emitted by a light source in a given direction) per metre square (cd/m^2). Surfaces lit by starlight may have a luminance level of approximately $10^{-3} cd/m^2$, while scenes lit by sunlight are close to $10^5 cd/m^2$ [LCTS05].

Figure 1: *An example of a CH site documented with LDR video. By starting from the western entrance, and moving towards the altar at a walking pace, the viewer obtains spatial awareness cues.*

The addition of HDR video content is useful in CH research for several reasons. Firstly, the extended light range collected is valuable in the pursuit of understanding and recreating the past through experimental archaeology. Secondly, it allows for temporal data acquisition of light. This enables documentation and investigation of movable light sources in areas in deep shadow or intense sunlight, colour properties of artificial light sources as well as the interplay of light through participating media. This accurate data can be reused for virtual archaeology applications.

Thirdly, video is a significantly faster approach to record data compared to traditional photography. Simplifying the data acquisition pipeline enables more measurements or video segments to be captured, in addition to reducing the potential of human error in data collection. Combining LDR photographs to HDR is a laborious process as it requires capture and processing of multiple LDR content. Software such as HDRShop [Tch01] or Picturenaut [MB07] exist to simplify this process. However, this doesn't make the pipeline automatic, and demands a human being to pay attention during all stages of data capture and process. Commercial solutions allow for native HDR photography acquisition, such as Panonscan [pan07] and SpheroCam HDR [Sph02]. Each photograph is captured by (automatically) combining multiple exposures and can take a few minutes to an hour to capture a single image. During this time however, objects may have moved or light conditions may have changed which can cause artefacts in the resultant HDR image.

A major problem after acquiring HDR content is the display of it. HDR video and still images cannot be properly displayed on commonplace monitors today because these are unable to deliver this high dynamic range. Tone Mapping Operators (TMO) attempt to appropriately map wider ranges of light to LDR display technologies [DCWP02]. Experimental HDR displays are currently being used by various research institutes and are expected to appear on the market at affordable prices once the technology has matured. The inverse problem of expanding the range of already existing LDR images and video is possible. This is known as Inverse or Reverse Tone Mapping [BDA*09]. Inverse Tone Mapping Operators are nevertheless unable to generate as accurate results as actual acquired HDR content.

3.1. Camera Specifications

The HDR video camera we have used in this paper acquires 20 f-stops up to 30 FPS in full High-Definition (HD) (1920 × 1080) resolution. Figure 2 shows a photograph of the HDR camera setup. Each raw data frame stores 15.8 MB of data, making 30 frames of raw data per second become 474 MB per second. The camera uses a fiber coupled storage unit and is capable of recording over 5 hours of data. The frames are converted to OpenEXR [Ind03] frames. The EXR images are approximately 7 MB in size per frame; 210 MB per second. Compression algorithms, such as that made available to this work [goH10], help make these substantial data files manageable.

Figure 2: *A photograph of the HDR video camera setup.*

4. Documentation and Experimental Archaeology

4.1. Site Documentation

Investigation of areas in deep shadow and sunlight through accurate documentation may provide insights into how sites were once used. For static images such as Figure 3, traditional D-SLR photography merged to HDR from LDR may be satisfactory. However, even static images would need to be displayed on HDR displays in order to represent the image as closely as the human eye would perceive them in reality. Tone mapping can help in this regard if no HDR display is available [LCTS05]. However, tone mapping operator can give results of varying quality, making Tone Mapping useful, but still difficult to completely recommend for CH documentation. Details about the scene can appear at various exposures while other details disappear. Figure 3 illustrates uses of HDR for site documentation; the visual impact of HDR images at various exposures (top) and tone mapped (bottom). The photograph is of a Byzantine church located in Cyprus named Panagia Angeloktisti.

