HOLOGRAPHICALLY DISPLAYING LIVE SCENES INCLUDING THREE-DIMENSIONAL OBJECTS

Abstract

Methods, apparatus, devices, subsystems, and systems for holographically displaying live scenes including one or more three-dimensional (3D) objects are provided. In one aspect, a method includes capturing optical holograms of a live scene, digitizing/processing the optical holograms, and holographically reconstructing the live scene based on the digitized/processed holograms. In another aspect, a method includes capturing images/videos of a live scene, computing corresponding holograms, and holographically reconstructing the live scene based on the computed holograms.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims priority to U.S. application Ser. No. 18/410,185 filed on Jan. 11, 2024, U.S. Provisional Patent Application Ser. No. 63/613,622 filed on Dec. 21, 2023, U.S. application Ser. No. 18/468,571 filed on Sep. 15, 2023, and U.S. Provisional Patent Application Ser. No. 63/501,928 filed on May 12, 2023, the entire contents of which are hereby incorporated by reference.

TECHNICAL FIELD
[0002] This disclosure relates to displaying three-dimensional (3D) objects, and more particularly to holographically displaying live scenes including 3D objects.
BACKGROUND
[0003] Advances in traditional two-dimensional (2D) projection and 3D rendering have led to new approaches for 3D displays, including numerous hybrid techniques that mix head and eye tracking with conventional display devices for virtual reality (VR), augmented reality (AR), and mixed reality (MR). These techniques attempt to replicate an experience of holographic imagery, combined with tracking and measurement-based calculations, to simulate stereo or in-eye light field that can be represented by an actual hologram. Holograms that offer a 3D view of objects provide a level of detail that is unattainable by regular two-dimensional (2D) images. Due to their ability to offer a realistic and immersive experience of 3D objects, holograms hold enormous potential for use in various fields, including medical imaging, manufacturing, and virtual reality.
SUMMARY
[0004] The present disclosure describes apparatus, devices, subsystems, and systems related to holographically displaying live scenes including one or more three-dimensional (3D) objects, for example, by i) capturing optical holograms of a live scene, digitizing/processing the optical holograms, and holographically reconstructing the live scene based on the digitized/processed holograms, and/or ii) capturing images/videos of a live scene, computing corresponding holograms, and holographically reconstructing the live scene based on the computed holograms.
[0005] One aspect of the present disclosure features a system including a holographic capturing system and a holographic display system. The holographic capturing system includes: an optical system configured to generate an optical hologram of a live scene that includes one or more three-dimensional (3D) objects; and an optical sensor configured to capture sequential optical holograms of the live scene and output sequential hologram data associated with the sequential optical holograms of the live scene, each optical hologram being associated with respective hologram data. The holographic display system configured to optically reconstruct the live scene in a 3D space

based on at least part of the sequential hologram data.

[0006] In some implementations, the system further includes a computing device coupled between the holographic capturing system and the holographic display system. The computing device is configured to receive the at least part of the sequential hologram data from the optical sensor and generate digital holograms associated with the live scene based on the at least part of the sequential hologram data. The holographic display system is configured to receive the digital holograms associated with the live scene from the computing device and reconstruct the live scene in the 3D space based on the digital holograms.

[0007] In some implementations, the holographic capturing system is configured to capture the sequential optical holograms and generate the sequential hologram data, without storing the sequential optical holograms and the sequential hologram data. The computing device is configured to process the at least part of the sequential hologram data to generate the digital holograms, without storing the at least part of the sequential hologram data and the digital holograms.

[0008] In some implementations, the holographic capturing system, the computing device, and the holographic display system are configured together to capture optical holograms of the live scene and optically reconstruct the live scene in real time.

[0009] In some implementations, a digital hologram includes an amplitude-like hologram, and the holographic display system includes a display for phase modulation.

[0010] In some implementations, the optical sensor includes a digital sensor, and the sequential hologram data includes a stream of digital data. The digital data can include an array of data bits.

[0011] In some implementations, the system further includes a frame grabber coupled to the optical sensor and configured to select respective hologram data of one or more optical holograms among the sequential optical holograms to be transmitted to the computing device.

[0012] In some implementations, the frame grabber includes a frame-buffer-based grabber configured to deposit the respective hologram data in a frame buffer of the frame grabber and subsequently into the computing device.

[0013] In some implementations, the frame grabber includes a first in, first out (FIFO)-based grabber configured to deposit the respective hologram data directly into the computing device.

[0014] In some implementations, the frame grabber is externally and respectively coupled to each of the optical sensor and the computing device.

[0015] In some implementations, the frame grabber is included in the optical sensor or in the computing device.

[0016] In some implementations, the optical sensor includes a plurality of sensing pixels in an active area of the optical sensor, and the holographic display system includes a display having a plurality of display elements. The computing device is configured to process the at least part of the sequential hologram data to generate the digital holograms associated with the live scene based on at least one of a pitch of the sensing pixels, a pitch of the display elements, a size of the active area of the optical sensor, or a size of the display.

[0017] In some implementations, the pitch of the sensing pixels is associated with a resolution of a captured optical hologram and a capturable size of a scene.

[0018] In some implementations, the pitch of the display elements is associated with an acceptable viewing angle of a reconstructed scene and the size of the display.

[0019] In some implementations, the computing device is configured to suppress a mismatch between a captured optical hologram of the live scene and a reconstruction of the live scene. The mismatch is associated with at least one of a difference between the pitch of the sensing pixels and the pitch of the display elements, or a difference between the size of the active area of the optical sensor and the size of the display.

[0020] In some implementations, the computing device is configured to perform at least one of: scaling a first digital hologram associated with a captured optical hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display elements, or adjusting the scaled

first digital hologram to generate a second digital hologram to be modulated on the display based on the size of the display and the size of the hologram data.

[0021] In some implementations, the computing device is configured to perform the scaling using at least one of one or more interpolation algorithms including linear interpolation, nearest neighbor interpolation, cubic spline interpolation, shape-preserving interpolation, Biharomic interpolation, and thin-plate spline interpolation.

[0022] In some implementations, the computing device is configured to resample a first digital hologram associated with a captured optical hologram to be a second digital hologram to be modulated on the display using Fourier transform and inverse Fourier transform, the first digital hologram being associated with the pitch of the sensing pixels, the second digital hologram being associated with the pitch of the display elements.

[0023] In some implementations, the computing device is configured to: perform the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and if the pitch of the sensing pixels is larger than the pitch of the display elements, perform zero-padding on the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display element, then perform the inverse Fourier transform on the transformed first digital hologram with the zero-padding to obtain the second digital hologram.

[0024] In some implementations, the computing device is configured to: perform the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and in response to determining the pitch of the sensing pixels is smaller than the pitch of the display elements, crop the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display elements, then perform the inverse Fourier transform on the cropped transformed first digital hologram to obtain the second digital hologram.

[0025] In some implementations, the computing device is configured to resample the first digital hologram to be the second digital hologram by respectively resampling central points of the plurality of sensing pixels of the optical sensor to match centroids of the plurality of display elements of the display.

[0026] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is regularly arranged in the display, and the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are regularly spaced.

[0027] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display, and the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced.

[0028] In some implementations, the computing device is configured to resample the regularly spaced center points of the plurality of sensing pixels to match the irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms. The plurality of display elements can form a Voronoi pattern.

[0029] In some implementations, the plurality of sensing pixels of the optical sensor is irregularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display, and the central points of the plurality of sensing pixels are irregularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced. In some implementations, an irregular pattern formed by the plurality of sensing pixels match an irregular pattern formed by the plurality of display elements.

[0030] In some implementations, the optical system includes an interferometer, and the optical hologram includes an interference pattern of an object beam interacting with the live scene and a reference beam interfering with the object beam by the interferometer.

[0031] In some implementations, the optical system includes: a coherent light source configured to

emit a coherent light beam; and a beam splitter configured to split the coherent light beam from the coherent light source into the object beam and the reference beam.

[0032] In some implementations, the optical system further includes a beam combiner, where the live scene is on an optical path of the object beam upstream the beam combiner, and where the beam combiner is configured to superimpose the reference beam and the object beam to form the interference pattern.

[0033] In some implementations, the optical sensor is arranged downstream of the beam combiner and configured to directly capture the interference pattern on an active area of the optical sensor.

[0034] In some implementations, there is no optical lens between the beam combiner and the optical sensor.

[0035] In some implementations, there is no optical lens on an optical path of the reference beam between the beam splitter and the beam combiner.

[0036] In some implementations, the live scene is transmissive, and the object beam travels through the live scene to be incident on the beam combiner.

[0037] In some implementations, the live scene is reflective, and where the optical system includes one or more reflective mirrors configured to guide the object beam towards the live scene with an angle such that the object beam is reflected or scattered from the live scene to be incident on the beam combiner.

[0038] In some implementations, the optical system further includes one or more optical lens on the optical path of the object beam between the live scene and the beam combiner and configured to magnify or demagnify the object beam after interacting with the live scene to be compatible with an active area of the optical sensor.

[0039] In some implementations, the optical system further includes an absorber arranged on a side surface of the beam combiner and configured to absorb another part of the reference beam propagating away from the interference pattern.

[0040] In some implementations, the optical system further includes one or more optical lens arranged between the beam splitter and the live scene and configured to magnify or demagnify the object beam to be compatible with an active area of the optical sensor.

[0041] In some implementations, the optical system includes a collimator arranged upstream the beam splitter and configured to collimate the coherent light beam from the coherent light source.

[0042] In some implementations, the optical system includes a phase adjuster arranged on an optical path of one of the object beam and the reference beam and configured to dynamically adjust a phase shift of the one of the object beam and the reference beam before the interference pattern is formed, and where the phase adjuster includes a phase shifter or a dynamic retarder.

[0043] In some implementations, the phase adjuster is configured to sequentially adjust the phase shift to be a series of predetermined values in a time period, such that the optical sensor captures corresponding sequential optical holograms of the live scene in the time period.

[0044] In some implementations, the system further includes a computing device coupled between the holographic capturing system and the holographic display system. The computing device is configured to generate a digital hologram of the live scene with noise suppression based on the corresponding sequential optical holograms.

[0045] In some implementations, the phase adjuster includes a liquid crystal cell configured to adjust the phase shift to be the series of predetermined values by corresponding voltages.

[0046] In some implementations, the liquid crystal cell is a single cell having a size no smaller than a size of the one of the object beam and the reference beam.

[0047] In some implementations, a correspondence between the predetermined values of the phase shift and the corresponding voltages is pre-calibrated and predetermined.

[0048] In some implementations, the computing device is configured to process the corresponding sequential optical holograms to obtain corresponding raw digital holograms, and the computing device is configured to perform one or more mathematical operations on the corresponding raw

digital holograms to generate the digital hologram of the live scene.

[0049] In some implementations, the series of predetermined values for the phase shift includes 0, pi/2, pi, 3pi/2, and the digital hologram is calculated based on an expression as follows:

$$final\_hologram = (hologram\_0 - hologram\_pi)/(hologram\_pi/2) - hologram\_3pi/2,$$

[0050] where final_hologram represents the digital hologram, hologram_0 represents a first corresponding raw digital hologram based on a first corresponding optical hologram with 0 phase shift, hologram_pi/2 represents a second corresponding raw digital hologram based on a second corresponding optical hologram with pi/2 phase shift, hologram_pi represents a third corresponding raw digital hologram based on a third corresponding optical hologram with pi phase shift, and hologram_3pi/2 represents a fourth corresponding raw digital hologram based on a fourth corresponding optical hologram with 3pi/2 phase shift.

[0051] In some implementations, the light coherent source includes a plurality of light elements, each coherent light element emitting a respective color.

[0052] In some implementations, the plurality of coherent light elements is configured to sequentially and alternatively emit light with the respective colors, and the holographic capturing system further includes a corresponding color filter arranged upstream the optical sensor for each coherent light element of the plurality of coherent light elements, and the corresponding color filter is configured to transmit light with a corresponding color from the coherent light element and block light with other colors to reach the optical sensor.

[0053] In some implementations, the plurality of coherent light elements is configured to emit light with the respective colors simultaneously. The holographic capturing system further includes a color filter array including groups of different color filters on a plurality of sensing pixels of the optical sensor, the different color filters being associated with the respective colors, each group of the different color filters being arranged on a corresponding group of adjacent sensing pixels of the plurality of sensing pixels.

[0054] In some implementations, the optical sensor is configured to determine hologram data for the respective colors based on a captured optical hologram captured by the corresponding groups of adjacent sensing pixels of the plurality of sensing pixels.

[0055] In some implementations, the system further includes a computing device coupled between the holographic capturing system and the holographic display system, and the computing device is configured to generate digital holograms for the respective colors based on a captured optical hologram captured by the corresponding groups of adjacent sensing pixels of the plurality of sensing pixels.

[0056] In some implementations, the holographic display system includes: a display including a plurality of display elements; and a driving device coupled to the display. The driving device is configured to: generate control signals for the plurality of display elements of the display based on a digital hologram associated with the live scene; and transmit the control signals to the display to modulate the plurality of display elements of the display based on the control signals.

[0057] In some implementations, the system further includes a computing device coupled between the holographic capturing system and the holographic display system. The computing device is configured to receive the at least part of the sequential hologram data from the optical sensor and generate digital holograms associated with the live scene based on the at least part of the sequential hologram data. The holographic display system is configured to receive the digital holograms associated with the live scene from the computing device and reconstruct the live scene in the 3D space based on the digital holograms.

[0058] In some implementations, the digital holograms include a series of groups of digital holograms for a plurality of colors, and the holographic display system further includes an illuminator including a plurality of coherent light elements for the plurality of colors.

[0059] In some implementations, the driving device is configured to: sequentially modulate the

display with a first digital hologram for a first color during a first time period and modulate the display with a second digital hologram for a second color during a second, sequential time period; and control the illuminator to sequentially turn on a first coherent light element to emit light with the first color during the first time period and a second coherent light element to emit light with the second color during the second, sequential time period.

[0060] In some implementations, the driving device includes at least one of a display driver coupled to the display, an illuminator driver coupled to the illuminator, or a memory coupled to at least one of the display driver or the illuminator driver.

[0061] In some implementations, the reconstructed live scene in the 3D space has one or more holography characteristics including occlusion, parallax, and accommodation.

[0062] Another aspect of the present disclosure features a method performed by the system as noted above.

[0063] Another aspect of the present disclosure features a method including: optically generating an optical hologram of a live scene that includes one or more three-dimensional (3D) objects; capturing sequential optical holograms of the live scene and generating sequential hologram data associated with the sequential optical holograms of the live scene, each optical hologram being associated with respective hologram data; and reconstructing the live scene in a 3D space based on at least part of the sequential hologram data.

[0064] In some implementations, the method further includes: processing the at least part of the sequential hologram data to generate digital holograms associated with the live scene. Reconstructing the live scene in a 3D space based on at least part of the hologram data includes: reconstructing the live scene in the 3D space based on the digital holograms.

[0065] In some implementations, each of the digital holograms includes an amplitude-like hologram. Reconstructing the live scene in the 3D space based on the digital holograms includes: modulating a display for phase modulation directly with the digital hologram.

[0066] In some implementations, the sequential hologram data includes a stream of digital data, and where the digital data includes an array of data bits.

[0067] In some implementations, the method further includes: selecting respective hologram data of one or more optical holograms among the sequential optical holograms by a frame grabber. Processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene includes: generating the digital holograms associated with the live scene based on the selected respective hologram data of the one or more optical holograms.

[0068] In some implementations, the frame grabber includes one of: a frame-buffer-based grabber configured to deposit the respective hologram data in a frame buffer of the frame grabber before transmitting for generating the digital holograms, or a first in, first out (FIFO)-based grabber configured to transmit the respective hologram data directly for generating the digital holograms.

[0069] In some implementations, processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene includes: processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene based on at least one of a pitch of sensing pixels of an optical sensor, a pitch of display elements of a display, a size of an active area of the optical sensor, or a size of the display.

[0070] In some implementations, the pitch of the sensing pixels is associated with a resolution of a captured optical hologram and a capturable size of a scene, and the pitch of the display elements is associated with an acceptable viewing angle of a reconstructed scene and the size of the display.

[0071] In some implementations, processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene includes: suppressing a mismatch between a captured optical hologram of the live scene and a reconstruction of the live scene. The mismatch is associated with at least one of a difference between the pitch of the sensing pixels and the pitch of the display elements, or a difference between the size of the active area of the optical sensor and the size of the display.

[0072] In some implementations, processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene includes at least one of: scaling a first digital hologram associated with a captured optical hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display elements, or cropping the scaled first digital hologram to generate a second digital hologram to be modulated on the display based on the size of the display and the size of the hologram data.

[0073] In some implementations, scaling the size of the first digital hologram associated with the captured optical hologram includes: using at least one of one or more interpolation algorithms including linear interpolation, nearest neighbor interpolation, cubic spline interpolation, shape-preserving interpolation, Biharomic interpolation, and thin-plate spline interpolation.

[0074] In some implementations, processing the at least part of the sequential hologram data to generate the digital holograms associated with the live scene includes: resampling a first digital hologram associated with a captured optical hologram to be a second digital hologram to be modulated on the display using Fourier transform (e.g., FFT) and inverse Fourier transform (e.g., inverse FFT), the first digital hologram being associated with the pitch of the sensing pixels, the second digital hologram being associated with the pitch of the display elements.

[0075] In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: performing the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and in response to determining the pitch of the sensing pixels is smaller than the pitch of the display elements, cropping the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display element, then performing the inverse Fourier transform on the cropped transformed first digital hologram to obtain the second digital hologram.

[0076] In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: performing the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and if the pitch of the sensing pixels is larger than the pitch of the display elements, adding one or more zero-pads to the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display element, then performing the inverse Fourier transform on the transformed first digital hologram with the added one or more zero-pads to obtain the second digital hologram.

[0077] In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: resampling the first digital hologram to be the second digital hologram by respectively resampling central points of the plurality of sensing pixels of the optical sensor to match centroids of a plurality of display elements of the display.

[0078] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is regularly arranged in the display, and the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are regularly spaced.

[0079] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display, and the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced.

[0080] In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: resampling the regularly spaced center points of the plurality of sensing pixels to match the irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms.

[0081] In some implementations, the plurality of sensing pixels of the optical sensor is irregularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display, the central points of the plurality of sensing pixels are irregularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced, and an irregular pattern formed by the plurality of sensing pixels match an irregular pattern formed by the plurality of display elements.

[0082] In some implementations, optically generating the optical hologram of the live scene includes: forming an interference pattern by interfering an object beam interacting with the live scene with a reference beam, where the object beam and the reference beam are coherent light beams, and the optical hologram includes the interference pattern.

[0083] In some implementations, capturing the sequential optical holograms of the live scene includes directly capturing the interference pattern on active area of an optical sensor.

[0084] In some implementations, the method further includes: magnifying or demagnifying the object beam after interacting with the live scene to be compatible with an active area of the optical sensor.

[0085] In some implementations, the method further includes: dynamically adjusting a phase shift of one of the object beam and the reference beam before the interference pattern is formed.

[0086] In some implementations, dynamically adjusting the phase shift of one of the object beam and the reference beam includes: sequentially adjusting the phase shift to be a series of predetermined values in a time period. Capturing the sequential optical holograms of the live scene includes: capturing corresponding sequential optical holograms of the live scene in the time period.

[0087] In some implementations, the method further includes: generating a digital hologram of the live scene with noise suppression based on the corresponding sequential optical holograms.

[0088] In some implementations, generating the digital hologram of the live scene with noise suppression based on the corresponding sequential optical holograms includes: processing the corresponding sequential optical holograms to obtain corresponding raw digital holograms, and performing one or more mathematical operations on the corresponding raw digital holograms to generate the digital hologram of the live scene.

[0089] In some implementations, the series of predetermined values for the phase shift includes 0, pi/2, pi, 3pi/2, and the digital hologram is calculated based on an expression as follows:

final_hologram=(hologram_0−hologram_pi)/(hologram_pi/2−hologram_3pi/2), [0090] where final_hologram represents the digital hologram, hologram_0 represents a first corresponding raw digital hologram based on a first corresponding optical hologram with 0 phase shift, hologram_pi/2 represents a second corresponding raw digital hologram based on a second corresponding optical hologram with pi/2 phase shift, hologram_pi represents a third corresponding raw digital hologram based on a third corresponding optical hologram with pi phase shift, and hologram_3pi/2 represents a fourth corresponding raw digital hologram based on a fourth corresponding optical hologram with 3pi/2 phase shift.

[0091] In some implementations, optically generating the optical hologram of the live scene includes: sequentially and alternatively emitting light with a plurality of colors to sequentially and alternatively generate optical holograms for the plurality of colors. Capturing the sequential optical holograms of the live scene includes: sequentially transmitting only light with an individual color, while blocking light with other colors.

[0092] In some implementations, optically generating the optical hologram of the live scene includes: emitting light with a plurality of colors simultaneously. Capturing the sequential optical holograms of the live scene includes: capturing the optical hologram by corresponding groups of adjacent sensing pixels of a plurality of sensing pixels of an optical sensor, with a color filter array arranged on the optical sensor, where the color filter array includes groups of different color filters on the plurality of sensing pixels of the optical sensor, the different color filters being associated

with the plurality of colors, each group of the different color filters being arranged on a corresponding group of adjacent sensing pixels of the plurality of sensing pixels.

[0093] In some implementations, generating sequential hologram data associated with the sequential optical holograms of the live scene includes: determining hologram data for each of the plurality of colors based on the optical hologram.

[0094] In some implementations, the method further includes: generating digital holograms for the plurality of colors based on the optical hologram, and reconstructing the live scene in a 3D space based on at least part of the hologram data includes: reconstructing the live scene in the 3D space based on the digital holograms.

[0095] In some implementations, reconstructing the live scene in a 3D space based on at least part of the hologram data includes: generating control signals for a plurality of display elements of a display based on a digital hologram associated with the live scene; and modulate the plurality of display elements of the display based on the control signals.

[0096] In some implementations, the method further includes: generating digital holograms associated with the live scene based on the at least part of the sequential hologram data. The digital holograms include a series of groups of digital holograms for a plurality of colors.

[0097] In some implementations, reconstructing the live scene in a 3D space based on at least part of the hologram data includes: sequentially modulating the display with a first digital hologram for a first color during a first time period and modulating the display with a second digital hologram for a second color during a second, sequential time period, and sequentially turning on a first coherent light element to emit light with the first color during the first time period and a second coherent light element to emit light with the second color during the second, sequential time period.

[0098] Another aspect of the present disclosure features a system including: a hologram generation system configured to generate one or more digital holograms corresponding to a live scene that includes one or more three-dimensional (3D) objects; and a holographic display system configured to reconstruct the live scene in a 3D space based on the one or more digital holograms. The hologram generation system includes: one or more scene acquisition devices configured to capture visual data of the live scene from one or more views, the visual data including at least one of one or more images or one or more videos; and a computing system configured to: obtain primitive data associated with the live scene based on the captured visual data of the live scene; and generate a digital hologram corresponding to the live scene based on the primitive data associated with the live scene and display element information of a display of the holographic display system.

[0099] In some implementations, the computing system includes a computing device coupled to the one or more scene acquisition devices and configured to: generate a 3D representation of the live scene based on the captured visual data of the live scene; and obtain primitive data of the 3D representation of the live scene based on the 3D representation of the live scene, where the primitive data associated with the live scene includes the primitive data of the 3D representation of the live scene.

[0100] In some implementations, the computing device is configured to generate the 3D representation of the live scene based on the captured visual data of the live scene using a 3D rendering algorithm.

[0101] In some implementations, the one or more scene acquisition devices are configured to transmit sequential visual data of the live scene to the computing device in a time period, the sequential visual data including first visual data and second visual data sequential to the first visual data. The computing device is configured to: generate a first 3D representation of the live scene based on the first visual data of the live scene using the 3D rendering algorithm, and generate a second 3D representation of the live scene by updating the first 3D representation of the live scene based on a difference between the first visual data and the second visual data using the 3D rendering algorithm.

[0102] In some implementations, the computing device is configured to: load the 3D representation

of the live scene into a 3D simulation application, and obtain the primitive data of the 3D representation of the live scene based on an output of the 3D simulation application that is associated with the 3D representation of the live scene.

[0103] In some implementations, the primitive data of the 3D representation of the live scene includes: data of a plurality of primitives corresponding to the 3D representation of the live scene, the data including primitive data of each primitive of the plurality of primitives, a primitive including at least one vertex, primitive data of the primitive including data of the at least one vertex.

[0104] In some implementations, the primitive data of the primitive includes at least one of: a primitive identifier of the primitive, at least one vertex identifier of the at least one vertex, coordinate information of the primitive in a 3D coordinate system, color information of the primitive, texture coordinate information of the primitive, shading information for the primitive, viewpoint dependent shading information associated with the primitive, or occlusion information of the primitive.

[0105] In some implementations, the computing system includes a processing device coupled to the computing device and configured to: for each primitive of the plurality of primitives, determining an electromagnetic (EM) field contribution to each of a plurality of display elements of the display based on primitive data of the primitive; and for each of the plurality of display elements of the display, generating a sum of the EM field contributions of the plurality of primitives to the display element, where the digital hologram includes the sums of the EM field contributions for the plurality of display elements of the display.

