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(54) **LOW-FOOTPRINT MODEL APPLICABLE TO OPTICAL FLOW ESTIMATION AND STEREO MATCHING**

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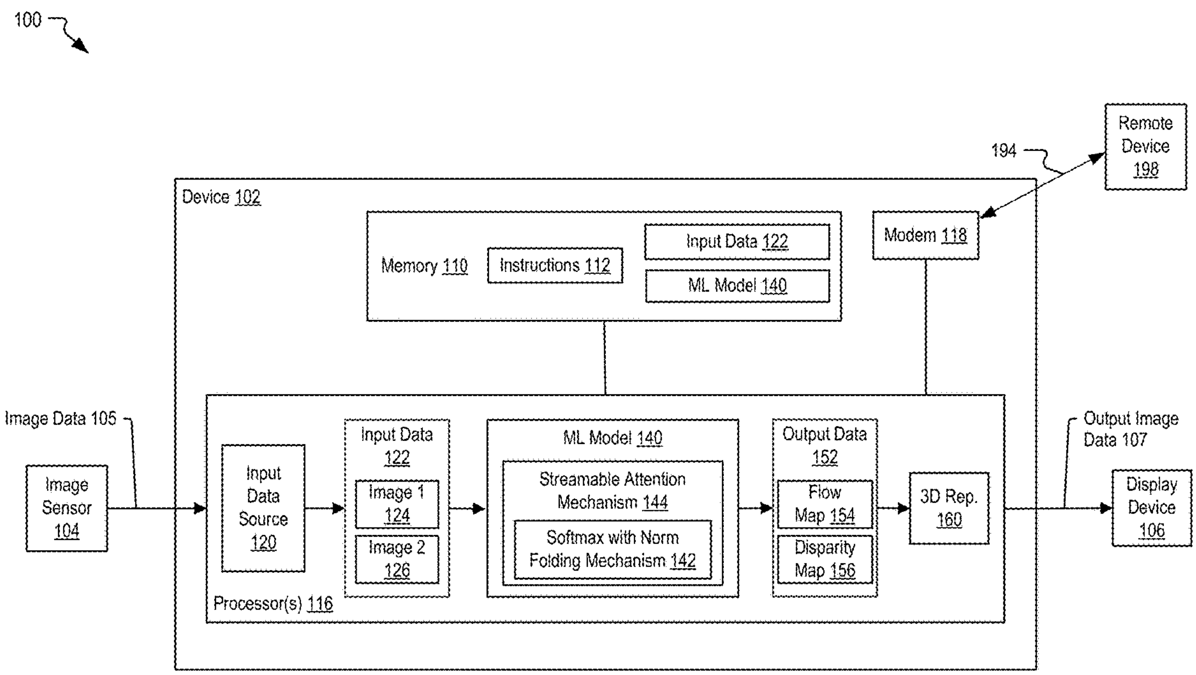
(52) **U.S. Cl.**
CPC ...... ***G06T 7/97*** (2017.01); *G06T 2207/20084* (2013.01)

(57) **ABSTRACT**

A device includes a memory configured to store input data, and also includes one or more processors configured to process the input data using a machine learning model that incorporates a softmax with norm folding mechanism.



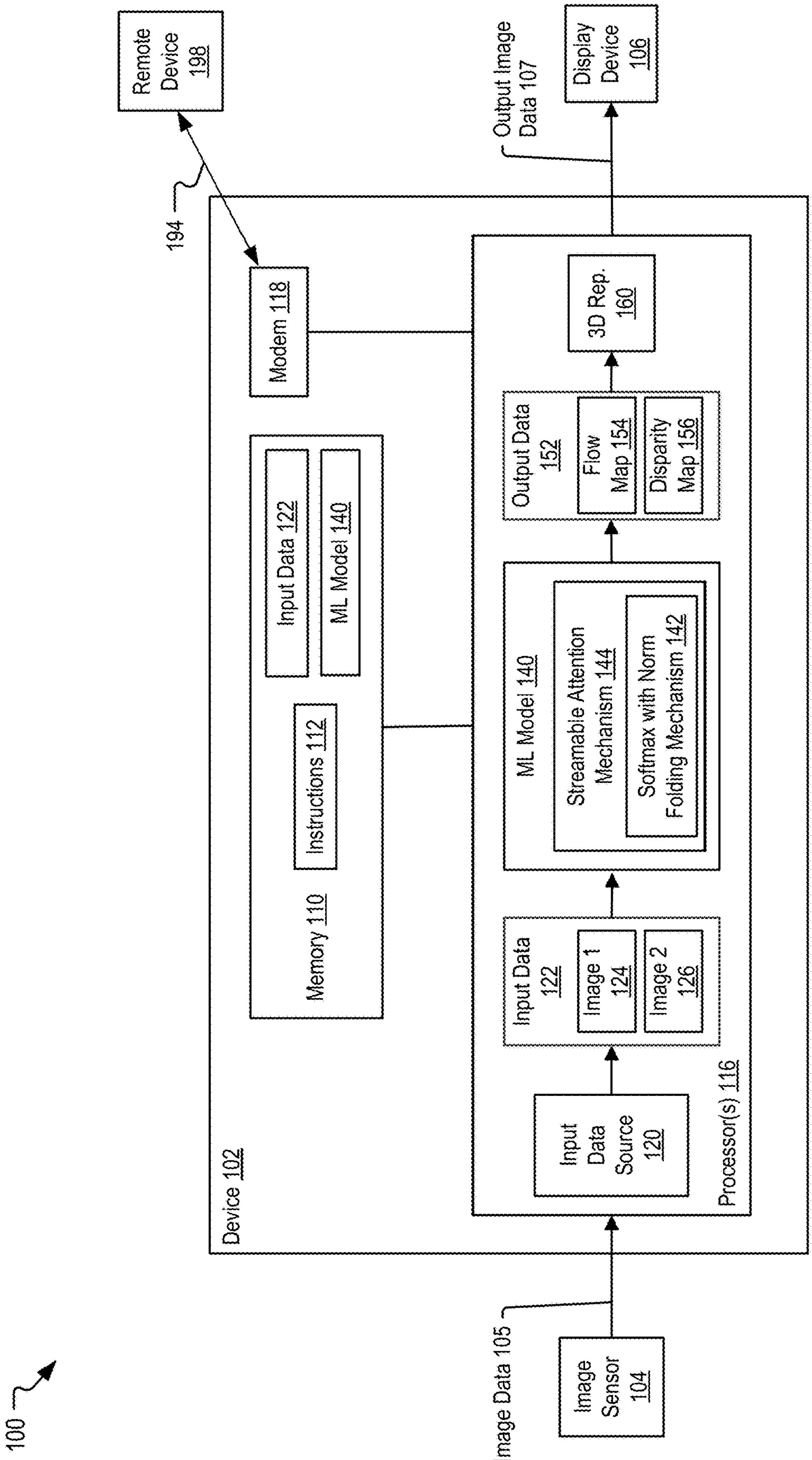

100
Image Sensor 104
Image Data 105
Device 102
Processor(s) 116
Input Data Source 120
Input Data 122
Image 1 124
Image 2 126
ML Model 140
Streamable Attention Mechanism 144
Softmax with Norm Folding Mechanism 142
Output Data 152
Flow Map 154
Disparity Map 156
3D Rep. 160
Memory 110
Instructions 112
Input Data 122
ML Model 140
Modem 118
194
Remote Device 198
Output Image Data 107
Display Device 106

FIG. 1

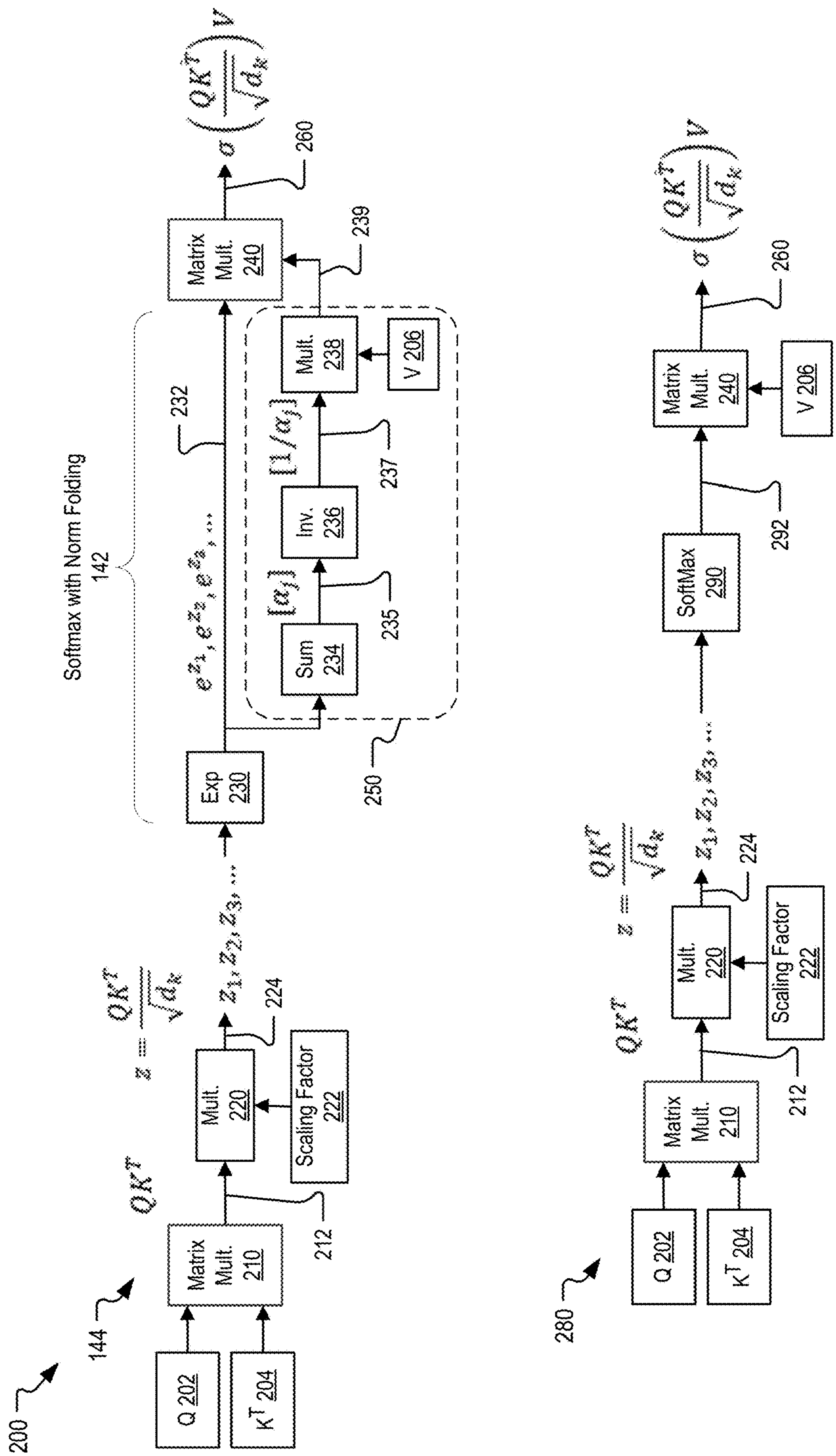

200
144
Q 202
K^T 204
Matrix Mult. 210
212
QK^T
Mult. 220
Scaling Factor 222
224
z = QK^T/√d_k
z_1, z_2, z_3, ...
Softmax with Norm Folding 142
Exp 230
e^{z_1}, e^{z_2}, e^{z_3}, ...
232
250
Sum 234
235
[α_j]
Inv. 236
237
[1/α_j]
Mult. 238
V 206
239
Matrix Mult. 240
260
σ(QK^T/√d_k)V
280
SoftMax 290
292

FIG. 2

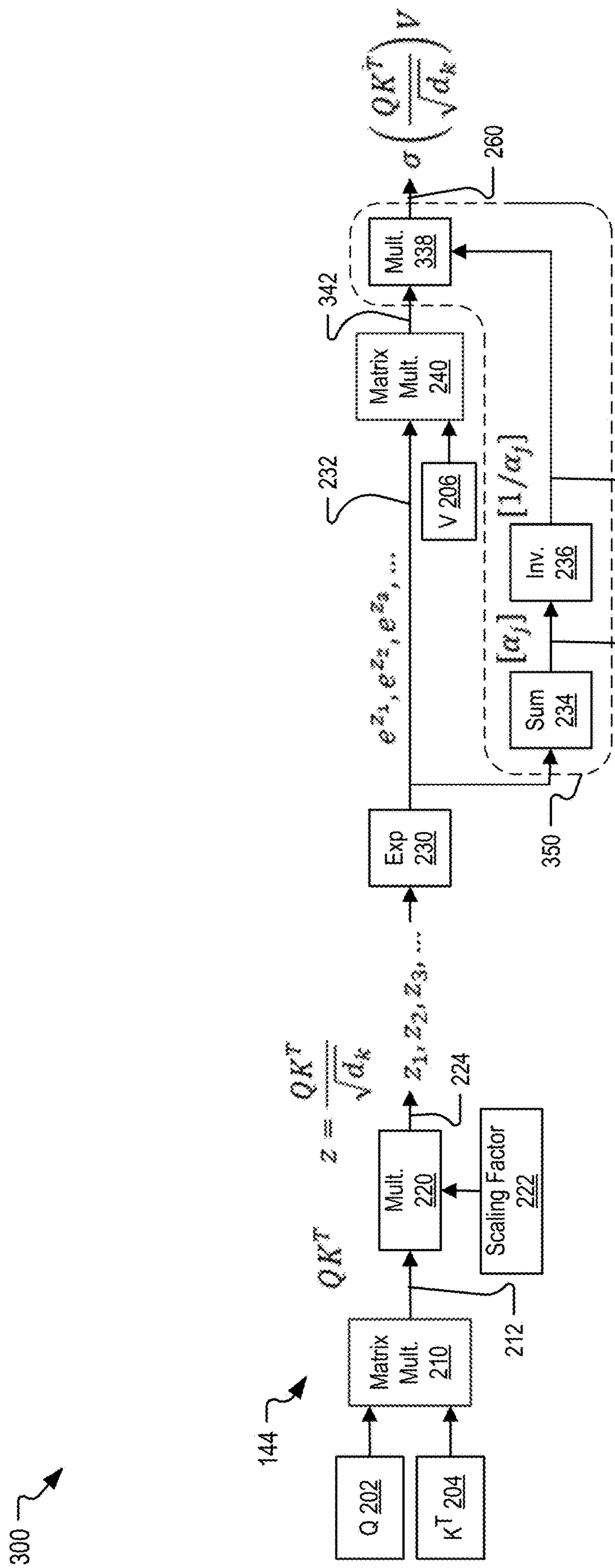

300
144
Q 202
$K^T$ 204
Matrix Mult. 210
212
$QK^T$
Mult. 220
Scaling Factor 222
$z = \frac{QK^T}{\sqrt{d_k}}$
224
$z_1, z_2, z_3, \ldots$
Exp 230
$e^{z_1}, e^{z_2}, e^{z_3}, \ldots$
232
V 206
Matrix Mult. 240
342
Mult. 338
260
$\sigma\left(\frac{QK^T}{\sqrt{d_k}}\right)V$
Sum 234
$[\alpha_j]$
235
Inv. 236
$[1/\alpha_j]$
237
350

