

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent Application Publication

20250265836

Kind Code

A1

Publication Date

August 21, 2025

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METHOD FOR TRAINING A MULTI-TASK NEURAL NETWORK

Abstract

Training a multi-task neural network. The multi-task neural network is configured to receive an input and to produce multiple outputs. During training task weights are computed to weight individual losses. A normalization function is applied to normalize the task weights.

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Family ID: 1000008475841

Appl. No.: 19/036123

Filed: January 24, 2025

Foreign Application Priority Data

EP	24 15 8197.4	Feb. 16, 2024
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Publication Classification

Int. Cl.: G06V10/96 (20220101); G06T7/11 (20170101); G06T7/50 (20170101); G06V10/764 (20220101); G06V10/774 (20220101); G06V10/776 (20220101); G06V10/82 (20220101)

U.S. Cl.:

CPC G06V10/96 (20220101); G06T7/11 (20170101); G06T7/50 (20170101); G06V10/764 (20220101); G06V10/774 (20220101); G06V10/776 (20220101); G06V10/82 (20220101); G06T2207/20081 (20130101); G06T2207/20084 (20130101)

Background/Summary

CROSS REFERENCE

[0001] The present application claims the benefit under 35 U.S.C. § 119 of European Patent Application No. EP 24 15 8197.4 filed on Feb. 16, 2024, which is expressly incorporated herein by reference in its entirety.

FIELD

[0002] The present invention relates to a method for training a multi-task neural network, a system for training a multi-task neural network, and a computer storage medium.

BACKGROUND INFORMATION

[0003] With the rise of neural networks in various domains, multi-task learning (MTL) has increased in relevance. Multi-task learning (MTL) aims at solving multiple tasks simultaneously in a mutually beneficial manner. MTL allows related tasks to share their knowledge, and thus allows learning to be done more efficiently. Furthermore, MTL increases the amount of available training data [3, 29, 33] (numbers in the square brackets refer to the numbered references below).

[0004] One of the major challenges is to find the right, implicit or explicit, balance between individual tasks to gain a good performance across tasks. An effective approach provides task-specific weights during optimization.

[0005] Not explicitly weighting tasks, also termed Equal Weighting (EW), has many potential pitfalls. Different tasks could be measured on various scales, such as meters and millimeters, which could lead to drastically different loss scalings across tasks. Furthermore, some tasks might be more difficult than others and require more resources. Thus, there have been various proposals for specialized weighing methods that dynamically adjust the weights along the course of training [21, 7, 15, 37, 20, 16, 2, 4, 22, 6].

[0006] Uncertainty Weighting (UW) is a gradient-based multi-task optimization (MTO) approach. In UW, the task weights are learned using gradient descent. However, UW also shows some drawbacks: First, we observe that UW can be affected by bad initialization and inertia. As uncertainty weights are usually initialized equally for all tasks, reaching their task- and epoch-specific optimal value via gradient descent might be slow, especially as task weights often differ in orders of magnitude. We refer to this phenomenon as update inertia. We have demonstrated this phenomenon empirically. Furthermore, we observed that UW is prone to overfitting.

[0007] Another approach to obtaining task weights is using a brute force grid search for optimal fixed weights, called Scalarization. Scalarization yields superior performance on a range of MTL problems. Loss weights are tuned by performing an extensive grid search, which is however computationally expensive. Scalarization can only be applied to problems with a small number of tasks, as the combinatorial complexity becomes prohibitive. The high computational cost makes the method inapplicable in many practical scenarios.

SUMMARY

[0008] It would be advantageous to have an improved method for training a multi-task neural network, in particular to compute task weights.

[0009] In an example embodiment of the present invention, the multi-task neural network is configured to receive an input and to produce multiple outputs, the multi-task neural network input comprising dimensional data obtained from a sensor. In an embodiment, computing task weights comprises applying a normalization function, so that the task weights are normalized. For example, one may first compute raw task weights, and then normalize the raw task weights by applying the normalization function. This can be done while iterating over the training set.