[0106] In some implementations, the computing device is configured to: generate the primitive data of the 3D representation of the live scene based on the output of 3D simulation application using an application programming interface (API). The computing device is configured to execute the API to: for each of a plurality of vertices of the plurality of primitives, associate a respective vertex identifier of the vertex with respective vertex data of the vertex, and store the association between the respective vertex identifier and the respective vertex data of the vertex in a memory of the computing device; and for each of the plurality of primitives, associate a respective primitive identifier of the primitive with one or more respective vertex identifiers of one or more vertices of the primitive in the memory, and store an association between the respective primitive identifier and the one or more respective vertex identifiers for the primitive in the memory.

[0107] In some implementations, the computing device is configured to execute the API to: determine primitive identifiers of multiple primitives associated with a command instruction, determine vertex identifiers associated with the primitive identifiers; and transmit a command including the command instruction, the vertex identifiers associated with the primitive identifiers, and the primitive identifiers of the multiple primitives, to the processing device, without the primitive data of the plurality of primitives. The command indicates drawing the multiple primitives according to the command instruction and based on at least one of the primitive identifiers of the multiple primitives or the vertex identifiers associated with the primitive identifiers.

[0108] In some implementations, the processing device includes: a command processor, a plurality of computing units, and an accumulator. The command processor is configured to: receive the command from the computing device, and process the command to obtain primitive data of the multiple primitives from the computing device based on the command. The plurality of computing units can be configured to calculate an electromagnetic (EM) field contribution of each of the multiple primitives to each of the plurality of display elements based on the primitive data of the multiple primitives. The accumulator can be configured to: accumulate EM field contributions of the multiple primitives to each of the plurality of display elements.

[0109] In some implementations, the command processor, the plurality of computing units, and the accumulator are connected in series, and the plurality of computing units are connected in parallel

between the command processor and the accumulator.

[0110] In some implementations, the digital hologram is a complex-valued hologram, a phase hologram, or an amplitude hologram.

[0111] In some implementations, the holographic display system includes a driving device coupled to the display and configured to: generate modulation control signals for a plurality of display elements of the display based on the digital hologram corresponding to the live scene.

[0112] In some implementations, the digital hologram is a complex-valued hologram, and the driving device is configured to: convert the complex-valued hologram to a phase-only hologram, and generate the respective modulation control signals for the plurality of display elements based on the phase-only hologram.

[0113] In some implementations, the holographic display system further includes an illuminator. The driving device is configured to: transmit an illumination control signal to the illuminator to activate the illuminator to illuminate light on the display such that the light is caused by modulated display elements of the display to form a volumetric light field corresponding to the live scene. The driving device is configured to: output the respective modulation control signal to each display element of the plurality of display elements, in coordination with transmitting the illumination control signal to the illuminator.

[0114] In some implementations, the driving device is configured to: sequentially output a first modulation control signal to modulate the display with a first digital hologram associated with a first color during a first time period, and a second modulation control signal to modulate the display with a second digital hologram associated with a second color during a second, sequential time period; and sequentially output a first illumination control signal to activate the illuminator to turn on a first coherent light element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator to turn on a second coherent light element to emit light with the second color during the second time period.

[0115] In some implementations, the hologram generation system is configured to generate sequential digital holograms corresponding to the live scene, and the holographic display system is configured to continuously reconstruct the live scene in the 3D space based on the sequential digital holograms.

[0116] Another aspect of the present disclosure features a method including: capturing visual data of a live scene from one or more views, the live scene including one or more three-dimensional (3D) objects, the visual data including at least one of one or more images or one or more videos; obtaining primitive data associated with the live scene based on the captured visual data of the live scene; generating one or more digital holograms corresponding to the live scene based on the primitive data associated with the live scene and display element information of a display; and reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms.

[0117] In some implementations, obtaining the primitive data associated with the live scene based on the captured visual data of the live scene includes: generating a 3D representation of the live scene based on the captured visual data of the live scene, and obtaining primitive data of the 3D representation of the live scene based on the 3D representation of the live scene, where the primitive data associated with the live scene includes the primitive data of the 3D representation of the live scene.

[0118] In some implementations, generating the 3D representation of the live scene based on the captured visual data of the live scene includes: processing the captured visual data of the live scene using a 3D rendering algorithm to generate the 3D representation of the live scene.

[0119] In some implementations, the method includes: generating sequential visual data of the live scene in a time period, the sequential visual data including first visual data and second visual data sequential to the first visual data; generating a first 3D representation of the live scene based on the first visual data of the live scene using the 3D rendering algorithm; and generating a second 3D

representation of the live scene by updating the first 3D representation of the live scene based on a difference between the first visual data and the second visual data using the 3D rendering algorithm.

[0120] In some implementations, obtaining the primitive data of the 3D representation of the live scene based on the 3D representation of the live scene includes: loading the 3D representation of the live scene into a 3D simulation application, and obtaining the primitive data of the 3D representation of the live scene based on an output of the 3D simulation application that is associated with the 3D representation of the live scene.

[0121] In some implementations, the primitive data of the 3D representation of the live scene includes: data of a plurality of primitives corresponding to the 3D representation of the live scene, the data including primitive data of each primitive of the plurality of primitives, a primitive including at least one vertex, primitive data of the primitive including data of the at least one vertex.

[0122] In some implementations, the primitive data of the primitive includes at least one of: a primitive identifier of the primitive, at least one vertex identifier of the at least one vertex, coordinate information of the primitive in a 3D coordinate system, color information of the primitive, texture coordinate information of the primitive, shading information for the primitive, viewpoint dependent shading information associated with the primitive, or occlusion information of the primitive.

[0123] In some implementations, generating the one or more digital holograms corresponding to the live scene includes: for each primitive of the plurality of primitives, determine an electromagnetic (EM) field contribution to each of a plurality of display elements of the display based on primitive data of the primitive; and for each of the plurality of display elements of the display, generate a sum of the EM field contributions of the plurality of primitives to the display element. A digital hologram includes the sums of the EM field contributions for the plurality of display elements of the display.

[0124] In some implementations, the method further includes: for each of a plurality of vertices of the plurality of primitives, associating a respective vertex identifier of the vertex with respective vertex data of the vertex, and storing the association between the respective vertex identifier and the respective vertex data of the vertex in a memory; and for each of the plurality of primitives, associating a respective primitive identifier of the primitive with one or more respective vertex identifiers of one or more vertices of the primitive in the memory, and storing an association between the respective primitive identifier and the one or more respective vertex identifiers for the primitive in the memory.

[0125] In some implementations, the method further includes: determining primitive identifiers of multiple primitives associated with a command instruction, determining vertex identifiers associated with the primitive identifiers; and generating a command including the command instruction, the vertex identifiers associated with the primitive identifiers, and the primitive identifiers of the multiple primitives. The command indicates drawing the multiple primitives according to the command instruction and based on at least one of the primitive identifiers of the multiple primitives or the vertex identifiers associated with the primitive identifiers.

[0126] In some implementations, the method includes: processing the command to obtain primitive data of the multiple primitives based on the command; calculating an electromagnetic (EM) field contribution of each of the multiple primitives to each of the plurality of display elements based on the primitive data of the multiple primitives; and accumulating EM field contributions of the multiple primitives to each of the plurality of display elements.

[0127] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: generating modulation control signals for a plurality of display elements of the display based on a digital hologram corresponding to the live scene.

[0128] In some implementations, the digital hologram is a complex-valued hologram, and the method includes: converting the complex-valued hologram to a phase-only hologram, and generating the respective modulation control signals for the plurality of display elements based on the phase-only hologram.

[0129] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: transmitting an illumination control signal to an illuminator to activate the illuminator to illuminate light on the display such that the light is caused by modulated display elements of the display to form a volumetric light field corresponding to the live scene, and outputting the respective modulation control signal to each display element of the plurality of display elements, in coordination with transmitting the illumination control signal to the illuminator.

[0130] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: sequentially outputting a first modulation control signal to modulate the display with information associated with a first color during a first time period, and a second modulation control signal to modulate the display with information associated with a second color during a second, sequential time period; and sequentially outputting a first illumination control signal to activate the illuminator to turn on a first coherent light element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator to turn on a second coherent light element to emit light with the second color during the second time period.

[0131] In some implementations, the method includes: generating sequential digital holograms corresponding to the live scene based on captured sequential visual data of the live scene; and continuously reconstructing the live scene in the 3D space based on the sequential digital holograms.

[0132] Another aspect of the present disclosure features a system for generating digital holograms corresponding to live scenes. The system includes: one or more scene acquisition devices and a computing system. The configured to capture visual data of a live scene from one or more views, the live scene including one or more three-dimensional (3D) objects, the visual data including at least one of one or more images or one or more videos. The computing system can be configured to: obtain primitive data associated with the live scene based on the captured visual data of the live scene; and generate a digital hologram corresponding to the live scene based on the primitive data associated with the live scene and display element information of a display.

[0133] In some implementations, the computing system is implemented by the computing system according to the computing system as described herein.

[0134] Another aspect of the present disclosure features a method performed by the system as described herein.

[0135] The present disclosure provides techniques that can overcome limitations present in known techniques. As an example, the techniques disclosed herein can capture and display live scenes including 3D objects in a real world in real time, without or with minimum latency, and/or with fast processing speed or minimized data processing. As another example, the techniques disclosed herein provide real 3D reconstruction using holography, which can be implemented without the use of cumbersome wearable devices, such as "3D glasses." As another example, the techniques disclosed herein can optionally be implemented without being limited by the accuracy of tracking mechanisms, the quality of the display devices, relatively long processing times and/or relatively high computational demands, and/or by an inability to display objects to multiple viewers simultaneously. As a further example, the techniques can be implemented without specialized tools and software to develop contents that extend above and beyond the tools and software used in conventional 3D content creation. Various embodiments can exhibit one or more of the foregoing advantages. For example, certain implementations of the present disclosure can produce real-time, full color, genuine 3D images that appear to be real 3D objects in the world and can be viewed

without encumbrances by multiple viewers simultaneously from different points.

[0136] In the present disclosure herein, the term "live scene" refers to real world scene, real life scene, or physical scene, in comparison to computer-generated scene or digital scene. A live scene can include one or more three-dimensional (3D) objects in real world. The term "real time" refers to events (e.g., capturing a live scene and holographic reconstruction of the live scene) happening instantaneously or a delay between sequential events being in a predetermined threshold (e.g., 10 milliseconds (ms), 50 ms, 66 ms, 100 ms, or any other suitable value).

[0137] The term "primitive" refers to a basic element for input or output within a computing system. The element can be a geometric element or a graphical element. For example, in vector computer graphics, CAD systems, and geographic information systems, geometric primitive (or prim) is the simplest (e.g., 'atomic' or irreducible) geometric shape that the system can handle (e.g., draw, store). The term "vertex" refers to a node of a primitive that can be connected with one or more other nodes to form the primitive.

[0138] The term "hologram" refers to a pattern displayed by (or uploaded to) a display which contains amplitude information or phase information, or some combination thereof, regarding an object. The term "optical hologram" refers to a physical representation of a hologram, e.g., an interference pattern between a reference beam and an object beam of coherent light (e.g., laser light). The term "digital hologram" refers to a digital representation of a hologram. The digital hologram can be generated by a) processing hologram data of the optical hologram, b) processing images/videos of the object itself, c) simulating an interference process on a computer using mathematical models and algorithms (which can be also called a computational hologram), or d) calculating electromagnetic contributions from primitives of the object to display elements (e.g., generated using Maxwell Holography). The term "amplitude-like hologram" can refer to a hologram performing like an amplitude hologram, though the hologram includes both amplitude information and phase information of an object that enable to reconstruct the object in a 3D space. The term "holographic reconstruction" refers to a volumetric light field (e.g., a holographic light field) from a display modulated with a hologram when illuminated.

[0139] As used herein, the term "irregular" represents "non-periodic" and/or "non-uniform". For example, the term "irregular shape" can indicate that a shape has sides and/or angles with different lengths and/or sizes. The term "irregular pattern" can indicate that: i) components (e.g., phasels) in an area of the pattern are arranged in a non-periodic way, and the components can be same or different from each other, or ii) the components have different irregular shapes.

[0140] Shading is a process of adding value to create an illusion of form, space, and light in a drawing. Shading can make a drawing appear three dimensional and create a convincing image. Shading can be different from techniques of adding shadows, such as shadow mapping or shadow volumes, which fall under global behavior of light. The term "shading information" refers to depiction information of depth perception in 3D models (e.g., within the field of 3D computer graphics) or illustrations (e.g., in visual art) by varying a level of darkness. Shading information can approximate a local behavior of light on an object's surface. The shading information can be obtained by any customary computer-generated imagery (CGI) surface shading method that involves modulating color or brightness of a surface of the primitive. Primitive data disclosed herein can include shading information associated with the primitive.

[0141] The term "view-dependent shading information" can be a larger generalization of the term "geometric specular reflection". Specular reflection is a subset of view-dependent shading. Specular reflection is something like a blurred, recolored image of a light source that is described by bi-directional reflectance distribution function ("BRDF") of a particular material, like plastic or shiny wood. View-dependent shading can encompass specular BRDFs as well as perfect mirror surfaces and image-based lighting. For example, to render a spherical Christmas decoration, an image of the environment surrounding the decoration and an environment that also includes the positions and sizes of each light source can be reflected, and the position of the viewer can be part

of that reflection calculation. The reflection appears to move as a viewpoint is changed, revealing different parts of the environment. Similarly, the position of the bright specular area on a plastic surface can be the sum of view-dependent projections of the Christmas lights reflected off the spherical decoration multiplied by the BRDF. Primitive data disclosed herein can include view-dependent shading information associated with the primitive.

[0142] The details of one or more implementations of the subject matter of this specification are set forth in the accompanying drawings and associated description. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

[0143] It is to be understood that various aspects of implementations can be combined in different manners. As an example, features from certain methods, devices, or systems can be combined with features of other methods, devices, or systems.

Description

DESCRIPTION OF DRAWINGS

[0144] FIG. **1**A illustrates a schematic diagram of an example system for capturing and displaying live scenes using computational approach.

[0145] FIG. **1**B illustrates an example holographic reconstruction for a live scene.

[0146] FIG. **2** illustrates a schematic diagram of an example system for capturing and displaying live scenes using optical approach.

[0147] FIG. **3**A illustrates a schematic diagram of an example holographic capturing system.

[0148] FIG. **3**B illustrates a schematic diagram of an example holographic capturing system for capturing a transparent object.

[0149] FIG. **3**C illustrates a schematic diagram of an example holographic capturing system for capturing an opaque object.

[0150] FIG. **3**D illustrates a schematic diagram of an example holographic capturing system for noise suppression.

[0151] FIG. **4**A illustrates an example of processing hologram-based images.

[0152] FIG. **4**B illustrates another example of processing hologram-based images.

[0153] FIG. **4**C illustrates an example of a raw hologram and a processed hologram with noise suppression.

[0154] FIG. **5**A illustrates an example system for 3D display including a reflective display with optically diffractive illumination.

[0155] FIG. **5**B illustrates another example system for 3D display including a reflective display with optically diffractive illumination.

[0156] FIG. **5**C illustrates another example system for 3D display including a transmissive display with optically diffractive illumination.

[0157] FIG. **5**D illustrates another example system for 3D display including a transmissive display with optically diffractive illumination.

[0158] FIG. **6**A illustrates an example of an irregular display.

[0159] FIG. **6**B illustrates an example of designing an irregular display.

[0160] FIGS. **7**A-**7**C illustrate example cues of holographically displaying objects, including occlusion (FIG. **7**A), parallax (FIG. **7**B), and accommodation (FIG. **7**C).

[0161] FIG. **8**A is a flowchart of an example process of holographically displaying a live scene.

[0162] FIG. **8**B is a flowchart of another example process of holographically displaying a live scene.

[0163] Like reference numbers and designations in the various drawings indicate like elements. It is also to be understood that the various exemplary implementations shown in the figures are

merely illustrative representations and are not necessarily drawn to scale.

DETAILED DESCRIPTION

[0164] Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth to provide a thorough understanding of the various described embodiments. However, it will be apparent to one of ordinary skill in the art that the various described embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

[0165] Several features are described hereafter that can each be used independently of one another or with any combination of other features. However, any individual feature may not address any of the problems discussed above or might only address one of the problems discussed above. Some of the problems discussed above might not be fully addressed by any of the features described herein. Although headings are provided, information related to a particular heading, but not found in the section having that heading, may also be found elsewhere in this description.

[0166] Implementations of the present disclosure are described herein according to the following general outline: [0167] 1. General overview [0168] 2. Example system with computational approach [0169] 3. Example system with optical approach [0170] 4. Example holographic capturing systems [0171] 5. Example holographic display systems [0172] 6. Example irregular display [0173] 7. Example holographic cues [0174] 8. Example Processes [0175] 9. Example Applications

1. General Overview

[0176] Implementations of the present disclosure feature techniques for enabling holographically displaying live scenes including one or more three-dimensional (3D) objects. A live scene can be a scene of an event happening in real world, real life, or in a physical space, e.g., a soccer game occurring in a stadium, which can be different from complex computer-generated or simulated or digitally animated scenes (e.g., by 3D simulation applications). The techniques enable to physically capture the live scene, to make holograms (e.g., single or multiple colors of holograms) of the live scene, and holographically display the live scene (in single or multiple colors), which can be implemented in real time, e.g., by transmitting captured data of the live scene to a holographic display system for reconstructing the live scene, without latency or with minimum latency, and/or without storing the captured data of the live scene and/or the generated holograms, and/or improving processing speed.

[0177] In some implementations, e.g., as illustrated in FIG. **1**, a live scene can be captured by one or more visual acquisition devices (e.g., cameras or image/video recorders) that can be arranged around the live scene and/or from one or more views. The one or more visual acquisition devices can generate visual data of the live scene that can include one or more images (or videos) of the live scene from the one or more views. The one or more visual acquisition devices can transmit (e.g., in real time) the visual data to a computing device. The computing device can generate corresponding digital holograms of the live scene based on the visual data. For example, the computing device can use a 3D rendering algorithm (e.g., NeRF) to generate a 3D representation of the live scene based on the visual data (e.g., from two or more views). The computing device can further use a 3D simulation application (e.g., Unity) to obtain primitive data of a plurality of primitives associated with the 3D representation of the live scene. A processing device (e.g., a phasel processing device) can then generate a digital hologram corresponding to the live scene, e.g., based on the primitive data associated with the live scene and display element information of a display to be modulated with the digital hologram, e.g., by using the techniques of MAXWELL HOLOGRAPHY® (or MAXWELL HOLOGRAPHY™), which can achieve faster processing speed for real time holography than conventional digital holography and/or computational holography. Then the digital hologram can be transmitted to a holographic display system, where

the display is modulated with the digital hologram to diffract light from an illuminator to reconstruct the live scene in a 3D space (e.g., as illustrated in FIG. **1**B). In some implementations, different colors (e.g., red, blue, and green) of digital holograms can be generated by the computing device and/or the processing device, and the holographic display system can reconstruct the live scene in the different colors, e.g., sequentially modulating the display with alternating holograms with the different colors.

[0178] The calculation (or computation) in MAXWELL HOLOGRAPHY® can be represented as Maxwell holographic calculation (or Maxwell holographic computation). In conventional digital holography, a digital intensity image of a hologram first undergoes processing such as complex wave retrieval, and the hologram is then numerically propagated by means of Fresnel approximation which describes wave propagation in free space to an image plane. This may result in a complex image containing both amplitude and phase information. In contrast, based upon Maxwell's Equations for electromagnetic fields, the Maxwell Holographic calculation approaches a hologram as a Dirichlet or Cauchy boundary condition problem for a general electric field, utilizing tools including field theory, topology, analytic continuation, and/or symmetry groups, which enables to solve for holograms in real time without the limitations of legacy holographic systems like conventional digital holography and achieve a faster processing speed.

[0179] In some implementations, e.g., as illustrated in FIG. **2**, a live scene is captured as optical holograms by a holographic capturing system (e.g., as illustrated in FIGS. **3**A-**3**C). An optical hologram of the live scene can be an interference pattern of an object beam interacting with the live scene and a reference beam interfering with the object beam, e.g., using an interferometer like Mach-Zehnder interferometer or Michelson interferometer. The object beam and the reference beam can be from a coherent light source (e.g., a laser). The optical hologram can be captured by a digital sensor (e.g., CCD or CMOS) that outputs hologram data of the optical hologram (e.g., an array of bits). The digital sensor can have a fast frame rate, e.g., 90 Hz, and a frame grabber can be used to select at least part of the hologram data to transmit to a computing device. The computing device can process the at least part of the hologram data to generate a digital hologram to be displayed by a display of a holographic display system. For example, the digital sensor and the display can have different pitches, and the computing device can convert the hologram data to a correct resolution for the display. The holographic display system can reconstruct the live scene in a 3D space based on the digital hologram. The digital hologram can perform like an amplitude hologram, which can simplify the processing of the hologram data and expedite the processing speed. The display (e.g., a phase-modulated liquid crystal on silicon (LCOS)) can be directly modulated with the digital hologram, without additional device for conversion. In some implementations, the coherent light source can include emit light with different colors (e.g., red, green, blue), for example, in an alternating way or a continuous way. One or more notch filters or a color filter array can be positioned before the digital sensor to generate optical holograms with the different colors, which can be processed to generate corresponding digital holograms with the different colors. The display can be sequentially modulated by the digital holograms with the different colors to reconstruct the live scene in the different colors.

2. Example System with Computational Approach

[0180] FIG. **1**A illustrates a schematic diagram of an example system **100** for capturing and displaying live scenes using computational approach. The system **100** can be configured to capture a live scene in a form of images/videos from different views/angles, generate a 3D digital representation of the live scene based on the images/videos, compute corresponding digital holograms, and then holographically reconstruct the live scene based on the digital holograms. As the digital holograms can be computed using Maxwell Holography calculation with high speed, the system **100** enables to holographically display the live scene in real time by dynamically capturing the live scene and displaying the digital holograms. As discussed with further details below, a number of techniques can be implemented in the system **100** to achieve 3D reconstruction/display

with fast computation speed, high display refresh rate, high image quality, and high performance.

[0181] In some implementations, the system **100** includes a hologram generation system **101** and a holographic display system **130**. The hologram generation system **101** is configured to generate one or more digital holograms corresponding to a live scene that can include one or more three-dimensional (3D) objects in a physical space. The holographic display system **130** is configured to reconstruct the live scene in a 3D space based on the one or more digital holograms.

[0182] In some implementations, e.g., as illustrated in FIG. **1**A, the hologram generation system **101** includes a scene acquisition system **102** and a computing system **103**. The scene acquisition system **102** can include one or more scene acquisition devices **104** (e.g., cameras, image recorders, or video recorders) configured to capture scene data of the live scene. The scene data can include visual data **105** (e.g., images and/or videos) and/or audio data (e.g., audios or sounds). The one or more scene acquisition devices **104** can be arranged around the live scene and be configured to capture corresponding scene data from different angles or views. In some implementations, the scene acquisition system **102** includes a buffer **106** configured to buffer the scene data from the one or more scene acquisition device s **104** before transmitting the scene data to the computing system **103**.

[0183] The scene acquisition system **102** can transmit the visual data **105** (e.g., images and/or videos of the live scene) to the computing system **103**. The computing system **103** can be configured to obtain primitive data associated with the live scene based on the captured visual data of the live scene and generate a digital hologram corresponding to the live scene based on the primitive data associated with the live scene and display element information of a display **150** (e.g., a phase-only LCOS) of the holographic display system **130**, e.g., using Maxwell Holography calculation. Data transmission between the scene acquisition system **102** and the computing system **103** can be through a wired connection, a wireless connection, or any high speed connection. Data transmission between the computing system **103** and the holographic display system **130** can be through a wired connection, a wireless connection, or any high speed connection.

[0184] In some implementations, the computing system **103** includes a computing device **110** and a processing device **120**. The computing device **110** is configured to prepare data for a list of primitives corresponding to the live scene, and transmit the data to the processing device **120** via an interface **115**, e.g., PCIe slot or any other high speed connection. The processing device **120** can be configured to compute electromagnetic (EM) field contributions from each of the list of primitives to each of display elements of the display **150** and output a hologram **127** to the holographic display system **130**, e.g., using Maxwell Holography Calculation. Herein, the hologram **127** refers to modulation data for the display **150**, which contains complex information, amplitude information or phase information, or some combination thereof, regarding the at least one object. A driving device **131** of the holographic display system **130** can be configured to generate control signals based on the hologram to modulate the display elements of the display **150**, which diffracts light **145** from an illuminator **140** of the holographic display system **130** to form a holographic light field **160** corresponding to the live scene in a 3D space. The holographic light field **160** can be a volumetric light field from the display **150** when illuminated, and can be also referred to holographic reconstruction. The holographic reconstruction includes a reconstructed scene corresponding to the live scene.

[0185] The processing device **120** can be implemented as, for example, an ASIC, an FPGA, an integrated circuit, one or more computing units, or any combination thereof. In some implementations, the processing device **120** is packaged as a circuit board integrated in the computing device **110** through a PCIe slot in the computing device **110**. In some implementations, the processing device **120** is integrated with the driving device **131**, e.g., to function as a controller, which can be externally coupled to the computing device **110** and the display **150** and/or the illuminator **140**. In some implementations, the processing device **120** and the driving device **131** are integrated with the display **150** (and optionally the illuminator **140**), e.g., attached together, to

form an integrated device, which can be referred to as a holographic display device or the holographic display system **130**.