FIG. 3

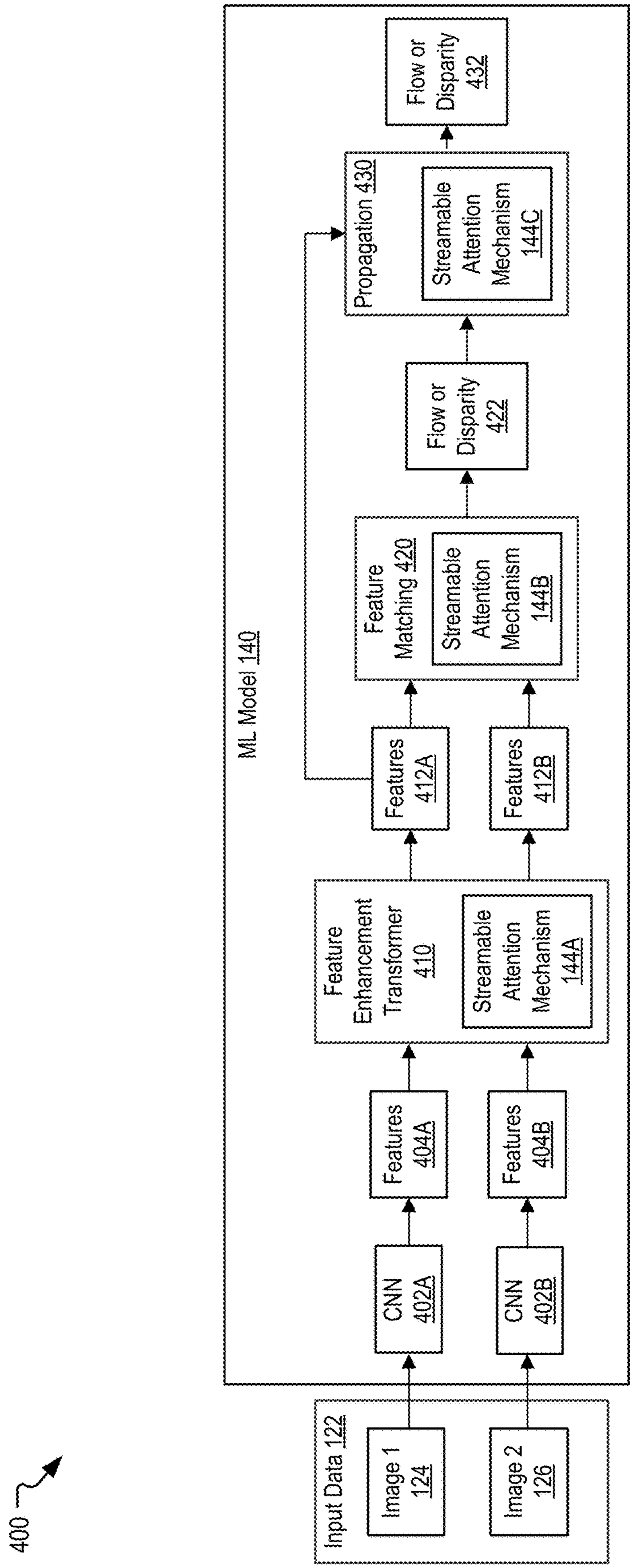

400
Input Data 122
Image 1 124
Image 2 126
ML Model 140
CNN 402A
CNN 402B
Features 404A
Features 404B
Feature Enhancement Transformer 410
Streamable Attention Mechanism 144A
Features 412A
Features 412B
Feature Matching 420
Streamable Attention Mechanism 144B
Flow or Disparity 422
Propagation 430
Streamable Attention Mechanism 144C
Flow or Disparity 432