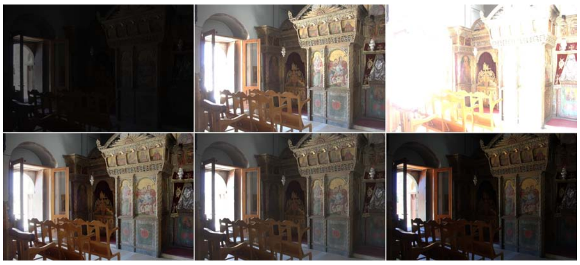

Figure 3: *Top (left to right): A D-SLR HDR image displayed in LDR at various exposures: 1) Underexposed 2) Middle exposure and 3) Overexposed. Bottom (left to right): Tone mapped LDR images 1) Reinhard and Devlin [RD05], 2) Ward [War94] and 3) Drago et al. [DMAC03].*

False colour is a simple approach to visualise ranges of light in an image. Three colour signal intensity per pixel is represented by RGB values. Rather than displaying the colours to form an image, we display meta data of what the colours represent. In Figure 4, a false colour comparison is made to visualise the range of luminance in an HDR image.

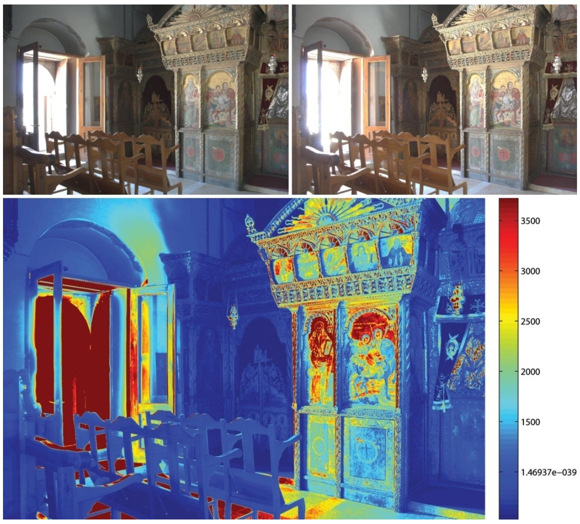

Figure 4: *D-SLR photograph example. Left: HDR, Right: LDR middle exposure, Bottom: HDR False colour in* cd/m^2.

4.2. Flame

Flames were a major source of lighting in the past that were created from arbitrary items or carefully selected ingredients. This was done in order to create a specific visual perception of the environment or for practical applications. Devlin and Chalmers [DC01] discuss an experimental archaeology approach to recreating Roman flames. Video footage of a flame can substitute its shape instead of using tessellated geometry, splines or particle systems. The shape can be represented as an impostor for the real flame as video using a simple green-screening technique, allowing for superimposing of the flame section in video footage into a virtual environment. Green backgrounds should be chosen for flames (and not blue) as the area close to the wick is often blue. Superimposing the HDR video flame would allow more accurate light values, especially used in conjunction with an HDR display that can reproduce these correct values. In a virtual environment, these values can be recreated using spectroradiometers [HMD*09]. Only the position from which the video footage was taken from will be valid (as with any impostor), unless multiple cameras acquire data from several positions. Figure 12 shows an example of a flame at various exposures. An HDR video camera becomes especially useful in this regard. It allows investigation of subtleties in flame light created using experimental archaeology. HDR and LDR footage of flames will reveal different visual impacts at various exposures.

Caustics are concentrations of light from reflected or refracted by curved surfaces. Typically, they are generated from light interacting with water, metallic objects or transparent objects such as glass. Scenes with moving objects or moving light may generate moving caustics. Because of the movements, this can be difficult to record as D-SLR HDR. Circumstances in which moving caustics are important include caustics from water pools or moving transparent or reflective containers that light interior environments; one example being downward caustics as simulated by Kider et al. [KFY*09]. Figure 5 shows a false colour comparison for a scene containing caustics. These values were confirmed by comparing the light intensities of the flame with spectrophotometer data.