[0186] The computing device **110** can be a computing device associated with a user (e.g., an operator, a developer, a programmer, a customer, or any suitable entity). The computing device **110** can be any appropriate type of device, e.g., a desktop computer, a personal computer, a notebook, a tablet computing device, a personal digital assistant (PDA), a network appliance, a smart mobile phone, a smartwatch, an enhanced general packet radio service (EGPRS) mobile phone, a media player, a navigation device, an email device, a game console, or any appropriate combination of any two or more of these computing devices or other computing devices.

[0187] The computing device **110** includes an operating system running a number of applications **111**, **112** as graphics engines. In some implementations, the computing device **110** is configured to generate a 3D representation of the live scene based on captured visual data of the live scene, e.g., using a 3D rendering algorithm or application **111**, and obtain primitive data of the 3D representation of the live scene based on the 3D representation of the live scene. The 3D representation of the live scene can be stored in a memory **118** of the computing device **110**.

[0188] In some examples, the 3D rendering algorithm or application **111** includes Neural radiance fields (NeRFs) algorithm. NeRFs is a technique that generates 3D representations (e.g., continuous volumetric scene) of an object or scene from 2D images (e.g., from a spare set of input views) by using advanced machine learning. The NeRFs technique involves encoding an entire object or scene into an artificial neural network, which predicts light intensity or radiance at any point in the 2D image to generate 3D views from different angles. NeRFs can generate highly realistic 3D objects automatically. Used with other techniques, NeRFs can be used for massively compressing 3D representations of the live scene, e.g., from gigabytes to tens of megabytes. In some examples, the NeRF algorithm represents a scene using a fully-connected (non-convolutional) deep network, whose input is a single continuous **5**D coordinate (spatial location (x, y, z) and viewing direction (θ, φ)) and whose output is the volume density and view-dependent emitted radiance at that spatial location. The NeRF algorithm can synthesize views by querying **5**D coordinates along camera rays and use volume rendering techniques to project the output colors and densities into an image. Because volume rendering is naturally differentiable, the input to optimize the 3D representation can be a set of images with known camera poses. NeRF has a number of advantages over photogrammetry. It can create more realistic 3D models, and it can do so with fewer images. NeRF is also more efficient, as it can generate new views of the 3D scene in real time.

[0189] In some implementations, the scene acquisition system **102** is configured to transmit sequential visual data of the live scene to the computing device **110** in a time period. The sequential visual data can include first visual data and second visual data sequential to the first visual data. The computing device **110** can be configured to: generate a first 3D representation of the live scene based on the first visual data of the live scene using the 3D rendering algorithm, and generate a second 3D representation of the live scene by updating the first 3D representation of the live scene based on a difference between the first visual data and the second visual data using the 3D rendering algorithm, which can increase the rendering speed of the 3D representation of the live scene.

[0190] In some implementations, the computing device **110** obtains primitive data of primitives of the 3D representation of the live scene from the 3D rendering algorithm, which can be used for generating digital holograms. The primitive data can include density, color, and/or texture.

[0191] In some implementations, the computing device **110** loads the 3D representation of the live scene from the 3D rendering algorithm or application **111** into a 3D simulation application **112**, and obtains the primitive data of the 3D representation of the live scene based on an output of the 3D simulation application that is associated with the 3D representation of the live scene. The 3D software application **112** can be, e.g., 3ds Max®, SOLIDWORKS®, Maya®, or Unity. In some implementations, one application **112** or multiple applications **112** (operating in parallel) is

configured to render the 3D representation of the live scene to obtain application scene data or graphics abstraction. In some cases, the application scene data is obtained by processing the graphics abstraction. The application scene data can be stored in the memory **118** of the computing device **110**. In some implementations, the application scene data is directly provided to the processing device **120** for further processing. In some implementations, the application scene data can be also provided to an application programming interface (API) **114** for further processing.

2.1 Application Programming Interface (API)

[0192] An API is a type of software interface. The API can specify the interface between a software application and another software application or computer programs, an operation system, computer hardware, or an external device. In the system **100**, the API **114** is configured to be a holographic API that enables a developer or a user to use the computing device **110** to interact with a holographic device, e.g., the processing device **120**. The holographic API can convert computer graphics primitives into discrete holographic scene primitives, allowing for rich holographic content generation utilizing general purpose and specially designed holographic computation hardware.

[0193] In some implementations, the API **114** specifies an interface between an application **112** and computer hardware (e.g., the memory **118**) of the computing device **110**, e.g., through a driver **116**. The driver **116** can include machine-readable or executable programming instructions or software. The driver **116** is configured to communicate between the API **114** with the memory **118**, e.g., to store data (such as tables and commands) from the API **114** in the memory **118**, or to retrieve data from the memory **118** to the API **114**.

[0194] The API **114** can obtain the application scene data from the application **112**. In some examples, the application scene data includes data of a plurality of primitives corresponding to one or more objects in the scene. In some examples, the API **114** processes the application scene data to obtain the data of the plurality of primitives. The plurality of primitives can be indexed in a particular order. The primitives can include at least one of a point primitive, a line primitive, or a polygon primitive (e.g., a triangle primitive). The data of the primitives can include primitive data of each primitive of the number of primitives. A primitive includes at least one vertex, and primitive data of the primitive can include vertex data of the at least one vertex. For example, a triangle primitive includes three vertices that are connected with each other.

[0195] In some examples, primitive data of a primitive includes at least one of: coordinate information of the primitive in a 3D coordinate system, color information of the primitive (e.g., a textured color, a gradient color or both), texture coordinate information of the primitive, viewpoint-dependent shading information (e.g., geometric specular reflection information) associated with the primitive, shading information associated with the primitive, or occlusion information associated with the primitive. The primitive data can also include a primitive identifier of the primitive among the number of primitives, and/or at least one vertex identifier of the at least one vertex.

[0196] In some examples, vertex data of a vertex includes at least one of: coordinate information of the vertex in the 3D coordinate system, color information associated with the vertex (e.g., a textured color, a gradient color or both), texture coordinate information associated with the vertex, viewpoint-dependent shading information (e.g., geometric specular reflection information) associated with the vertex, shading information associated with the vertex, or occlusion information associated with the vertex. Th vertex data can also include a vertex identifier of the vertex.

[0197] In some implementations, the API **114** can adjust vertex data of vertices of multiple primitives associated with an object or a holographic scene, e.g., in response to receiving a user input, a trigger signal or command, or a predetermined command. Based on a result of the adjusting, the API **114** can update the vertex data of the vertices in the memory **118** for further processing. For example, gaps between adjacent primitives can be adjusted to avoid kissing or overlapping, or to create an overlapping effect by adjusting coordinate information of the vertices.

[0198] The API **114** can be configured to process primitive data of the plurality of primitives and/or

vertex data of a plurality of vertices (or vertexes) of the plurality of primitives to obtain data that can be processable by the processing device **120**, including, but not limited to, generating a table showing information of vertices for each primitive, organizing vertices for parallel processing, and/or generating commands for the processing device **120** to draw primitives.

[0199] In some implementations, the API **114** is configured to: for each of a plurality of vertices of the number of primitives, associate a respective vertex identifier of the vertex with respective vertex data of the vertex, and store the association between the respective vertex identifier and the respective vertex data of the vertex, for example, together with the respective vertex data, in the memory **118**. The API **114** can determine the respective vertex identifiers of the plurality of vertices based on an order of the plurality of vertices in a vertex stream corresponding to the plurality of primitives.

[0200] The API **114** can store the associations for the vertices in a table in the memory **118**. The table can include information associated with the vertices, including, but not limited to, vertex identifier (No.), 3D coordinates (x, y, z), color information, texture mapping information, occlusion information, shading information, and/or viewpoint dependent shading information.

[0201] In some implementations, the API **114** is configured to: for each of the plurality of primitives, associate a respective primitive identifier of the primitive with one or more respective vertex identifiers of one or more vertices of the primitive (and optionally respective primitive data of the primitive) in the memory **118**, and store an association between the respective primitive identifier and the one or more respective vertex identifiers for the primitive (and optionally respective primitive data of the primitive) in the memory **118**. The API **114** can determine the respective primitive identifiers of the plurality of primitives based on an order of the plurality of primitives in a primitive stream corresponding to the scene.

[0202] The API **114** can store the associations for the vertices in a table in the memory **118**. The table can include information associated with the primitives, including, but not limited to, primitive identifier (No.), vertex identifiers of vertices of the primitives, color information (PC), texture mapping information (PT), occlusion information (PO), shading information (PS), and/or viewpoint dependent shading information (PVDS).

[0203] In some implementations, the API **114** generates a command to be sent to the processing device **120**. The command can be generated based on an instruction, e.g., from the application **112** or a processor of the computing device **110**. The instruction can indicate reconstructing a holographic scene including one or more objects. For example, the command can include a command instruction for drawing a series of primitives associated with the one or more objects.

[0204] In some cases, the API **114** can determine primitive identifiers of the series of primitives associated with the command instruction and transmit the command including the command instruction and the primitive identifiers to the processing device **120** for further processing. In some cases, the API **114** can determine vertex identifiers associated with the primitive identifiers, and transmit the command including the command instruction with the vertex identifiers (and optionally the primitive identifiers) to the processing device **120** for further processing. The command can instruct the processing device **120** to draw the series of primitives based on the primitive identifiers, the vertex identifiers, or a combination thereof. In some examples, the API **114** generates an index table showing the associations between each primitive identifier and its associated vertex identifiers. The API **114** can also generate a vertex table listing the vertex identifiers associated with the command, optionally with vertex data associated with the vertex identifiers. The index table and the vertex table for the command can be stored in the memory **118**. In some cases, the index table and the vertex table is stored in a buffer (or cache) **119** of the memory **118**. The buffer **119** can be a ring buffer.

[0205] In some examples, the API **114** transmits a command list to the processing device **120**. The command list can include a number of DRAW commands. Each DRAW command specifies a command instruction (e.g., DRAW type and count) and associated vertices (e.g., vertex_ptr) and

indexes (e.g., index_ptr). The vertex_ptr can be vertex identifiers associated with the Draw command, and the index_ptr can be the association between each primitive and vertex identifiers. In such a way, a size of the DRAW command can be very small, and the DRAW command can be transmitted to the processing device **120** for processing with a high speed. The DRAW command can be cached in the buffer **119** of the memory **118** and then be transmitted to the processing device **120** through the interface **115**. Compared to transmitting primitive data or vertex data of a number of primitives corresponding to a holographic scene (or one or more objects) from the API **114** to the processing device **120**, transmitting the DRAW command (or the command list) can be much efficient and faster. Moreover, the vertex_ptr and index_ptr include information of the number of primitives in the same DRAW command, which enables the processing device **120** to perform parallel processing to increase a computation speed.

2.2 Processing Device

[0206] The processing device **120** is in communication with the computing device **110** and configured to generate a hologram corresponding to a holographic scene to be reconstructed based on data transmitted from the computing device **110**. The holographic scene includes one or more objects (e.g., 2D or 3D) in a 3D coordinate system. The data can include information of primitives corresponding to the one or more objects. The hologram corresponds to electromagnetic (EM) contributions from the primitives to display elements (or phasels) of the display **150**. The processing device **120** can be referred to be a phasel processing unit (PPU). The processing device **120** is configured to compute the EM contributions with high speed, e.g., by parallel processing, simplified expressions, and/or any other techniques described with further details below.

[0207] The processing device **120** can include at least one of: an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA), a programmable gate array (PGA), a central processing unit (CPU), a graphics processing unit (GPU), a phasel processing unit (PPU), or standard computing units. In some implementations, the processing device **120** communicates with the computing device **110** through peripheral component interconnect express (PCIe). The interface **115** can be a PCIe slot of the computing device **110**. The processing device **120** can be an integrated chip insertable in the PCIe slot of the computing device **110**. In some implementations, the processing device **120** is configured to be integrated with the driving device **131**, optionally with the display **150** and/or the illuminator **140** in a package, external to the computing device **110**. The processing device **120** can communicate with the computing device **110** via a wired or wireless connection, e.g., USB-C connection or any other high speed serial connection. In some implementations, the API **114** (and optionally the driver **116**) can be implemented in the processing device **120**.

[0208] In some implementations, the processing device **120** includes a command processor **122**, a local memory **123**, a plurality of computing units **124**, and at least one accumulator **126** that can be coupled in series. The plurality of computing units **124** can be coupled in parallel, e.g., for parallel processing. In some implementations, a group of computing units **124** is coupled in series, and multiple groups are coupled in parallel with each other. In some implementations, the processing device **120** includes multiple accumulators **126** that can be coupled in parallel, and each accumulator **126** is coupled to a respective group of computing units **124**.

[0209] The command processor **122** is in communication with the computing device **110** (e.g., the buffer **119** in the memory **118**) and configured to receive a command from the computing device **110**. The command can include information of a plurality of primitives corresponding to at least one object. The information can include primitive identifiers of the plurality of primitives, vertex identifiers associated with the primitive identifiers, and an index table showing associations between the primitive identifiers and the vertex identifiers. The command can include an instruction for drawing the plurality of primitives based on the information. As noted above, the command can include no primitive data of the plurality of primitives and no vertex data of vertices of the plurality of primitives.

[0210] The command processor **122** is configured to: process the command to identify the primitive identifiers or vertex identifiers and obtain primitive data of the plurality of primitives from the computing device **110** based on the primitive identifiers or vertex identifiers. For example, the command processor **122** retrieves the primitive data from the memory **118** based on the primitive identifiers in the command. In some implementations, the command processor **122** retrieves the vertex data of the vertices based on the vertex identifiers in the command.

[0211] In some implementations, an object is represented by a large number of primitives. Drawing the object can be executed by a series of commands, where each command is associated with a respective small group of primitives. In such a way, a size of each command can become smaller. The transmission speed for transmitting the command, the retrieved primitive data, and/or the retrieved vertex data from the computing device **110** to the command processor **122** can be faster. The processing speed of the processing device **120** can be also faster.

[0212] In some implementations, as noted above, the API **114** in the host device **110** can decode the object to obtain vertex information of vertices associated with the object and/or primitive information of primitives associated with the object that can be stored in the memory **118** (e.g., in the buffer **119**). Before sending commands to the processing device **120**, the API **114** can first transmit the vertex information of the vertices and/or the primitive information of the primitives (e.g., stored in the buffer **119**) to the processing device **120**. The vertex information of the vertices and/or the primitive information of the primitives can be stored in the local memory **123**. After the API **114** sends a command to the command processor **122** in the processing device **120**, the command processor **122** can retrieve corresponding index information (e.g., the index table **422** of FIG. **4**B) from the memory **118** in the host device **110** and corresponding vertex information (e.g., in the table **400** of FIG. **4**A or the vertex table **424** of FIG. **4**B) from the local memory **123** in the processing device **120**, and execute the command based on the retrieved corresponding index information and the retrieved corresponding vertex information. In such a way, the API **114** only needs to transmit the index information from the host device **110** to the processing device **120**, without transmitting the vertex information, which can reduce data over the interface **115** and increase a transmission speed.

[0213] Different from a conventional 3D graphics system, which takes a 3D scene and renders it on to a 2D display device, the system **100** is configured to produce a 3D output such as a holographic reconstruction in a form of a light field, e.g., a 3D volume of light. In a hologram, each display element can contribute to every part of the holographic reconstruction of the scene. Hence, each display element may potentially be modulated for every part of the scene, e.g., each primitive in the list of primitives generated by the application **112**, for complete holographic reproduction of the scene. In some implementations, modulation of certain elements can be omitted or simplified based on, for example, an acceptable level of accuracy in the reproduced scene or in some region of the scene, or occlusion.

[0214] In some implementations, the processing device **120** is configured to compute an EM field contribution, e.g., phase, amplitude, or both, from each primitive to each display element, and generate, for each display element, a sum of the EM field contributions from the list of primitives to the display element. This can be done either by running through every primitive and accruing its contribution to a given display element, or by running through each display element for each primitive, or by a hybrid blend of these two techniques.

[0215] The processing device **120** can compute the EM field contribution from each primitive to each display element based on a predetermined expression for the primitive. Different primitives can have corresponding expressions. In some cases, the predetermined expression is an analytic expression. In some cases, the predetermined expression is determined by solving Maxwell's Equations with a boundary condition defined at the display **150**. The boundary condition can include a Dirichlet boundary condition or a Cauchy boundary condition. Then, the display element can be modulated based on the sum of the EM field contributions, e.g., by modulating at least one

of a refractive index, an amplitude index, a birefringence, or a retardance of the display element.

[0216] If values of an EM field, e.g., a solution to the Maxwell Equations, at each point on a surface that bounds the field are known, an exact, unique configuration of the EM field inside a volume bounded by a boundary surface can be determined. The list of primitives (or a holographic reconstruction of a corresponding hologram) and the display **150** define a 3D space, and a surface of the display **150** forms a portion of a boundary surface of the 3D space. By setting EM field states (e.g., phase or amplitude or phase and amplitude states) on the surface of the display **150**, for example, by illuminating light on the display surface, the boundary condition of the EM field can be determined. Due to time symmetry of the Maxwell Equations, as the display elements are modulated based on the EM field contributions from the primitives corresponding to the hologram, a volumetric light field corresponding to the hologram can be obtained as the holographic reconstruction.

[0217] For example, a line primitive of illumination at a specific color can be set in front of the display **150**. An analytic expression for a linear aperture can be written as a function in space. Then the EM field contribution from the line primitive on a boundary surface including the display **150** can be determined. If EM field values corresponding to the computed EM field contribution are set in the display **150**, due to time-symmetry of the Maxwell Equations, the same linear aperture used in the computation can appear at a corresponding location, e.g., a coordinate position of the linear primitive in the 3D coordinate system and with the specific color.

[0218] In some examples, suppose that there is a line of light between two points A and B in the 3D space. The light is evenly lit and has an intensity I per line distance l. At each infinitesimal dl along the line from A to B, an amount of light proportional to I*dl is emitted. The infinitesimal dl acts as a delta (point) source, and the EM field contribution from the infinitesimal dl to any point on a boundary surface around a scene corresponding to a list of primitives can be determined. Thus, for any display element of the display **150**, an analytic equation that represents the EM field contribution at the display element from the infinitesimal segment of the line can be determined. A special kind of summation/integral that marches along the line and accrues the EM field contribution of the entire line to the EM field at the display element of the display can be determined as an expression. Values corresponding to the expression can be set at the display element, e.g., by modulating the display element and illuminating the display element. Then, through time reversal and a correction constant, the line can be created in the same location defined by points A and B in the 3D space.

[0219] Referring to FIG. **1**A, after the command processor **122** obtains the primitive data or vertex data of the plurality of primitives, the command processor **122** transmits the primitive data or vertex data to the plurality of computing units **124** for further processing. The computing units **124** are configured to, for each primitive of the plurality of primitives, determine an EM field contribution of the primitive to each of a plurality of display elements of the display **150** in a 3D coordinate system based on the primitive data or vertex data of the plurality of primitives. The plurality of computing units **124** can be operated in parallel. The accumulator **126** is configured to accumulate EM field contributions of the plurality of primitives to each of the plurality of display elements from the plurality of computing units **124** and generate a respective sum of EM field contributions of the plurality of primitives to each of the plurality of display elements. The accumulator **126** can generate a hologram comprising a respective sum of the EM field contributions of the plurality of primitives for each of the plurality of display elements.

[0220] The 3D coordinate system can be, e.g., Cartesian coordinate system XYZ, polar coordinate system, cylindrical coordinate system, or spherical coordinate system. The plurality of display elements in the display **150** can also have corresponding coordinate information in the 3D coordinate system. The primitives at coordinate locations can represent a 3D object adjacent to the plurality of display elements, e.g., in front of the display elements, behind the display elements, or straddling the display elements.

[0221] In some implementations, a computing unit **124** is configured to determine at least one distance between a display element of the display **150** and a primitive based on coordinate information of the display element and coordinate information of the primitive, and determine the EM field contribution of the primitive to the display element based on a predetermined expression for the primitive and the at least one distance. The predetermined expression can be determined based on at least one of: analytically calculating an EM field propagation from the primitive to the display element, a solution of Maxwell's equations with a boundary condition defined by the display, or at least one function from a group of functions comprising a sine function, a cosine function, and an exponential function, where determining the EM field contribution includes identifying a value of the at least one function in a table stored in a memory.

[0222] In some implementations, adjacent first and second primitives have at least one shared vertex. A computing unit **124** can determine a first EM field contribution of the first primitive to a display element of the display **150** based on primitive data of the first primitive and determining a second EM field contribution of the second primitive to the display element of the display based on the first EM field contribution and primitive data of the second primitive, e.g., by a distance between coordinates of the first primitive and the second primitive.

[0223] In some implementations, a computing unit **124** (or a phasel processing unit) is configured to determine a first EM contribution of a primitive to a first display element of the display **150** and determine a second EM contribution of the primitive to a second display element of the display based on the first EM contribution, the second display element being adjacent to the first display element.

[0224] The computing units **124** can determine the EM field contributions from the plurality of primitives to the display elements of the display **150** in parallel. In some implementations, the computing units **124** are configured to determine a first EM field contribution of a first primitive to a first display element in parallel with determining a second EM field contribution of a second primitive to the first display element. In some implementations, the computing units **124** are configured to determine a first EM field contribution of a first primitive to a first display element in parallel with determining a second EM field contribution of a second primitive to a second display element. In some implementations, the computing units **124** are configured to determine a first EM field contribution of a first primitive to a first display element in parallel with determining a second EM field contribution from the first primitive to a second display element.

[0225] In some implementations, the computing units **124** are configured to determine first respective EM field contributions from a first primitive of the plurality of primitives to each display element of the plurality of display elements, and, in parallel, determine second respective EM field contributions from a second primitive of the plurality of primitives to each display element of the plurality of display elements. The accumulator **126** can be configured to accumulate the EM field contributions for each display element of the plurality of display elements by adding the first and second respective EM field contributions corresponding to the display element.

[0226] In some implementations, the processing device **120** is configured to obtain sums of EM field contributions for the plurality of display elements of the display **150** by pipeline processing of determining the EM field contributions of each of the plurality of primitives to each of the plurality of display elements and generating the sum of the EM field contribution from the plurality of primitives to each of the plurality of display elements.

[0227] The processing device **120** can perform pipeline calculation using the computing units **124**. As noted above, the processing device **120** obtains the sum of the EM field contribution from the plurality of primitives to each display element through a series of steps. For example, calculating a predetermined expression can be divided into multiple steps. Each row can represent a respective series of steps for a corresponding display element. Steps for multiple display elements can be executed in parallel. After a first step for a first display element is completed, a second step for the first display element is executed, meanwhile, a first step for a second display element is executed

(e.g., based on a result of the first step for the first display element). Then, after the second step for the first display element is completed and the first step for the second display element is also completed, a third step for the first display element is executed, a second step for the second display element can be also executed (e.g., based on a result of the second step for the first display element and a result of the first step for the second display element). Meanwhile, a first step for the third display element can be executed (e.g., based on the result of the first step for the second display element and/or the result of the first step of the first display element). In such a way, except a latency period at the beginning of the computation, the processing device **120** enables to execute the steps for the plurality of display elements in parallel according to the pipeline calculation. In some implementations, to improve computation speed and/or accuracy, the processing device **120** calculates one or more mathematical functions using fixed point number representations, updated floating point number presentations, or a combination thereof.

[0228] In some implementations, the processing device **120** calculates respective EM field contributions of each primitive of the plurality of primitives to each display element of the plurality of display elements. The calculation of the respective EM field contributions can be without at least one of: expanding a geometry of the object into the plurality of display elements; applying visibility tests before packing wavefronts; or decision making or communication between parallel calculations for different primitives of the plurality of primitives. The calculation of the respective EM field contributions can be configured to cause at least one of: tuning parallel calculations for multiple primitives to speed, cost, size or energy optimization; reducing latency between initiating a draw and a result being ready for display; increasing an accuracy using fixed point number representations; skipping unpacking and repacking of float point number representations between mathematical operations; or optimizing computation speed by optimizing mathematical functions.

[0229] After obtaining primitive data or vertex data associated with a plurality of primitives, the processing device **120** can be configured to adjust the primitive data or the vertex data of at least one of the plurality of primitives according to a corresponding setting, and compute EM field contributions associated with the at least one of the plurality of primitives based on the adjusted primitive data or vertex data.

[0230] In some examples, the processing device **120** adjusts primitive data or vertex data of at least one of adjacent primitives to generate a gap between the adjacent primitives, such that there is no shared vertex between the adjacent primitives. The gap can be identical to or greater than a predetermined diffraction limit of the display. The processing device **120** can determine the EM field contribution of the at least one of the adjacent primitives based on the adjusted vertex data associated with the at least one of the adjacent primitives.

[0231] After obtaining sums of EM field contributions for the plurality of elements of the display **150**, the processing device **120** (e.g., the accumulator **126**) can generate a hologram based on the sums of the EM field contributions. In some examples, the hologram is a complex-valued hologram. The processing device **120** can further convert the complex-valued hologram to an amplitude-only hologram or a phase-only hologram. The processing device **120** can also transmit the complex-valued hologram to the driving device **131** that can convert the complex-valued hologram to a phase-only hologram or an amplitude-only hologram.

[0232] In some examples, the hologram is a phase hologram or an amplitude hologram. The processing device **120** can also transmit the phase hologram or the amplitude hologram to the driving device **131**. The driving device **131** can then generate corresponding control signals for modulating the plurality of display elements based on the hologram.