FIG. 4

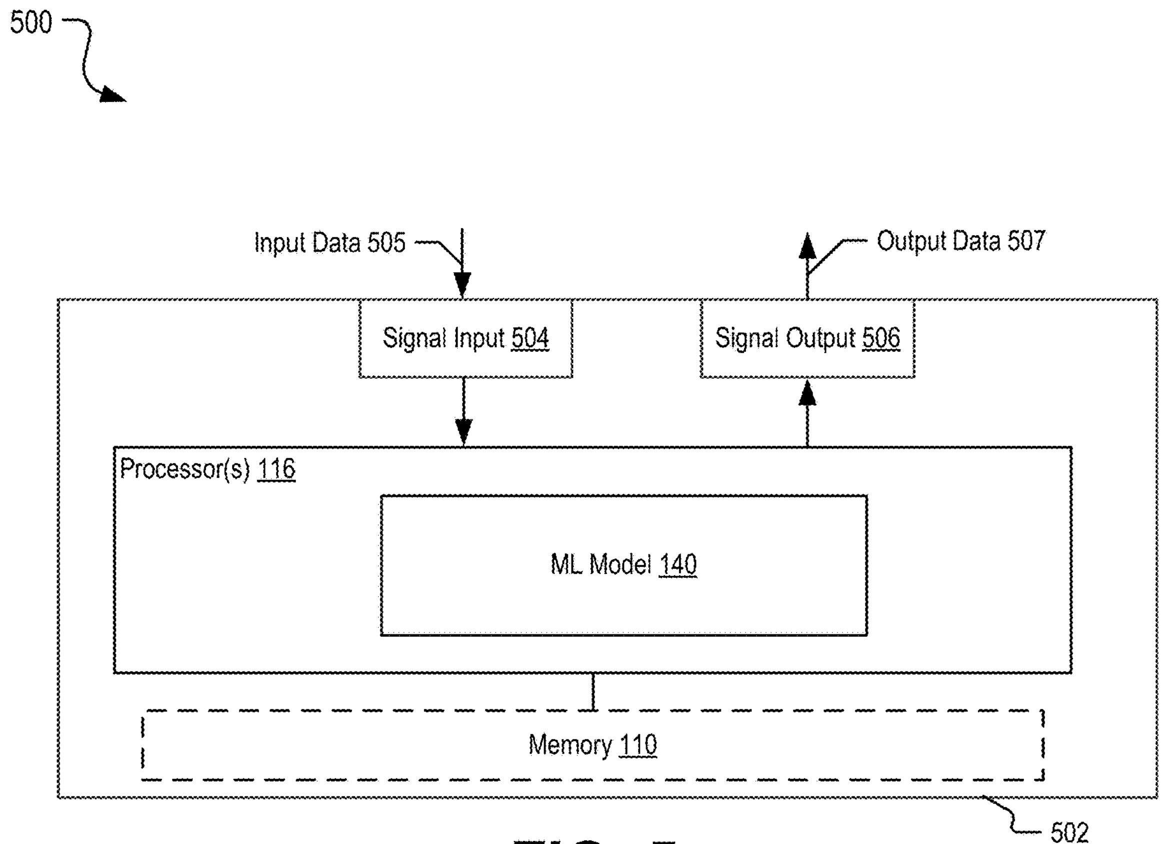

500
Input Data 505
Output Data 507
Signal Input 504
Signal Output 506
Processor(s) 116
ML Model 140
Memory 110
502

FIG. 5

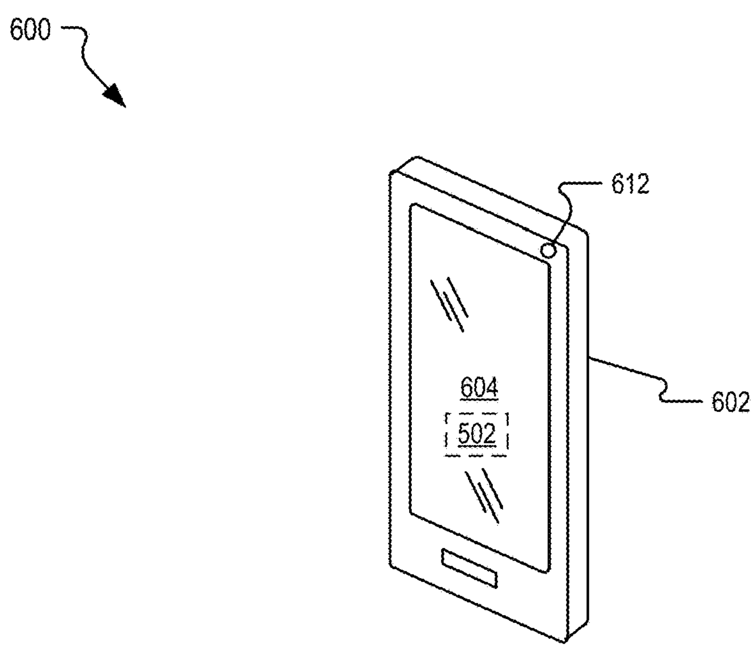

600
612
604
502
602

FIG. 6

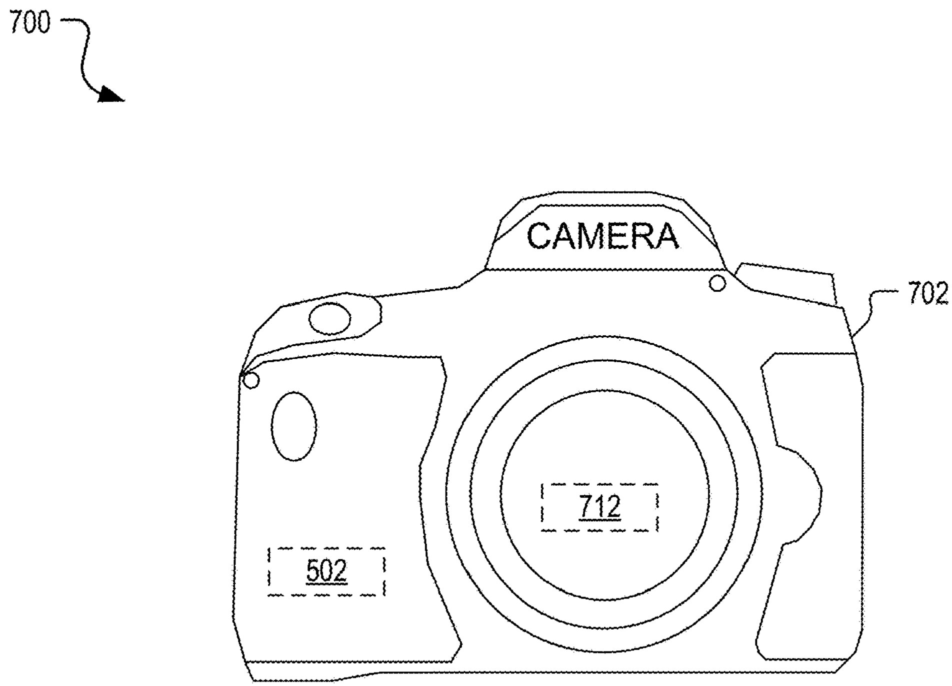



FIG. 7

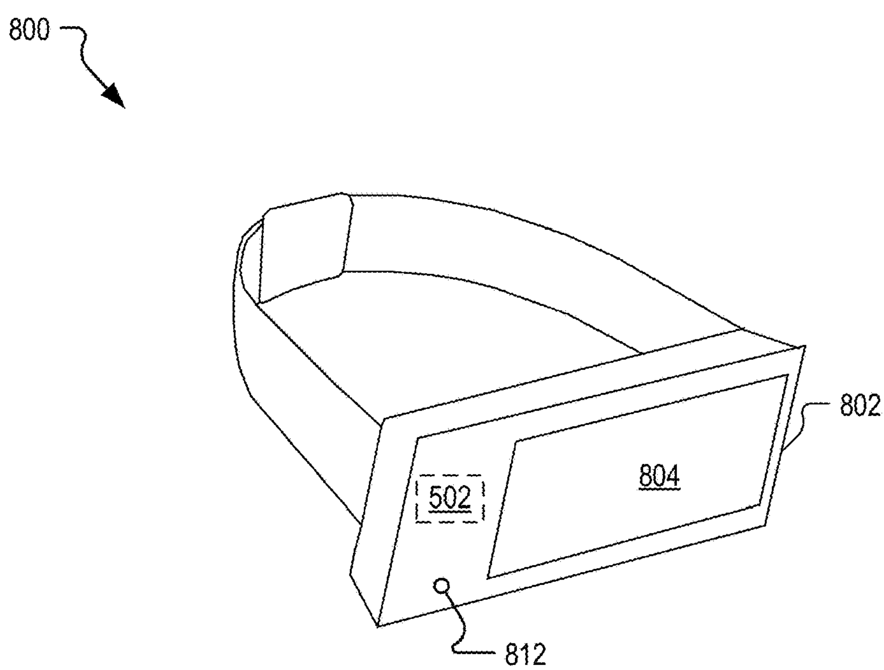



FIG. 8

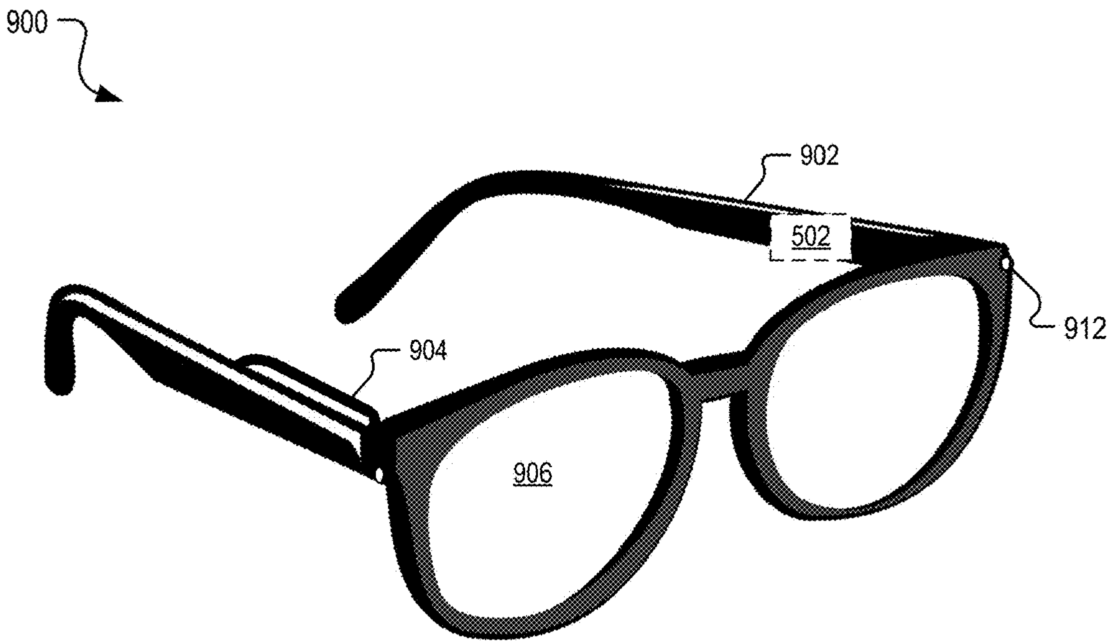



FIG. 9

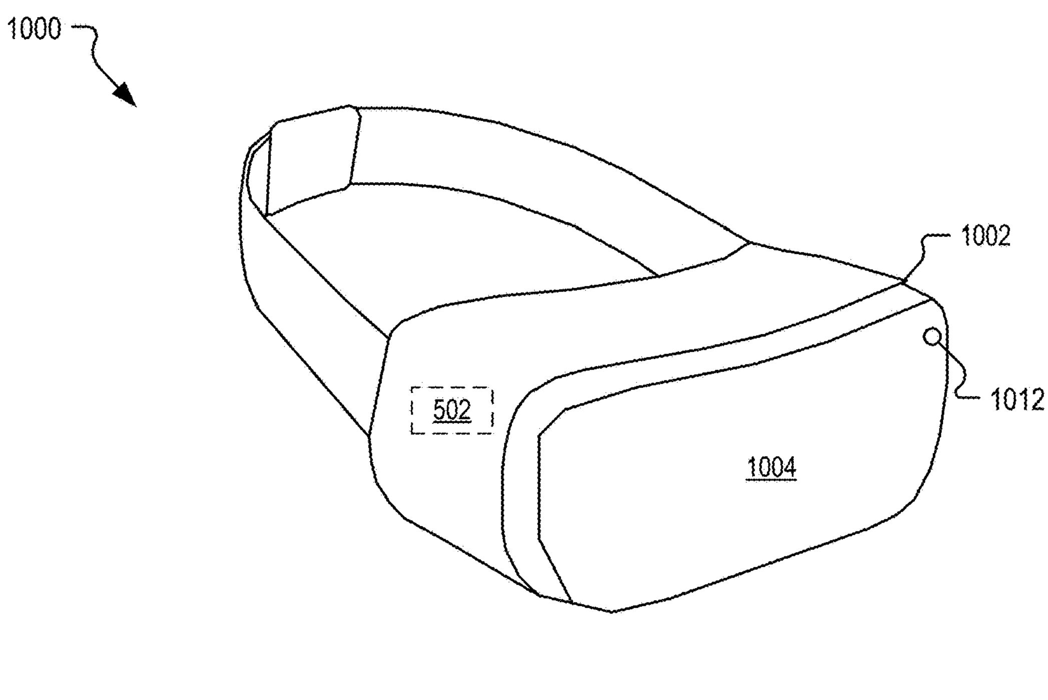



FIG. 10

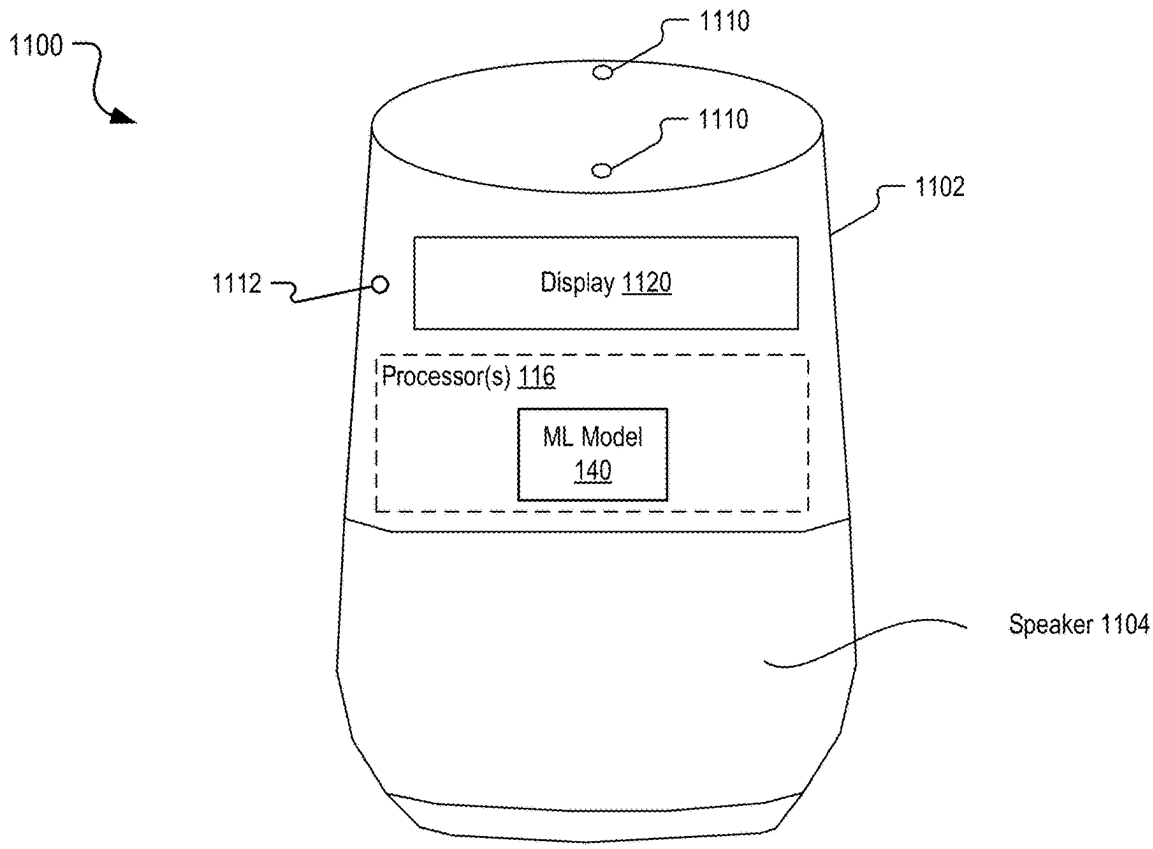

1100
1110
1110
1102
1112
Display 1120
Processor(s) 116
ML Model
140
Speaker 1104

FIG. 11

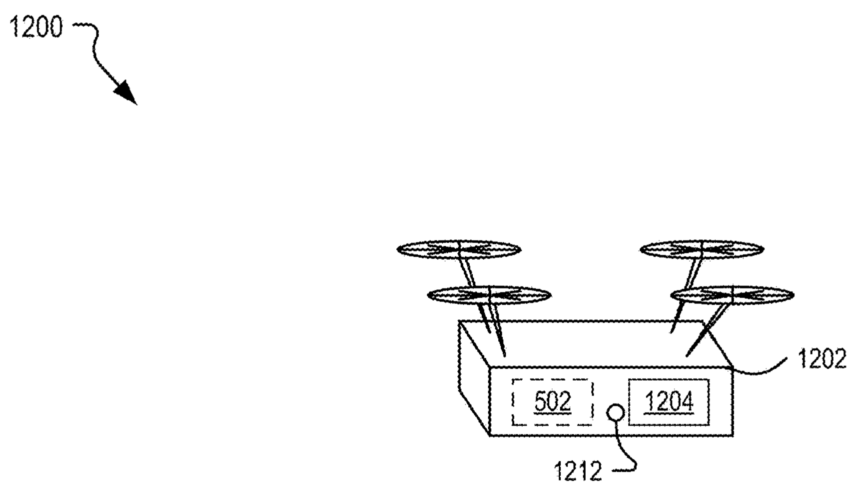

1200
1202
502
1204
1212

FIG. 12

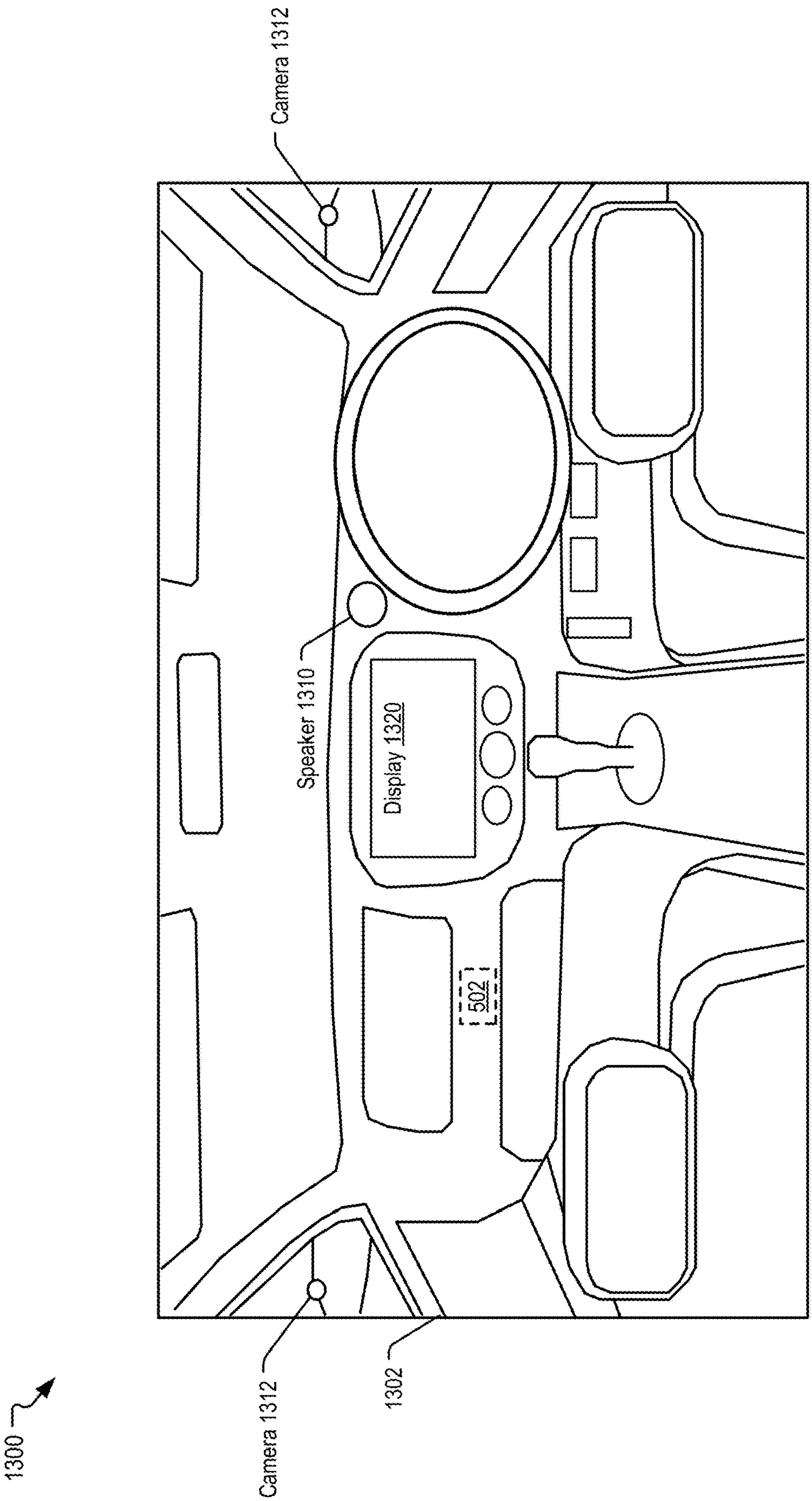

Camera 1312
Speaker 1310
Display 1320
502
Camera 1312
1302
1300

FIG. 13

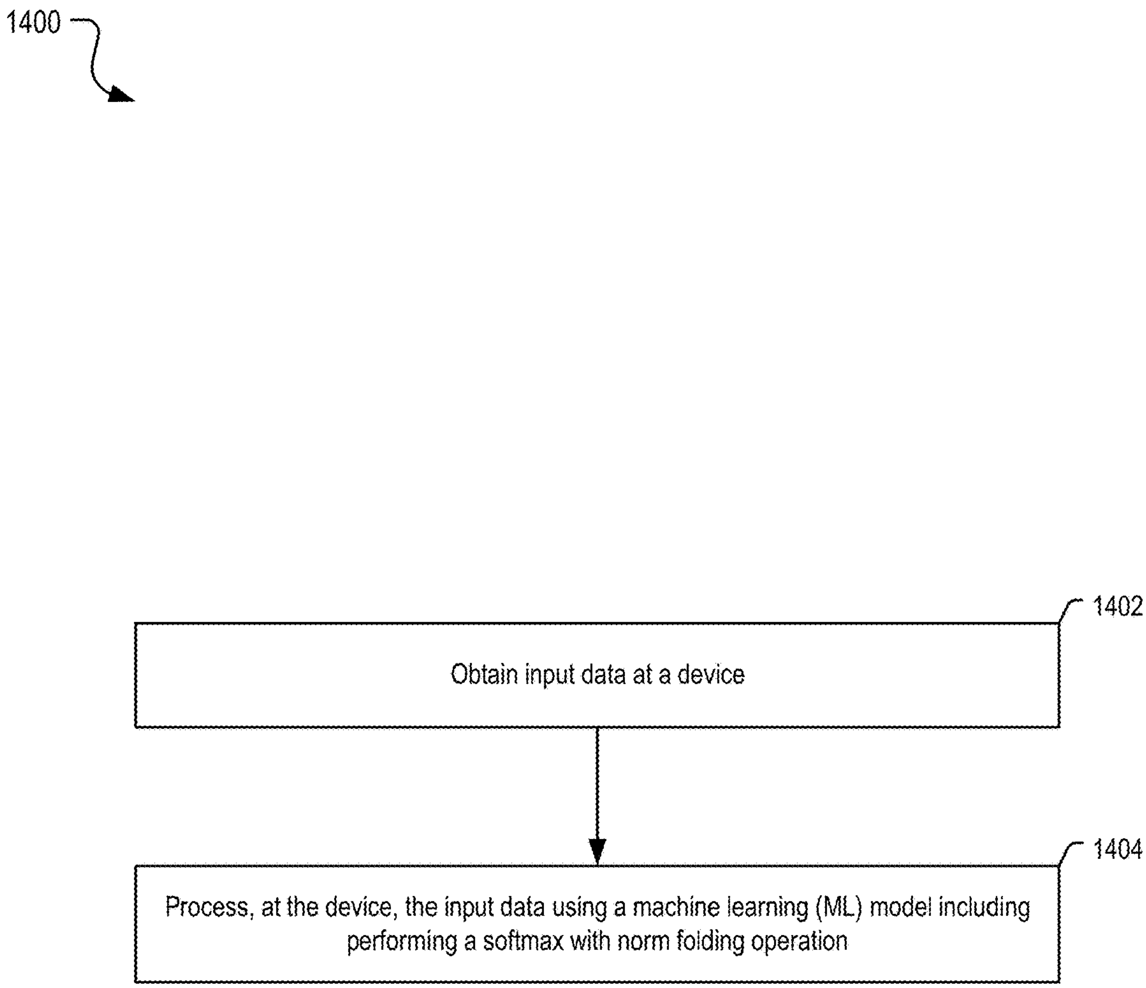

1400
1402
Obtain input data at a device
1404
Process, at the device, the input data using a machine learning (ML) model including performing a softmax with norm folding operation

FIG. 14

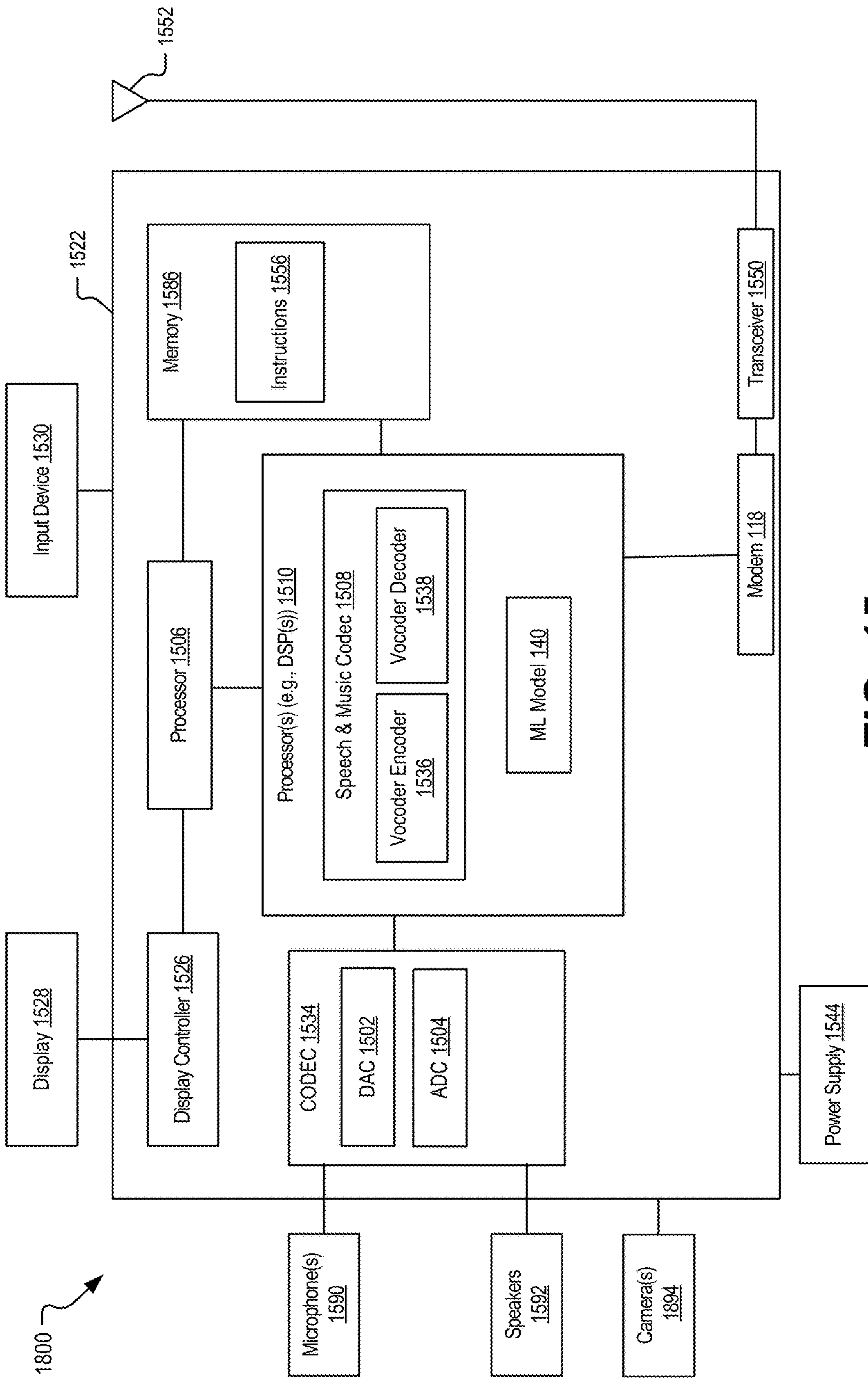

1552
1522
1800
Input Device 1530
Display 1528
Memory 1586
Instructions 1556
Processor 1506
Display Controller 1526
Processor(s) (e.g., DSP(s)) 1510
Speech & Music Codec 1508
Vocoder Decoder 1538
Vocoder Encoder 1536
ML Model 140
CODEC 1534
DAC 1502
ADC 1504
Transceiver 1550
Modem 118
Power Supply 1544
Microphone(s) 1590
Speakers 1592
Camera(s) 1894

FIG. 15

# LOW-FOOTPRINT MODEL APPLICABLE TO OPTICAL FLOW ESTIMATION AND STEREO MATCHING

## I. FIELD

**[0001]** The present disclosure is generally related to low-footprint models that are applicable to optical flow estimation and stereo matching.