Combining LDR images of moving light sources such as caustics is considerably difficult as it may cause banding-like artefacts, or in the case of flame illumination ghosting as illustrated in Figure 6. This can be removed by ghost removal algorithms [PH08, MPC09], but adds a layer of complexity to the pipeline, and complete removal of ghosting cannot be guaranteed. Capturing HDR video content at 30 FPS is fast enough to minimise such ghosting artefacts within most scenes.

4.3. Participating Media

Some past environments included the intentional and unintentional presence of fog, smoke or dust particles. These

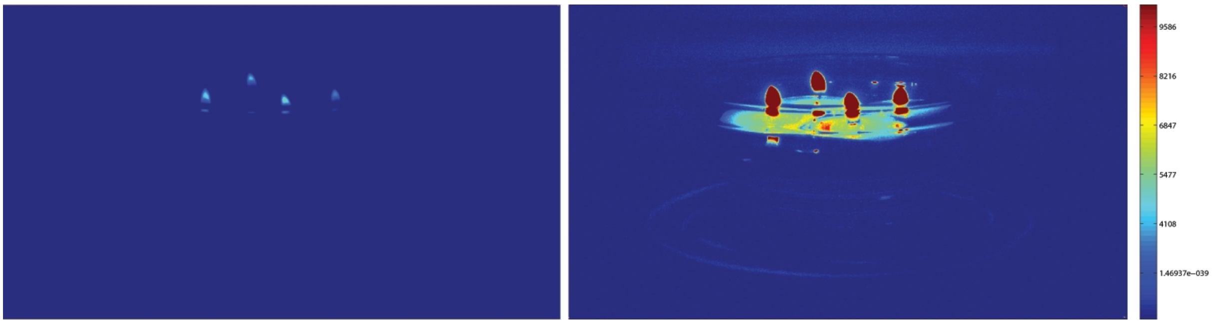

Figure 5: *Candle light and caustics. Left: LDR false colour, with no caustics. Right: HDR false colour image from the video camera. Caustics appear much clearer.*

Figure 6: *An example of caustics acquired by assembling LDR images to HDR. If the flames and water are not still enough, artefacts become apparent.*

elements can significantly alter the visual perception of an environment dependent on the time of day. Figure 7 is an HDR photograph example of sunbeams entering the Red Monastery in Egypt. Light shining through the window enters the building at various angles depending on time of day and year. The sunbeams are only visible at middle to greater exposures, however the outside is only fully viewable at lower exposures. To our knowledge, the documentation and analysis of participating media in a CH context is still a largely unexplored topic. Gutierrez et al. [GSGC08] discussed the importance of participating media from a CH reconstruction and simulation standpoint. They simulate the participating media using heuristics. Empirical data recorded with HDR video can potentially help improve these heuristics, see Figure 8 for an example.

Larger dust particles can become highly visible in interior environments, especially if there is great difference in contrast present in the scene. Moving dust particles and smoke in particular are dynamic elements of a scene that need to be taken into consideration. Static HDR photography can capture some of these instances of light interaction, such as the sunbeams in Figure 7. Faster moving and more visible participating mediums such as smoke are more difficult to acquire. Smoke can stem from burning materials such as candles, wood and incense, and can be recreated through experimental archaeology approaches. Clouds and fog are sky elements that deliver great levels of contrast. If the sun is behind a thick layer of clouds, the thickest sections may remain dark, while less condense areas will be lit. While not particular immediately associated with CH, clouds can also have an impact on the visual perception of a CH site. Sites placed in higher locations such as mountains where clouds can be seen at ground level and coastal environments will be prone to greater occurrences of fog or clouds. Their visual impact on CH environments can also be investigated through HDR video.