[0233] For display zero order suppression, display zero order light can be deviated from a reconstruction cone of a holographic scene formed by diffracted first order light from the display. To achieve this, in some implementations, the processing device **120** can change the hologram for the plurality of display elements. In some implementations, instead of the processing device **120**, the driving device **131** can change the hologram for the plurality of display elements after receiving

the hologram from the processing device **120**.

[0234] The hologram can be changed, e.g., by the processing device **120** or the driving device **131**, by adjusting a respective phase for each of the plurality of display elements. Th respective phase can be adjusted, e.g., by adding a corresponding phase to the respective phase for each of the plurality of display elements.

[0235] In some examples, the corresponding phase for each of the plurality of display elements can be expressed as:

[00001] $\emptyset = 2\pi(x\cos\theta + y\sin\theta)/\lambda$, [0236] where Ø represents the corresponding phase for the display element, λ represents a wavelength of light to be incident on the display element with an incident angle, θ represents an angle corresponding to a redirecting angle of an optically redirecting device (e.g., the zero order redirecting grating structure **508-3** of FIG. **5**A) configured to redirect light from the display **150**, and x and y represent coordinates of the display element in a global 3D coordinate system where the EM field contribution of each of the plurality of display elements to the display element is determined. Adding these corresponding phases to the hologram can have a same or similar effect of preconfiguring the hologram using a software application (e.g., Unity), where a construction cone including one or more corresponding virtual objects is rotated with a corresponding angle.

[0237] In some examples, the corresponding phase for each of the plurality of display elements is expressed as:

[00002] $\emptyset = \frac{\pi}{\lambda f}(ax^2 + by^2)$, [0238] where Ø represents the corresponding phase for the display element, a and b represent constants, λ represents a wavelength of light to be incident on the display, f represents a focal length of an optically diverging component configured to diverge light from the display, x and y represent coordinates of the display element in a coordinate system where the EM field contribution of each of the plurality of display elements to the display element is determined. Adding these corresponding phases to the hologram can have a same or similar effect of preconfiguring the hologram using a software application (e.g., Unity), where a construction cone including one or more corresponding virtual objects is moved close or away from the display **150**, such that the display zero order light is diverged by the optically diverging component (e.g., an optical lens) downstream the display **150**.

[0239] In some implementations, instead of adjusting the hologram, the processing device **120** can adjust the primitive data or vertex data associated with the plurality of primitives. The adjusted primitive data of the plurality of primitives corresponds to a virtual object moved with respect to the display in a global 3D coordinate system. The processing device **120** can then determine EM field contribution of a primitive to each of the plurality of display elements of the display based on the adjusted primitive data of the primitive in the 3D coordinate system.

[0240] In some examples, the adjusted primitive data of the plurality of primitives corresponds to the virtual object rotated with an angle with respect to the display in the global 3D coordinate system, and the angle corresponds to a redirecting angle of an optically redirecting device (e.g., the zero order redirecting grating structure **508-3** of FIG. **5**A) configured to redirect light from the display, such that modulated light by the plurality of display elements forms a holographic scene, while display zero order light from the display is redirected away from the holographic scene.

[0241] In some examples, the adjusted primitive data of the plurality of primitives corresponds to the virtual object moved, with respect to the display, in the global 3D coordinate system, along a direction perpendicular to the display with a distance. The distance corresponds to a focal length of an optically diverging component (e.g., an optical lens) configured to diverge light from the display, such that modulated light by the plurality of display elements forms a holographic scene without divergence, while display zero order light from the display is diverged and suppressed in the holographic scene.

[0242] In some implementations, primitive data of a primitive includes texture coordinate information of the primitive. In some cases, the primitive data obtained from the API **114** can

include values associated with discrete cosine transform (DCT) amplitudes for pixels of an image to be mapped on a specified surface of one or more primitives of the plurality of primitives, where the DCT amplitudes for the pixels of the image are associated with DCT weights of the pixels of the image. In some cases, after obtaining the primitive data, the processing device **120** can adjust the primitive data to include the values associated with the DCT amplitudes for the pixels of the image. For each primitive of the plurality of primitives, the processing device **120** can calculate the EM field contribution from each of the one or more primitives to each of the plurality of display elements with the values associated with the DCT amplitudes for the pixels of the image.

[0243] In some implementations, primitive data of a primitive includes occlusion information of the primitive. In some examples, the processing device **120** can determine one or more particular display elements that make no contribution to a reconstruction of a given primitive based on occlusion information of the given primitive. For each of the one or more particular display elements, the processing device **120** can generate a respective sum of EM field contributions of the plurality of primitives to the particular display element by excluding an EM field contribution of the given primitive to the particular display element. In some examples, the processing device **120** can be configured to: for each display element of the plurality of display elements, determine a respective part of a given primitive that make no EM field contribution to the display element based on occlusion information of the given primitive, and generate a sum of EM field contributions from the plurality of primitives to the display element by excluding an EM field contribution from the respective part of the given primitive to the display element.

[0244] In some implementations, primitive data of a primitive includes viewpoint dependent shading information for the primitive. The processing device **120** can be configured to: determine a respective EM field contribution of each primitive of the plurality of primitives to each display element of the plurality of display elements by taking into consideration of the viewpoint dependent shading information for the primitive.

[0245] In some implementations, the display **150** is a regular display where the plurality of display elements have a same shape and are spaced evenly in a display area. In some implementations, the display **150** is an irregular display where the plurality of display elements form an irregular pattern, e.g., having different shapes or sizes and/or being irregularly positioned, for example, as illustrated in FIG. **6**A below.

[0246] For either a regular display or an irregular display, the processing device **120** can be configured to: obtain information of the display **150** that includes coordinate information of a plurality of points corresponding to the plurality of display elements. For each primitive of the plurality of primitives, the processing device **120** determines the electromagnetic (EM) field contribution to each of the plurality of display elements of the display based on the primitive data of the display by: calculating, in a three-dimensional (3D) coordinate system, EM propagation from the primitive to the display based on coordinate information of the primitive and coordinate information of a point corresponding to the display element.

[0247] In some implementations, for the irregular display, each of the plurality of display elements has a respective shape of a plurality of shapes in an area of the display, each of the plurality of shapes uniquely enclosing a respective point of the plurality of points, adjacent shapes of the plurality of shapes being different from each other. The coordinate information of the plurality of points includes coordinate information of a plurality of spaced points in the area of the display and offset data including a respective offset between each point of the plurality of points and a corresponding space point of the plurality of space points.

2.3 Driving Device

[0248] The driving device **131** is coupled to the processing device **120** and is configured to receive a hologram from the processing device **120** (e.g., from the accumulator **126**). The hologram is for modulating the display **150**, and can include: for each display element of the plurality of display elements, a respective sum of electromagnetic (EM) field contributions of a plurality of primitives

corresponding to at least one object to the display element. The driving device **131** can be configured to: generate, for each display element of the plurality of display elements, a respective modulation control signal (e.g., a voltage signal) based on the respective sum of EM field contributions of the plurality of primitives to the display element, and output the respective modulation control signal to each display element of the plurality of display elements for modulating the display element.

[0249] In some implementations, e.g., as illustrated in FIG. **1**A, the driving device **131** includes a driving memory **132** coupled to the processing device **120**, an illuminator driver **134** coupled to the driving memory **132** and the illuminator **140**, and a display driver **136** coupled to the driving memory **132** and the display **150**. The driving memory **132** can include a first memory buffer coupled to the display driver **136** and a second memory buffer coupled to the illuminator driver **134**. The second memory buffer can be configured to store information for controlling amplitude and/or brightness of light emitting elements in the illuminator **140**. The second memory buffer can have a smaller size than the first memory buffer.

[0250] The driving memory **132** is configured to receive and store the hologram from the processing device **120**. In some cases, the hologram is a phase-only hologram. In some cases, the hologram is a complex-valued hologram. The driving device **131** can convert the complex-valued hologram to a phase-only hologram, and generate the respective modulation control signals for the plurality of display elements based on the phase-only hologram. The driving device **131** can also store the phase-only hologram in the driving memory **132**, together with the complex-valued hologram. The phase-only hologram for the display **150** can include a respective phase for each of the plurality of display elements of the display **150**. The respective phase corresponds to a sum of electromagnetic (EM) field contributions of the plurality of primitives corresponding to at least one object to the display element.

[0251] In some implementations, the display driver **136** includes a phase converter **137** and a scanning out unit **138**. The phase converter **137** is configured to convert a respective phase for each of the plurality of display elements into a corresponding modulation control signal (e.g., a voltage signal), and the scanning out unit **138** is configured to transmit the corresponding modulation control signal to the display element. The phase converter **137** can sequentially and continuously convert the respective phases for the plurality of display elements, and the scanning out unit **138** can sequentially and continuously transmit the corresponding modulation control signals to the plurality of display elements once each of the corresponding modulation control signals is generated by the phase converter **137**.

[0252] In some implementations, the phase converter **137** is included in the processing device **120** and coupled to the accumulator **126**. The phase converter **137** can convert a complex hologram from the accumulator **126** into a phase hologram. The phase hologram can be transmitted from the processing device **120** to the driving device **130**, and can be stored in the driving memory **132** of the driving device **130**.

[0253] In some implementations, the phase converter **137** and the driving memory **132** are both in the processing device **120**, where the driving memory **132** is included in the local memory **123** and the phase converter **137** is coupled to the accumulator **126** and coupled to the local memory **123**. In such a way, the processing device **120** can directly output a phase hologram to the driving device **130**. The driving device **130** can include the illuminator driver **134** and the display driver **136** including only the scanning out unit **139**, which can greatly simply the driving device **130** and can be integrated with the display **150**.

[0254] The display driver **136** and the display **150** can be connected using an interface, e.g., low voltage differential signal (LVDS) interface. The display driver **136** can be configured to drive a digital signal to the display **150** using the interface. For example, the digital signal can be a 9-bit digital value which can be turned into 512 different voltage signals for modulating display elements of the display **150**.

[0255] Besides display elements, the display **150** can include digital circuits and analog circuits. The digital circuits can be configured to receive a digital data for modulating the elements, and optionally perform data processing on the digital phase signals (e.g., to reduce noise in the phases for the display elements). The analog circuits can include digital to analog converters (DACs), drivers, and row scanners. The DACs are configured to convert the digital data for the display elements into analog voltage signals. The drivers are coupled to the digital circuits and configured to drive the analog voltage signals to corresponding display elements. The row scanners can be configured to sequentially select a row of display elements for modulating the row of display elements using corresponding voltage signals driven from the drivers.

[0256] The illuminator driver **134** can be configured to: transmit an illumination control signal (e.g., for amplitude and/or brightness control) to the illuminator **140** to activate the illuminator **140** to illuminate light on the display **150** such that light is caused by the modulated display elements of the display **150** to form a volumetric light field corresponding to the at least one object, e.g., the holographic light field **160**. The resulting volumetric light field corresponds to a solution of Maxwell's equations with a boundary condition defined by the modulated elements of the display **150**. The display driver **136** and the illuminator driver **134** can be configured to communicate with each other, such that outputting the respective modulation control signal to each display element of the plurality of display elements by the display driver **136** is in coordination with transmitting the illumination control signal to the illuminator **140** by the illuminator driver **134**.

[0257] In some implementations, the illuminator **140** includes two or more light emitting elements each configured to emit light with a different color (e.g., red, blue, or green), and the illuminator driver **134** can sequentially transmit a respective illumination control signal to sequentially activate each of the two or more light emitting elements of the illuminator.

[0258] In some implementations, the display driver **136** sequentially outputs: i) a first modulation control signal to modulate the display **150** with information associated with a first color during a first time period, and ii) a second modulation control signal to modulate the display **150** with information associated with a second color during a second, sequential time period. The illuminator driver **134** can sequentially output a first illumination control signal to activate the illuminator **140** to turn on a first light emitting element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator **140** to turn on a second light emitting element to emit light with the second color during the second time period.

2.4 Display

[0259] The display **150** includes a number of display elements. In some implementations, the display **150** includes a spatial light modulator (SLM). The SLM can be a phase SLM, an amplitude SLM, or a phase and amplitude SLM. In some examples, the display **150** is a digital micro-mirror device (DMD), a liquid crystal on silicon (LCOS) device, Optically addressed spatial light modulators (OASLMs), or any other type of light modulator that is capable of performing holography.

[0260] In some implementations, the display **150** is a regular display where the plurality of display elements have a same shape and are spaced evenly in a display area (e.g., as illustrated in FIG. **6**A below). In some implementations, the display **150** is an irregular display where the plurality of display elements form an irregular pattern, e.g., having different shapes or sizes and/or being irregular positioned, for example, as illustrated in FIG. **6**A or FIG. **6**B below.

[0261] The display elements of the display **150** can be modulated by the modulated control signals from the display driver **136**. Each modulated control signal is for modulating a respective display element based on a sum of EM field contributions from a plurality of primitives corresponding to a scene (e.g., including one or more objects) for the respective display element.

[0262] In some implementations, a number of light emitting elements in the illuminator **140** can be smaller than a number of the display elements of the display **150**, as long as light from the light emitting elements can illuminate over substantially a total surface of the display **150**. For example,

an illuminator having 64×64 OLEDs (organic light emitting diodes) can be used for a display having 1024×1024 elements. The driving device **131** (e.g., the illuminator driver **134**) can be configured to simultaneously activate the number of lighting elements of the illuminator **140**.

[0263] The illuminator **140** can include one or more coherent light sources (e.g., lasers), one or more semi-coherent light sources (e.g., LEDs (light emitting diodes) or superluminescent diodes (SLEDs)), one or more incoherent light sources, or a combination of such sources. In some implementations, the illuminator **140** is a monochromatic light source configured to emit a substantially monochromatic light, e.g., a red light, a green light, a yellow light, or a blue light. In some implementations, the illuminator **140** includes two or more light emitting elements, e.g., lasers or light emitting diodes (LEDs), each configured to emit light with a different color. For example, the illuminator **140** can include red, green, and blue lighting elements.

[0264] To display a full-color 3D object, three or more separate holograms for colors including at least red, green, and blue, can be computed, e.g., by the processing device **120**. That is, at least three EM field contributions from corresponding primitives to the display elements can be obtained. The display elements can be modulated sequentially based on the at least three EM field contributions and the illuminator **140** can be controlled to sequentially turn on the at least red, green and blue lighting elements sequentially. For example, the driving device **131** can first transmit a first timing signal to turn on a blue lighting element and transmit first modulation control signals corresponding to a blue hologram to display elements of the display **150**. After the blue hologram on the display **150** is illuminated with the blue light for a first period of time, the driving device **131** can transmit a second timing signal to turn on a green lighting element and transmit second control signals corresponding to a green hologram to display elements of the display **150**. After the green hologram on the display **150** is illuminated with the green light for a second period of time, the driving device **131** can transmit a third timing signal to turn on a red lighting element and transmit third control signals corresponding to a red hologram to display elements of the display **150**. After the red hologram on the display **150** is illuminated with the red light for a third period of time, the driving device **131** can repeat the above steps. Depending on temporal coherence-of vision effect in an eye of a viewer, the three colors can be combined in the eye to give an appearance of full color. In some cases, the illuminator **140** is switched off during a state change of the display image (or holographic reconstruction) and switched on when a valid image (or holographic reconstruction) is presented for a period of time. This can also depend on the temporal coherence of vision to make the image (or holographic reconstruction) appear stable.

[0265] In some implementations, the display **150** has a resolution small enough to diffract visible light, e.g., on an order of 0.5 μm or less. The illuminator **140** can include a single, white light source and the emitted white light can be diffracted by the display **150** into different colors for holographic reconstructions.

[0266] As discussed in further detail below with respect to FIGS. **5A-5D**, there can be different configurations for the system **100**. The display **150** can be reflective or transmissive. The display **150** can have various sizes, ranging from a small scale (e.g., 1-10 cm on a side) to a large scale (e.g., 100-1000 cm on a side). Illumination from the illuminator **140** can be from the front of the display **150** (e.g., for a reflective or transflective display) or from the rear of the display **150** (e.g., for a transmissive display). The illuminator **140** can provide uniform illumination across the display **150**. In some implementations, an optical waveguide can be used to evenly illuminate a surface of the display **150**.

[0267] In some implementations, the illuminator driver **134** and the illuminator **140** are integrated together as an illumination device, and the display driver **136** and the display **150** are integrated together as a display device. The driving memory **132** can be separated from the illuminator device and the display device, or the driving memory **132** can be integrated with one of the illuminator device and the display device. The illuminato device and the display device can communicate with each other.

[0268] In some implementations, the processing device **120** and the driving device **131** are integrated together as a controller for the display **150** and/or the illuminator **140**. In some implementations, the processing device **120**, the driving device **131**, and the display **150** are integrated together as a single unit. The single unit can also be integrated with the illuminator **140**. The single units can be arranged (or tiled) in arrays to form a larger device.

[0269] In some implementations, the driving device **131**, the illuminator **140**, and the display **150** are integrated together as a single unit, e.g., as a holographic display device. The processing device **120** can be integrated in the computing device **110**, e.g., through a PCIe slot. As noted above, the computing device **110** can generate application scene data using a 3D simulation application (e.g., the application **112**), the application scene data including information of a plurality of primitives corresponding to at least one object and generate the primitive data of the plurality of primitives corresponding to the at least one object based on the application scene data using the API **114**. The API **114** can be configured to adjust initial primitive data of the plurality of primitives generated from the application scene data to generate the primitive data of the plurality of primitives, vertex data of vertices associated with the plurality of primitives, and/or tables and commands, e.g., as discussed with details in section 2.1.

[0270] In some implementations, an optically diffractive device, e.g., a field grating device, a waveguide device, or a lightguide device, as illustrated in FIGS. **5**A to **5**D, is coupled between the illuminator **140** and the display **150** and is configured to diffract light from the illuminator **140** into the display **150** that then diffracts the light to a viewer's eyes. The optically diffractive device can be positioned adjacent to the display **150**, e.g., as illustrated in FIGS. **5**A to **5**D.

[0271] In some examples, the light from the illuminator **140** can be incident on the optically diffractive device with a large incident angle from a side, such that the illuminator **140** does not block the viewer's view of the display **150**. In some examples, the diffracted light from the optically diffractive device can be diffracted at a nearly normal incident angle into the display, such that the light can relatively uniformly illuminate the display **150** and be diffracted to the viewer's eyes with reduced (e.g., minimized) loss.

[0272] The optically diffractive device can include a field grating structure (e.g., the field grating structure **508-1** of FIG. **5**A) formed on a first side of a substrate (e.g., the substrate **508-2** of FIG. **5**A) and configured to suppress color crosstalk between different colors of light incident on the display **150** and/or a zero order redirecting structure (e.g., the zero order redirecting grating structure **508-3** of FIG. **5**A) formed on a second, opposite side of the substrate and configured to suppress display zero order light. In some implementations, example optically diffractive devices are configured and performed as described in international application PCT/US2021/50271 entitled "DISPLAYING THREE-DIMENSIONAL OBJECTS" and filed on Sep. 14, 2021 and international application PCT/US2021/50275 entitled "RECONSTRUCTING OBJECTS WITH DISPLAY ZERO ORDER LIGHT SUPPRESSION" and filed on Sep. 14, 2021, which are commonly-owned and fully incorporated herein by reference.

[0273] In some implementations, the field grating structure includes at least one optically diffractive components and at least one of one or more color-selective polarizers or at least one of one or more reflective layers or one or more transmissive layers. In some implementations, e.g., as discussed with further details in section 4.5, the field grating structure includes at least one diffraction grating with a low diffraction efficiency for the light from the illuminator **140**. The diffraction efficiency can be lower than a predetermined threshold, e.g., 20%, 15%, or 10%. In some implementations, a coupling device is arranged between the illuminator **140** and the optically diffractive device (e.g., the field grating structure). The illuminator **140** can illuminate a plurality of different colors of light. The coupling device can be configured to receive the plurality of different colors of light from the illuminator **140** and to output the plurality of different colors of light to the optically diffractive device.

[0274] In some implementations, the coupling device includes: a prism element between the

illuminator **140** and the optical diffractive device and configured to receive the plurality of different colors of light from an input surface of the prism element; one or more expansion gratings adjacent an exit surface of the prism element, each of the one or more expansion gratings configured to expand a beam profile of a different corresponding color of light by a factor in at least one dimension; and one or more reflectors downstream of the one or more expansion gratings, each of the one or more reflectors being configured to reflect a respective color of light into the optically diffractive device, where a tilt angle of each of the one or more reflectors is independently adjustable to cause a uniformity of diffraction from the optical diffractive device to the display **150**.

[0275] In some implementations, the optically diffractive device (e.g., the field grating structure) is positioned facing a display surface of the display **150** along a perpendicular direction to the display surface. In some implementations, the coupling device is configured to couple the plurality of different colors of light into the optically diffractive device (e.g., the field grating structure) from a bottom surface or a top surface of the coupling device. In some implementations, the coupling device is configured to couple the plurality of different colors of light into the optically diffractive structure (e.g., the field grating structure) from a side surface of the coupling device.

[0276] In some implementations, a plurality of optical components arranged between the illuminator **140** and the display **150** can be configured for dispersion compensation. For example, at least one first optical component (e.g., a diffraction grating) is configured to cause a positive optical dispersion for light incident on the display, and at least one second optical component (e.g., another diffraction grating) can be configured to cause a negative optical dispersion for the light, the light having a spectral bandwidth with a peak wavelength. The positive optical dispersion and the negative optical dispersion can be compensated with each other, such that a holographic scene reconstructed from the light has no or little light dispersion.

2.5 Example Holographic Reconstruction for a Live Scene

[0277] FIG. **1**B illustrates an example holographic reconstruction for a live scene. A system **170** can include a computing device, e.g., the computing device **110** of FIG. **1**A optionally with the processing device **120** of FIG. **1**A, and a holographic display device **172**, e.g., the holographic display **150** of FIG. **1**A optionally with the processing device **120** of FIG. **1**A and/or the driving device **131** of FIG. **1**A. A user can use an input device, e.g., a keyboard **174** and/or a mouse **176**, to operate the system **170**. The computing device or the holographic display device **172** can include a holographic renderer, e.g., implemented by the processing device **120** of FIG. **1**A, to render a 3D representation of a live scene (e.g., a soccer game in a stadium) to generate corresponding graphic data for the live scene. The graphic data can include respective primitive data for a list of primitives corresponding to the live scene.

[0278] The holographic display device **172** can include a processing device (e.g., the processing device **120** of FIG. **1**A), a driving device (e.g., the driving device **131** of FIG. **1**A), and a display **173** (e.g., the display **150** of FIG. **1**A). The processing device can compute a respective sum of EM field contributions from the primitives to each display element of the display **173** and generate control signals for modulating each display element based on the respective sum of EM field contributions. The holographic display device **172** can further include an illuminator (e.g., the illuminator **140** of FIG. **1**A). The driving device can generate a timing control signal to activate the illuminator. When light from the illuminator illuminates a surface of the display **173**, the modulated display elements can cause the light to propagate in the 3D space to form a volumetric light field corresponding to a holographic reconstruction **178** for the live scene, e.g., a soccer game in a stadium including two players and a soccer ball. Thus, the 3D holographic reconstruction **178** of the live scene are displayed as respective holographic reconstructions floating in the 3D space in front of, behind, or straddling the display **173**.

3. Example System with Optical Approach

[0279] FIG. **2** illustrates a schematic diagram of an example system **200** for capturing and displaying live scenes using optical approach. Different from the system **100** of FIG. **1**A where

visual data of a live scene is captured and processed to generate a 3D digital representation of the live scene and further a corresponding computed hologram for holographic reconstruction, the system **200** is configured to capture real optical holograms of a live scene (e.g., an interference pattern associated with the live scene) using a digital sensor (e.g., CCD or CMOS) that outputs digital hologram data, without post-processing, to a holographic display system for holographic reconstruction in real time, e.g., with an acceptable quality. Optionally, the digital hologram data can be processed by a computing device to generate a corresponding digital hologram to be the holographic display system for holographic reconstruction, which, for example, can increase the quality of the reconstructed live scene. If the processing speed is fast, the capturing and displaying of the live scene can be still realized in real time.

[0280] In some implementations, e.g., as illustrated in FIG. **2**, the system **200** includes a holographic capturing system **210** and a holographic display system **230**. The holographic capturing system **210** can include an optical system **212** configured to generate an optical hologram of a live scene and an optical sensor **214** configured to capture sequential optical holograms of the live scene and output sequential hologram data associated with the sequential optical holograms of the live scene, each optical hologram being associated with respective hologram data. The live scene can include one or more three-dimensional (3D) objects in a real world or a physical space. The holographic display system **230** can be configured to optically reconstruct the live scene in a 3D space based on at least part of the sequential hologram data.

[0281] In some implementations, the system **200** further includes a computing device **220** coupled between the holographic capturing system **210** and the holographic display system **230**. The computing device **220** can be configured to receive the at least part of the sequential hologram data from the optical sensor **214** and generate digital holograms **226** associated with the live scene based on the at least part of the sequential hologram data. The holographic display system **230** can be configured to receive the digital holograms **226** associated with the live scene from the computing device and reconstruct the live scene in the 3D space based on the digital holograms **226**.