## II. DESCRIPTION OF RELATED ART

**[0002]** Advances in technology have resulted in smaller and more powerful computing devices. For example, there currently exist a variety of portable personal computing devices, including wireless telephones such as mobile and smart phones, tablets and laptop computers that are small, lightweight, and easily carried by users. These devices can communicate voice and data packets over wireless networks. Further, many such devices incorporate additional functionality such as a digital still camera, a digital video camera, a digital recorder, and an audio file player. Also, such devices can process executable instructions, including software applications, such as a web browser application, that can be used to access the Internet. As such, these devices can include significant computing capabilities.

**[0003]** Such computing devices often incorporate functionality to perform multi-image processing techniques that involve comparisons between pairs of images, such as to track motion of objects between sequential video frames using optical flow (OF) techniques or to estimate depth information based on the visual disparity between corresponding points of a pair of stereo images, referred to herein as depth from stereo (DFS). However, conventional methods for OF and DFS estimation typically have a large memory requirement or "footprint" that can render such techniques impractical for use in a resource-constrained environment.

**[0004]** As an example, methods for OF and DFS estimation conventionally rely on the use of cost volumes, which are large data structures that are used to store values associated with cost calculations for individual paths, displacements, or disparities. As a simplified example, DFS estimation uses stereo matching for a left image and a right image and includes performing feature extraction to generate a feature map for the left image having dimensions of height (H) and width ($W_L$) and a feature map for the right image having dimensions of H and $W_R$. A cost volume is generated that stores the three-dimensional (H, $W_R$, $W_L$) interaction data, such as correlation values, which are then processed to determine a disparity—the size of a pixel offset between the left and right image-associated with each row of the images. For OF estimation, the cost volume to store the interaction data between the feature map of a first image "t" having dimensions $H_t$, $W_t$ and the feature map of a next image "t+1" having dimensions $H_{t+1}$, $W_{t+1}$ is even larger and requires storage of four-dimensional ($H_t$, $W_t$, $H_{t+1}$, $W_{t+1}$) interaction data. Both DFS and OF also require additional memory for intermediate calculations.

**[0005]** In a particular example, evaluation of a softmax operation in a conventional model includes performing multiple passes over the input data. For example, because the softmax operation includes generating a series of normalized values based on an input tensor, such as a matrix of input data, a first pass is used to generate a series of values based on the input data, and a second pass is used to normalize the values based on a sum of the intermediate values. This multi-pass evaluation requires buffering of the input tensor to sequentially traverse tensor entries and also creates a "break point" in the computation pipeline that prevents further processing until the multi-pass evaluation is completed. The impact of multi-pass softmax evaluation is heightened when the softmax is used in an attention mechanism, such as in a transformer, as the input tensor involves quadratic complexity. To illustrate, when evaluating two sets of input data associated with two images and each having a size of order N (e.g., O(N)), the complexity associated with processing the input tensor is of $O(N^2)$

**[0006]** Some devices, such as graphics processing units (GPUs) that are specialized for high-volume computations, can include a large enough on-chip memory for the cost volumes and intermediate computations that are needed for DFS and OF. However, such devices are expensive and consume large amounts of power, and are therefore not practical for use in a resource-constrained environment, such as a mobile phone or an extended reality (XR) headset.

## III. SUMMARY

**[0007]** According to a particular implementation of the techniques disclosed herein, a device includes a memory configured to store input data. The device also includes one or more processors configured to process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

**[0008]** According to a particular implementation of the techniques disclosed herein, a method includes obtaining input data at a device. The method also includes processing, at the device, the input data using a machine learning (ML) model including performing a softmax with norm folding operation.

**[0009]** According to a particular implementation of the techniques disclosed herein, a non-transitory computer-readable medium stores instructions that, when executed by one or more processors, cause the one or more processors to obtain input data and to process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

**[0010]** Other implementations, advantages, and features of the present disclosure will become apparent after review of the entire application, including the following sections: Brief Description of the Drawings, Detailed Description, and the Claims.

## IV. Brief Description of the Drawings

**[0011]** FIG. **1** is a block diagram illustrating an example of an implementation of a system operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0012]** FIG. **2** is a block diagram illustrating an example of components and operations that can be implemented in the system of FIG. **1**, in accordance with some examples of the present disclosure.

**[0013]** FIG. **3** is a block diagram illustrating an example of components and operations that can be implemented in the system of FIG. **1**, in accordance with some examples of the present disclosure.

**[0014]** FIG. **4** is a block diagram illustrating an example of a low-footprint model having a depth from stereo or optical flow architecture that can be implemented in the system of FIG. **1**, in accordance with some examples of the present disclosure.

**[0015]** FIG. **5** is a block diagram illustrating an implementation of an integrated circuit operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0016]** FIG. **6** is a diagram of an implementation of a portable electronic device operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0017]** FIG. **7** is a diagram of a camera operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0018]** FIG. **8** is a diagram of a wearable electronic device operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0019]** FIG. **9** is a diagram of an extended reality device, such as augmented reality glasses, operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0020]** FIG. **10** is a diagram of a headset, such as a virtual reality, mixed reality, or augmented reality headset, operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0021]** FIG. **11** is a diagram of a voice-controlled speaker system operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0022]** FIG. **12** is a diagram of a first example of a vehicle operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0023]** FIG. **13** is a diagram of a second example of a vehicle operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0024]** FIG. **14** is a diagram of a particular implementation of a method of performing input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

**[0025]** FIG. **15** is a block diagram of a particular illustrative example of a device that is operable to perform input data processing using a low-footprint model, in accordance with some examples of the present disclosure.

## V. DETAILED DESCRIPTION

**[0026]** Systems and methods to perform input data processing using a low-footprint model are disclosed. Conventional methods for performing techniques such as OF and DFS estimation typically have a large memory footprint that can render such techniques impractical for use in a resource-constrained environment. For example, methods for OF and DFS estimation conventionally rely on the use of cost volumes, which are large data structures that are used to store values associated with cost calculations for individual paths, displacements, or disparities. Some such conventional methods can include evaluation of a softmax operation that includes performing multiple passes over the input data, which can require a large amount of buffering and creates a break point in the computation pipeline that prevents further processing until the multi-pass evaluation is completed.

**[0027]** The disclosed techniques enable performance of input data processing, such as for performing OF and DFS estimation, with significantly reduced memory usage as compared to conventional approaches. The use of relatively low-footprint models according to the present techniques enables processing for applications such as OF and DFS estimation to be efficiently performed in resource-constrained environments.

**[0028]** In accordance with the present techniques, instead of performing conventional OF or DFS processing using cost volumes, a machine-learning model that includes an attention mechanism is used to generate probabilistic geometry measures without generating a cost volume data structure. To illustrate, according to a first aspect, the probabilistic measures are used to regress on geometric coordinates without the use of a cost volume. Elimination of the cost volume reduces memory usage associated with OF or DFS processing.

**[0029]** According to a second aspect, the disclosed techniques improve the operation of the softmax compute path in the attention mechanism. For example, a norm folding mechanism is incorporated in the softmax compute path that applies a normalization factor at a later point in the compute path as compared to conventional multi-pass techniques. As a result, the data flow in the attention computation remains "streamable"—that is, no buffering or execution breakpoint is needed even for large input data sizes—and enables depth-first computation without requiring softmax memory buffering.

**[0030]** According to a third aspect, the disclosed techniques include using just-in-time regression for OF or DFS geometric coordinates. For example, each matrix in the attention mechanism has a linear space complexity with respect to the token size, e.g., $O(N)$. As compared to conventional attention mechanisms in which quadratic memory buffering (e.g., $O(N^2)$) is required, the matrix multiplication is instead performed with suitable partitioning of the matrices in the rows of one matrix and the columns of the other matrix, such that quadratic buffering is no longer needed in the memory. Depth-first computation may also be applied to reduce the amount of buffering in the computation pipeline.

**[0031]** Combining the above aspects into a single, low-footprint model for processing input data, such as for OF or DFS estimation, can greatly enhance operation of a device implementing the model. Further, operation can also be enhanced in devices that implement fewer than all of the above aspects. In particular, each of the above aspects independently improves performance of OF or DFS estimation by reducing memory usage, which reduces read/write accesses that may otherwise result from overflow memory accesses when the memory usage exceeds available on-chip memory capacity. Reduction in overflow memory accesses can directly result in reduced latency and power consumption and therefore improves the performance of a device implementing one or more of the disclosed techniques.

**[0032]** Although the following description is primarily directed to examples of the present techniques in the context of using OF and DFS estimation, the present techniques are not limited to OF and DFS applications. For example, the present techniques can also be used to reduce memory usage and improve performance in applications such as large language models, transformer models such as for computer vision, diffusion models such as for text-to-image generative models, etc., that may incorporate attention and/or softmax mechanisms. To illustrate, in some embodiments the present techniques are used to improve performance in large language models (LLMs), large vision models (LVMs), large multimodal models (LMMs), or a combination thereof.

**[0033]** Particular aspects of the present disclosure are described below with reference to the drawings. In the description, common features are designated by common reference numbers. As used herein, various terminology is used for the purpose of describing particular implementations only and is not intended to be limiting of implementations. For example, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. Further, some features described herein are singular in some implementations and plural in other implementations. To illustrate, FIG. **1** depicts a device **102** including one or more processors ("processor(s)" **116** of FIG. **1**), which indicates that in some implementations the device **102** includes a single processor **116** and in other implementations the device **102** includes multiple processors **116**. For ease of reference herein, such features are generally introduced as "one or more" features and are subsequently referred to in the singular or optional plural (as indicated by "(s)" in the name of the feature) unless aspects related to multiple of the features are being described.

**[0034]** In some drawings, multiple instances of a particular type of feature are used. Although these features are physically and/or logically distinct, the same reference number is used for each, and the different instances are distinguished by addition of a letter to the reference number. When the features as a group or a type are referred to herein, e.g., when no particular one of the features is being referenced, the reference number is used without a distinguishing letter. However, when one particular feature of multiple features of the same type is referred to herein, the reference number is used with the distinguishing letter. For example, referring to FIG. **4**, multiple convolutional neural networks (CNNs) are illustrated and associated with reference numbers **402**A and **402**B. When referring to a particular one of these CNNs, such as a CNN **402**A, the distinguishing letter "A" is used. However, when referring to any arbitrary one of these CNNs or to these CNNs as a group, the reference number **402** is used without a distinguishing letter.

**[0035]** As used herein, the terms "comprise," "comprises," and "comprising" may be used interchangeably with "include," "includes," or "including." Additionally, it will be understood that the term "wherein" may be used interchangeably with "where." As used herein, "exemplary" may indicate an example, an implementation, and/or an aspect, and should not be construed as limiting or as indicating a preference or a preferred implementation. As used herein, an ordinal term (e.g., "first," "second," "third," etc.) used to modify an element, such as a structure, a component, an operation, etc., does not by itself indicate any priority or order of the element with respect to another element, but rather merely distinguishes the element from another element having a same name (but for use of the ordinal term). As used herein, the term "set" refers to one or more of a particular element, and the term "plurality" refers to multiple (e.g., two or more) of a particular element.

**[0036]** As used herein, "coupled" may include "communicatively coupled," "electrically coupled," or "physically coupled," and may also (or alternatively) include any combinations thereof. Two devices (or components) may be coupled (e.g., communicatively coupled, electrically coupled, or physically coupled) directly or indirectly via one or more other devices, components, wires, buses, networks (e.g., a wired network, a wireless network, or a combination thereof), etc. Two devices (or components) that are electrically coupled may be included in the same device or in different devices and may be connected via electronics, one or more connectors, or inductive coupling, as illustrative, non-limiting examples. In some implementations, two devices (or components) that are communicatively coupled, such as in electrical communication, may send and receive signals (e.g., digital signals or analog signals) directly or indirectly, via one or more wires, buses, networks, etc. As used herein, "directly coupled" may include two devices that are coupled (e.g., communicatively coupled, electrically coupled, or physically coupled) without intervening components.

**[0037]** In the present disclosure, terms such as "obtaining," "determining," "calculating," "estimating," "shifting," "adjusting," etc. may be used to describe how one or more operations are performed. It should be noted that such terms are not to be construed as limiting and other techniques may be utilized to perform similar operations. Additionally, as referred to herein, "obtaining," "generating," "calculating," "estimating," "using," "selecting," "accessing," and "determining" may be used interchangeably. For example, "obtaining," "generating," "calculating," "estimating," or "determining" a parameter (or a signal) may refer to actively generating, estimating, calculating, or determining the parameter (or the signal) or may refer to using, selecting, retrieving, receiving, or accessing the parameter (or signal) that is already generated, such as by another component or device.

**[0038]** As used herein, the term "machine learning" should be understood to have any of its usual and customary meanings within the fields of computers science and data science, such meanings including, for example, processes or techniques by which one or more computers can learn to perform some operation or function without being explicitly programmed to do so. As a typical example, machine learning can be used to enable one or more computers to analyze data to identify patterns in data and generate a result based on the analysis. For certain types of machine learning, the results that are generated include data that indicates an underlying structure or pattern of the data itself. Such techniques, for example, include so called "clustering" techniques, which identify clusters (e.g., groupings of data elements of the data).

**[0039]** For certain types of machine learning, the results that are generated include a data model (also referred to as a "machine-learning model" or simply a "model"). Typically, a model is generated using a first data set to facilitate analysis of a second data set. For example, a first portion of a large body of data may be used to generate a model that can be used to analyze the remaining portion of the large body of data. As another example, a set of historical data can be used to generate a model that can be used to analyze future data.

**[0040]** Since a model can be used to evaluate a set of data that is distinct from the data used to generate the model, the model can be viewed as a type of software (e.g., instructions, parameters, or both) that is automatically generated by the computer(s) during the machine learning process. As such, the model can be portable (e.g., can be generated at a first computer, and subsequently moved to a second computer for further training, for use, or both). Additionally, a model can be used in combination with one or more other models to perform a desired analysis. To illustrate, first data can be provided as input to a first model to generate first model output data, which can be provided (alone, with the first data, or with other data) as input to a second model to generate second model output data indicating a result of a desired analysis. Depending on the analysis and data involved, different combinations of models may be used to generate such results. In some examples, multiple models may provide model output that is input to a single model. In some examples, a single model provides model output to multiple models as input.

**[0041]** Examples of machine-learning models include, without limitation, perceptrons, neural networks, support vector machines, regression models, decision trees, Bayesian models, Boltzmann machines, adaptive neuro-fuzzy inference systems, as well as combinations, ensembles and variants of these and other types of models. Variants of neural networks include, for example and without limitation, prototypical networks, autoencoders, transformers, self-attention networks, convolutional neural networks, deep neural networks, deep belief networks, etc. Variants of decision trees include, for example and without limitation, random forests, boosted decision trees, etc.

**[0042]** Since machine-learning models are generated by computer(s) based on input data, machine-learning models can be discussed in terms of at least two distinct time windows—a creation/training phase and a runtime phase. During the creation/training phase, a model is created, trained, adapted, validated, or otherwise configured by the computer based on the input data (which in the creation/training phase, is generally referred to as "training data"). Note that the trained model corresponds to software that has been generated and/or refined during the creation/training phase to perform particular operations, such as classification, prediction, encoding, or other data analysis or data synthesis operations. During the runtime phase (or "inference" phase), the model is used to analyze input data to generate model output. The content of the model output depends on the type of model. For example, a model can be trained to perform classification tasks or regression tasks, as non-limiting examples. In some implementations, a model may be continuously, periodically, or occasionally updated, in which case training time and runtime may be interleaved or one version of the model can be used for inference while a copy is updated, after which the updated copy may be deployed for inference.

**[0043]** In some implementations, a previously generated model is trained (or re-trained) using a machine-learning technique. In this context, "training" refers to adapting the model or parameters of the model to a particular data set. Unless otherwise clear from the specific context, the term "training" as used herein includes "re-training" or refining a model for a specific data set. For example, training may include so called "transfer learning." In transfer learning a base model may be trained using a generic or typical data set, and the base model may be subsequently refined (e.g., re-trained or further trained) using a more specific data set.

