ABSTRACT

FVV Live is a novel real-time, low-latency, end-to-end free viewpoint system including capture, transmission, synthesis, and visualization and control on a mobile terminal. The system has been specially designed for low-cost and real-time operation, only using off-the-shelf components.

Index Terms— Free Viewpoint Video, Real-Time

1. INTRODUCTION

Immersive video technologies have experienced significant development over the past few years. One such technology is Free Viewpoint Video (FVV), which enables users to navigate a scene by placing a virtual camera ideally at any viewpoint of their choosing. This functionality has the potential to improve user experience in many applications such as broadcasting of any kind of events (sports, performances, etc.) or interactive video communications (telepresence).

As it is typical of 3D reconstruction systems, FVV systems need to see the 3D scene from many reference viewpoints (i.e., cameras) and integrate the information from them to synthesize a model or virtual view of the scene. However, unlike static 3D reconstruction applications, FVV systems need to simultaneously capture many synchronized video streams, which means that the sheer amount of input data easily exceeds the capabilities of any single computer. Therefore, FVV systems are inherently distributed, they need distinct nodes devoted to capture and synthesis, and some means to efficiently encode and transmit data among them.

Thus, the design and development of FVV systems presents a number of challenges regarding video quality, cost, and other functional requirements such as real-time operation, which are frequently at odds with one another. Clearly, high video quality benefits from having more and higher resolution cameras, but that increases the cost and the amount of data to be transmitted and processed, making it (even) more difficult to meet real-time constraints, which is already hard with few cameras due to the high computational complexity of typical view synthesis algorithms. In fact, expensive systems in commercial operation such as Intel True View [1] or 4DReplay [2] have been designed to maximize visual quality but at the cost of sacrificing real-time operation despite using tens of processing nodes.

In this paper, we present FVV Live, a novel end-to-end real-time, low-cost, FVV system that coordinates several nodes covering the various stages of the system, from capture to transmission, synthesis, and finally visualisation and control from a mobile terminal. FVV Live was conceived from the outset with the two key constraints of low-cost, only resorting to consumer-grade electronics, and real-time operation. These two constraints have informed many of the decisions taken during the design and development of the system. While other systems have been proposed in the literature or in the industry, FVV Live remains, to our knowledge, the only system operating in real-time and, furthermore, at a substantially lower cost than other proposals.

2. CAPTURE AND TRANSMISSION

The first stage of the FVV system is the capture of video streams from the scene. Stemming from the low-cost requirement, we evaluated several consumer depth cameras, but most of these devices project infrared light patterns. While this is perfectly adequate for a single camera, whenever multiple such cameras operate simultaneously, their infrared light patterns projected at the same time on the scene interfere with one another, which drastically decreases the quality of the depth estimation.

Consequently, we chose the Stereolabs ZED cameras, which estimate depth thanks to a purely passive approach, and therefore can be used together with any number of them at the same time. Figure 1 shows our capture setup with nine ZED cameras. Professional multi-camera setups typically use hardware dedicated clock sources to synchronize the capture of frames among all cameras, but the ZED camera, which is a consumer-grade device, offers no such facility. Each camera is simply attached to the controlling computer via a high-speed USB connection.
USB 3.0 link, so we have developed our own software synchronization scheme using timestamps and a shared clock source, distributed using PTP (IEEE 1588-2002).

![Fig. 2. Sample frame, colour (l) and depth (r) information.](image)

Each camera yields regular pictures plus their corresponding depth estimation (not actually computed by the camera, but by software on the GPU of the controlling node), as shown in figure 2. The sequence of regular pictures is compressed with standard (lossy) video codecs, which cannot be blindly applied to depth data. Firstly, more than 8 bits per pixel are required to maintain proper reconstruction quality and, furthermore, lossy coding schemes are unacceptable because the structure of the scene would be altered. Therefore, we have adapted a lossless 4:2:0 video codec to transport 12 bits per pixel of depth information by carefully arranging depth data from each $2 \times 2$ pixel substructure as shown in figure 3.

![Fig. 3. Adaptation of $2 \times 2$ pixel cells to 4:2:0 sampling structures to transport 12 bpp of depth data.](image)

### 3. SYNTHESIS AND VISUALIZATION

A dedicated server receives video and depth streams from the capture nodes and generates the synthetic view according to the viewpoint and camera orientation selected by the user. In principle, if enough computational power and network capacity were available it would be desirable to use as much information about the scene as possible to compute the virtual view. However, even the most powerful computers cannot tackle problems like multi-view stereo [3] in real-time, so there is not much value in transmitting all available data. In recognizing this fact, and considering that real-time operation is irreplaceable for us, we dynamically select the three reference cameras closest to the virtual viewpoint, as shown in figure 4, warp them to the virtual viewpoint using DIBR techniques, and mix their contributions to produce the synthesized view of the foreground. Although we only use the three closest cameras to synthesize the view, we actually transmit the five closest to ease handovers, having the cameras that will be needed next as reference “on call”.

![Fig. 4. Dynamic selection of reference cameras for the virtual view synthesis.](image)

To reduce the amount of data to transmit and process, we observe that the colour of the background may change over time due to shadows or illumination changes, but not its structure (depth). Consequently, we can afford to generate a detailed model of the depth of the background during system calibration (offline) using techniques that are too costly to be used in real time (e.g., Shape from Motion, Multiview Stereo), so that during online operation we need to send depth information only about the foreground. Finally, we synthesize the virtual view using a combination of layers from both background and foreground information to produce a natural result at reduced computational cost.

![Fig. 5. Synthetic view of the same instant shown in figure 2.](image)

Thanks to its careful design and optimization, FVV Live is capable of delivering good quality results, as shown in figure 5 (see https://www.gti.ssr.upm.es/fvvlive for video demos), while maintaining real-time operation at Full HD resolution at 30 fps.

### 4. REFERENCES

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