[0282] In some implementations, the system **200** includes one or more holographic capturing systems **210**, e.g., positioned around a live scene (e.g., a soccer game in a stadium), and configured to capture optical holograms of the live scene from one or more different views. The one or more holographic capturing systems **210** can be coupled to one or more computing devices **220** that can be operated in parallel. Data transmission between the holographic capturing system **210** and the computing device **220** can be through a wired connection, a wireless connection, or any high speed connection. Data transmission between the computing device **220** and the holographic display system **230** can be through a wired connection, a wireless connection, or any high speed connection.

[0283] In some implementations, to achieve real-time display of a live scene, the holographic capturing system **210** is configured to capture the sequential optical holograms and generate the sequential hologram data, without storing the sequential optical holograms and the sequential hologram data. The computing device **220** can also be configured to process the at least part of the sequential hologram data to generate the digital holograms, without storing the at least part of the sequential hologram data and the digital holograms. The holographic capturing system **210**, the computing device **220**, and the holographic display system **230** are configured together to capture optical holograms of the live scene and optically reconstruct the live scene in real time.

[0284] A refresh rate of capturing and displaying a live scene can be limited by a refresh rate (or frame rate) of an optical sensor of the holographic capturing system **210** (e.g., 90 frames per second) and a refresh rate (or frame rate) of a display of the holographic display system **230** (e.g., 30 frames per second). For real-time holography, a limit is 15 frames per second, so a value larger than that obeys a persistence of vision property of human eye and brain, which indicates that reconstruction of a live scene at a rate of more than 15 frames per second can make the live scene continuous to human eye and brain.

3.1 Holographic Capturing System

[0285] Referring to FIG. **2**, the holographic capturing system **210** includes the optical system **212** and the optical sensor **214**. The optical system **212** can include a holographic setup configured to generate an optical hologram. For example, the holographic setup can include an interferometer (e.g., Mach-Zehnder interferometer or Michelson interferometer), Gabor's holographic setup (e.g., inline), or Leith-Upatnieks holographic setup (e.g., off-axis). For illustration, Mach-Zehnder interferometer is described as an example holographic setup of the optical system **212**, e.g., as illustrated with further details in FIGS. **3**A-**3**D. The optical hologram includes an interference pattern associated with a live scene, e.g., an interference between an object beam interacting with the live scene and a reference beam interacting with the object beam.

[0286] The optical sensor **214** is configured to capture the optical hologram and output hologram data of the optical hologram. The optical sensor **214** can be a digital sensor, e.g., a digital camera like CCD or CMOS. The optical sensor **214** can include a number of sensing pixels in an active area of the optical sensor **214**. The optical hologram, e.g., an interference pattern, can be formed on the number of sensing pixels. The hologram data can include an array of data bits, e.g., bit "0" and "1". In some examples, the array of data bits includes a one-dimensional data array (e.g., 1×12,000,000). In some examples, the array of data bits includes a two-dimensional data array (e.g., 3,000×4,000). In some implementations, the optical sensor **214** includes a buffer for buffering the hologram data. The optical sensor **214** can output sequential hologram data of sequential optical holograms of a live scene, e.g., a stream of array of data bits.

[0287] In some implementations, a frame rate of the optical sensor **214** is comparable to a processing speed of the computing device **200**. The optical sensor **214** can directly transmit the hologram data of the optical holograms to the computing device **200** for processing.

[0288] In some implementations, the optical sensor **214** has a high frame rate, e.g., 90 Hz, that is, the optical sensor **214** can capture 90 images (e.g., optical holograms) per second. The frame date of the optical sensor **214** can be higher than the processing speed of the computing device **220**. In some implementations, the system **200** includes a frame grabber **216** coupled between the optical sensor **214** and the computing device **220** and configured to select part of hologram data of the optical holograms to transmit to the computing device **220**. For example, if the frame rate of the optical sensor **214** is 90 Hz and the computing device **220** can process 30 images per second, the frame grabber **216** can select just one third of the images captured by the optical sensor **214** to transmit to the computing device **220**. As an example, the frame grabber **216** can select the 1st image, 4.sup.th image, 7.sup.th image, . . . , 88.sup.th image out of the 90 images to transmit to the computing device **220**.

[0289] The frame grabber **216** can be coupled to the optical sensor **214** by, for example, a wired connection such as one or more transmission cables or a wireless connection. The frame grabber **216** can be coupled to the computing device **220**, by, for example, an interface **215** (e.g., the interface **115** of FIG. **1**A) that can be a PCIe slot or any other high speed connection. In some implementations, e.g., as illustrated in FIG. **2**, the frame grabber **216** is included in the holographic capturing system **210** (e.g., integrated with the optical sensor **214**). In some implementations, the frame grabber **216** is integrated in the computing device **220**, e.g., by a PCIe slot.

[0290] In some implementations, the frame grabber **216** includes a first in, first out (FIFO)-based grabber configured to deposit hologram data outputted from the optical sensor **214** directly into the computing device **220**. In some implementations, the frame grabber **216** includes a frame-buffer-based grabber configured to deposit hologram data outputted from the optical sensor **214** in a frame buffer of the frame grabber and subsequently into the computing device **220**.

[0291] In some implementations, the frame grabber **216** includes at least one of a grabber, a frame buffer, or a controller (e.g., a Direct Memory Access (DMA) controller). The grabber can include a set of hardware resources taking in charge all timing and control task required by the optical sensor **214**, and conditioning the digital hologram data provided by the optical sensor **214**. The frame

buffer can include an internal storage area large enough to hold a full frame image issued by the optical sensor **214**. The controller is configured to transfer the stored image from the frame buffer into a memory **222** of the computer device **220**, e.g., in a DMA (Direct Memory Access) fashion. This transfer does not require any CPU intervention (e.g., an intervention of a processor **224** of the computing device **220**).

[0292] In some implementations, the optical system **212** generates optical holograms with different colors (e.g., red, green, blue), for example, using a coherent light source including coherent light elements with the different colors (e.g., lasers with different colors).

[0293] In some implementations, the coherent light elements are sequentially and alternatively emit coherent light beams with respective colors, e.g., red, green, and blue (RGB). For each color, the holographic capturing system **210** includes a corresponding color filter arranged upstream the optical sensor **214** for each coherent light element when the coherent light element emits a corresponding coherent light beam with the color. The corresponding color filter can be a notch filter configured to transmit light with the color and block light with other colors to reach the optical sensor **214**. The optical sensor **214** can capture sequential groups of optical holograms with the different colors, each group including corresponding optical holograms with the different colors (e.g., red optical hologram, green optical hologram, blue optical hologram). In some implementations, the frame grabber **216** selects alternatively hologram data of one of the optical holograms with the different colors from a group, e.g., red, green, blue from adjacent three groups. In such a way, the processing speed of the computing device **220** can match up with the transmitted hologram data from the frame grabber **216**.

[0294] In some implementations, the coherent light elements with the different colors emit corresponding coherent light beams with respective colors simultaneously. The holographic capturing system **210** can further include a color filter array position on the active area of the optical sensor **214**. The color filter array can include groups of different color filters on a plurality of sensing pixels of the optical sensor. The different color filters are associated with the respective colors, and each group of the different color filters is arranged on a corresponding group of adjacent sensing pixels of the plurality of sensing pixels. Hologram data for the respective colors can be determined based on a captured optical hologram captured by the corresponding groups of adjacent sensing pixels of the plurality of sensing pixels.

[0295] In some implementations, the color filter array includes a Bayer filter mosaic that is a color filter array for arranging RGB color filters on a square grid of photosensors. The Bayer filter mosaic has a particular arrangement of color filters (or filter pattern) to create a color image. The filter pattern can be half green, one quarter red, and one quarter blue, e.g., BGGR, RGBG, GRBG, or RGGB. The color image is color-coded with Bayer filter colors, and an image with an individual color can be reconstructed after interpolating missing color information. Demosaicing can be performed in different ways. In some examples, the color value of the pixels of the same color in the neighborhood is interpolated. For example, once the sensing pixels have been exposed to an optical hologram, each sensing pixel can be read. A sensing pixel with a green filter provides an exact measurement of the green component. The red and blue components for this sensing pixel are obtained from the neighbors. For a green pixel, two red neighbors can be interpolated to yield the red value, also two blue pixels can be interpolated to yield the blue value.

[0296] In some implementations, the optical sensor **214** is configured to perform the demosaicing to generate respective hologram data with the different colors based on a same optical hologram captured by the optical sensor **214** with the Bayer filter mosaic. In some implementations, the computing device **220** is configured to perform the demosaicing to generate respective hologram data with the different colors based on a same optical hologram captured by the optical sensor **214** with the Bayer filter mosaic, and further to generate digital holograms for the different colors.

3.2 Computing Device

[0297] The computing device **220** can be a computing device associated with a user (e.g., an

operator, a developer, a programmer, a customer, or any suitable entity). The computing device **220** can be any appropriate type of device, e.g., a desktop computer, a personal computer, a notebook, a tablet computing device, a personal digital assistant (PDA), a network appliance, a smart mobile phone, a smartwatch, an enhanced general packet radio service (EGPRS) mobile phone, a media player, a navigation device, an email device, a game console, or any appropriate combination of any two or more of these computing devices or other computing devices.

[0298] In some implementations, the computing device **220** includes at least one memory **222** and at least one processor **224**. As noted above, the memory **222** can receive and store hologram data of optical holograms of a live scene from the holographic capturing system **210** (e.g., from the optical sensor **214** or the frame grabber **216**). As the optical sensor **214** can be a digital sensor (e.g., CCD or CMOS) that only picks up intensities of an optical hologram (e.g., interference pattern), the hologram data of the optical hologram can be an array of data bits. The processor **224** can be configured to process the hologram data to generate corresponding digital holograms **226** to be transmitted to the holographic display system **230** for holographic reconstruction of the live scene in a 3D space. As discussed with further details below, the processor **224** can perform at least one of resolution correction, subtractions, adding zero-pads, divisions, Fast Fourier Transforms (FFTs), inverse FFTs, or any other mathematical operations, e.g., as illustrated in FIGS. **4**A-**4**C.

[0299] In some implementations, the optical sensor **214** includes a plurality of sensing pixels in an active area of the optical sensor, and the holographic display system **230** includes a display **250** having a plurality of display elements. The processor **224** is configured to process the at least part of the sequential hologram data to generate the digital holograms associated with the live scene based on at least one of a pitch of the sensing pixels, a pitch of the display elements, a size of the active area of the optical sensor, or a size of the display.

[0300] The pitch of the sensing pixels can be associated with a resolution of a captured optical hologram and a capturable size of a scene. On one hand, the optical sensor **214** needs to have small sensing pixels enough to record a high-resolution image. On the other hand, the optical sensor **214** also needs to be large enough so it records a large enough scene. In some examples, the pitch of the sensing pixels of the optical sensor **214** is about 3.45 μm.

[0301] The pitch of the display elements is associated with an acceptable viewing angle of a reconstructed scene and the size of the display. On one hand, the pixel pitch of the display needs to be small enough so the display reconstructs a 3D object or scene with an acceptable viewing angle. Besides a small pixel pitch, the size of the display needs to be large so one can see a scene large enough to be meaningful once viewed directly. In some examples, the pitch of the display elements of the display **250** is about 3.74 μm.

[0302] As noted above, an optical hologram (e.g., an interferogram) can be captured with the optical sensor **214** and be displayed on the display **250** in real-time with no post-processing by the computing device **220**, and the holographic reconstruction may have an acceptable quality. A higher quality of the holographic reconstruction can be achieved with a level of post-processing by the computing device **220**. A reason for the post-processing is unequal pixel size of the sensing pixels of the optical sensor **214** and the display elements of the display **250**. In some examples, the pitch of the sensing pixels of the optical sensor **214** is 3.45 μm and the pitch of the display elements of the display **250** is 3.74 μm, which creates a mismatch between the recording process and the display process, e.g., a mismatch between a captured optical hologram of the live scene and a reconstruction of the live scene. Another mismatch is the size of the display **250** and the active area of the optical sensor **214**. The size of the display **250** is identical to a number of pixels multiplied by a pixel size. If the active area of the optical sensor **214** is larger than the size of the display **250**, a live scene captured by the optical sensor **214** cannot be fully displayed by a smaller display **250**. On the contrary, if the active area of the optical sensor **214** is smaller than the size of the display **250**, a live scene captured by the optical sensor **214** is only displayed by part of the display **250**.

[0303] In some implementations, the mismatch between a captured optical hologram of the live

scene and a reconstruction of the live scene is associated with at least one of a difference between the pitch of the sensing pixels of the optical sensor **214** and the pitch of the display elements of the display **250**, or a difference between the size of the active area of the optical sensor **214** and the size of the display **250**. The computing device **220** (e.g., the processor **224**) can be configured to suppress the mismatch by post-processing hologram data of the optical holograms to generate corresponding digital holograms **226**.

[0304] In some implementations, the computing device **220** is configured to perform at least one of scaling a first digital hologram associated with a captured optical hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display elements or adjusting the scaled first digital hologram to generate a second digital hologram to be modulated on the display **250** based on the size of the display **250** and the size of the hologram data.

[0305] For example, assuming that

[00003] pixelpitch_Display $= L$, pixelpitch_Sensor $= C$, ratio $= L / C$, and post_hologram $=$ recorded_hologram $\times$ ratio, [0306] where pixelpitch_Display and pixelpitch_Sensor represent the pitch of the display elements of the display **250** and the pitch of the sensing pixels of the optical sensor **214**, respectively. recorded_hologram and post_hologram represent a digital hologram before processing and a digital hologram after processing, respectively. Then the post_hologram can be further adjusted to be displayed on the display **250**.

[0307] During the resampling, the computing device **220** can use at least one of one or more interpolation algorithms, e.g., linear interpolation, nearest neighbor interpolation, cubic spline interpolation, shape-preserving interpolation, Biharomic interpolation, or thin-plate spline interpolation. For example, in linear interpolation, if a new pixel is added between two adjacent pixels, a value of that new pixel can be an average value of the two adjacent pixels.

[0308] The computing device **200** can be configured to resample a digital hologram such that the resampled digital hologram can be modulated on the display **250** with a same sampling frequency. One way to achieve this is to use Fourier transforms to find a range of spatial frequencies making up the digital hologram associated with an optical hologram captured by the optical sensor **214** with a particular pixel pitch and then process (e.g., crop or add) frequencies and resample on a grid equal to the pixel pitch of the display **250**. In some implementations, the computing device **220** is configured to resample a first digital hologram associated with a captured optical hologram to be a second digital hologram to be modulated on the display **250** using Fourier transform (e.g., FFTs) and inverse Fourier transform (e.g., inverse FFT). The first digital hologram is associated with the pitch of the sensing pixels, and the second digital hologram is associated with the pitch of the display elements.

[0309] FIG. **4**A illustrates an example 400 of data processing hologram-based images. The computing device **220** can receive hologram data (e.g., an array of data bits) of an optical hologram captured by the optical sensor **214** and convert the hologram data (e.g., 1×12,000,000) to be an image **402** with X×Y pixels (e.g., 3,000×4,000). The computing device **220** can perform Fourier transform (e.g., FFT) on the image **402** in time domain to obtain image **404** in frequency domain that can still have X×Y pixels.

[0310] Zero-padding a FFT can increase a resolution of the frequency domain results, which can be useful for a narrow band with limited data. In some implementations, if the pitch of the sensing pixels is larger than the pitch of the display elements, the computing device **220** processes the image **404** in frequency domain to perform zero-padding on the image **404** based on a ratio between the pitch of the sensing pixels and the pitch of the display element. As shown in FIG. **4**A, zeros **405** can be added around the image **404** to obtain image **406** having M×N pixels that can match the pitch of the display element, e.g., using the expression: post_hologram=recorded_hologram×ratio. The computing device **220** can further perform an inverse Fourier transform (e.g., inverse FFT) on the transformed image **406** with the zero padding in frequency domain to obtain image **408** with M×N pixels in time domain. The image **408** can be a

new hologram with correct sampling frequency. The zero padding may add background noise but also makes the resampling to a correct resolution. The image **408** in time domain can be a digital hologram (e.g., hologram **226**). As the optical sensor **214** (e.g., digital CCD or CMOS) only pick up intensities of the optical hologram (e.g., interference pattern), the digital hologram performs like an amplitude hologram (or an amplitude-like hologram), thought the digital hologram still contains both amplitude information and phase information of a live scene, which enable to reconstruct the live scene in a 3D space. The display **250** (e.g., LCoS) can convert the digital hologram (e.g., amplitude-like hologram) into a phase hologram as orientations of liquid crystals determine phases of the display elements thus causing different refractive indices for different display elements to reconstruct 3D objects in the live scene.

[0311] FIG. **4**B illustrates another example 430 of data processing hologram-based images. Similar to the example 400 of FIG. **4**A, the computing device **220** can receive hologram data (e.g., an array of data bits) of an optical hologram captured by the optical sensor **214** and convert the hologram data (e.g., 1×12,000,000) to be an image **432** with X×Y pixels (e.g., 3,000×4,000). The computing device **220** can perform Fourier transform (e.g., FFT) on the image **432** in time domain to obtain image **434** in frequency domain that can still have X×Y pixels.

[0312] If the pixel pitch of the sensing pixels of the optical sensor **214** is smaller than the pixel pitch of the display elements of the display **250**, the computing device **220** can be configured to crop the image **432** based on a ratio between the pitch of the sensing pixels and the pitch of the display elements to obtain image **436** with M×N pixels, e.g., using the expression: post_hologram=recorded_hologram×ratio. Then, e.g., as illustrated in FIG. **4**B, the computing device **220** can further perform an inverse Fourier transform (e.g., inverse FFT) on the transformed image **436** in frequency domain to obtain image **438** with M×N pixels in time domain. The image **438** can be a new hologram with correct sampling frequency. In such a way, information that the display **250** cannot display due to large pixel pitch of the display elements can be got rid of.

[0313] The computing device **220** can be configured to resample a first digital hologram to be a second digital hologram by respectively resampling central points of the plurality of sensing pixels of the optical sensor **214** to match centroids of the plurality of display elements of the display **250**. In some implementations, the plurality of sensing pixels of the optical sensor **214** is regularly arranged in the active area of the optical sensor **214**, and the plurality of display elements is regularly arranged in the display **250**, and the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display **250** are regularly spaced.

[0314] In some implementations, the plurality of sensing pixels of the optical sensor **214** is regularly arranged in the active area of the optical sensor **214**, and the plurality of display elements is irregularly arranged in the display **250**. The central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced, e.g., as illustrated in FIGS. **6**A-**6**B. The plurality of display elements can form an irregular pattern (e.g., a Voronoi pattern). The irregular pattern of the display **250** can greatly reduce or eliminate diffractive aberrations, among other effects and thus improve image quality. The computing device **220** can be configured to resample the regularly spaced center points of the plurality of sensing pixels to match the irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms (e.g., Gaussian weighting or optimized Windowed-Sync weighting).

[0315] In some implementations, the plurality of sensing pixels of the optical sensor is irregularly arranged in the active area of the optical sensor **214**, and the plurality of display elements is irregularly arranged in the display **250**. The central points of the plurality of sensing pixels are irregularly spaced, and the centroids of the plurality of display elements of the display **250** are irregularly spaced. An irregular pattern formed by the plurality of sensing pixels can match an

irregular pattern formed by the plurality of display elements.

[0316] Unwanted noise may exist in captured optical holograms. The unwanted noise can include zero-order noise resulting from an undiffracted part of the reference beam or the object beam. The unwanted noise can also include noise coming from cover plates in front of the optical sensor **214**, which can add interference patterns (like diffraction gratings or Gabor zone plates) with different frequencies depending on flatness of the cover plates, sometimes low-frequency ones and sometimes high-frequency ones. Post-processing on the captured optical holograms can get rid of those types of noises because they are constant parts of the optical holograms and won't change due to additional phaseshifts on an optical path in the optical system **212**.

[0317] In some implementations, e.g., as discussed with further details in FIG. **3**D, to remove unwanted noise from the captured optical holograms by the optical sensor **214**, known phaseshifts can be introduced in one of coherent light beams (reference beam or object beam) in the optical system **212**, e.g., by adding a phase adjuster such as a phase shifter or dynamic retarder controllable by voltages. Then, the computing device **220** can process hologram data of the captured optical holograms, e.g., using one or more mathematical operations like subtraction and/or division to get new digital holograms with lower levels of noise.

[0318] As noted above, in conventional digital holography, a digital intensity image of a hologram first undergoes processing such as complex wave retrieval, and the hologram is then numerically propagated by means of Fresnel approximation which describes wave propagation in free space to an image plane. This may result in a complex image containing both amplitude and phase information. In contrast, the computing device **220** can generate digital holograms (e.g., amplitude-like holograms) with simpler processing as discussed above to therefore improve the processing speed and achieve holographic reconstruction or display in real time.

3.3 Holographic Display System

[0319] The holographic display system **230** can be similar to the holographic display system **130** of FIG. **1**A. As shown in FIG. **2**, the holographic display system **230** includes a driving device **231**, an illuminator **240** (e.g., the illuminator **140** of FIG. **1**A), and the display **250** (e.g., the display **150** of FIG. **1**A or the display device **172** of FIG. **1**B). The driving device **231** can include a driving memory **232** (e.g., the driving memory **132** of FIG. **1**A) coupled to the computing device **220**, an illuminator driver **234** (e.g., the illuminator driver **134** of FIG. **1**A) coupled to the driving memory **232** and the illuminator **240**, and a display driver **236** (e.g., the display driver **136** of FIG. **1**A) coupled to the driving memory **232** and the display **250**.

[0320] The driving memory **232** can be configured to receive and store the hologram **226** from the computing device **220**. In some cases, the hologram is an amplitude-like digital hologram corresponding to an interference pattern associated with the live scene.

[0321] In some implementations, the display driver **236** is configured to convert the hologram **226** into corresponding modulation control signals (e.g., a voltage signal) for the plurality of display elements of the display **250**. The display **250** (e.g., LCoS) can convert the hologram **226** (e.g., amplitude-like hologram) into a phase hologram as orientations of liquid crystals determine phases of the display elements thus causing different refractive indices for different display elements to reconstruct 3D objects in the live scene. The illuminator driver **234** can be configured to: transmit an illumination control signal (e.g., for amplitude and/or brightness control) to the illuminator **240** to activate the illuminator **240** to illuminate light on the display **250** such that light is caused by the modulated display elements of the display **250** to form a volumetric light field **260** corresponding to the live scene, e.g., the holographic light field **160** of FIG. **1**A or the 3D holographic reconstruction **178** of FIG. **1**B. The display driver **236** and the illuminator driver **234** can be configured to communicate with each other, such that outputting the respective modulation control signal to each display element of the plurality of display elements by the display driver **236** is in coordination with transmitting the illumination control signal to the illuminator **240** by the illuminator driver **234**.

[0322] In some implementations, the illuminator **240** includes two or more light emitting elements each configured to emit light with a different color (e.g., red, blue, or green), and the illuminator driver **234** can sequentially transmit a respective illumination control signal to sequentially activate each of the two or more light emitting elements of the illuminator. In some implementations, the display driver **236** sequentially outputs: i) a first modulation control signal to modulate the display **250** with information associated with a first color during a first time period, and ii) a second modulation control signal to modulate the display **250** with information associated with a second color during a second, sequential time period. The illuminator driver **234** can sequentially output a first illumination control signal to activate the illuminator **240** to turn on a first light emitting element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator **240** to turn on a second light emitting element to emit light with the second color during the second time period.

[0323] In some implementations, the display **250** includes a spatial light modulator (SLM). The SLM can be a phase SLM, an amplitude SLM, or a phase and amplitude SLM. In some examples, the display **250** is a digital micro-mirror device (DMD), a liquid crystal on silicon (LCOS or LCoS) device, Optically addressed spatial light modulators (OASLMs), or any other type of light modulator that is capable of performing holography.

[0324] In some implementations, the display **250** is a regular display where the plurality of display elements have a same shape and are spaced evenly in a display area. In some implementations, the display **250** is an irregular display where the plurality of display elements form an irregular pattern, e.g., having different shapes or sizes and/or being irregular positioned, for example, as illustrated in FIG. **6**A or FIG. **6**B below.

[0325] As discussed in further detail below with respect to FIGS. **5**A-**5**D, there can be different configurations for the system **200**. The display **250** can be reflective or transmissive. The display **250** can have various sizes, ranging from a small scale (e.g., 1-10 cm on a side) to a large scale (e.g., 100-1000 cm on a side). Illumination from the illuminator **240** can be from the front of the display **250** (e.g., for a reflective or transflective display) or from the rear of the display **250** (e.g., for a transmissive display). The illuminator **240** can provide uniform illumination across the display **250**. In some implementations, an optical waveguide can be used to evenly illuminate a surface of the display **250**.

4. Example Holographic Capturing Systems

[0326] FIG. **3**A illustrates a schematic diagram of an example holographic capturing system **300** that can be implemented as the holographic capturing system **210** of FIG. **2**. The holographic capturing system **300** is configured to generate an optical hologram of a live scene using a holographic setup **301** and to capture the optical hologram using an optical sensor **320**. The holographic setup **301** can be implemented as the optical system **212** of FIG. **2**.

[0327] For illustration, a Mach-Zehnder (MZ) interferometer is implemented in the holographic capturing system **300** as an example of the holographic setup **301**. The MZ interferometer can be configured to determine relative phase shift variations between two collimated beams derived by splitting light from a single coherent source. The phase shift variations can be caused by a scene or a change in a length of one of optical paths of the collimated beams.