**[0044]** A data set used during training is referred to as a "training data set" or simply "training data". The data set may be labeled or unlabeled. "Labeled data" refers to data that has been assigned a categorical label indicating a group or category with which the data is associated, and "unlabeled data" refers to data that is not labeled. Typically, "supervised machine-learning processes" use labeled data to train a machine-learning model, and "unsupervised machine-learning processes" use unlabeled data to train a machine-learning model; however, it should be understood that a label associated with data is itself merely another data element that can be used in any appropriate machine-learning process. To illustrate, many clustering operations can operate using unlabeled data; however, such a clustering operation can use labeled data by ignoring labels assigned to data or by treating the labels the same as other data elements.

**[0045]** Training a model based on a training data set generally involves changing parameters of the model with a goal of causing the output of the model to have particular characteristics based on data input to the model. To distinguish from model generation operations, model training may be referred to herein as optimization or optimization training. In this context, "optimization" refers to improving a metric, and does not mean finding an ideal (e.g., global maximum or global minimum) value of the metric. Examples of optimization trainers include, without limitation, backpropagation trainers, derivative free optimizers (DFOs), and extreme learning machines (ELMs). As one example of training a model, during supervised training of a neural network, an input data sample is associated with a label. When the input data sample is provided to the model, the model generates output data, which is compared to the label associated with the input data sample to generate an error value. Parameters of the model are modified in an attempt to reduce (e.g., optimize) the error value. As another example of training a model, during unsupervised training of an autoencoder, a data sample is provided as input to the autoencoder, and the autoencoder reduces the dimensionality of the data sample (which is a lossy operation) and attempts to reconstruct the data sample as output data. In this example, the output data is compared to the input data sample to generate a reconstruction loss, and parameters of the autoencoder are modified in an attempt to reduce (e.g., optimize) the reconstruction loss.

**[0046]** Referring to FIG. **1**, a particular illustrative aspect of a system **100** is depicted that includes a device **102** that is configured to perform input data processing using a low-footprint model. For example, the device **102** is configured to process input data **122** using a machine learning (ML) model **140** that includes a softmax with norm folding mechanism **142**. Use of the softmax with norm folding mechanism **142** reduces the buffering requirements of conventional softmax mechanisms and can further reduce the footprint of the ML model **140** by enabling depth-first computation, as described further below.

**[0047]** Optionally, the device **102** includes, or is coupled to, one or more image sensors **104**. The image sensor **104** is configured to generate image data **105** that, in some embodiments, corresponds to the input data **122**. In a particular embodiment, the image sensor **104** corresponds to or is incorporated into a camera, such as a still image camera, a video camera, a stereo camera, a thermal imaging camera, one or more other types of camera, or a combination thereof. According to an aspect, the image data **105** includes data (e.g., pixel values) of individual images, video data, or a combination thereof.

**[0048]** The device **102** includes a memory **110** coupled to the one or more processors **116** and configured to store instructions **112** and input data **122**, such as individual images or data corresponding to images included in video data (e.g., video frames). For example, the memory **110** may include a first image **124** and a second image **126** as part of the input data **122** to be processed at the ML model **140**, as described in further detail below. The memory **110** may also store data (e.g., parameters, such as weights and biases) associated with one or more ML models, such as the ML model **140**, that may be implemented at the one or more processors **116**. In a particular implementation, the memory **110** corresponds to a dynamic random access memory (DRAM) of a double data rate (DDR) memory subsystem.

**[0049]** The one or more processors **116** are configured to execute the instructions **112** to perform operations associated with the ML model **140**. In various implementations, some or all of the functionality associated with ML model **140** is performed via execution of the instructions **112** by the one or more processors **116**, performed by processing circuitry of the one or more processors **116** in a hardware implementation, or a combination thereof.

**[0050]** The one or more processors **116** may include an input data source **120** coupled to the ML model **140** and configured to provide the input data **122** to the ML model **140**. For example, the input data source **120** may correspond to the image sensor **104**, a portion of one or more of media files (e.g., a media file including the input images **124**, **126** that is retrieved from the memory **110**), one or more other sources of image information, such as from a remote media server, or a combination thereof.

**[0051]** The one or more processors **116** are configured to process the input data **122** using the ML model **140** that incorporates the softmax with norm folding mechanism **142** to generate output data **152**. To illustrate, in a particular embodiment, the input data **122** includes the first image **124** and the second image **126**, and the ML model **140** corresponds to an OF or DFS architecture that generates a flow map **154** or a disparity map **156**, respectively, such as described further with reference to FIG. **4**. According to an aspect, instead of performing conventional OF or DFS using cost volumes, the ML model **140** is used to generate probabilistic geometry measures without generating a cost volume data structure.

**[0052]** As illustrated, the softmax with norm folding mechanism **142** is included in a streamable attention mechanism **144** of the ML model **140**. In general, an attention function can be calculated as:

$$\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right) V = PV,$$

where Q can correspond to a matrix of features of one image (e.g., a feature map), K can correspond to a matrix of features of the other image, $\sqrt{d_k}$ is a constant normalization factor, and V can correspond to a matrix of displacement values (e.g., values of $\Delta x$ for DFS, or $\Delta x$, $\Delta y$ for OF). In this example, P represents a matrix of probability values (in the range [0,1]) which, when multiplied by the displacement values in V, result in expectation values. Q, K, and V can each have linear complexity (e.g., O(N)), and a naive approach to computing $QK^T$ has quadratic complexity (e.g., $O(N^2)$), which is similar to a conventional cost volume approach.

**[0053]** Conventionally, the softmax function,

$$\text{softmax}(z)_i = \sigma(z)_i = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}} \text{ for } i = 1, \ldots, K \text{ and}$$

$$z = (z_1, \ldots, z_K) \in \mathbb{R}^K,$$

is computed using a multi-pass technique in which the numerator values $e^{z_i}$ are computed, the denominator is computed as the accumulated sum over the numerator values, and the values of $\sigma(z)_i$ are computed by dividing each numerator value by the denominator. Such a multi-pass approach requires buffering of the values that are generated in each pass. As a result, a stream of input values sent to the softmax computation block is interrupted due to the buffering, creating a computation pipeline break point that prevents further processing until the multi-pass evaluation is completed. In some examples, latency that is incurred while buffering the incoming values for the softmax computation can be prohibitive. In some instances, the amount of data to be buffered can exceed the capacity of an on-chip memory of the processor **116**, and data transfers of the buffered data to and from a higher capacity storage (e.g., the memory **110**) of the device **102** are performed, resulting in additional increases in latency and power consumption.

**[0054]** The disclosed techniques improve the operation of the softmax compute path, including incorporating a norm folding mechanism, so that the data flow in the streamable attention mechanism **144** remains "streamable"—that is, no buffering or execution breakpoint is needed even for large sizes of Q and K—and enables depth-first computation. Examples of computational components (e.g., network layers) of the streamable attention mechanism **144**, including the softmax with norm folding mechanism **142**, are depicted in FIG. **2** and FIG. **3** and compared to an example of a conventional attention mechanism that is depicted in FIG. **2**.

**[0055]** According to an aspect, the ML model **140** is configured to perform regression for OF or DFS geometric coordinates using just-in-time computations. Just-in-time computations can enable the one or more processors **116** to compute and consume computation as late as possible to avoid having to store computation results for later use. In general, there is a basic unit of operands that is needed at any given time during processing of the input data **122** at the ML model **140**, and once computations have completed for that scope of operands, all intermediate computations are no longer needed and can be discarded, and a next batch of operands is loaded into memory. For example, during the softmax computation to determine $P_{ij}$ based on the row $Q_i$ and the column $K_j$, the device **102** loads $Q_i$ and $K_j$ into memory (either in their entirety or as a series of partitioned portions, as described below) and evaluates the inner product of $Q_i$ and $K_j$ to determine $P_{ij}$. Reading any rows besides $Q_i$ or any columns besides $K_j$ into memory would be premature and unnecessarily increase memory usage beyond that required for the computation.

**[0056]** To illustrate, in a naive computation approach, all entries of $Q_i$ and $K_j$ are loaded into memory and all of the intermediate computations for $Q_i$ and $K_j$ are stored. If $Q_i$ and $K_j$ each have size "S," the amount of memory needed to store $Q_i$ and $K_j$ is 2S, and the amount of memory needed to store all of the intermediate computations is $S^2$. However, by partitioning $Q_i$ and $K_j$ into basic units of operands that are loaded into memory on an as-needed basis and performing just-in-time computations, the amount of memory used to process the input data **122** at the ML model **140** can be significantly reduced. For example, a basic unit of operands can be 64 entries from each of Qi and Kj, and computation of the accumulation of numerator terms for the softmax operation can be performed for a first set of 64 entries of $Q_i$ and $K_j$, followed by a next set of 64 entries of $Q_i$ and $K_j$, and so on, until all entries of $Q_i$ and $K_j$, have been processed, and an accumulated total of all the numerator terms has been generated.

**[0057]** According to an aspect, the one or more processors **116** are configured to perform depth-first computations in which intermediate computations are calculated and consumed for one unit of operands before processing a next unit of operands, thus circumventing the need to store the intermediate computations for later use and providing enhanced efficiency.

**[0058]** The output data **152** can include information generated as a result of processing the input data **122** at the ML model **140**. For example, in embodiments in which the ML model **140** has an OF architecture, the output data **152** can include a flow map **154**. In general, an optical flow can indicate a pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer (e.g., the image sensor **104**, a robotic device, etc.) and a scene. The flow map **154** can include optical flow information that may be used to measure the motion of the device **102** relative to an object or scene. The optical flow information may also be used to measure visual motion or relative motion between the device **102** and one or more other objects in the vicinity of the device **102**. In addition, or alternatively, the device **102** may use the optical flow information for motion detection, object segmentation, stereo disparity measurements, etc.

**[0059]** In embodiments in which the ML model **140** has a DFS architecture, the output data **152** can include a disparity map **156**. The disparity map **156** can be used to generate depth information, such a depth map, that may be employed in a number of different embodiments, such as for navigation in an environment to avoid obstacles or to plan routes. To illustrate, the device **102** can be implemented in, or may correspond to, a fully autonomous, semi-autonomous, or fully user-controlled drone or other motorized vehicle. In some embodiments, the device **102** (e.g., the image sensor **104**) may capture images of one or more objects or a scene and generate depth maps from those images. Such depth maps may be used to determine distances between objects in the scene, heights of objects, etc.

**[0060]** In some embodiments, the one or more processors **116** may generate or update a 3D representation **160** of an object or scene based on the image data **105** and the output data **152**. For example, the one or more processors **116** may process the output data **152** to determine 3D characteristics of an object in the input data **122**, such as height, depth, etc., to generate the 3D representation **160**. The one or more processors **116** may update or refine the 3D representation **160** based on updated information in the input data **122** and/or the output data **152**, such as in response to the image sensor **104** capturing additional images of the object that differ from previous images due to relative motion between the device **102** and the object. The one or more processors **116** may be configured to generate one or more 2D images representing the 3D representation **160** of the object or scene, such as from a novel viewpoint of the 3D representation, to display to a user of the device **102**, as an illustrative, non-limiting example.

**[0061]** Although in some embodiments the ML model **140** may be trained at the device **102**, in other embodiments the ML model **140** is not trained at the device **102**. To illustrate, the ML model **140** may be trained at a remote device, such as a remote device **198**, and the trained ML model **140** may be transmitted to the device **102** and stored in the memory **110**.

**[0062]** The device **102** optionally includes or is coupled to a display device **106**. The display device **106** is configured to display output image data **107** corresponding to the output data **152** for viewing by a user of the device **102**. For example, in some embodiments in which the one or more processors **116** generate the 3D representation **160** of an object or scene based on the image data **105**, the one or more processors **116** may generate the output image data **107** based on the 3D representation **160**, such as in an extended reality application.

**[0063]** The device **102** optionally includes a modem **118** that is coupled to the one or more processors **116** and configured to enable communication with one or more other devices, such as via one or more wireless networks. According to some aspects, the modem **118** is configured to receive the image data **105**, the input data **122**, or both, from a second device, such as image data (e.g., included in video data) that is streamed via a wireless transmission **194** from a remote device, such as the remote device **198** (e.g., a remote server) for processing at the device **102**. According to some aspects, the modem **118** is configured to send data corresponding to the output data **152**, the 3D representation **160**, or both, to a second device, such as image data (e.g., associated with the 3D representation **160**) that is streamed via the wireless transmission **194** to a remote device **198** (e.g., a remote server or user device) for storage or playback.

**[0064]** A technical advantage of using the ML model **140** is that, as compared to conventional techniques, the ML model **140** is a low-footprint model that can be run using reduced memory usage, which reduces read/write accesses that may otherwise result from overflow memory accesses when the memory usage exceeds available on-chip memory capacity. Reduction in overflow memory accesses can directly result in reduced latency and power consumption, which improves the overall performance of the device **102**.

**[0065]** According to some aspects, the one or more processors **116** are integrated in an integrated circuit, such as illustrated in FIG. **5**. According to some aspects, the one or more processors **116** are integrated in at least one of a mobile phone or a tablet computer device, such as illustrated in FIG. **6**, a camera device, such as illustrated in FIG. **7**, or a wearable electronic device, such as illustrated in FIG. **8**. According to some aspects, the one or more processors **116** are integrated in a headset device that includes a display and that is configured, when worn by a user, to display an output image based on an output of the ML model **140**, such as illustrated in FIG. **9** and FIG. **10**. According to some aspects, the one or more processors **116** are integrated in a voice-controlled speaker system, such as illustrated in FIG. **11**. According to some aspects, the one or more processors **116** are integrated in a vehicle that also includes one or more cameras configured to capture image data corresponding to the input data **122**, such as illustrated in FIG. **12** and FIG. **13**.

**[0066]** It should be understood that one or more aspects of the device **102** may have been omitted from the above description for clarity of explanation. For example, although in some embodiments the input data **122** matches the image data **105**, in other embodiments the input data **122** may be the result of additional processing that is performed on the image data **105**. Such additional processing can include cropping, zooming, tone mapping, color enhancement, upscaling, or downscaling, as illustrative, non-limiting examples.

**[0067]** Although OF and DFS are described as example architectures of the ML model **140**, it should be noted that the present techniques are not limited to OF and DFS applications. In a particular example, the cost-volume-less OF and DFS processing eliminates the quadratic memory requirement associated with on-device attentions and transformers for determining OF, DFS, and stereo matching/depth estimation, such as depth estimation for spatial matching and OF estimation for temporal matching, which enables improved performance in applications such as mobile cameras, autonomous vehicles, extended reality headset devices (e.g., glasses), etc. In another example, the streamable softmax and attention processing (e.g., of the streamable attention mechanism **144** and the softmax with norm folding mechanism **142**) can help remove execution pipelining and memory bottlenecks associated with operating transformer models on mobile devices, such as computer vision and language models in which the softmax function can be responsible for more than half of the total latency of the model. In another example, the elimination of the quadratic memory requirement by use of the streamable softmax processing improves the operation of the device **102** in embodiments in which the ML model **140** is a diffusion model, such as a text-to-image generative model on a mobile device. In another example, the streaming pipelining and the elimination of the quadratic memory requirement associated with on-device attentions and transformers, enabled by the streamable attention of the present disclosure, improves the performance associated with running large language models (LLMs), such as LLMs with very large token sizes, and LLMs on mobile devices with relatively constrained on-device memory. According to some embodiments, the present techniques are used to improve performance in language models such as LLMs, vision models such as LVMs, and/or multi-modal models such as LMMs (which may be viewed as an extension of LLMs or LVMs that operate on multi-modal input data). For example, the present techniques can be implemented in an LMM that processes input data corresponding to multiple modalities of input/sensor sources, such as audio, speech, text, images, videos etc., and that incorporates neural network processing, including a streamable attention mechanism, that provides improved performance to handle a large size of attention tokens, in a similar manner as for LLMs or LVMs.

**[0068]** FIG. **2** depicts an example **200** of components and operations that may be implemented in the device **102** of FIG. **1**, according to some examples of the present disclosure. In particular, the example **200** illustrates components and operations that may be implemented in the streamable attention mechanism **144**.