[0010] In an advantageous way to compute the raw task weights, they are chosen to scale the corresponding multiple individual losses to a constant. For example, the task weights $\omega_{\text{sub}.i}$ may

be chosen proportional to $1/L_{\text{sub},i}$, so that $\omega_{\text{sub},i}L_{\text{sub},i}$ is a constant, e.g., is 1. This also means that the total loss $L = \sum \omega_{\text{sub},i}L_{\text{sub},i}$ is a constant, e.g., equals the number of tasks. This can be done for each training batch.

[0011] The multi-task neural network is particularly useful in situations in which multiple information needs to be extracted from the same data. For example, the input data may represent a real-world environment of a mechanical agent, e.g., a robot or vehicle, operating in the environment. The input data may contain multiple input modalities. Given such information, there are various information that may need to be extracted, e.g., object segmentation, object classification, distance estimation, and so on. The multi-task neural network may be trained to infer a state of the environment. A similar problem arises when deriving a state of the mechanical agent; here the input may contain various data that represent the state of the agent.

[0012] In an example embodiment of the present invention, an analytically optimal uncertainty solution is computed, which is particularly strong in scenarios with highly imbalanced losses. In an embodiment, Soft Optimal Uncertainty Weighting (UW-SO) normalizes this optimal solution with a normalization function, e.g., a softmax function with a temperature parameter. An extensive set of experiments were run across various loss weighting methods with different datasets and architectures.

[0013] A device configured to train a multi-task neural network according to an example embodiment of the present invention is an electronic device, e.g., a computer.

[0014] An example embodiment of the method of the present invention may be implemented on a computer as a computer implemented method, or in dedicated hardware, or in a combination of both. Executable code for an embodiment of the method may be stored on a computer program product. Examples of computer program products include memory devices, optical storage devices, integrated circuits, servers, online software, etc. Preferably, the computer program product comprises non-transitory program code stored on a computer readable medium for performing an embodiment of the method when said program product is executed on a computer.

[0015] In an example embodiment of the present invention, the computer program comprises computer program code adapted to perform all or part of the steps of an embodiment of the method when the computer program is run on a computer. Preferably, the computer program is embodied on a computer readable medium.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Further details, aspects, and example embodiments will be described, by way of example only, with reference to the figures. Elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. In the figures, elements which correspond to elements already described may have the same reference numerals.

[0017] FIG. 1A schematically shows an example of an embodiment of a system for training a multi-task neural network,

[0018] FIG. 1B schematically shows an example of an embodiment of a system for evaluating a multi-task neural network, according to the present invention.

[0019] FIG. 2 schematically shows an example of an embodiment of training set, according to the present invention.

[0020] FIG. 3A schematically shows an example of an embodiment of multi-task neural network, according to the present invention.

[0021] FIG. 3B schematically shows an example of an embodiment of training a multi-task neural network, according to the present invention.

[0022] FIG. 4A schematically shows an example of weight ratio development for an example

embodiment of training a multi-task neural network, according to the present invention.

[0023] FIG. 4B schematically shows an example of loss development for an example embodiment of training a multi-task neural network, according to the present invention.

[0024] FIG. 5 schematically shows an example of performance for different choices of T in an example embodiment of the present invention.

[0025] FIG. 6A schematically shows an example of task weight development for a segmentation task in an example embodiment of the present invention.

[0026] FIG. 6B schematically shows an example of task weight development for a depth task in an example embodiment of the present invention.

[0027] FIG. 6C schematically shows an example of task weight development for a normal task in an example embodiment of the present invention.

[0028] FIG. 7 schematically shows an example of an example embodiment of a method for training a multi-task neural network, according to the present invention.

[0029] FIG. 8A schematically shows a computer readable medium having a writable part comprising a computer program according to an example embodiment of the present invention.

[0030] FIG. 8B schematically shows a representation of a processor system according to an example embodiment of the present invention.