[0328] In some implementations, as illustrated in FIG. **3**A, the holographic capturing system **300** includes a coherent light source **302** (e.g., a laser source) configured to emit a coherent light beam. The coherent light beam can be collimated using a collimator **304** (e.g., an optical lens), and then be split by a beam splitter **306** into two optical beams: one as an object beam **303** and the other one as a reference beam **305**. The holographic setup **301** can include a number of reflective mirrors **308***a*, **308***b* to guide the object beam **303** and the reference beam **305** to an optical combiner **310** (e.g., a beam splitter). The beam combiner **310** is configured to superimpose the reference beam **305** and the object beam **303** to form an interference pattern **330**. The optical sensor **320** can be positioned downstream the beam combiner **310** to capture the interference pattern **330** on an active

area of the optical sensor **320**.

[0329] The optical sensor **320** can be similar to, or same as, the optical sensor **214** of FIG. **2**. The optical sensor **320** can be a digital optical camera (e.g., CCD or CMOS) configured to record the interference pattern **330** as an array of data bits. As the scene does not need to be imaged, there is no lens on the optical sensor **320** or between the beam combiner **310** and the optical sensor **320**, and the interference pattern **330** is directly captured on the active area of the optical sensor **320**. Also, there is no optical lens on an optical path of the reference beam **305** between the beam splitter **306** and the beam combiner **310**.

[0330] In some implementations, the holographic setup **301** includes one or more optical lens arranged between the beam splitter **306** and the scene and configured to magnify or demagnify the object beam **303** to be compatible with the active area of the optical sensor **320**. In some implementations, the holographic setup **301** includes one or more optical lens on an optical path of the object beam **303** between the scene and the beam combiner **310** and configured to magnify or demagnify the object beam **303** after interacting with the scene to be compatible with the active area of the optical sensor **320**.

[0331] In some implementations, the holographic setup **301** further includes an optical absorber **312** arranged on a side surface of the beam combiner **310** and configured to absorb part of the reference beam **310** propagating away from the interference pattern **330**.

[0332] As discussed below, the holographic setup **301** can be configured to operate in a transmission mode for capturing optical holograms of transparent objects or in a reflection mode for capturing optical holograms of reflective objects.

[0333] FIG. **3**B illustrates a schematic diagram of an example holographic capturing system **300***a* for capturing a transparent object **340** in an optical path of the object beam **303**. The holographic capturing system **300***a* can be same as the holographic capturing system **300** of FIG. **3**A, and a holographic setup **301***a* can be same as the holographic setup **301** of FIG. **3**A. The object beam **303** travels through the transparent object **340** to be incident on the beam combiner **310**. The object beam **303** interacting with the transparent object **340** interacts with the reference beam **305** to form an interference pattern **330***a* that is captured by the optical sensor **320**.

[0334] FIG. **3**C illustrates a schematic diagram of an example holographic capturing system **300***b* for capturing an opaque or reflective object **350**. Compared to the holographic capturing system **300***a* of FIG. **3**B, the holographic capturing system **300***b* includes at least one more reflective mirror **308***c* in a holographic setup **301***b*. The reflective mirror **308***c* can be arranged in an optical path of the object beam **303** and configured with the reflective mirror **308***a* together to guide the object beam **303** towards the opaque object **350** with an angle such that the object beam **303** is reflected or scattered from the opaque object **350** to be incident on the beam combiner **310**. The object beam **303** interacting with the transparent object **340** interacts with the reference beam **305** to form an interference pattern **330***b* that is captured by the optical sensor **320**.

[0335] FIG. **3**D illustrates a schematic diagram of an example holographic capturing system **300***c* with noise removal. As noted above, a phase adjuster (e.g., a phase shifter or dynamic retarder) can be added in the holographic capturing system **300***c* to remove noise in optical holograms captured by the optical sensor **320**. The phase adjuster can introduce phase shifts in one of the reference beam **305** and the object beam **303**. For illustration, a phase adjuster **360** is added to an optical path of the reference beam **305** in the holographic capturing system **300***b* of FIG. **3**C to form the holographic capturing system **300***c* with a holographic setup **301***c*.

[0336] The phase adjuster **360** can be configured to dynamically adjust a phase shift of the reference beam **305** to therefore a phase difference between the object beam **303** interacted with a scene and the reference beam **305** before an optical hologram (or interference pattern) **300***c* is formed on the optical sensor **320**.

[0337] In some implementations, the phase adjuster **360** is configured to sequentially adjust the phase shift of the reference beam **305** to be a series of predetermined values in a time period, such

that the optical sensor **320** captures corresponding sequential optical holograms of the scene in the time period. In some examples, the phase adjuster **360** includes a liquid crystal (LC) cell configured to adjust the phase shift to be the series of predetermined values by corresponding voltages. The LC cell can be a single cell having a size no smaller than a size of the reference beam **305** such that all the optical holograms can be adjusted with the phase shift. The LC cell can be pre-calibrated to determine a correspondence between the predetermined values of the phase shift and the corresponding voltages.

[0338] In some implementations, a computing device (e.g., the computing device **220** of FIG. **2**) is configured to receive hologram data of optical holograms captured by the optical sensor **320**. The computing device can be configured to generate a digital hologram of the scene with noise suppression based on the corresponding sequential optical holograms. For example, the computing device can be configured to process the corresponding sequential optical holograms to obtain corresponding raw digital holograms, and to perform one or more mathematical operations on the corresponding raw digital holograms to generate the digital hologram of the scene.

[0339] In some implementations, the series of predetermined values for the phase shift comprises 0, pi/2, pi, 3pi/2, and the digital hologram is calculated based on an expression as follows:

[00004]final_hologram = (hologram_0 - hologram_pi) / (hologram_pi / 2 - hologram_3pi / 2),

[0340] where final_hologram represents the digital hologram, hologram_0 represents a first corresponding raw digital hologram based on a first corresponding optical hologram with 0 phase shift, hologram_pi/2 represents a second corresponding raw digital hologram based on a second corresponding optical hologram with pi/2 phase shift, hologram_pi represents a third corresponding raw digital hologram based on a third corresponding optical hologram with pi phase shift, and hologram_3pi/2 represents a fourth corresponding raw digital hologram based on a fourth corresponding optical hologram with 3pi/2 phase shift. For example, diagram (a) of FIG. **4**C shows a raw digital hologram **450**, e.g., hologram_0 with 0 phase shift, and diagram (b) of FIG. **4**C shows a processed digital hologram **460** calculated based on the above expression, e.g., final_hologram. It can be shown that compared to the raw digital hologram **450**, noise has been suppressed or eliminated in the processed digital hologram **460**.

5. Example Holographic Display Systems

5.1 Example System Setups

[0341] A system for 3D display can have a reflective display or transmissive display with front illumination, back illumination, waveguide illumination, or optically diffractive illumination. For illustration, FIGS. **5**A-**5**D show implementations of example systems for 3D displays with optically diffractive illumination. Any one of the systems can correspond to, for example, the system **100** of FIG. **1**A, the system **170** of FIG. **1**B, or the system **200** of FIG. **2**. FIGS. **5**A and **5**B show example systems having reflective displays with optically diffractive illumination using a transmissive grating structure (FIG. **5**A) and a reflective grating structure (FIG. **5**B). FIGS. **5**C and **5**D show example systems having transmissive displays with optically diffractive illumination using a reflective grating structure (FIG. 5C) and a transmissive grating structure (FIG. 5D).

[0342] FIG. **5**A illustrates a system **500** for 3D display including a reflective display **504** with optically diffractive illumination, e.g., using an optically diffractive device **508**. The optically diffractive device **508** can be considered as a lightguide (or a waveguide) device for guiding light. The optically diffractive device **508** can be a transmissive field grating based structure that can include one or more transmissive holographic gratings. The reflective display **504** can be the display **150** of FIG. **1**A, the holographic display device **172** of FIG. **1**B, the display **250** of FIG. **2**. In some examples, the reflective display **504** is a reflective LCOS device.

[0343] A controller **502** can be configured to receive graphic data corresponding to one or more objects from a computer **501** (e.g., the computing device **110** of FIG. **1**A or the computing device **220** of FIG. **2**), perform computation on graphic data or process hologram data, and/or generate and transmit control signals for modulation to the display **504** through a memory buffer **503** (e.g., the

memory **132** of FIG. **1**A or the memory **232** of FIG. **2**). The controller **502** can be also coupled to an illuminator **506** (e.g., the illuminator **140** of FIG. **1**A or the illuminator **240** of FIG. **2**) and be configured to provide a timing signal to activate the illuminator **506** to provide light. In some implementations, the controller **502** includes a processing device (e.g., the processing device **120** of FIG. **1**A or the processor **224** of FIG. **2**) and a driving device (e.g., the driving device **131** of FIG. **1**A or **231** of FIG. **2**). In some implementations, the controller **502** includes the driving device, and the processing device is integrated in the computer **501**.

[0344] The light is diffracted by the optically diffractive device **508** to be incident on the display **504** and then diffracted by the display **504** to form a holographic light field **509** corresponding to the one or more objects. The display **504** can include a back mirror on the back of the display **504** and can reflect the light towards the viewer. The optically diffractive device **508** can be optically transparent. The illuminator **506** can be positioned below the display **504**, which can allow the illuminator **506** to be mounted or housed with other components of the system **500** and to be below an eyeline of the viewer.

[0345] Bragg selectivity allows off-axis illumination light to be diffracted from the optically diffractive device **508** towards the display **504** while the returning light diffracted from the display **504** can be close to on axis and hence be off-Bragg to the gratings in the optically diffractive device **508** and hence can pass through the optically diffractive device **508** almost perfectly to the viewer without being diffracted again by the gratings in the optically diffractive device **508**. In some implementations, the light from the illuminator **506** can be incident on the optically diffractive device **508** with a large incident angle from a side of the display **504**, such that the illuminator **506** does not block the viewer's view and is not intrusive into the holographic light field **509**. The incident angle can be a positive angle or a negative angle with respect to a normal line of the display **504**. For illustration, the incident angle is presented as a positive angle. For example, the incident angle can be in a range from 70 degrees to 90 degrees, e.g., in a range from 80 degrees to 90 degrees. In a particular example, the incident angle is 84 degrees. The diffracted light from the optically diffractive device **508** can be diffracted at close to normal incidence into the display **504**, such that the light can uniformly illuminate the display **504** and can be diffracted back near-normally through the optically diffractive device **508** to the viewer's eyes with minimized power loss due to undesired reflections, diffractions, and/or scatterings within or at the surfaces of the optically diffractive device **508**. In some examples, the diffracted angle from the optically diffractive device **508** to the reflective display **504** can be in a range of −10° (or 10 degrees) to 10° (or 10 degrees), e.g., from −7° to 7°, or from 5° to 7°. In a particular example, the diffracted angle is 6°. In another example, the diffracted angle is 0°.

[0346] In some implementations, as illustrated in FIG. **5**A, the optically diffractive device **508** is arranged in front of the reflective display **504**, e.g., along the Z direction towards the viewer. The optically diffractive device **508** can include a field grating structure **508-1** positioned on a substrate **508-2**. A back surface of the field grating structure **508-1** faces a front surface of the reflective display **504**, and a front surface of the field grating structure **508-1** is attached to the substrate **508-2**. The light from the illuminator **506** can be incident on the front surface of the field grating structure **508-1** through the substrate **508-2**, e.g., from a side surface of the substrate **508-2**. For example, the substrate **508-2** can have a wedged side surface, such that the light at a large incident angle can have less reflection loss.

[0347] If a diffraction efficiency of a diffractive structure, e.g., a holographic grating, is less than 100%, light incident at an incident angle can be diffracted by the diffractive structure into zero and first orders. Light of first order (or first order light) is diffracted by the diffractive structure at a diffracted angle towards the display to therein diffract again to reconstruct a holographic light field **509**. The first order can be also called first diffraction order. Light in the zero order (or zero order light, or undiffracted light, or the undiffracted order) is undiffracted (or undeflected) by the diffractive structure and transmitted by the diffractive structure at an angle corresponding to the

incident angle. The zero order light may cause an undesired effect such as a ghost image, e.g., when the zero order light is incident upon the reflective display **508**-1 directly or subsequent to reflection off surfaces within the optically diffractive device **508**.

[0348] To eliminate the undesired effect, the field grating structure **508**-1 can be spaced from the display **504**. In some implementations, a back surface of the field grating structure **508**-1 is spaced from a front surface of the display **504** by a gap. The gap can have any suitable distance, e.g., 1 mm. The gap can be filled with air or any lower-refractive-index material to satisfy total internal reflection (TIR) on an interface. For example, air has a refractive index (e.g., n≈1.0) which is much smaller than that of a back layer of the field grating structure **508**-1 (e.g., n≈1.5), and hence any residual light at the incident angle (e.g., >70°) can be totally internally reflected by the back surface of the field grating structure **508**-1 when the incident angle is larger than a critical angle (e.g., ≈41.8° for n≈1.5). That is, the residual light at the incident angle cannot reach the reflective display **504** to cause the undesired effect. In some examples, at least one of the front surface of the reflective display **504** or the back surface of the field grating structure **508**-1 is treated with an anti-reflection coating, which can substantially reduce a part of the holographic light field reflected from the reflective display **504** back towards the reflective display **504** from the back of the field grating structure **508**-1 which otherwise could cause further ghost images. In some examples, the back surface of the field grating structure **508**-1 can be protected by an additional layer, e.g., a glass layer.

[0349] In some implementations, instead of being spaced with a gap, the back surface of the field grating structure **508**-1 can be attached to the front surface of the reflective display **504** using an intermediate layer. The intermediate layer can be an optically clear adhesive (OCA) layer with a refractive index substantially lower than that of the back layer of the field grating structure **508**-1, such that total internal reflection (TIR) can occur and the residual zero order light can be totally reflected at the interface between the intermediate layer and the back layer of the field grating structure **508**-1 back into the optically diffractive structure **508**.

[0350] In some implementations, the field grating structure **508**-1 and the display **504** can be separated with a gap so that any residual light cannot reach the display **504**. The gap can be filled with any suitable transparent material, index-matching fluid, or OCA. In some implementations, the field grating structure **508**-1 can be formed in a cover layer (e.g., a cover glass) of the display **504**.

[0351] In some cases, to illuminate a whole surface of the reflective display **504** by light diffracted from an active area of the field grating structure **508**-1, the active area of the field grating structure **508**-1 can be no smaller than an area of the whole surface of the reflective display **504**. In some implementations, the field grating structure **508**-1 and the reflective display **504** have a rectangular shape with a height along the X direction and a width along the Y direction. The active area of the field grating structure **508**-1 can have a height no smaller than a height of the reflective display **504** and a width no smaller than a width of the reflective display **504**. If there is a substantial gap between the field grating structure **508**-1 and the reflective display **504**, the field grating structure **508**-1 and the substrate **508**-2 can be enlarged further so that an expanding cone (or frustrum) of light from the reflective display **504**, e.g., the holographic light field **509**, can be seen through the front of the optically diffractive device **508** over an entire vertical and horizontal field of view (around the +Z axis) of the holographic light field **509**. The substrate **508**-2 can be a little wider and higher than the field grating structure **508**-1.

[0352] As light is incident on the field grating structure **508**-1 at a substantially off-axis angle in a dimension, e.g., the Z direction, the light can be narrower by the cosine of the incidence angle in that dimension. The light from the illuminator **506** can have a narrow rectangular shape incident into the field grating structure **508**-1 which can then expand the light to a large rectangular shape incident into the reflective display **504**. One or more optical components, e.g., mirrors, prisms, optical slabs, and/or optical fillers, can be arranged between and within the illuminator **506**, the

optically diffractive structure **508**, and the reflective display **504** to further expand the light and to filter its bandwidth. In some examples, the expanded light can have a beam area somewhat smaller than the active area of the reflective display **504**, such that the edges and surrounding area of the illuminated area of the reflective display **504** are not noticeable in reflection or scatter towards the viewer. In some examples, the expanded light can have a beam area somewhat larger than the active area of the reflective display **504**, such that the edges of the illuminated area of the reflective display **504** are fully illuminated even if the edges of the expanded light are not uniform, e.g., because of diffraction off masking edges.

[0353] In some implementations, the illuminator **506** can include one or more color light emitting elements, e.g., red, blue, or green color lasers (or LEDs), configured to emit light of corresponding colors. The optically diffractive device **508** can be configured to diffract a plurality of different colors of light at respective diffracted angles that are substantially identical to each other. Each of the respective diffracted angles can be in a range of 0° to +10°, e.g., substantially identical to 0°, + or −1°, + or −2°, + or −3°, + or −4°, + or −5°, + or −6°, + or −7°, + or −8°, + or 9°, or + or −10°.

[0354] In some implementations, the controller **502** is configured to sequentially modulate the display **504** with information associated with a plurality of colors of light in a series of time periods. For example, the information can include a series of color holograms or color images. The controller **502** can control the illuminator **506** to sequentially emit each of the plurality of colors of light to the optically diffractive device **508** during a respective time period of the series of time periods, such that each of the plurality of colors of light is diffracted by the optically diffractive device **508** to the reflective display **504** and diffracted by modulated display elements of the reflective display **504** to form a respective color three-dimensional holographic light field **509** corresponding to the object during the respective time period. Depending on temporal coherence-of vision effect in an eye of a viewer, the plurality of colors can be combined in the eye to give an appearance of full color. In some cases, the illuminator **506** is switched off among different light emitting elements during a state change of the display image (or holographic reconstruction) such as during black-insertion subframes between color subframes or during blanking or retrace periods of a video source or during LC rise, fall, or DC-balancing inversion transitions, or during system warm-up, or when the intended holographic light field is completely black, or during a calibration procedure, and is switched on when a valid image (or holographic reconstruction) is presented for a period of time. This can also rely on persistence of vision to make the image (or holographic reconstruction) appear stable and flicker-free.

[0355] If a part of the holographic light field **509** appears in front of the display **504**, as illustrated by a light field **509-1** in FIG. **5**A, that part of the holographic light field **509** is a real part of the reconstructed image or holographic reconstruction (also called a real image or a real holographic reconstruction). When a viewer sees a point of light in front of the display **504**, there really is light being reflected from the display **504** to that point. If a part of the light field **509** appears to the viewer to be behind (or inside) the display **504**, as illustrated by a light field **509-2** in FIG. **5**A, that part of the holographic light field **509** is a virtual part of the reconstructed image or holographic reconstruction (also called a virtual image or a virtual holographic reconstruction). When the viewer sees a point of light which appears to be behind or inside the display **504**, there is actually no light being diffracted from the display **504** to that virtual point: rather, part of the light diffracted from the display **504** appears to be originated at that virtual point.

[0356] The computer **501** and/or the controller **502** can be configured to adjust a computation (e.g., by equations) of the information (e.g., a two-dimensional hologram, image, or pattern) to be modulated in the display **504** to move the reconstructed holographic light field **509** back and forth along a direction (e.g., the Z direction) normal to the display **504**. The computation can be based on a holographic rendering process. In some cases, the holographic light field **509** can be fully in front of the display **504**. In some cases, the holographic light field **509** can appear to be all behind the display **504**. In some cases, as illustrated in FIG. **5**A, the holographic light field can have one part

in front of the display **504**, e.g., the real part **509-1**, and another part appearing to be behind the display, e.g., the virtual part **509-2**. That is, the light field **509** can appear to straddle a surface of the display **504**, which can be called image planning.

[0357] The optically diffractive device **508** can be implemented in different configurations. In some implementations, the optically diffractive device **508** includes a holographic grating, e.g., a Bragg grating, for a particular color, and the holographic light field **509** can correspond to the particular color. In some implementations, the optically diffractive device **508** includes multiple holographic gratings for different colors in a single recording layer.

[0358] In some implementations, the field grating structure **508-1** of the optically diffractive device **508** includes multiple holographic gratings for different colors in different recording layers. A grating for a particular color can diffract not only light of the particular color, but also light of other colors, which can cause crosstalk among the different colors. In some examples, the field grating structure **508-1** of the optically diffractive device **508** can include multiple holographic gratings with one or more color-selective polarizers to suppress (e.g., eliminate or minimize) color crosstalk. In some examples, the field grating structure **508-1** of the optically diffractive device **508** can include multiple holographic gratings with one or more reflective layers for light of different colors incident at respective incident angles to suppress color crosstalk and zero order light. In some examples, the field grating structure **508-1** of the optically diffractive device **508** can include multiple holographic gratings with one or more color-selective polarizers, and one or more reflective layers to suppress color crosstalk and zero order diffraction. Each of the color-selective polarizers can be configured for a single color or multiple colors. Each of the reflective layers can be configured for a single color or multiple colors. In some implementations, example field grating structures are configured and performed as described in international application PCT/US2021/50271 entitled "DISPLAYING THREE-DIMENSIONAL OBJECTS" and filed on Sep. 14, 2021, which is commonly-owned and fully incorporated herein by reference.

[0359] To improve an effect of a reconstructed holographic scene and thus a performance of a display system, it is desirable to suppress (or even eliminate) display zero order light in the reconstructed holographic scene. The display zero order light can include any unwanted light from the display, e.g., light reflected/diffracted at gaps between display elements, reflected light from the display elements, or reflected light from a display cover on the display. In some implementations, the optically diffractive device **508** is configured to suppress display zero order light by at least one of: zero order light deviation, zero order light blocking, or zero order light redirection. In some implementations, example optically diffractive device **508** are configured and performed as described in international application PCT/US2021/50275 entitled "RECONSTRUCTING OBJECTS WITH DISPLAY ZERO ORDER LIGHT SUPPRESSION" and filed on Sep. 14, 2021, which is commonly-owned and fully incorporated herein by reference.

[0360] In some examples, for zero order light deviation, the field grating structure **508-1** the optically diffractive device **508** can be configured to couple input light to illuminate the display **504** at an incident angle larger than a half of a viewing angle of a reconstructed cone that forms the holographic scene. The display zero order light propagates away from the display **504** at a reflected angle identical to the incident angle. A hologram corresponding to the holographic scene can be preconfigured such that diffracted first order light propagates away from the display to form the reconstruction cone in a same way as that when the incident angle is 0°. Thus, the display zero order light is deviated from the reconstruction cone and accordingly the holographic scene.

[0361] In some examples, for zero order light blocking, display zero order light can be first deviated away from diffracted first order light according to the zero order light deviation and then blocked (or absorbed) by an optically blocking component (e.g., a metamaterial layer or an anisotropic optical element such as a louver film). The optically blocking component is configured to transmit a light beam having an angle smaller than a predetermined angle and block a light beam having an angle larger than the predetermined angle. The predetermined angle can be smaller than

the incident angle of the input light and larger than a half of the viewing angle of the reconstruction cone. The optically blocking component can be formed on a side of the optically diffractive device **508** that is opposite to the field grating structure **508-1**.

[0362] In some examples, for zero order light redirection, display zero order light can be first deviated away from diffracted first order light according to the zero order light deviation and then redirected even further away from the diffracted first order light by a redirecting grating structure **508-3** in the optically diffractive device **508**. When the input light includes different colors of light simultaneously or sequentially, the optically diffractive component can include one or more corresponding diffractive gratings that are configured to diffract the different colors of light towards different directions in a plane or in space to reduce color crosstalk among the different colors of light. The redirecting grating structure **508-3** can be formed on a side of the substrate **508-2** that is opposite to the field grating structure **508-1**.

[0363] FIG. **5**B illustrates another system **510** for 3D display including a reflective display **514** with optically diffractive illumination, e.g., using an optically diffractive device **518**. The reflective display **514** can be similar to, or same as, the reflective display **504** of FIG. **5**A. Different from the optically diffractive device **508** of the system **500** of FIG. **5**A, the optically diffractive device **518** of the system **510** can have a reflective field grating based structure that can include a reflective field grating structure **518-1** and a substrate **518-2**. The substrate **518-2** can be a glass substrate. The reflective field grating structure **518-1** can include one or more reflective holographic gratings for one or more different colors. The reflective field grating structure **518-1** is arranged on a front surface of the substrate **518-2**, e.g., along Z direction. An illuminator **506** is arranged behind the reflective field grating structure **518-1** and configured to illuminate light on the reflective field grating structure **518-1** at a large incident angle. The light is diffracted back (along-Z direction) to the reflective display **514** that further diffracts the light back through the optically diffractive device **518** to form a holographic light field **519**. The holographic light field **519** can be similar to, or same as, the holographic light field **509** of FIG. **5**A, and can include a real holographic reconstruction **519-1** (e.g., **509-1** of FIG. **5**A) and a virtual holographic reconstruction **519-2** (e.g., **509-2** of FIG. **5**A). In some implementations, the optically diffractive device **518** also includes a redirecting grating structure (e.g., redirecting grating structure **508-3** of FIG. **5**A) for display zero order suppression. For example, the redirecting grating structure can be formed on a side of the field grating structure **518-1** that is away from the reflective display **514**, e.g., by attaching the redirecting grating structure to the field grating structure **518-1** using an adhesive material with a low refractive index, such that: i) light diffracted by the field grating structure **518-1** is reflected back by an interface between the field grating structure **518-1** and the adhesive material to the reflective display **514**, and ii) light diffracted by the reflective display **514** is transmitted through the adhesive material to the redirecting grating structure.