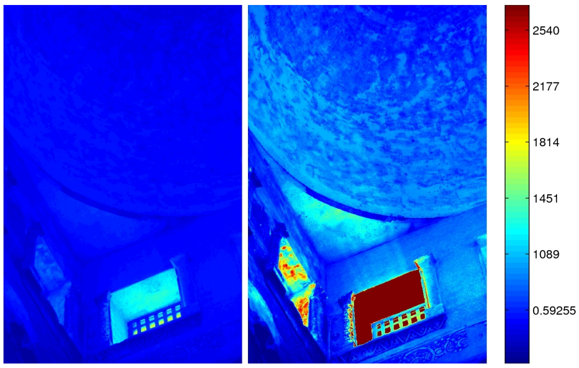

Figure 8: *Figure 7 in false colour. Left: LDR. Right: HDR. The presence of sunbeams is significantly clearer in the HDR false colour representation.*

4.4. The Distant Scene

Sky illumination analysis is largely unexplored for CH applications. This is likely due to the fact that it is impossible to recreate past sunlight, unless simulated through heuristics in virtual environments. Results are considerably difficult to validate as the modern scene and astronomical data are the

Figure 7: *D-SLR photograph example of sunbeams entering the Red Monastery in Egypt. Sunbeams are only visible at middle to overexposed photographs. The exterior however, is only visible at lower exposures.*

only points of reference available. The predictable nature of daylight and most night skies makes analysis of the distant scene (represented as the sky) of a CH site arguably the least important element in terms HDR video.

Stumpfel et al. [SJW*04] and Happa et al. [HAD*09] describe data acquisition methods that have been employed for CH purposes. Both methods suggest uses of light data acquisition of modern day lighting for CH environments. Traditional IBL from HDR photography will in most cases suffice for scene illumination analysis. An obvious extension is sequential environment map to represent the far distant sky and employ them for CH reconstructions. Debevec et al. [DTG*04] demonstrated acquisition of light probes of the sky around the Parthenon at several intervals. However, there are certain instances that may be subjected to different skies, in which case static light is simply not good enough. Examples of this include the areas subjected to very strong winds such as environments located on the seaside or in mountain terrains. Other examples include solar eclipses, midnight sun and Auroras. However, these are rare occurrences and not commonly considered in typical CH contexts. See figure 9 for an examples of acquired sunlight and simulated sunlight.

Figure 9: *Top: Sunlight and clouds in various exposures. Bottom: A mirrored hemisphere of an interior environment; here, a multi-light cabinet simulating sunlight.*

The use of sequential light probes for incident light fields is not a novel concept. Their uses for CH virtual relighting however should be further investigated, as they can be used for investigate changes in lighting conditions of interior and exterior of CH environments. Recreating past environments with distant scenes represented as HDR video light probes allow for real world re-enactments (from an illumination standpoint) that can then be recorded and reused for experimental archaeology purposes, see Figure 10.

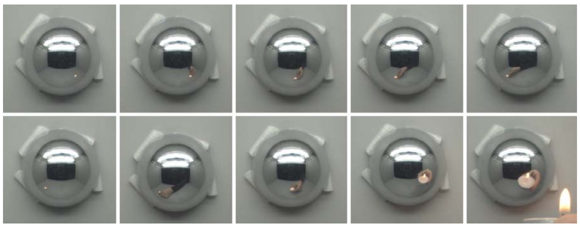

Figure 10: *Frames of half a mirrored sphere with a moving light source in a multi-light cabinet simulating sunlight. This illustrates potential uses of moving light sources for real-time light probes. A moving flame can be re-enacted from a real world scenario before relighting a virtual objects occupying the same space as the mirrored sphere. Documentation of sunlight can potentially also be done in this manner.*

5. Discussion

The main advantage of HDR video is the extended information in light provided. The temporal advantages of HDR recording has not yet been fully explored. Examples of items with subsurface scattering properties, such as gemstones or transparent liquids may provide new insight to the past. Highly specular materials such as gold mosaics combine subsurface scatting through glass with specular highlight from metallic surfaces. These are attributes that can be well-recorded through general HDR photography approaches, however movements in the lighting or object imminently makes HDR video an attractive addition to the analysis pipeline.