**[0069]** The streamable attention mechanism **144** is configured to receive first data (Q) **202** and second data (K) **204**. Each of the first data (Q) **202** and the second data (K) **204** may correspond to a matrix of features values (e.g., a feature map) of a corresponding input image. According to an aspect, the second data **204** represents a transpose of a matrix of feature values (e.g., $K^T$). In a particular embodiment, the first data **202** corresponds to features associated with the first image **124**, and the second data **204** corresponds to features associated with the second image **126**. The streamable attention mechanism **144** also receives third data (V) **206** that corresponds to a displacement matrix of coordinates, as described further below.

**[0070]** The streamable attention mechanism **144** is configured to generate a softmax input stream **224** based on a first matrix multiplication operation **210** of a particular row of the first data **202** and a corresponding row of the second data **204**. To illustrate, a stream of values **212** (e.g., $QK^T$) that are output from the first matrix multiplication operation **210** are scaled by a scaling factor **222** (e.g., $\sqrt{d_k}$) at a multiplication operation **220** to generate the softmax input stream **224** (e.g., $z_1, z_2, z_3, \ldots$, corresponding to elements of the tensor $z=QK^T/\sqrt{d_k}$).

**[0071]** An exponentiation operation **230** of the softmax with norm folding mechanism **142** is applied to the softmax input stream **224** to generate a stream of softmax numerator values **232** (e.g., $e^{z_1}, e^{z_2}, e^{z_3}, \ldots$). The exponentiation of each element of the softmax input stream **224** is performed in the 1-pass traversal of z, as each entry $z_i$ is individually available in the softmax input stream **224**. The exponentiation of each element of the softmax input stream **224** is not dependent on any other element in the softmax input stream **224**. Thus, the exponentiation operation **230** is streamable, as no buffering is required.

**[0072]** The stream of softmax numerator values **232** is input, in a first processing path, as a first input to a second matrix multiplication operation **240**. In a second processing path parallel to the first processing path, an accumulation sum **235** of the softmax numerator values **232** is generated at a sum operation **234** along the same 1-pass traversal of Z. The accumulation sum **235** can include parallel evaluation of M attention functions (M is a positive integer) and correspond to a norm vector $[\alpha_j]$, with $j=1, 2, \ldots, M$, and $\alpha \triangleq \Sigma_i e^{z_i}$, for a suitable range of $i=1, 2, \ldots, K$ associated with the attention function.

**[0073]** The streamable attention mechanism **144** is configured to perform a norm operation **250** to apply the accumulation sum **235** to the third data (V) **206** to generate a second input **239** to the second matrix multiplication operation **240**. For example, after all of the softmax numerator values **232** have been accumulated into the accumulation sum **235**, the norm operation **250** includes applying an inverse operation **236** to generate the inverse of the accumulation sum **235**, represented as an inverse accumulation sum **237** (e.g., a norm vector $N=[1/\alpha_j]$). The inverse accumulation sum **237** is multiplied with the elements of the third data (V) **206** at a multiplication operation **238** to generate the second input **239** to the second matrix multiplication operation **240**.

**[0074]** The second matrix multiplication operation **240** multiplies the softmax numerator values **232** with the second input **239** (e.g., the product of the inverse accumulation sum **237** with the third data (V) **206**) to generate the attention output values **260**, e.g., $\sigma(QK^T/\sqrt{d_k})$).

**[0075]** Applying the inverse accumulation sum **237** at a later stage in the computation flow (e.g., not immediately applying the inverse accumulation sum **237** to the softmax numerator values **232** to generate normalized softmax values) is referred to as "norm folding" and can be used with or without depth-first computation, according to design choice. The use of norm folding enables the processing of the stream of softmax numerator values **232** to continue without interruption due to buffering. The norm folding may be implemented as dynamic norm folding in embodiments in which the point in the computation flow where the inverse accumulation sum **237** is applied is selected based on one or more factors, such as a size of the input images. For example, the inverse accumulation sum **237** may be applied earlier in the computation flow (e.g., applied to V **206** prior to input to the second matrix multiplication operation **240**) for smaller images (e.g., Video Graphics Array (VGA)) and may be applied later in the computation flow (e.g., applied after the second matrix multiplication operation **240**, such as depicted in FIG. **3**) for larger images (e.g., 4K).

**[0076]** For purposes of comparison, an example **280** depicts a conventional attention mechanism. The softmax input stream **224** is generated in a substantially similar manner as described for the example **200** and provided to a conventional softmax computation block **290**. An output **292** of the conventional softmax computation block **290** and the third data (V) **206** are multiplied at the second matrix multiplication operation **240** to generate the attention output values **260**. Because a conventional softmax computation includes one pass that accumulates all of the numerator values (e.g., $e^{z_1}$, $e^{z_2}$, $e^{z_3}$, . . . ) to compute the denominator (e.g., $\Sigma_{j=1}^{K} e^{z_j}$), and another pass that divides each numerator value by the denominator, the stream is interrupted since the incoming values have to be buffered until the denominator is computed. For very large inputs (e.g., each row of Q and column of K can have millions of entries), the latency incurred while buffering the incoming values for the conventional softmax computation block **290** can be prohibitive. Further adding to the latency, the amount of data to be buffered can exceed the capacity of on-chip memory, requiring use of transfers (e.g., direct memory access (DMA) writes/reads) to/from a slower storage, which are typically performed as block-wise data transfers and do not support random accesses, thus incurring extra delay and power consumption.

**[0077]** As compared to the example **280**, the softmax with norm folding mechanism **142** of the example **200** enables data flow in the attention computation to remain "streamable"—that is, no buffering or execution breakpoint is needed even for large sizes of Q and K—and enables depth-first computation.

**[0078]** To illustrate, in the example **200**, each of the values $z_1$, $z_2$, $z_3$, . . . of the softmax input stream **224** is processed at the exponentiation operation **230** to generate corresponding softmax numerator values $e^{z_i}$, and the resulting stream of softmax numerator values **232** are input as a row of elements into a second matrix multiplication block. Due to the norm folding in the example **200**, the "norm" operation—i.e., the division by the accumulated sum $\alpha$—is not performed directly to the numerator values as in the conventional softmax processing of the example **280**. Instead, the norm operation is "folded" into another operation—that is, the norm is applied to the numerator values indirectly, during the second matrix multiplication operation **240**, after being multiplied to elements of V **206**. As a result, no buffering or execution breakpoint interrupts the streamability of the attention computation.

**[0079]** FIG. **3** depicts an example **300** of components and operations that may be implemented in the device **102** of FIG. **1**, according to some examples of the present disclosure. In particular, the example **300** illustrates components and operations that may be implemented in the streamable attention mechanism **144** in accordance with another example of norm folding.

**[0080]** In the example **300**, the softmax input stream **224** is generated in a substantially similar manner as described for the example **200** and provided to the exponentiation operation **230**. The stream of softmax numerator values **232** is input, in a first processing path, as a first input to the second matrix multiplication operation **240**. Also in the first processing path, the third data (V) **206** is input to the second matrix multiplication operation **240**, which operates to generate an output **342**.

**[0081]** The streamable attention mechanism **144** is configured to perform a norm operation **350** to apply the accumulation sum **235** to an output **342** of the second matrix multiplication operation **240**, such as by dividing the output **342** by the accumulation sum **235** (or equivalently, multiplying the output **342** by the inverse accumulation sum **237**). For example, in a second processing path parallel to the first processing path, after all of the softmax numerator values **232** have been accumulated into the accumulation sum **235**, the norm operation **350** includes applying the inverse operation **236** to generate the inverse accumulation sum **237**. The inverse accumulation sum **237** is multiplied, at a multiplication operation **338**, with the output **342** of the second matrix multiplication operation **240** to generate the attention output values **260**.

**[0082]** Thus, in the example of FIG. **3**, norm folding is illustrated in which the norm is applied to the output **342** of the second matrix multiplication operation **240**. In general, the norm folding can be applied even later in the processing to ensure that the norm computation does not interrupt the streamability of the attention computation. According to some aspects, the attention mechanism can employ dynamic norm folding in which the location of the norm folding is dynamically selected, such as based on the sizes of Q and K.

**[0083]** Although the examples of FIG. **2** and FIG. **3** are illustrated and described in terms of operations performed by functional blocks, it should be understood that, in some embodiments, each of the operations or functional blocks generally corresponds to functions performed by one or more respective layers of a neural network.

**[0084]** FIG. **4** depicts an example **400** of the ML model **140** as a low-footprint model having an OF or DFS architecture that can be implemented in the system **100** of FIG. **1**, in accordance with some examples of the present disclosure.

**[0085]** As shown in FIG. **4**, the ML model **140** includes a convolutional neural network (CNN) **402**A to perform feature extraction for the first image **124** to generate features **404**A (e.g., a feature map) and a CNN **402**B to perform feature extraction for the second image **126** to generate features **404**B (e.g., a feature map).

**[0086]** A feature enhancement transformer **410** is configured to process the features **404**A and **404**B to generate enhanced features **412**A and **412**B, respectively. For example, the feature enhancement transformer **410** may be configured to perform self-attention processing, cross-attention processing, or a combination thereof, on the features **404**A and **404**B.

**[0087]** Feature matching is performed on the enhanced features **412**A and **412**B at a feature matching block **420** to generate an output **422**. In an example, the feature matching block **420** can include or correspond to a softmax matching layer. The output **422** includes flow or disparity information based on whether the ML model **140** is configured to perform OF or DFS processing.

**[0088]** Propagation is performed on the output **422** and the enhanced features **412**A at a propagation block **430**, such as a self-attention layer. The propagation improves occluded and out-of-boundary pixels to generate an output **432** of the ML model **140**. The output **432** includes flow or disparity information based on whether the ML model **140** is configured to perform OF or DFS processing.

**[0089]** According to an aspect, the feature enhancement transformer **410** includes a streamable attention mechanism **144**A, the feature matching block **420** includes a streamable attention mechanism **144**B, and the propagation block **430** includes a streamable attention mechanism **144**C. Each of the streamable attention mechanisms **144**A-C enables its respective processing block **410**, **420**, or **430** to perform attention processing without the quadratic memory requirement of conventional attention mechanisms that include conventional multi-pass softmax operations, and can help remove execution pipelining and memory bottlenecks associated with operating transformer models on mobile devices.

**[0090]** As illustrated, the ML model **140** has an overall architecture resembling a GMFlow model in which conventional attention mechanisms have been replaced by streamable attention mechanisms **144**. Although GMFlow is a transformer-based model that does not explicitly compute a cost volume, the various softmax operations that are performed in GMFlow (e.g., in the feature enhancement transformer **410**, in the feature matching block **420**, and in the propagation block **430**) can require a substantially similar amount of memory as a conventional cost volume approach.

**[0091]** Table 1 depicts an illustrative, non-limiting example of comparisons between the ML model **140**, a CNN-based RAFT (Recurrent All-Pairs Field Transforms for Optical Flow) model, and a transformer-based GMFlow model. Data for the RAFT model is based on "RAFT: Recurrent All-Pairs Field Transforms for Optical Flow, ECCV 2020, and data for the GMFlow model is based on "GMFlow: Unifying Flow, Stereo, and Depth Estimation," TPAMI IEEE 2023.

TABLE 1

| Optical Flow | Dataset #1: Flying Things | | | Dataset #2: Sintel | | Cost Vol Eq. Size on NSP |
|---|---|---|---|---|---|---|
| Model | EPE: clean | S0_10 | S0_40 | EPE: clean | EPE: final | (VGA input) |
| RAFT | 4.25 | 0.53 | 1.31 | 1.41 | 2.69 | 30.6 MB |
| GMFlow | 2.80 | 0.53 | 1.01 | 1.08 | 2.48 | 23.0 MB |
| FIG. 4 | 2.83 | 0.48 | 0.99 | 1.11 | 2.57 | 1.2 MB |

**[0092]** In the example depicted in Table 1, the cost volume equivalent memory size (e.g., amount of memory used for a cost volume data structure and/or associated with cost-volume related computations) on a neural signal processor (NSP) using VGA input for the RAFT model is 30.6 megabytes (MB), 23.0 MB for the GMFlow model, and 1.2 MB for the ML model **140** of FIG. **4**. Thus, the ML model **140** has approximately a 95% reduction in the associated memory usage as compared to the GMFlow model, with substantially similar performance metrics such as endpoint error (EPE) while keeping the model math equivalent. As a result, the associated memory usage of the ML model **140** can remain within the local memory capacity of an NSP, such as an 8 MB vector tightly coupled memory (VTCM) that may be used in mobile devices.

**[0093]** Although the particular example of the ML model **140** depicted in FIG. **4** has an overall architecture resembling that of GMFlow, in other embodiments the techniques disclosed herein can be used in conjunction with a variety of different architectures. For example, in other embodiments, feature extraction processing can omit the CNNs **402**, the feature enhancement transformer **410**, or both (e.g., another type of feature extractor can instead be used), the propagation block **430** can be omitted and/or replaced with another mechanism to improves occluded and out-of-boundary pixels, or a combination thereof.

**[0094]** FIG. **5** is a block diagram illustrating an implementation **500** of the device **102** as an integrated circuit **502** for performing input data processing using a low-footprint model. The integrated circuit **502** includes the one or more processors **116**, which include the ML model **140** (e.g., including the softmax with norm folding mechanism **142** in the streamable attention mechanism **144**). For example, the ML model **140** may include one or more of the components of the example **200** FIG. **2**, the example **300** of FIG. **3**, the example **400** of FIG. **4**, or any combination thereof. The integrated circuit **502** also includes a signal input **504**, such as a bus interface, to enable input data **505**, such as the image data **105** or the input data **122**, to be received. The integrated circuit **502** includes a signal output **506**, such as a bus interface, to enable outputting of output data **507**, such as the output data **152**, the output image data **107**, or the 3D representation **160**. Optionally, the integrated circuit **502** also includes the memory **110**, the image sensor **104**, the input data source **120**, the modem **118**, a display engine, etc. The integrated circuit **502** enables implementation of input data processing (e.g., optical flow or depth from stereo processing) using a low-footprint model as a component in a system that performs image processing, such as depicted in FIG. **1**.

**[0095]** FIG. **6** depicts an implementation **600** in which the device **102** includes a mobile device **602**, such as a phone or tablet, as illustrative, non-limiting examples. The mobile device **602** includes a display screen **604** and a camera **612** (e.g., the image sensor **104**). The ML model **140** is integrated in the mobile device **602**, such as in the integrated circuit **502**, which is illustrated using dashed lines to indicate internal components that are not generally visible to a user of the mobile device **602**. In a particular example, the ML model **140** operates to perform input data processing (e.g., optical flow or depth from stereo processing). For example, the mobile device **602** may generate the image data **105** from the camera **612**, process the image data **105** using the ML model **140**, and display the resulting output image data **107** at the display screen **604** and/or transmit the resulting output image data **107**, the output data **152**, and/or the 3D representation **160** to another device, such as the remote device **198**.

**[0096]** FIG. **7** depicts an implementation **700** in which the device **102** includes a portable electronic device that corresponds to a camera device **702**. The camera device **702** includes an image sensor **712**, such as the image sensor **104**. The ML model **140** is integrated in the camera device **702**, such as in the integrated circuit **502**. In a particular example, the ML model **140** operates to perform input data processing (e.g., optical flow or depth from stereo processing). For example, the camera device **702** may generate the image data **105** from the image sensor **712**, process the image data **105** using the ML model **140**, and display the resulting output image data **107** at a display screen of the camera device **702**, store the resulting output image data **107**, the output data **152**, and/or the 3D representation **160** at a memory of the camera device **702**, and/or transmit the resulting output image data **107**, the output data **152**, and/or the 3D representation **160** to another device, such as the remote device **198**.

**[0097]** FIG. **8** depicts an implementation **800** of a wearable electronic device **802**, illustrated as a "smart watch." In a particular aspect, the wearable electronic device **802** includes the device **102**. The wearable electronic device **802** includes a display screen **804** and a camera **812** (e.g., the image sensor **104**). The ML model **140** is integrated in the wearable electronic device **802**, such as in the integrated circuit **502**. In a particular example, the wearable electronic device **802** includes a haptic device that provides a haptic notification (e.g., vibrates) associated with display of image or video data that is based on image or video data that been captured by the camera **812** and processed by the ML model **140**, such as the output image data **107**, which may be displayed via the display screen **804**. For example, the haptic notification can cause a user to look at the wearable electronic device **802** to watch video playback.