[0364] FIG. **5**C illustrates another system **520** for 3D display including a transmissive display **524** with optically diffractive illumination, e.g., using an optically diffractive device **528**. Similar to the optically diffractive structure **518** of FIG. **5**B, the optically diffractive structure **528** can be a reflective field grating based structure that can include a reflective field grating structure **528-1** and a substrate **528-2**. The substrate **528-2** can be a glass substrate. The reflective field grating structure **528-1** can include one or more reflective holographic gratings for one or more different colors. Different from the optically diffractive structure **518** of FIG. **5**B, the reflective field grating structure **528-1** in the optically diffractive structure **528** is arranged on a back surface of the substrate **528-2**. An illuminator **506** is arranged before the reflective field grating structure **528-1** and configured to illuminate light on the reflective field grating structure **528-1** at a large incident angle. The light is diffracted back (along-Z direction) to the transmissive display **524** that further diffracts the light to form a holographic light field **529**. The holographic light field **529** can be similar to, or same as, the holographic light field **509** of FIG. **5**A, and can include a real holographic reconstruction **529-1** (e.g., **509-1** of FIG. **5**A) and a virtual holographic reconstruction

529-2 (e.g., **509-2** of FIG. **5**A). In some implementations, the optically diffractive device **528** also includes a redirecting grating structure (e.g., redirecting grating structure **508-3** of FIG. **5**A) for display zero order suppression.

[0365] FIG. **5**D illustrates another system **530** for 3D display including a transmissive display **534** with optically diffractive illumination, e.g., using an optically diffractive device **538**. The transmissive display **534** can be the same as the transmissive display **524** of FIG. **5**C. Similar to the optically diffractive structure **508** of FIG. **5**A, the optically diffractive structure **538** can be a transmissive field grating based structure that can include a transmissive field grating structure **538-1** and a substrate **538-2**. The substrate **538-2** can be a glass substrate. The transmissive field grating structure **538-1** can include one or more transmissive holographic gratings for one or more different colors. Different from the optically diffractive structure **508** of FIG. **5**A, the transmissive field grating structure **538-1** in the optically diffractive structure **538** is arranged on a front surface of the substrate **538-2**. An illuminator **506** is arranged behind the transmissive field grating structure **538-1** and configured to illuminate light on the transmissive field grating structure **538-1** at a large incident angle. The light is diffracted forward (along+Z direction) to the transmissive display **534** that further diffracts the light to form a holographic light field **539**. The holographic light field **539** can be similar to, or same as, the holographic light field **509** of FIG. **5**A, and can include a real holographic reconstruction **539-1** (e.g., **509-1** of FIG. **5**A) and a virtual holographic reconstruction **539-2** (e.g., **509-2** of FIG. **5**A). In some implementations, the optically diffractive device **538** also includes a redirecting grating structure (e.g., redirecting grating structure **508-3** of FIG. **5**A) for display zero order suppression.

6. Example Irregular Displays

[0366] In a display (e.g., an LCOS device), a circuit chip, e.g., a complementary metal-oxide-semiconductor (CMOS) chip or equivalent, controls the voltage on reflective metal electrodes buried below the chip surface, each controlling one phasel (or display element). A common electrode for all the phasels is supplied by a transparent conductive layer made of indium tin oxide on the cover glass. In some examples, a chip can have 1024×768 plates, each with an independently addressable voltage. The phasels can have identical sizes and same shape (e.g., square). When the phasel gap becomes comparable to the incident light wavelength, diffraction effect can appear in the periodic structure of the display, which may cause severe light loss.

[0367] In some implementations, e.g., as illustrated in FIG. **6**A, a display **600** includes a number of nonuniform (or irregular) phasels **602**. The nonuniform shapes of the phasels **602** can greatly reduce or eliminate diffractive aberrations, among other effects and thus improve image quality. The plurality of phasels **602** can form an irregular pattern. In some implementations, the irregular pattern includes a Voronoi pattern. In some implementations, the irregular pattern includes a HOLOCHROME® (or HOLOCHROME™) pattern. At least two phasels **602** in the display **600** have different shapes. For example, adjacent phasels **602** can have different shapes. In some examples, at least one phasel **602** has an irregular polygon shape.

[0368] In some cases, a gap between adjacent phasels of the display **600** is smaller than a wavelength of an incident light, which may mitigate light loss between the adjacent phasels. In some examples, the wavelength of the incident light is about 450 nm (e.g., for blue color), about 530 nm (e.g., for green color of light), or about 630 nm (e.g., for red color of light), while the gap can be about 200 nm. In some cases, a size distribution of the plurality of phasels **602** of the display **600** can be around a value that is identical to a spatial frequency response of the display **600**, e.g., 3 μm. A size of a phasel can be referred to a maximum width of the phasel.

[0369] In some implementations, each phasel **602** encloses a corresponding spaced point **604**. As illustrated in FIG. **6**A, the corresponding spaced point **604** can be in a random position within a shape of the phasel **602**, e.g., at a center or at an edge of the phasel **602**. The phasels **602** can be designed and/or fabrication based on the spaced points **604**. In some implementations, the based points **604** form an irregular pattern. The irregular pattern of the spaced points **604** can be same as

or different from the irregular pattern of the phasels **602**.

[0370] In some implementations, although shapes and/or areas of the phasels **602** form an irregular pattern, the spaced points **604** can form a regular shape, e.g., a square shape. A distance between centers of adjacent based points **604** can be identical among the spaced points **604**. For example, the spaced points **604** can be center points of phasels of a regular display. In such a way, the display **600** can be fabricated using a same backplane for the regular display. In some implementations, the spaced points **604** are regularly spaced with a first spacing period in a first region and with a second spacing period in a second region of the display **600**. The second spacing period can be different from the first spacing period. In some embodiments, the spaced points **604** correspond to conductive vias that are electrically connected to a phasel driving circuitry.

[0371] As described herein, an irregular display (e.g., the display **600** of FIG. **6**A) can be used as a display (e.g., the display **150** of FIG. **1**A, the display device **172** of FIG. **1**B, the display **250** of FIG. **2**, the reflective display **504** of FIG. **5**A, the reflective display **514** of FIG. **5**B, the transmissive display **524** of FIG. **5**C, the transmissive display **534** of FIG. **5**D). The irregular display can be used in a system for 3D display (e.g., the system **100** of FIG. **1**A, the system **170** of FIG. **1**B, the system **200** of FIG. **2**, the system **500** of FIG. **5**A, the system **510** of FIG. **5**B, the system **520** of FIG. **5**C, the system **530** of FIG. **5**D). The irregular display can be configured to reduce or eliminate diffraction effects, diffractive aberrations, aliasing, or among other effects, and thus improve the quality of reconstructed images, objects, or scenes.

[0372] In some implementations, an irregular display or irregular phasels as described herein can be also used for image or video capturing (or sensing). For example, a device with an array of irregular pixels (e.g., irregular phasels **602** of FIG. **6**A) can be implemented as a camera (e.g., a scene acquisition device **104** of FIG. **1**A) or an optical sensor (e.g., the optical sensor **214** of FIG. **2**) can be configured to capture interference patterns, images, or videos. The array of irregular pixels can form a photodiode array. The device can also include one or more other components, e.g., driving circuitry, optical lens, or color filters.

[0373] The irregular pixels can form an irregular pattern, e.g., a Voronoi pattern. The device with irregular pixels can reduce or eliminate a number of potential issues. For example, aliasing is a phenomenon where a digital camera has trouble translating an intricate pattern, which can be caused when digital information is broken down into pixels and bits and can result in a number of odd visual artifacts in images (or photos) or videos. A camera with irregular pixels can be configured to remove such aliasing issues (e.g., moiré or glitch problems/effects) in captured images or videos. Additionally or alternatively, the irregular pattern of the irregular pixels of the camera can get rid of unwanted regular diffraction that may appear due to regular pixels.

[0374] FIG. **6**B illustrates an example 610 of designing an irregular display **630** based on a regular display **620**. The regular display **620** includes an array of phasels **622** each having a center point **624** (shown as "o" symbol in FIG. **6**B). The center point **624** can be a center point of a corresponding conductive via coupled to a display element to be formed. The regular display **620** can have a square shape, and each phasel **622** can also have a square shape. The center points **624** can also form a square shape.

[0375] In comparison, the irregular display **630** can be similar to, or same as, the irregular display **600** of FIG. **6**A. The irregular display **630** includes a plurality of phasels **632** (e.g., the phasels **602** of FIG. **6**A). Each phasel **632** has a respective point **634** (shown as solid dot "." symbol in FIG. **6**B) within the phasel **632**. A shape of the phasel **632** can be generated based on the respective point **634** according to an irregular pattern (e.g., a Voronoi pattern). The respective point **634** can be referred to as a seed point (or seed center) of the phasel **632**. In some examples, the phasel **632** has a polygon shape, and the respective point **634** is a polygon centroid of the phasel **632**. In some examples, the respective point **634** is different from a polygon centroid of the phasel **632**.

[0376] A number of the phasels **622** of the regular display **620** is identical to a number of the phasels **632** of the irregular display **630**. Each phasel **632** can also enclose a corresponding center

point **624** of the regular display **620** that has an offset **636** from the respective point **634** of the phasel **632**. The offsets **636** for the phasels **632** can be different from each other, e.g., as illustrated in FIG. **6**B. The respective points **634** of the phasels **632** can be irregularly positioned within an area of the irregular display **630**. The irregular display **630** can have a larger area than the regular display **620**. An outline of the irregular display **630** can be a regular shape, e.g., a rectangular or square shape.

[0377] As discussed above, in a system for holographically capturing and displaying a live scene in real time (e.g., the system **200** of FIG. **2**), an optical sensor for capturing optical holograms (e.g., the optical sensor **214** of FIG. **2**) and/or a display modulated with holograms for holographic reconstruction (e.g., the display **250** of FIG. **2**) can be irregular.

[0378] In some implementations, a plurality of sensing pixels of the optical sensor is regularly arranged in an active area of the optical sensor, and a plurality of display elements is irregularly arranged in the display (e.g., as shown in FIG. **6**A-**6**B). The central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced, e.g., as illustrated in FIGS. **6**A-**6**B. The plurality of display elements can form an irregular pattern (e.g., a Voronoi pattern). The irregular pattern of the display can greatly reduce or eliminate diffractive aberrations, among other effects and thus improve image quality. The computing device can be configured to resample the regularly spaced center points of the plurality of sensing pixels to match the irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms (e.g., Gaussian weighting or optimized Windowed-Sync weighting).

[0379] The computing device can sample regular spaced center points of a regular grid to calculate irregular spaced centroids of an irregular grid. As an example, weighted averages of four-adjacent regular points can be used to calculate a phase at an irregular position. As another example, a weighted sum of regular points around an irregular target point with a Gaussian or optimized Windowed-Sync weighting algorithm.

[0380] In some implementations, the computing device is configured to perform the resampling based on a predetermined relationship between regular center points of a regular display (e.g., the center points **624** of the regular display **620** of FIG. **6**B) and corresponding seed points of the irregular display (e.g., the points **634** of the irregular display **630** of FIG. **6**C) or centroids of the irregular display.

[0381] In some implementations, the plurality of sensing pixels of the optical sensor is irregularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display. The central points of the plurality of sensing pixels are irregularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced. An irregular pattern formed by the plurality of sensing pixels can match an irregular pattern formed by the plurality of display elements.

7. Example Holographic Cues

[0382] As noted above, real-time holography may require reconstruction of a live scene at a rate of more than 15 frames per second, which can make the live scene continuous to human eye and brain. Besides time, the real-time holography may also need to contain 3 main holographic cues: occlusion, parallax, and accommodation. Systems disclosed herein (e.g., the system **100** of FIG. **1**A or the system **200** of FIG. **2**) can implement real-time holography.

[0383] FIGS. **7**A-**7**C illustrate example cues of holographically displaying objects, including occlusion (FIG. **7**A), parallax (FIG. **7**B), and accommodation (FIG. **7**C).

[0384] As illustrated in diagram **700** of FIG. **7**A, occlusion is a process whereby an occluded object **702** is hidden or obscured from prominence or view by an occluder **704**. In holography, if a viewer changes viewing angles, the occlude object **702** may be visible from some viewing angles. In contrast, 2D screens don't have this feature, where it doesn't matter how a viewer looks at the

images, a scene stays the same, and blocked objects remain blocked with changing viewing angles.

[0385] Parallax is a characteristic in which each eye sees a different perspective of objects in a scene. For example, in holography, as illustrated in FIG. **7**B, a left eye sees a scene **710** where a cylinder-shaped object **712** is separated from a cuboid-shaped object **714** are separated from each other, while a right eye sees a different scene **720** where the cylinder-shaped object **712** and the cuboid-shaped object **714** overlap with each other. In contrast, in a 2D display, images are the same regardless of a viewing angle from the left eye or the right eye.

[0386] Accommodation is the feature where the eyes can feel depths of objects in a scene. For example, as illustrated in diagram **730** of FIG. **7**C, a cylinder-shaped object **732** is positioned farther from an eye of a viewer than a cuboid-shaped object **734**. In holography, a depth of the cylinder-shaped object **732** is greater than a depth of the cuboid-shaped object **734**. In contrast, in a 2D display, the eye of the viewer stays focused on a surface of a 2D screen, and there is no depth information shown on the surface of the screen.

8. Example Processes

[0387] FIG. **8**A is a flowchart of an example process **800** of holographically displaying a live scene. The process **800** can be performed by a system such as the system **200** of FIG. **2**. The live scene can include one or more three-dimensional (3D) objects. The live scene can be a scene or event occurring in real world or real life, or in a physical space. The live scene can be captured and displayed by the system in real time.

[0388] In some implementations, the system includes a holographic capturing system (e.g., the holographic capturing system **210** of FIG. **2**) and a holographic display system (e.g., the holographic display system **230** of FIG. **2**). The holographic capturing system can include: an optical system (e.g., the optical system **212** of FIG. **2** or the holographic setup **300** of FIG. **3**A, **300***a* of FIG. **3**B, **300***b* of FIG. **3**C, or **300***c* of FIG. **3**D) and an optical sensor (e.g., the optical sensor **214** of FIG. **2**, or **320** of FIGS. **3**A-**3**D). In some implementations, the system further includes a computing device (e.g., the computing device **220** of FIG. **2**) coupled between the holographic capturing system and the holographic display system.

[0389] At **802**, the optical system optically generates an optical hologram of the live scene. At **804**, the optical sensor captures sequential optical holograms of the live scene and generates sequential hologram data associated with the sequential optical holograms of the live scene. Each optical hologram can be associated with respective hologram data. At **806**, the holographic display system reconstructs the live scene in a 3D space based on at least part of the sequential hologram data.

[0390] In some implementations, the computing device processes the at least part of the sequential hologram data to generate digital holograms (e.g., the hologram **226** of FIG. **2**) associated with the live scene, and the holographic display system reconstructs the live scene in the 3D space based on the digital holograms. Each of the digital holograms can include an amplitude-like hologram, and the amplitude-like program can directly modulate a display (e.g., the display **250** of FIG. **2**) of the holographic display system for holographic reconstruction of the live scene. The display can be phase modulated.

[0391] In some implementations, the optical sensor is a digital sensor (e.g., CCD or CMOS), and the sequential hologram data includes a stream of digital data. The digital data can include an array of data bits (e.g., 0 or 1).

[0392] In some implementations, the system includes a frame grabber (e.g., the frame grabber **216** of FIG. **2**). The process **800** can further include: selecting respective hologram data of one or more optical holograms among the sequential optical holograms by the frame grabber. The computing device can generate the digital holograms associated with the live scene based on the selected respective hologram data of the one or more optical holograms.

[0393] In some implementations, the frame grabber includes a frame-buffer-based grabber configured to deposit the respective hologram data in a frame buffer of the frame grabber before transmitting for generating the digital holograms. In some implementations, the frame grabber

includes a first in, first out (FIFO)-based grabber configured to transmit the respective hologram data directly for generating the digital holograms.

[0394] In some implementations, the computing device processes the at least part of the sequential hologram data to generate the digital holograms associated with the live scene based on at least one of a pitch of sensing pixels of an optical sensor, a pitch of display elements of a display, a size of an active area of the optical sensor, or a size of the display. The pitch of the sensing pixels can be associated with a resolution of a captured optical hologram and a capturable size of a scene, and the pitch of the display elements can be associated with an acceptable viewing angle of a reconstructed scene and the size of the display.

[0395] In some implementations, the computing device suppresses a mismatch between a captured optical hologram of the live scene and a reconstruction of the live scene. The mismatch can be associated with at least one of a difference between the pitch of the sensing pixels and the pitch of the display elements, or a difference between the size of the active area of the optical sensor and the size of the display.

[0396] In some implementations, the computing device processes the at least part of the sequential hologram data to generate the digital holograms associated with the live scene by scaling a first digital hologram associated with a captured optical hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display elements, and/or adjusting the scaled first digital hologram to generate a second digital hologram to be modulated on the display based on the size of the display and the size of the hologram data.

[0397] In some implementations, the computing device scales the size of the first digital hologram associated with the captured optical hologram by using at least one of one or more interpolation algorithms comprising linear interpolation, nearest neighbor interpolation, cubic spline interpolation, shape-preserving interpolation, Biharomic interpolation, and thin-plate spline interpolation.

[0398] In some implementations, the computing device processes the at least part of the sequential hologram data to generate the digital holograms associated with the live scene by resampling a first digital hologram associated with a captured optical hologram to be a second digital hologram to be modulated on the display using Fourier transform and inverse Fourier transform, the first digital hologram being associated with the pitch of the sensing pixels, the second digital hologram being associated with the pitch of the display elements.

[0399] In some implementations, e.g., as illustrated in FIG. **4**B, the computing device resamples the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display by first performing the Fourier transform on the first digital hologram to generate a transformed first digital hologram. If the pitch of the sensing pixels is smaller than the pitch of the display elements, the computing device crops the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display element, then performing the inverse Fourier transform on the cropped transformed first digital hologram to obtain the second digital hologram.

[0400] In some implementations, e.g., as illustrated in FIG. **4**A, the computing device resamples the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display by first performing the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and if the pitch of the sensing pixels is larger than the pitch of the display elements, performing zero-padding to the transformed first digital hologram based on a ratio between the pitch of the sensing pixels and the pitch of the display element, then performing the inverse Fourier transform on the transformed first digital hologram with the added one or more zero-pads to obtain the second digital hologram.

[0401] In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: resampling the first digital hologram to be the second digital hologram by respectively resampling

central points of the plurality of sensing pixels of the optical sensor to match centroids of a plurality of display elements of the display.

[0402] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is regularly arranged in the display. The central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are regularly spaced.

[0403] In some implementations, the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display (e.g., as illustrated in FIG. **6**A or **6**B). The central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced. In some implementations, resampling the first digital hologram associated with the captured optical hologram to be the second digital hologram to be modulated on the display includes: resampling the regularly spaced center points of the plurality of sensing pixels to match the irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms.

[0404] In some implementations, the plurality of sensing pixels of the optical sensor is irregularly arranged in the active area of the optical sensor, and the plurality of display elements is irregularly arranged in the display. The central points of the plurality of sensing pixels are irregularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced. An irregular pattern formed by the plurality of sensing pixels can match an irregular pattern formed by the plurality of display elements.

[0405] In some implementations, the optical system forms an interference pattern by interfering an object beam (e.g., the object beam **303** of FIGS. **3**A-**3**D) interacting with the live scene with a reference beam (e.g., the reference beam **305** of FIGS. **3**A-**3**D). The object beam and the reference beam are coherent light beams, and the optical hologram includes the interference pattern. The optical sensor can directly capture the interference pattern on an active area of the optical sensor. The optical system can magnify or demagnify the object beam after interacting with the live scene to be compatible with the active area of the optical sensor.

[0406] In some implementations, the process **800** includes: dynamically adjusting a phase shift of one of the object beam and the reference beam before the interference pattern is formed, e.g., by a phase adjuster such as the phase adjuster **360** of FIG. **3**D. The phase adjuster can include a phase shifter or a dynamic retarder. The phase adjuster can include a liquid crystal cell. The phase adjuster can be configured to dynamically adjusting the phase shift of the one of the object beam and the reference beam by sequentially adjusting the phase shift to be a series of predetermined values in a time period. The optical sensor can capture corresponding sequential optical holograms of the live scene in the time period.

[0407] The process **800** can further include: generating a digital hologram of the live scene with noise suppression based on the corresponding sequential optical holograms, e.g., by the computing device. The computing device can process the corresponding sequential optical holograms to obtain corresponding raw digital holograms, and perform one or more mathematical operations on the corresponding raw digital holograms to generate the digital hologram of the live scene. In some examples, the series of predetermined values for the phase shift comprises 0, pi/2, pi, 3pi/2, and the digital hologram is calculated based on an expression as follows: final_hologram=(hologram_0-hologram_pi)/(hologram_pi/2-hologram_3pi/2), where final_hologram represents the digital hologram, hologram_0 represents a first corresponding raw digital hologram based on a first corresponding optical hologram with 0 phase shift, hologram_pi/2 represents a second corresponding raw digital hologram based on a second corresponding optical hologram with pi/2 phase shift, hologram_pi represents a third corresponding raw digital hologram based on a third corresponding optical hologram with pi phase shift, and hologram_3pi/2 represents a fourth

corresponding raw digital hologram based on a fourth corresponding optical hologram with 3pi/2 phase shift.

[0408] In some implementations, optically generating the optical hologram of the live scene includes: sequentially and alternatively emitting light with a plurality of colors to sequentially and alternatively generate optical holograms for the plurality of colors. Capturing the sequential optical holograms of the live scene can include: sequentially transmitting only light with an individual color, while blocking light with other colors.

[0409] In some implementations, optically generating the optical hologram of the live scene includes: emitting light with a plurality of colors simultaneously. Capturing the sequential optical holograms of the live scene can include: capturing the optical hologram by corresponding groups of adjacent sensing pixels of a plurality of sensing pixels of the optical sensor, with a color filter array (e.g., Bayer filter) arranged on the optical sensor. The color filter array can include groups of different color filters on the plurality of sensing pixels of the optical sensor, the different color filters being associated with the plurality of colors, each group of the different color filters being arranged on a corresponding group of adjacent sensing pixels of the plurality of sensing pixels. Generating sequential hologram data associated with the sequential optical holograms of the live scene can include: determining hologram data for each of the plurality of colors based on the optical hologram.

[0410] In some implementations, the process **800** further includes: generating digital holograms for the plurality of colors based on the optical hologram, and reconstructing the live scene in a 3D space based on at least part of the hologram data includes: reconstructing the live scene in the 3D space based on the digital holograms.

[0411] In some implementations, reconstructing the live scene in a 3D space based on at least part of the hologram data includes: generating control signals for a plurality of display elements of the display based on a digital hologram associated with the live scene, and modulate the plurality of display elements of the display based on the control signals.

[0412] In some implementations, the process further includes: generating digital holograms associated with the live scene based on the at least part of the sequential hologram data. The digital holograms can include a series of groups of digital holograms for a plurality of colors.

[0413] In some implementations, reconstructing the live scene in a 3D space based on at least part of the hologram data includes: sequentially modulating the display with a first digital hologram for a first color during a first time period and modulating the display with a second digital hologram for a second color during a second, sequential time period, and sequentially turning on a first light emitting element to emit light with the first color during the first time period and a second light emitting element to emit light with the second color during the second, sequential time period.

[0414] FIG. **8**B is a flowchart of another example process **850** of holographically displaying a live scene. The process **850** can be performed by a system such as the system **100** of FIG. **1**A. The live scene can include one or more three-dimensional (3D) objects. The live scene can be a scene or event occurring in real world or real life, or in a physical space. The live scene can be captured and displayed by the system in real time.

[0415] In some implementations, the system includes a hologram generation system (e.g., the hologram generation system **101** of FIG. **1**A) configured to generate one or more digital holograms corresponding to the live scene and a holographic display system (e.g., the holographic display system **130** of FIG. **1**A) configured to reconstruct the live scene in a 3D space based on the one or more digital holograms. The hologram generation system can include one or more scene acquisition devices (e.g., **104** of FIG. **1**A) and a computing system (e.g., **103** of FIG. **1**A). The computing system can include a computing device (e.g., the computing device **110** of FIG. **1**A) coupled to the one or more scene acquisition devices and a processing device (e.g., the processing device **120** of FIG. **1**A) coupled to the computing device.

[0416] At **852**, visual data of the live scene is captured from one or more views, e.g., by the one or

more scene acquisition devices. At **854**, primitive data associated with the live scene is obtained based on the captured visual data of the live scene (e.g., by the computing device). At **856**, a digital hologram (e.g., the hologram **127** of FIG. **1**A) corresponding to the live scene is generated (e.g., by the processing device) based on the primitive data associated with the live scene and display element information of a display (e.g., the display **150** of FIG. **1**A) of the holographic display system. At **858**, the live scene is reconstructed in a 3D space by modulating the display with the one or more digital holograms, e.g., by the holographic display system.

[0417] In some implementations, obtaining the primitive data associated with the live scene based on the captured visual data of the live scene includes: generating a 3D representation of the live scene based on the captured visual data of the live scene, and obtaining primitive data of the 3D representation of the live scene based on the 3D representation of the live scene, e.g., by the computing device. The primitive data associated with the live scene includes the primitive data of the 3D representation of the live scene. The 3D presentation of the live scene can be generated by processing the captured visual data of the live scene using a 3D rendering algorithm (e.g., NeRF).