An important element to remember with HDR is the fact that employing HDR technologies or methodologies does not guarantee wider ranges of light during data capture. A wider light range will be acquired, but the extent is scene dependent. For instance, uniform intensity of light in a scene will decrease the overall span of dynamic range. More light does not translate to greater dynamic range. Both dark and

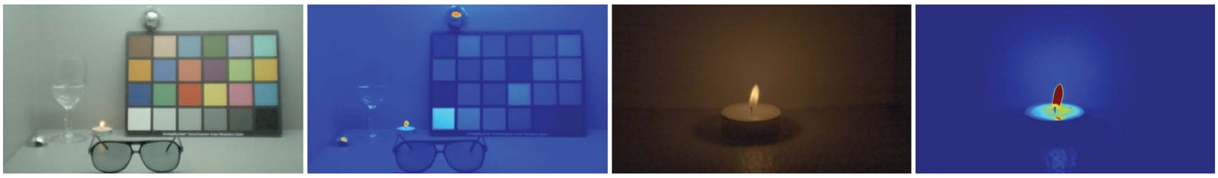

Figure 11: *Demonstrating scene-dependency in HDR. Left: Evenly lit items in a box with simulated sunlight will not hold a greater dynamic range. Right: Close-up of a candle lit in a fully dark room will hold a greater dynamic range.*

light must interplay in an image for HDR to be useful. In order to make the most out of HDR photography and video content, it is vital to use HDR technology to its strengths and select appropriate scenes which make it worthwhile to use HDR. The left image in Figure 11 shows various evenly lit items placed in a box that simulates sunlight, leaving little dynamic range to be recorded, except for the areas occupied by mirrored spheres and candles. Nevertheless, as these smaller items take up little space of the overall image, less information about their dynamic range is acquired. A single candle lit in a dark room will contain a vast dynamic range, particular details will be well-captured if the camera is close enough.

By adding a gamma response curve (e.g. gamma 2.2) it is possible to display LDR content at various exposures as a simple approach to expand light information. This can in some cases give LDR images convincing HDR-like results, similar to inverse tone mapping. In HDR however, information about the light will remain visible even at lower exposures, unlike LDR images that will darken the overall image only, as illustrated in Figure 12.

Figure 12: *Top: LDR video frame (with added gamma response curve 2.2); as the exposure decreases, more details are lost. Bottom: Same scene, recorded as HDR video. Top/Bottom are displayed at the same stops. At lower exposures, light information in HDR frames remain visible.*

5.1. Current Limitations

Currently the use of the HDR video camera is limited to controlled environments for several reasons. These include: physical size of the camera setup, data storage size necessary for HDR video, the fragility of fiber optic cables (necessary for transfer speeds), and cost of the camera. At considerably darker environments (night sky), the camera will struggle to acquire noise free images. Conventional LDR photography will also struggle in this regard. The time it takes to acquire a single middle exposed photograph, sky objects such as stars, (brightly shining) planets and the moon will have changed their positions. Its limited portability currently prohibits extended experimental use, including tests involving translation of the camera in physical world space. Currently, the limitations displaying these results is also dependent on output capabilities of the display in use.

6. Conclusions and Future Work

In this paper we have investigated some of the immediate benefits and limitations of novel HDR video recording equipment for CH documentation and experimental archaeology. HDR video permits us to document greater ranges of light for dynamic scenes. The visual perception of a site, flame light, skylight, and participating media are all relevant and useful to study to get better insight of the past through experimental archaeology. Environments with moving objects or light sources would also benefit from HDR video capture. This includes items such as luminaires, moving ornaments, objects with subsurface scattering properties or liquids such as water.

Through experimental archaeology we can collect empirical data that may provide more information about the acquired data than current technologies can acquire. However, despite its benefits in better data acquisition; HDR video technology needs to mature in order for it to become a viable means for archaeologists and art historians to be able to regularly use in their work pipeline. The paper should be considered a proof-of-concept for future research. All HDR video in this paper has been acquired under very controlled circumstances. We aim to further investigate uses of HDR video both within and outside the CH domain.

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