**[0098]** FIG. **9** depicts an implementation **900** in which the device **102** includes a portable electronic device that corresponds to an extended reality device, such as augmented reality or mixed reality glasses **902**. The glasses **902** include a holographic projection unit **904** configured to project visual data onto a surface of a lens **906** or to reflect the visual data off of a surface of the lens **906** and onto the wearer's retina. The glasses **902** include a camera **912**, such as the image sensor **104**. The ML model **140** is integrated in the glasses **902**, such as in the integrated circuit **502**. In a particular example, the ML model **140** operates to perform input data processing (e.g., optical flow or depth from stereo processing). For example, the image data **105** may be received from the camera **912**, processed using the ML model **140**, and the resulting output image data **107** (e.g., an output image based on an output of the ML model **140**) may be displayed via a projection onto the surface of the lens **906** to enable display of images and/or video associated with augmented reality, mixed reality, or virtual reality scenes to the user while the glasses **902** are worn.

**[0099]** FIG. **10** depicts an implementation **1000** in which the device **102** includes a portable electronic device that corresponds to a virtual reality, augmented reality, or mixed reality headset **1002**. The headset **1002** includes a camera **1012**, such as the image sensor **104**, and a visual display device **1004**. The ML model **140** is integrated in the headset **1002**, such as in the integrated circuit **502**. In a particular example, the ML model **140** operates to perform input data processing (e.g., optical flow or depth from stereo processing). For example, the image data **105** may be received from the camera **1012**, processed using the ML model **140**, and the resulting output image data **107** (e.g., an output image based on an output of the ML model **140**) may be displayed at the visual display device **1004** to enable display of images and/or video associated with augmented reality, mixed reality, or virtual reality scenes to the user while the headset **1002** is worn.

**[0100]** FIG. **11** is an implementation **1100** of a wireless speaker and voice activated device **1102**. In a particular aspect, the wireless speaker and voice activated device **1102** includes the device **102**. The wireless speaker and voice activated device **1102** can have wireless network connectivity and is configured to execute an assistant operation. The one or more processors **116** are included in the wireless speaker and voice activated device **1102** and include the ML model **140**.

**[0101]** The wireless speaker and voice activated device **1102** includes a camera **1112**, such as the image sensor **104**, and a display device **1120**. In a particular example, the ML model **140** operates to perform input data processing (e.g., optical flow or depth from stereo processing). For example, the image data **105** may be received from the camera **1112** and processed using the ML model **140**, and the resulting output image data **107** (e.g., an output image based on an output of the ML model **140**) may be displayed at the display device **1120** and/or transmitted to a remote device for playback at the remote device.

**[0102]** In a particular aspect, the wireless speaker and voice activated device **1102** includes one or more microphones **1110** and one or more speakers **1104**. During operation, in response to receiving a verbal command via one or more microphones **1110**, the wireless speaker and voice activated device **1102** can execute assistant operations, such as via execution of a voice activation system (e.g., an integrated assistant application). The assistant operations can include adjusting a temperature, activating the camera **1112** to capture video or image content and displaying output image or video data based on the captured video content (e.g., the output image data **107**) at the display device **1120**, etc. For example, the assistant operations are performed responsive to receiving a command after a keyword or key phrase (e.g., "hello assistant").

**[0103]** FIG. **12** depicts an implementation **1200** in which the device **102** corresponds to or is integrated within a vehicle **1202**, illustrated as a manned or unmanned aerial device (e.g., a package delivery drone). The ML model **140** is integrated in the vehicle **1202**, such as in the integrated circuit **502**. The vehicle **1202** may also include a display device **1204** configured to display an output based on processing input data at the ML model **140**, such as the output image data **107**.

**[0104]** In some implementations, the vehicle **1202** is manned (e.g., carries a pilot, one or more passengers, or both), the display device **1204** is internal to a cabin of the vehicle **1202**, and the input data processing (e.g., optical flow or depth from stereo processing) is performed using image and/or video capture via one or more cameras **1212**

may be used to generate navigational information, such as based on depth or flow information and/or based on a 3D representation (e.g., the 3D representation **160**) corresponding to one or more objects or a scene in the proximity of the vehicle **1202**, such as for playback to a pilot or a passenger of the vehicle **1202** and/or for semi-autonomous or autonomous operation of the vehicle **1202**. In another implementation, the vehicle **1202** is unmanned, the input data processing (e.g., optical flow or depth from stereo processing) is performed using image and/or video capture via one or more cameras **1212** to generate navigational information corresponding to one or more objects or a scene in the proximity of the vehicle **1202**, which may be displayed to a remote operator of the vehicle **1202** and/or used for semi-autonomous or autonomous operation of the vehicle **1202**.

**[0105]** In some embodiments, the display device **1204** and the camera **1212** are mounted to an external surface of the vehicle **1202**, and the input data processing at the ML model **140** is performed during video playback to one or more viewers external to the vehicle **1202**. For example, the vehicle **1202** may move (e.g., circle an outdoor audience during a concert) while playing out video or images based on video or image data captured via the camera **1212**.

**[0106]** FIG. **13** depicts an implementation **1300** in which the device **102** corresponds to, or is integrated within, a vehicle **1302**, illustrated as a car. The ML model **140** is integrated in the vehicle **1302**, such as in the integrated circuit **502**. In a particular example, the ML model **140** operates to perform input data processing based on image data received from one or more cameras **1312**. The input data processing (e.g., optical flow or depth from stereo processing) may be used to generate navigational information, such as based on depth or flow information and/or based on a 3D representation (e.g., the 3D representation **160**) corresponding to one or more objects or a scene in the proximity of the vehicle **1302**, such as for playback to an operator of the vehicle **1302** via a display screen **1320** or a speaker **1310**, and/or for semi-autonomous or autonomous operation of the vehicle **1302**.

**[0107]** For example, in a particular embodiment, the vehicle **1302** may generate the image data **105** from the one or more cameras **1312**, process the image data **105** at the ML model **140**, and display the resulting output image data **107** at the display screen **1320** of the vehicle **1302**, store the resulting output image data **107**, the output data **152**, and/or the 3D representation **160** at a memory of the vehicle **1302**, and/or transmit the resulting output image data **107**, the output data **152**, and/or the 3D representation **160** to another device, such as the remote device **198**. In a particular embodiment, one or more of the cameras **1312** can be mounted to capture an interior scene including one or more other passengers of the vehicle **1302**, such as to monitor children in a rear seat of the vehicle **1302**. Additionally, or alternatively, one or more of the cameras **1312** can correspond to forward-facing camera and/or rear-facing cameras that capture fields of view external to the vehicle **1302** in conjunction with autonomous or driver-assisted operation of the vehicle **1302**.

**[0108]** FIG. **14** illustrates an example of a method **1400** of input data processing. One or more operations of the method **1400** may be performed by at least one of the device **102**, the one or more processors **116**, or the system **100** of FIG. **1**, as an illustrative, non-limiting example.

**[0109]** The method **1400** includes, at block **1402**, obtaining input data at a device. For example, the input data **122** may be obtained from the input data source **120**, via the image data **105** from the image sensor **104**, or from the remote device **198**.

**[0110]** The method **1400** includes, at block **1404**, processing, at the device, the input data using a machine learning (ML) model including performing a softmax with norm folding operation. For example, the device **102** processes the input data **122** at the ML model **140** that includes the softmax with norm folding mechanism **142**. In some embodiments, the softmax with norm folding operation is included in a streamable attention operation of the ML model, such as performed by the streamable attention mechanism **144** in accordance with the example **200** of FIG. **2** or the example **300** of FIG. **3**. According to an aspect. The input data includes a first image and a second image, such as the first image **124** and the second image **126**, and the ML model corresponds to a depth from stereo or optical flow architecture, such as described with reference to the example **400** of FIG. **4**.

**[0111]** In some embodiments, the streamable attention operation includes generating a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data. For example, the softmax input stream **224** is generated based on the first matrix multiplication operation **210** of the example **200** or the example **300**. The streamable attention operation may also include applying an exponentiation operation of the softmax with norm folding operation to the softmax input stream to generate a stream of softmax numerator values, such as the steam of softmax numerator values **232** generated by applying the exponentiation operation **230** to the softmax input stream **224** of the example **200** or the example **300**. The streamable attention operation may include providing the stream of softmax numerator values as a first input to a second matrix multiplication operation, such as the second matrix multiplication operation **240** of the example **200** or the example **300**, and generating an accumulation sum of the softmax numerator values. For example, the sum operation **234** of the example **200** or the example **300** generates the accumulation sum **235**, which is inverted and applied at a later stage of the attention computation path via a norm folding operation.

**[0112]** By processing the input data using an ML model including performing the softmax with norm folding operation, the device can avoid the conventional buffering of the stream of softmax numerator values (e.g., buffering of the softmax numerator values until a normalization value has been computed and applied to the buffered softmax numerator values), reducing latency associated with the softmax operation and also avoiding additional latency and power consumption associated with performing data transfers to/from another storage of the device **102** that may otherwise arise in conjunction with the buffering. In addition, avoiding buffering of the stream of softmax numerator values enables use of just-in-time computations, depth-first computations, or both, associated with processing of the softmax numerator values, reducing the total amount of memory used to process the input data at the ML model.

**[0113]** The method **1400** of FIG. **15** may be implemented by a field-programmable gate array (FPGA) device, an application-specific integrated circuit (ASIC), a processing unit such as a central processing unit (CPU), a digital signal processor (DSP), a controller, another hardware device, firmware device, or any combination thereof. As an example, the method **1400** of FIG. **14** may be performed by a processor that executes instructions, such as described with reference to FIG. **15**.

**[0114]** Referring to FIG. **15**, a block diagram of a particular illustrative implementation of a device is depicted and generally designated **1500**. In various implementations, the device **1500** may have more or fewer components than illustrated in FIG. **15**. In an illustrative implementation, the device **1500** may correspond to the device **102** of FIG. **1**. In an illustrative implementation, the device **1500** may perform one or more operations described with reference to FIGS. **1-14**.

**[0115]** In a particular implementation, the device **1500** includes a processor **1506** (e.g., a CPU). The device **1500** may include one or more additional processors **1510** (e.g., one or more DSPs). In a particular implementation, the one or more processors **116** of FIG. **1** correspond to the processor **1506**, the processors **1510**, or a combination thereof. For example, the processors **1510** may include the ML model **140**. For example, the ML model **140** may include one or more of the components of the example **200** of FIG. **2**, the example **300** of FIG. **3**, the example **400** of FIG. **4**, or a combination thereof. The processors **1510** may also include a speech and music coder-decoder (CODEC) **1508**. The speech and music CODEC **1508** may include a voice coder ("vocoder") encoder **1536**, a vocoder decoder **1538**, or a combination thereof.

**[0116]** In this context, the term "processor" refers to an integrated circuit consisting of logic cells, interconnects, input/output blocks, clock management components, memory, and optionally other special purpose hardware components, designed to execute instructions and perform various computational tasks. Examples of processors include, without limitation, CPUs, digital signal processors DSPs, neural processing units (NPUs), graphics processing units (GPUs), FPGAs, microcontrollers, quantum processors, coprocessors, vector processors, other similar circuits, and variants and combinations thereof. In some cases, a processor can be integrated with other components, such as communication components, input/output components, etc. to form a system on a chip (SOC) device or a packaged electronic device.

**[0117]** Taking CPUs as a starting point, a CPU typically includes one or more processor cores, each of which includes a complex, interconnected network of transistors and other circuit components defining logic gates, memory elements, etc. A core is responsible for executing instructions to, for example, perform arithmetic and logical operations. Typically, a CPU includes an Arithmetic Logic Unit (ALU) that handles mathematical operations and a Control Unit that generates signals to coordinate the operation of other CPU components, such as to manage operations a fetch-decode-execute cycle.

**[0118]** CPUs and/or individual processor cores generally include local memory circuits, such as registers and cache to temporarily store data during operations. Registers include high-speed, small-sized memory units intimately connected to the logic cells of a CPU. Often registers include transistors arranged as groups of flip-flops, which are configured to store binary data. Caches include fast, on-chip memory circuits used to store frequently accessed data. Caches can be implemented, for example, using Static Random-Access Memory (SRAM) circuits.

**[0119]** Operations of a CPU (e.g., arithmetic operations, logic operations, and flow control operations) are directed by software and firmware. At the lowest level, the CPU includes an instruction set architecture (ISA) that specifies how individual operations are performed using hardware resources (e.g., registers, arithmetic units, etc.). Higher level software and firmware is translated into various combinations of ISA operations to cause the CPU to perform specific higher-level operations. For example, an ISA typically specifies how the hardware components of the CPU move and modify data to perform operations such as addition, multiplication, and subtraction, and high-level software is translated into sets of such operations to accomplish larger tasks, such as adding two columns in a spreadsheet. Generally, a CPU operates on various levels of software, including a kernel, an operating system, applications, and so forth, with each higher level of software generally being more abstracted from the ISA and usually more readily understandable by human users.

**[0120]** GPUs, NPUs, DSPs, microcontrollers, coprocessors, FPGAs, ASICS, and vector processors include components similar to those described above for CPUs. The differences among these various types of processors are generally related to the use of specialized interconnection schemes and ISAs to improve a processor's ability to perform particular types of operations. For example, the logic gates, local memory circuits, and the interconnects therebetween of a GPU are specifically designed to improve parallel processing, sharing of data between processor cores, and vector operations, and the ISA of the GPU may define operations that take advantage of these structures. As another example, ASICs are highly specialized processors that include similar circuitry arranged and interconnected for a particular task, such as encryption or signal processing. As yet another example, FPGAs are programmable devices that include an array of configurable logic blocks (e.g., interconnect sets of transistors and memory elements) that can be configured (often on the fly) to perform customizable logic functions.

**[0121]** The device **1500** may include a memory **1586** and a CODEC **1534**. The memory **1586** may include instructions **1556** that are executable by the one or more additional processors **1510** (or the processor **1506**) to implement the functionality described with reference to the processor **116**. In a particular example, the memory **1586** corresponds to the memory **110** and the instructions **1556** correspond to the instructions **112** of FIG. **1**. The device **1500** may include the modem **118** coupled, via a transceiver **1550**, to an antenna **1552**. The device **1500** may also include one or more cameras **1594**, one or more of which may correspond to the image sensor **104**.

**[0122]** The device **1500** may include a display **1528**, such as the display device **106**, coupled to a display controller **1526**. One or more speakers **1592**, one or more microphones **1590**, or a combination thereof, may be coupled to the CODEC **1534**. The CODEC **1534** may include a digital-to-analog converter (DAC) **1502** and an analog-to-digital converter (ADC) **1504**. In a particular implementation, the CODEC **1534** may receive analog signals from the microphones **1590**, convert the analog signals to digital signals using the analog-to-digital converter **1504**, and send the digital signals to the speech and music codec **1508**. In a particular implementation, the speech and music codec **1508** may provide digital signals to the CODEC **1534**. The CODEC **1534** may convert the digital signals to analog signals using the digital-to-analog converter **1502** and may provide the analog signals to the speakers **1592**.

**[0123]** In a particular implementation, the device **1500** may be included in a system-in-package or system-on-chip device **1522**. In a particular implementation, the memory **1586**, the processor **1506**, the processors **1510**, the display controller **1526**, the CODEC **1534**, and the modem **118** are included in a system-in-package or system-on-chip device **1522**. In a particular implementation, an input device **1530** (e.g., a keyboard, a touchscreen, or a pointing device) and a power supply **1544** are coupled to the system-in-package or system-on-chip device **1522**. Moreover, in a particular implementation, as illustrated in FIG. **15**, the cameras **1594**, the display **1528**, the input device **1530**, the speakers **1592**, the microphones **1590**, the antenna **1552**, and the power supply **1544** are external to the system-in-package or system-on-chip device **1522**. In a particular implementation, each of the cameras **1594**, the display **1528**, the input device **1530**, the speakers **1592**, the microphones **1590**, the antenna **1552**, and the power supply **1544** may be coupled to a component of the system-in-package or system-on-chip device **1522**, such as an interface or a controller.