[0418] In some implementations, the process **850** includes: generating sequential visual data of the live scene in a time period (e.g., by the one or more scene acquisition devices), the sequential visual data including first visual data and second visual data sequential to the first visual data; generating a first 3D representation of the live scene based on the first visual data of the live scene using the 3D rendering algorithm, and generating a second 3D representation of the live scene by updating the first 3D representation of the live scene based on a difference between the first visual data and the second visual data using the 3D rendering algorithm.

[0419] In some implementations, obtaining the primitive data of the 3D representation of the live scene based on the 3D representation of the live scene includes: loading the 3D representation of the live scene into a 3D simulation application (e.g., Unity), and obtaining the primitive data of the 3D representation of the live scene based on an output of the 3D simulation application that is associated with the 3D representation of the live scene.

[0420] In some implementations, the primitive data of the 3D representation of the live scene includes: data of a plurality of primitives corresponding to the 3D representation of the live scene, the data comprising primitive data of each primitive of the plurality of primitives, a primitive comprising at least one vertex, primitive data of the primitive comprising data of the at least one vertex. The primitive data of the primitive can include at least one of: a primitive identifier of the primitive, at least one vertex identifier of the at least one vertex, coordinate information of the primitive in a 3D coordinate system, color information of the primitive, texture coordinate information of the primitive, shading information for the primitive, viewpoint dependent shading information associated with the primitive, or occlusion information of the primitive.

[0421] In some implementations, generating the one or more digital holograms corresponding to the live scene includes: for each primitive of the plurality of primitives, determining an electromagnetic (EM) field contribution to each of a plurality of display elements of the display based on primitive data of the primitive; and for each of the plurality of display elements of the display, generating a sum of the EM field contributions of the plurality of primitives to the display element. A digital hologram can include the sums of the EM field contributions for the plurality of display elements of the display.

[0422] In some implementations, the process **850** further includes: for each of a plurality of vertices of the plurality of primitives, associating a respective vertex identifier of the vertex with respective vertex data of the vertex, and storing the association between the respective vertex identifier and the respective vertex data of the vertex in a memory; and for each of the plurality of primitives, associating a respective primitive identifier of the primitive with one or more respective vertex identifiers of one or more vertices of the primitive in the memory, and storing an association between the respective primitive identifier and the one or more respective vertex identifiers for the primitive in the memory.

[0423] In some implementations, the process **850** further includes: determining primitive identifiers of multiple primitives associated with a command instruction, determining vertex identifiers associated with the primitive identifiers; and generating a command including the command instruction, the vertex identifiers associated with the primitive identifiers, and the primitive identifiers of the multiple primitives. The command indicates drawing the multiple primitives according to the command instruction and based on at least one of the primitive identifiers of the multiple primitives or the vertex identifiers associated with the primitive identifiers.

[0424] In some implementations, the process **850** includes: processing the command to obtain primitive data of the multiple primitives based on the command; calculating an electromagnetic (EM) field contribution of each of the multiple primitives to each of the plurality of display elements based on the primitive data of the multiple primitives; and accumulating EM field contributions of the multiple primitives to each of the plurality of display elements.

[0425] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: generating modulation control signals for a plurality of display elements of the display based on a digital hologram corresponding to the live scene. The digital hologram can be a complex-valued hologram, and the process **850** can include: converting the complex-valued hologram to a phase-only hologram, and generating the respective modulation control signals for the plurality of display elements based on the phase-only hologram.

[0426] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: transmitting an illumination control signal to an illuminator (e.g., the illuminator **140** of FIG. **1**A) to activate the illuminator to illuminate light on the display such that the light is caused by modulated display elements of the display to form a volumetric light field corresponding to the live scene, and outputting the respective modulation control signal to each display element of the plurality of display elements, in coordination with transmitting the illumination control signal to the illuminator.

[0427] In some implementations, reconstructing the live scene in a 3D space by modulating the display with the one or more digital holograms includes: sequentially outputting a first modulation control signal to modulate the display with information associated with a first color during a first time period, and a second modulation control signal to modulate the display with information associated with a second color during a second, sequential time period; and sequentially outputting a first illumination control signal to activate the illuminator to turn on a first light emitting element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator to turn on a second light emitting element to emit light with the second color during the second time period.

[0428] In some implementations, the process **850** includes: generating sequential digital holograms corresponding to the live scene based on captured sequential visual data of the live scene and continuously reconstructing the live scene in the 3D space based on the sequential digital holograms.

9. Example Applications

[0429] Systems, methods, and techniques implemented herein can be applied to any suitable applications.

[0430] For example, a system (e.g., the system **100** of FIG. **1**A or the system **200** of FIG. **2**) can be used to holographically display a live scene, for example, holographically broadcasting a live game, such as a soccer game as discussed above.

[0431] As another example, a system (e.g., the system **100** of FIG. **1**A or the system **200** of FIG. **2**) can be used to holographically display moving objects. One or more objects can be put on a rotating stage. As the rotating stage rotates, optical holograms or scene data of the rotating objects can be captured and then reconstructed by a holographic display simultaneously.

[0432] As another example, a system (e.g., the system **100** of FIG. **1**A or the system **200** of FIG. **2**) can make holographic stop-motion animations. Stop motion is an animated filmmaking technique

in which objects are physically manipulated in small increments between individually photographed frames so that the objects appear to exhibit independent motion or change when the series of frames is played back.

[0433] As another example, a system (e.g., the system **100** of FIG. **1**A or the system **200** of FIG. **2**) can capture scenes with optical effects. One can add optical effects in the scene like introducing prisms or mirrors and create artistic holographic scenes.

[0434] Implementations of the subject matter and the functional operations described in this specification can be implemented in digital electronic circuitry, in tangibly embodied computer software or firmware, in computer hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Implementations of the subject matter described in this specification can be implemented as one or more computer programs, such as, one or more modules of computer program instructions encoded on a tangible, non-transitory computer-storage medium for execution by, or to control the operation of, data processing apparatus. Alternatively or in addition, the program instructions can be encoded on an artificially generated propagated signal, such as, a machine-generated electrical, optical, or electromagnetic signal that is generated to encode information for transmission to suitable receiver apparatus for execution by a data processing apparatus. The computer-storage medium can be a machine-readable storage device, a machine-readable storage substrate, a random or serial access memory device, or a combination of one or more of them.

[0435] The terms "data processing apparatus," "computer," or "electronic computer device" (or equivalent as understood by one of ordinary skill in the art) refer to data processing hardware and encompass all kinds of apparatus, devices, and machines for processing data, including by way of example, a programmable processor, a computer, or multiple processors or computers. The apparatus can also be or further include special purpose logic circuitry, for example, a central processing unit (CPU), an FPGA (field programmable gate array), or an ASIC (application-specific integrated circuit). In some implementations, the data processing apparatus and special purpose logic circuitry may be hardware-based and software-based. The apparatus can optionally include code that creates an execution environment for computer programs, for example, code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of one or more of them. The present specification contemplates the use of data processing apparatuses with or without conventional operating systems.

[0436] A computer program, which may also be referred to or described as a program, software, a software application, a module, a software module, a script, or code, can be written in any form of programming language, including compiled or interpreted languages, or declarative or procedural languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data, for example, one or more scripts stored in a markup language document, in a single file dedicated to the program in question, or in multiple coordinated files, for example, files that store one or more modules, sub-programs, or portions of code. A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network. While portions of the programs illustrated in the various figures are shown as individual modules that implement the various features and functionality through various objects, methods, or other processes, the programs may instead include a number of sub-modules, third-party services, components, libraries, and such, as appropriate. Conversely, the features and functionality of various components can be combined into single components as appropriate.

[0437] The processes and logic flows described in this specification can be performed by one or more programmable computers executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed

by, and apparatus can also be implemented as, special purpose logic circuitry, such as, a CPU, a GPU, an FPGA, or an ASIC.

[0438] Computers suitable for the execution of a computer program can be based on general or special purpose microprocessors, both, or any other kind of CPU. Generally, a CPU will receive instructions and data from a read-only memory (ROM) or a random access memory (RAM) or both. The main elements of a computer are a CPU for performing or executing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to, receive data from or transfer data to, or both, one or more mass storage devices for storing data, for example, magnetic, magneto-optical disks, or optical disks. However, a computer need not have such devices. Moreover, a computer can be embedded in another device, for example, a mobile telephone, a personal digital assistant (PDA), a mobile audio or video player, a game console, a global positioning system (GPS) receiver, or a portable storage device, for example, a universal serial bus (USB) flash drive, to name just a few.

[0439] Computer readable media (transitory or non-transitory, as appropriate) suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, for example, erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), and flash memory devices; magnetic disks, for example, internal hard disks or removable disks; magneto-optical disks; and CD-ROM, DVD-R, DVD-RAM, and DVD-ROM disks. The memory may store various objects or data, including caches, look-up-tables, classes, frameworks, applications, backup data, jobs, web pages, web page templates, database tables, repositories storing business and dynamic information, and any other appropriate information including any parameters, variables, algorithms, instructions, rules, constraints, or references thereto. Additionally, the memory may include any other appropriate data, such as logs, policies, security or access data, reporting files, as well as others. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0440] To provide for interaction with a user, implementations of the subject matter described in this specification can be implemented on a computer having a display device, for example, a cathode ray tube (CRT), liquid crystal display (LCD), light emitting diode (LED), holographic or light field display, or plasma monitor, for displaying information to the user and a keyboard and a pointing device, for example, a mouse, trackball, or trackpad by which the user can provide input to the computer. Input may also be provided to the computer using a touchscreen, such as a tablet computer surface with pressure sensitivity, a multi-touch screen using capacitive or electric sensing, or other type of touchscreen. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, for example, visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

[0441] The term "graphical user interface," or "GUI," may be used in the singular or the plural to describe one or more graphical user interfaces and each of the displays of a particular graphical user interface. Therefore, a GUI may represent any graphical user interface, including but not limited to, a web browser, a touch screen, or a command line interface (CLI) that processes information and efficiently presents the information results to the user. In general, a GUI may include multiple user interface (UI) elements, some or all associated with a web browser, such as interactive fields, pull-down lists, and buttons operable by the business suite user. These and other UI elements may be related to or represent the functions of the web browser.

[0442] Implementations of the subject matter described in this specification can be implemented in a computing system that includes a back-end component, for example, as a data server, or that

includes a middleware component, for example, an application server, or that includes a front-end component, for example, a client computer having a graphical user interface or a web browser through which a user can interact with an implementation of the subject matter described in this specification, or any combination of one or more such back-end, middleware, or front-end components. The components of the system can be interconnected by any form or medium of wireline or wireless digital data communication, for example, a communication network. Examples of communication networks include a local area network (LAN), a radio access network (RAN), a metropolitan area network (MAN), a wide area network (WAN), worldwide interoperability for microwave access (WIMAX), a wireless local area network (WLAN) using, for example, 602.11 a/b/g/n and 602.20, all or a portion of the Internet, and any other communication system or systems at one or more locations. The network may communicate with, for example, internet protocol (IP) packets, frame relay frames, asynchronous transfer mode (ATM) cells, voice, video, data, or other suitable information between network addresses.

[0443] The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

[0444] In some implementations, any or all of the components of the computing system, both hardware and software, may interface with each other or the interface using an application programming interface (API) or a service layer. The API may include specifications for routines, data structures, and object classes. The API may be either computer language-independent or-dependent and refer to a complete interface, a single function, or even a set of APIs. The service layer provides software services to the computing system. The functionality of the various components of the computing system may be accessible for all service consumers via this service layer. Software services provide reusable, defined business functionalities through a defined interface. For example, the interface may be software written in any suitable language providing data in any suitable format. The API and service layer may be an integral or a stand-alone component in relation to other components of the computing system. Moreover, any or all parts of the service layer may be implemented as child or sub-modules of another software module, enterprise application, or hardware module without departing from the scope of this specification.

[0445] While this specification contains many specific implementation details, these should not be construed as limitations on the scope of any invention or on the scope of what may be claimed, but rather as descriptions of features that may be specific to particular implementations of particular inventions. Certain features that are described in this specification in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination. Moreover, although features may be described as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

[0446] Particular implementations of the subject matter have been described. Other implementations, alterations, and permutations of the described implementations are within the scope of the following claims as will be apparent to those skilled in the art. While operations are depicted in the drawings or claims in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed (some operations may be considered optional), to achieve desirable results. In certain circumstances, multitasking or parallel processing may be advantageous and performed as deemed appropriate.

[0447] For the sake of brevity, conventional techniques for construction, use, and/or the like of

holographic gratings, LCOS devices, and other optical structures and systems may not be described in detail herein. Furthermore, the connecting lines shown in various figures contained herein are intended to represent example functional relationships, signal or optical paths, and/or physical couplings between various elements. It should be noted that many alternative or additional functional relationships, signal or optical paths, or physical connections may be present in an example holographic grating, LCOS, or other optical structure or system, and/or component thereof.

[0448] The detailed description of various example embodiments herein makes reference to the accompanying drawings and pictures, which show various example embodiments by way of illustration. While these various example embodiments are described in sufficient detail to enable those skilled in the art to practice the disclosure, it should be understood that other example embodiments may be realized and that logical, optical, and mechanical changes may be made without departing from the spirit and scope of the disclosure. Thus, the detailed description herein is presented for purposes of illustration only and not of limitation. For example, the steps recited in any of the method or process descriptions may be executed in any suitable order and are not limited to the order presented unless explicitly so stated. Moreover, any of the functions or steps may be outsourced to or performed by one or more third parties. Modifications, additions, or omissions may be made to the systems, apparatuses, and methods described herein without departing from the scope of the disclosure. For example, the components of the systems and apparatuses may be integrated or separated. Moreover, the operations of the systems and apparatuses disclosed herein may be performed by more, fewer, or other components and the methods described may include more, fewer, or other steps.

[0449] As used in this document, "each" refers to each member of a set or each member of a subset of a set. Furthermore, any reference to singular includes plural example embodiments, and any reference to more than one component may include a singular example embodiment. Although specific advantages have been enumerated herein, various example embodiments may include some, none, or all of the enumerated advantages.

[0450] Benefits, other advantages, and solutions to problems have been described herein with regard to specific example embodiments. However, the benefits, advantages, solutions to problems, and any elements that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as critical, required, or essential features or elements of the disclosure. The scope of the disclosure is accordingly limited by nothing other than the appended claims, in which reference to an element in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." Moreover, where a phrase similar to 'at least one of A, B, and C' or 'at least one of A, B, or C' is used in the claims or specification, it is intended that the phrase be interpreted to mean that A alone may be present in an example embodiment, B alone may be present in an example embodiment, C alone may be present in an example embodiment, or that any combination of the elements A, B and C may be present in a single example embodiment; for example, A and B, A and C, B and C, or A and B and C.

[0451] Accordingly, the earlier provided description of example implementations does not define or constrain this specification. Other changes, substitutions, and alterations are also possible without departing from the spirit and scope of this specification.

Claims

1.-130. (canceled)

131. A system comprising: a holographic generation system configured to generate one or more holograms corresponding to a live scene that comprises one or more three-dimensional (3D) objects; and a holographic display system configured to optically reconstruct the live scene in a 3D space based on the one or more holograms, wherein the holographic display system comprises a

display having a plurality of display elements that form an irregular pattern.

132. The system of claim 131, wherein the holographic generation system comprises a holographic capturing system including: an optical system configured to generate an optical hologram of the live scene; and an optical sensor configured to capture sequential optical holograms of the live scene and output sequential hologram data associated with the sequential optical holograms of the live scene, each optical hologram being associated with respective hologram data, wherein the holographic display system is configured to optically reconstruct the live scene in the 3D space based on at least part of the sequential hologram data.

133. The system of claim 132, wherein the holographic generation system further comprises a computing device coupled between the holographic capturing system and the holographic display system, wherein the computing device is configured to receive the at least part of the sequential hologram data from the optical sensor and generate digital holograms associated with the live scene based on the at least part of the sequential hologram data, and wherein the holographic display system is configured to receive the digital holograms associated with the live scene from the computing device and reconstruct the live scene in the 3D space based on the digital holograms.

134. The system of claim 133, wherein the holographic capturing system is configured to capture the sequential optical holograms and generate the sequential hologram data, without storing the sequential optical holograms and the sequential hologram data, and wherein the computing device is configured to process the at least part of the sequential hologram data to generate the digital holograms, without storing the at least part of the sequential hologram data and the digital holograms.

135. The system of claim 133, wherein the optical sensor comprises a digital sensor, and the sequential hologram data comprises a stream of digital data, and wherein the digital data comprises an array of data bits.

136. The system of claim 133, wherein the holographic generation system comprises a frame grabber coupled to the optical sensor and configured to select respective hologram data of one or more optical holograms among the sequential optical holograms to be transmitted to the computing device.

137. The system of claim 133, wherein the optical sensor comprises a plurality of sensing pixels in an active area of the optical sensor, and wherein the computing device is configured to process the at least part of the sequential hologram data to generate the digital holograms associated with the live scene based on at least one of a pitch of the plurality of sensing pixels, a pitch of the plurality of display elements, a size of the active area of the optical sensor, or a size of the display.

138. The system of claim 137, wherein the pitch of the plurality of sensing pixels is associated with a resolution of a captured optical hologram and a capturable size of a scene, and wherein the pitch of the plurality of display elements is associated with an acceptable viewing angle of a reconstructed scene and the size of the display.

139. The system of claim 137, wherein the computing device is configured to suppress a mismatch between a captured optical hologram of the live scene and a reconstruction of the live scene, and wherein the mismatch is associated with at least one of a difference between the pitch of the plurality of sensing pixels and the pitch of the plurality of display elements, or a difference between the size of the active area of the optical sensor and the size of the display.

140. The system of claim 137, wherein the computing device is configured to perform at least one of scaling a first digital hologram associated with a captured optical hologram based on a ratio between the pitch of the plurality of sensing pixels and the pitch of the plurality of display elements, or adjusting the scaled first digital hologram to generate a second digital hologram to be modulated on the display based on the size of the display and the size of the hologram data.

141. The system of claim 137, wherein the computing device is configured to resample a first digital hologram associated with a captured optical hologram to be a second digital hologram to be modulated on the display using Fourier transform and inverse Fourier transform, the first digital

hologram being associated with the pitch of the plurality of sensing pixels, the second digital hologram being associated with the pitch of the plurality of display elements.

142. The system of claim 141, wherein the computing device is configured to: perform the Fourier transform on the first digital hologram to generate a transformed first digital hologram, and if the pitch of the plurality of sensing pixels is larger than the pitch of the plurality of display elements, perform zero-padding on the transformed first digital hologram based on a ratio between the pitch of the plurality of sensing pixels and the pitch of the plurality of display elements, then perform the inverse Fourier transform on the transformed first digital hologram with the zero-padding to obtain the second digital hologram, or if the pitch of the plurality of sensing pixels is smaller than the pitch of the plurality of display elements, crop the transformed first digital hologram based on a ratio between the pitch of the plurality of sensing pixels and the pitch of the plurality of display elements, then perform the inverse Fourier transform on the cropped transformed first digital hologram to obtain the second digital hologram.

143. The system of claim 141, wherein the computing device is configured to resample the first digital hologram to be the second digital hologram by respectively resampling central points of the plurality of sensing pixels of the optical sensor to match centroids of the plurality of display elements of the display, and wherein the plurality of sensing pixels of the optical sensor is regularly arranged in the active area of the optical sensor, and wherein the central points of the plurality of sensing pixels are regularly spaced, and the centroids of the plurality of display elements of the display are irregularly spaced.

144. The system of claim 143, wherein the computing device is configured to resample regularly spaced center points of the plurality of sensing pixels to match irregularly spaced centroids of the plurality of display elements by determining a position of each centroid of the plurality of display elements based on a weighted sum of adjacent center points around the centroid using one or more weighting algorithms.

145. The system of claim 132, wherein the optical system comprises: an interferometer, wherein the optical hologram comprises an interference pattern of an object beam interacting with the live scene and a reference beam interfering with the object beam by the interferometer; a coherent light source configured to emit a coherent light beam; a beam splitter configured to split the coherent light beam from the coherent light source into the object beam and the reference beam; and a beam combiner, wherein the live scene is on an optical path of the object beam upstream the beam combiner, and wherein the beam combiner is configured to superimpose the reference beam and the object beam to form the interference pattern.

146. The system of claim 145, wherein the optical sensor is arranged downstream of the beam combiner and configured to directly capture the interference pattern on an active area of the optical sensor, and wherein there is no optical lens between the beam combiner and the optical sensor, and wherein there is no optical lens on an optical path of the reference beam between the beam splitter and the beam combiner.

147. The system of claim 132, wherein the holographic display system further comprises a driving device coupled to the display, wherein the driving device is configured to: generate control signals for the plurality of display elements of the display based on a digital hologram associated with the live scene; and transmit the control signals to the display to modulate the plurality of display elements of the display based on the control signals.

148. The system of claim 147, wherein the holographic generation system further comprises a computing device coupled between the holographic capturing system and the holographic display system, wherein the computing device is configured to receive the at least part of the sequential hologram data from the optical sensor and generate digital holograms associated with the live scene based on the at least part of the sequential hologram data, and wherein the holographic display system is configured to receive the digital holograms associated with the live scene from the computing device and reconstruct the live scene in the 3D space based on the digital holograms.

149. The system of claim 148, wherein the digital holograms comprise a series of groups of digital holograms for a plurality of colors, and wherein the holographic display system further comprises an illuminator comprising a plurality of coherent light elements for the plurality of colors, and wherein the driving device is configured to: sequentially modulate the display with a first digital hologram for a first color during a first time period and modulate the display with a second digital hologram for a second color during a second, sequential time period; and control the illuminator to sequentially turn on a first coherent light element to emit light with the first color during the first time period and a second coherent light element to emit light with the second color during the second, sequential time period.

150. The system of claim 131, wherein the holographic generation system comprises: one or more scene acquisition devices configured to capture visual data of the live scene from one or more views, the visual data comprising at least one of one or more images or one or more videos; and a computing system configured to: obtain primitive data associated with the live scene based on the captured visual data of the live scene; and generate a digital hologram corresponding to the live scene based on the primitive data associated with the live scene and display element information of the display of the holographic display system.

151. The system of claim 150, wherein the computing system comprises a computing device coupled to the one or more scene acquisition devices and configured to: generate a 3D representation of the live scene based on the captured visual data of the live scene; and obtain primitive data of the 3D representation of the live scene based on the 3D representation of the live scene, wherein the primitive data associated with the live scene comprises the primitive data of the 3D representation of the live scene.

152. The system of claim 151, wherein the one or more scene acquisition devices are configured to transmit sequential visual data of the live scene to the computing device in a time period, the sequential visual data comprising first visual data and second visual data sequential to the first visual data, and wherein the computing device is configured to: generate a first 3D representation of the live scene based on the first visual data of the live scene using a 3D rendering algorithm, and generate a second 3D representation of the live scene by updating the first 3D representation of the live scene based on a difference between the first visual data and the second visual data using the 3D rendering algorithm.

153. The system of claim 151, wherein the computing device is configured to: load the 3D representation of the live scene into a 3D simulation application, and obtain the primitive data of the 3D representation of the live scene based on an output of the 3D simulation application that is associated with the 3D representation of the live scene.

154. The system of claim 153, wherein the primitive data of the 3D representation of the live scene comprises: data of a plurality of primitives corresponding to the 3D representation of the live scene, the data comprising primitive data of each primitive of the plurality of primitives, a primitive comprising at least one vertex, primitive data of the primitive comprising data of the at least one vertex.

155. The system of claim 154, wherein the primitive data of the primitive comprises at least one of: a primitive identifier of the primitive, at least one vertex identifier of the at least one vertex, coordinate information of the primitive in a 3D coordinate system, color information of the primitive, texture coordinate information of the primitive, shading information for the primitive, viewpoint dependent shading information associated with the primitive, or occlusion information of the primitive.

156. The system of claim 154, wherein the computing system comprises a processing device coupled to the computing device and configured to: for each primitive of the plurality of primitives, determine an electromagnetic (EM) field contribution to each of a plurality of display elements of the display based on primitive data of the primitive; and for each of the plurality of display elements of the display, generate a sum of the EM field contributions of the plurality of primitives

to the display element, wherein the digital hologram comprises the sums of the EM field contributions for the plurality of display elements of the display.

157. The system of claim 150, wherein the holographic display system comprises a driving device coupled to the display and configured to: generate modulation control signals for a plurality of display elements of the display based on the digital hologram corresponding to the live scene.

158. The system of claim 157, wherein the holographic display system further comprises an illuminator, wherein the driving device is configured to: transmit an illumination control signal to the illuminator to activate the illuminator to illuminate light on the display such that the light is caused by modulated display elements of the display to form a volumetric light field corresponding to the live scene, and wherein the driving device is configured to: output the respective modulation control signal to each display element of the plurality of display elements, in coordination with transmitting the illumination control signal to the illuminator.

159. The system of claim 157, wherein the driving device is configured to: sequentially output a first modulation control signal to modulate the display with a first digital hologram associated with a first color during a first time period, and a second modulation control signal to modulate the display with a second digital hologram associated with a second color during a second time period sequential to the first time period; and sequentially output a first illumination control signal to activate the illuminator to turn on a first coherent light element to emit light with a first color during the first time period, and a second illumination control signal to activate the illuminator to turn on a second coherent light element to emit light with the second color during the second time period.

160. The system of claim 150, wherein the hologram generation system is configured to generate sequential digital holograms corresponding to the live scene, and wherein the holographic display system is configured to continuously reconstruct the live scene in the 3D space based on the sequential digital holograms.