**[0124]** The device **1500** may include a smart speaker, a speaker bar, a mobile communication device, a smart phone, a cellular phone, a laptop computer, a computer, a tablet, a personal digital assistant, a display device, a television, a gaming console, a music player, a radio, a digital video player, a digital video disc (DVD) player, a tuner, a camera, a navigation device, a vehicle, a headset, an augmented reality headset, a mixed reality headset, a virtual reality headset, an aerial vehicle, a home automation system, a voice-activated device, a wireless speaker and voice activated device, a portable electronic device, a car, a vehicle, a computing device, a communication device, an internet-of-things (IoT) device, a virtual reality (VR) device, a base station, a mobile device, or any combination thereof.

**[0125]** In conjunction with the described techniques, an apparatus includes means for obtaining input data. In an example, the means for obtaining input data can include input data source **120**, the image sensor **104**, the modem **118**, the one or more processors **116**, the device **102**, the system **100**, one or more other circuits or devices to obtain input data, or a combination thereof.

**[0126]** The apparatus also includes means for processing the input data using a machine learning model that incorporates means for performing a softmax with norm folding operation. In an example, the means for processing the input data using a machine learning model that incorporates means for performing a softmax with norm folding operation can include the one or more processors **116**, the ML model **140** executed by the one or more processors **116**, the device **102**, the system **100**, one or more other circuits or devices to process the input data using a machine learning model that incorporates means for performing a softmax with norm folding operation, or a combination thereof. In an example, means for performing a softmax with norm folding operation can include the one or more processors **116**, the softmax with norm folding mechanism **142**, the streamable attention mechanism **144**, the device **102**, the system **100**, one or more other circuits or devices to perform a softmax with norm folding operation, or a combination thereof.

**[0127]** In some implementations, a non-transitory computer-readable medium (e.g., a computer-readable storage device, such as the memory **110**) includes instructions (e.g., the instructions **112**) that, when executed by one or more processors (e.g., the one or more processors **116**), cause the one or more processors to perform operations corresponding to at least a portion of any of the techniques described with reference to FIGS. **1-13**, the method of FIG. **14**, or any combination thereof. In an example, the instructions, when executed by the one or more processors, cause the one or more processors to obtain input data (e.g., the input data **122**). The instructions, when executed by the one or more processors, also cause the one or more processors to process the input data using a machine learning model (e.g., the ML model **140**) that incorporates a softmax with norm folding mechanism (e.g., the softmax with norm folding mechanism **142**).

**[0128]** Particular aspects of the disclosure are described below in the following sets of interrelated Examples:

**[0129]** According to Example 1, a device includes a memory configured to store input data; and one or more processors configured to process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

**[0130]** Example 2 includes the device of Example 1, wherein the input data includes a first image and a second image, and wherein the ML model corresponds to a depth from stereo or optical flow architecture.

**[0131]** Example 3 includes the device of Example 1 or Example 2, wherein the softmax with norm folding mechanism is included in a streamable attention mechanism.

**[0132]** Example 4 includes the device of Example 3, wherein the streamable attention mechanism is configured to generate a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data; apply an exponentiation operation of the softmax with norm folding mechanism to the softmax input stream to generate a stream of softmax numerator values; input the stream of softmax numerator values as a first input to a second matrix multiplication operation; and generate an accumulation sum of the softmax numerator values.

**[0133]** Example 5 includes the device of Example 4, wherein the streamable attention mechanism is configured to perform a norm operation to apply the accumulation sum to third data to generate a second input to the second matrix multiplication operation.

**[0134]** Example 6 includes the device of Example 4, wherein the streamable attention mechanism is configured to perform a norm operation to apply the accumulation sum to an output of the second matrix multiplication operation.

**[0135]** Example 7 includes the device of any of Examples 4 to 6, wherein: the first data corresponds to features associated with a first image; the second data corresponds to features associated with a second image; and a second input to the second matrix multiplication operation corresponds to a displacement matrix of coordinates.

**[0136]** Example 8 includes the device of any of Examples 1 to 7, wherein the ML model generates probabilistic geometry measures without generating a cost volume data structure.

[0137] Example 9 includes the device of any of Examples 1 to 8, wherein the ML model is configured to perform regression for depth from stereo or optical flow geometric coordinates using just-in-time computations.

[0138] Example 10 includes the device of any of Examples 1 to 9 and further includes an image sensor configured to generate image data corresponding to the input data.

[0139] Example 11 includes the device of any of Examples 1 to 10 and further includes a modem coupled to the one or more processors, the modem configured to receive image data corresponding to the input data from a second device.

[0140] Example 12 includes the device of any of Examples 1 to 11, wherein the one or more processors are integrated in a headset device that includes a display, and wherein the headset device is configured, when worn by a user, to display an output image based on an output of the ML model.

[0141] Example 13 includes the device of any of Examples 1 to 11, wherein the one or more processors are integrated in at least one of a mobile phone, a tablet computer device, a wearable electronic device, or a camera device.

[0142] Example 14 includes the device of any of Examples 1 to 11, wherein the one or more processors are integrated in a vehicle, the vehicle further including one or more cameras configured to capture image data corresponding to the input data.

[0143] Example 15 includes the device of any of Examples 1 to 14, wherein the one or more processors are included in an integrated circuit.

[0144] Example 16 includes the device of any of Examples 1 to 15, wherein the ML model includes a language model, a vision model, or a multi-modal model.

[0145] According to Example 17, a method includes obtaining input data at a device; and processing, at the device, the input data using a machine learning (ML) model including performing a softmax with norm folding operation.

[0146] Example 18 includes the method of Example 17, wherein the input data includes a first image and a second image, and wherein the ML model corresponds to a depth from stereo or optical flow architecture.

[0147] Example 19 includes the method of Example 17 or Example 18, wherein the softmax with norm folding operation is included in a streamable attention operation of the ML model.

[0148] Example 20 includes the method of Example 19, wherein the streamable attention operation includes: generating a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data; applying an exponentiation operation of the softmax with norm folding operation to the softmax input stream to generate a stream of softmax numerator values; providing the stream of softmax numerator values as a first input to a second matrix multiplication operation; and generating an accumulation sum of the softmax numerator values.

[0149] Example 21 includes the method of Example 20, wherein the streamable attention operation includes performing a norm operation to apply the accumulation sum to third data to generate a second input to the second matrix multiplication operation.

[0150] Example 22 includes the method of Example 20, wherein the streamable attention operation includes performing a norm operation to apply the accumulation sum to an output of the second matrix multiplication operation.

[0151] Example 23 includes the method of any of Examples 20 to 22, wherein: the first data corresponds to features associated with a first image; the second data corresponds to features associated with a second image; and a second input to the second matrix multiplication operation corresponds to a displacement matrix of coordinates.

[0152] Example 24 includes the method of any of Examples 17 to 23, wherein the ML model generates probabilistic geometry measures without generating a cost volume data structure.

[0153] Example 25 includes the method of any of Examples 17 to 24, wherein the ML model performs regression for depth from stereo or optical flow geometric coordinates using just-in-time computations.

[0154] Example 26 includes the method of any of Examples 17 to 25 and further includes receiving image data corresponding to the input data.

[0155] Example 27 includes the method of any of Examples 17 to 26 and further includes receiving image data corresponding to the input data from a second device.

[0156] Example 28 includes the method of any of Examples 17 to 27 and further includes displaying an output image based on an output of the ML model.

[0157] Example 29 includes the method of any of Examples 17 to 28, wherein the ML model includes a language model, a vision model, or a multi-modal model.

[0158] According to Example 30, a non-transitory computer-readable medium storing instructions that, when executed by one or more processors, cause the one or more processors to obtain input data; and process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

[0159] Example 31 includes the non-transitory computer-readable medium of Example 30, wherein the softmax with norm folding mechanism is included in a streamable attention mechanism.

[0160] Example 32 includes the non-transitory computer-readable medium of Example 30 or Example 31, wherein the instructions, when executed by the one or more processors, cause the one or more processors to generate, at the streamable attention mechanism, a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data; apply, at the streamable attention mechanism, an exponentiation operation of the softmax with norm folding mechanism to the softmax input stream to generate a stream of softmax numerator values; input, at the streamable attention mechanism, the stream of softmax numerator values as a first input to a second matrix multiplication operation; and generate, at the streamable attention mechanism, an accumulation sum of the softmax numerator values.

[0161] Example 33 includes the non-transitory computer-readable medium of Example 32, wherein the instructions, when executed by the one or more processors, cause the one or more processors to perform, at the streamable attention mechanism, a norm operation to apply the accumulation sum to third data to generate a second input to the second matrix multiplication operation.

[0162] Example 34 includes the non-transitory computer-readable medium of Example 32, wherein the instructions, when executed by the one or more processors, cause the one or more processors to perform, at the streamable attention mechanism, a norm operation to apply the accumulation sum to an output of the second matrix multiplication operation.

**[0163]** Example 35 includes the non-transitory computer-readable medium of any of Examples 32 to 34, wherein: the first data corresponds to features associated with a first image; the second data corresponds to features associated with a second image; and a second input to the second matrix multiplication operation corresponds to a displacement matrix of coordinates.

**[0164]** Example 36 includes the non-transitory computer-readable medium of any of Examples 30 to 35, wherein the instructions, when executed by the one or more processors, cause the one or more processors to generate, at the ML model, probabilistic geometry measures without generating a cost volume data structure.

**[0165]** Example 37 includes the non-transitory computer-readable medium of any of Examples 30 to 36, wherein the instructions, when executed by the one or more processors, cause the one or more processors to perform regression, at the ML model, for depth from stereo or optical flow geometric coordinates using just-in-time computations.

**[0166]** Example 38 includes the non-transitory computer-readable medium of any of Examples 30 to 37, wherein the ML model includes a language model, a vision model, or a multi-modal model.

**[0167]** According to Example 39, an apparatus includes means for obtaining input data; and means for processing the input data using a machine learning (ML) model that incorporates means for performing a softmax with norm folding operation.

**[0168]** Example 40 includes the apparatus of Example 39, wherein the input data includes a first image and a second image, and wherein the ML model corresponds to a depth from stereo or optical flow architecture.

**[0169]** Example 41 includes the apparatus of Example 39 or Example 40, wherein the means for performing a softmax with norm folding operation is included in a means for performing a streamable attention operation.

**[0170]** Example 42 includes the apparatus of Example 41, wherein the means for performing a streamable attention operation includes: means for generating a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data; means for applying an exponentiation operation of the softmax with norm folding operation to the softmax input stream to generate a stream of softmax numerator values; means for providing the stream of softmax numerator values as a first input to a second matrix multiplication operation; and means for generating an accumulation sum of the softmax numerator values.

**[0171]** Example 43 includes the apparatus of Example 42, wherein the means for performing a streamable attention operation includes means for performing a norm operation to apply the accumulation sum to third data to generate a second input to the second matrix multiplication operation.

**[0172]** Example 44 includes the apparatus of Example 42, wherein the means for performing a streamable attention operation includes means for performing a norm operation to apply the accumulation sum to an output of the second matrix multiplication operation.

**[0173]** Example 45 includes the apparatus of any of Examples 42 to 44, wherein: the first data corresponds to features associated with a first image; the second data corresponds to features associated with a second image; and a second input to the second matrix multiplication operation corresponds to a displacement matrix of coordinates.

**[0174]** Example 46 includes the apparatus of any of Examples 39 to 45, wherein the means for processing the input data using an ML model generates probabilistic geometry measures without generating a cost volume data structure.

**[0175]** Example 47 includes the apparatus of any of Examples 39 to 46, wherein the means for processing the input data using an ML model performs regression for depth from stereo or optical flow geometric coordinates using just-in-time computations.

**[0176]** Example 48 includes the apparatus of any of Examples 39 to 47 and further includes means for receiving image data corresponding to the input data.

**[0177]** Example 49 includes the apparatus of any of Examples 39 to 48 and further includes means for receiving image data corresponding to the input data from a second device.

**[0178]** Example 50 includes the apparatus of any of Examples 39 to 49 and further includes means for displaying an output image based on an output of the ML model.

**[0179]** Example 51 includes the apparatus of any of Examples 39 to 50, wherein the ML model includes a language model, a vision model, or a multi-modal model.

**[0180]** Those of skill would further appreciate that the various illustrative logical blocks, configurations, circuits, and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software executed by a processing device such as a hardware processor, or combinations of both. Various illustrative components, blocks, configurations, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or executable software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

**[0181]** The steps of a method or algorithm described in connection with the implementations disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in a memory device, such as random access memory (RAM), magnetoresistive random access memory (MRAM), spin-torque transfer MRAM (STT-MRAM), flash memory, read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), registers, hard disk, a removable disk, a compact disc read-only memory (CD-ROM), or any other form of non-transient storage medium known in the art. An exemplary memory device is coupled to the processor such that the processor can read information from, and write information to, the memory device. In the alternative, the memory device may be integral to the processor. The processor and the storage medium may reside in an application-specific integrated circuit (ASIC). The ASIC may reside in a computing device or a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a computing device or a user terminal.

**[0182]** The previous description of the disclosed implementations is provided to enable a person skilled in the art to make or use the disclosed implementations. Various modifications to these implementations will be readily apparent to those skilled in the art, and the principles defined herein may be applied to other implementations without departing from the scope of the disclosure. Thus, the present disclosure is not intended to be limited to the implementations shown herein but is to be accorded the widest scope possible consistent with the principles and novel features as defined by the following claims.

What is claimed is:

**1**. A device comprising:

a memory configured to store input data; and

one or more processors configured to process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

**2**. The device of claim **1**, wherein the input data includes a first image and a second image, and wherein the ML model corresponds to a depth from stereo or optical flow architecture.

**3**. The device of claim **1**, wherein the ML model includes a language model, a vision model, or a multi-modal model.

**4**. The device of claim **1**, wherein the softmax with norm folding mechanism is included in a streamable attention mechanism.

**5**. The device of claim **4**, wherein the streamable attention mechanism is configured to:

generate a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data;

apply an exponentiation operation of the softmax with norm folding mechanism to the softmax input stream to generate a stream of softmax numerator values;

input the stream of softmax numerator values as a first input to a second matrix multiplication operation; and

generate an accumulation sum of the softmax numerator values.

**6**. The device of claim **5**, wherein the streamable attention mechanism is configured to perform a norm operation to apply the accumulation sum to third data to generate a second input to the second matrix multiplication operation.

**7**. The device of claim **5**, wherein the streamable attention mechanism is configured to perform a norm operation to apply the accumulation sum to an output of the second matrix multiplication operation.

**8**. The device of claim **5**, wherein:

the first data corresponds to features associated with a first image;

the second data corresponds to features associated with a second image; and

a second input to the second matrix multiplication operation corresponds to a displacement matrix of coordinates.

**9**. The device of claim **1**, wherein the ML model generates probabilistic geometry measures without generating a cost volume data structure.

**10**. The device of claim **1**, wherein the ML model is configured to perform regression for depth from stereo or optical flow geometric coordinates using just-in-time computations.

**11**. The device of claim **1**, further comprising an image sensor configured to generate image data corresponding to the input data.

**12**. The device of claim **1**, further comprising a modem coupled to the one or more processors, the modem configured to receive image data corresponding to the input data from a second device.

**13**. The device of claim **1**, wherein the one or more processors are integrated in a headset device that includes a display, and wherein the headset device is configured, when worn by a user, to display an output image based on an output of the ML model.

**14**. The device of claim **1**, wherein the one or more processors are integrated in at least one of a mobile phone, a tablet computer device, a wearable electronic device, or a camera device.

**15**. The device of claim **1**, wherein the one or more processors are integrated in a vehicle, the vehicle further including one or more cameras configured to capture image data corresponding to the input data.

**16**. The device of claim **1**, wherein the one or more processors are included in an integrated circuit.

**17**. A method comprising:

obtaining input data at a device; and

processing, at the device, the input data using a machine learning (ML) model including performing a softmax with norm folding operation.

**18**. The method of claim **17**, wherein the softmax with norm folding operation is included in a streamable attention operation of the ML model.

**19**. The method of claim **18**, wherein the streamable attention operation includes:

generating a softmax input stream based on a first matrix multiplication operation of a particular row of first data and a corresponding row of second data;

applying an exponentiation operation of the softmax with norm folding operation to the softmax input stream to generate a stream of softmax numerator values;

providing the stream of softmax numerator values as a first input to a second matrix multiplication operation; and

generating an accumulation sum of the softmax numerator values.

**20**. A non-transitory computer-readable medium storing instructions that, when executed by one or more processors, cause the one or more processors to:

obtain input data; and

process the input data using a machine learning (ML) model that incorporates a softmax with norm folding mechanism.

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