REFERENCE SIGNS LIST

[0031] The following list of references and abbreviations corresponds to FIGS. 1-6C, 8A-8B, and is provided for facilitating the interpretation of the drawings and shall not be construed as limiting the present invention. [0032] **110** a training system for training a multi-task neural network [0033] **120** an evaluating system for evaluating a multi-task neural network [0034] **111, 121** a processor system [0035] **112, 122** storage [0036] **113, 123** communication interface [0037] **200** a training set [0038] **210, 220** a training pair [0039] **211, 221** a training input [0040] **212-214** multiple training outputs [0041] **222-224** multiple training outputs [0042] **301** an input [0043] **321-323** a task-specific head [0044] **331-333** a task-specific output [0045] **341-343** a task-specific loss [0046] **350** a raw task weights unit [0047] **351-353** a raw task weight [0048] **360** normalization function [0049] **361-363** a task weight [0050] **370** a weighted loss unit [0051] **380** a learning unit [0052] **411** Uncertainty Weighting [0053] **412** Soft Optimal Uncertainty Weighting [0054] **413** Equal Weighting [0055] **421** Uncertainty Weighting Train [0056] **422** Uncertainty Weighting Test [0057] **423** Soft Optimal Uncertainty Weighting Train [0058] **424** Soft Optimal Uncertainty Weighting Test [0059] **611** Scalar [0060] **612** Equal Weighting [0061] **613** Uncertainty Weighting [0062] **614** Geometric Loss Strategy [0063] **615** Impartial Multi-Task Learning [0064] **616** Optimal Uncertainty Weighting [0065] **617** Soft Optimal Uncertainty Weighting [0066] **11000, 1001** a computer readable medium [0067] **1010** a writable part [0068] **1020** a computer program [0069] **1110** integrated circuit(s) [0070] **1120** a processing unit [0071] **1122** a memory [0072] **1124** a dedicated integrated circuit [0073] **1126** a communication element [0074] **1130** an interconnect [0075] **1140** a processor system

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0076] While the presently disclosed subject matter is susceptible of embodiment in many different forms, there are shown in the drawings and will herein be described in detail one or more specific embodiments, with the understanding that the present disclosure is to be considered as exemplary of the principles of the presently disclosed subject matter and not intended to limit it to the specific embodiments shown and described.

[0077] In the following, for the sake of understanding, elements of embodiments are described in operation. However, it will be apparent that the respective elements are arranged to perform the functions being described as performed by them.

[0078] Further, the subject matter that is presently disclosed is not limited to the embodiments only, but also includes every other combination of features described herein or recited in connection with mutually different embodiments.

[0079] FIG. 1A schematically shows an example of an embodiment of a system **110** for training a multi-task neural network. FIG. 1B schematically shows an example of an embodiment of a system **120** for evaluating a multi-task neural network.

[0080] Training system **110** is configured to train a multi-task neural network. The multi-task neural network is configured to receive an input (x) and to produce multiple outputs ($y_{sub.1}$, $y_{sub.2}$, . . . , $y_{sub.k}$).

[0081] Training system **110** repeatedly evaluates the multi-task neural network for a training input to obtain multiple outputs of the multi-task neural network; one output for each task of the neural network. Accordingly, for each of the tasks a loss may be computed that indicates how well the multi-task neural network performed on that task. Using those losses directly for training the network does not work well. The losses may be on different scales, which could lead to drastically different loss scalings across tasks. Accordingly, training system **110** first computes raw task weights based on the multiple individual losses, and then applies a normalization function thereto. The normalized task weights are then used to weight the task specific losses, which in turn are used to train the network.

[0082] Evaluating system **120** is configured to evaluate the trained multi-task neural network. For example, training system **110** may transfer the trained multi-task neural network to evaluating system **120**. For example, system **120** may be an autonomous vehicle using the trained multi-task neural network to evaluate sensor data; system **120** may use one, or more, or all of the outputs to derive a control signal to control the autonomous vehicle, e.g., an actuator thereof.

[0083] The computer code for evaluating neural network may be shared between training system **110** and evaluating system **120** in large part. If evaluating system **120** is not configured for further training the neural network, then evaluating system **120** does not need code to compute task weights. Furthermore, although not strictly necessary, training system **110** will typically compute all outputs of the multi-task neural network for each training input. Evaluating system **120** may do the same, but may also be configured to only compute a desired output of the multiple possible outputs, thus saving on computing resources.

[0084] System **110** and/or system **120** may be implemented in a single device, e.g., a computer. They may also be implemented as a distributed system, e.g., geographically distributed, the parts of a system communicating through a computer network.

[0085] Typically, systems **110** and **120** are different systems. However, it is possible to use the same system for both. For example, a system may be configured for a training phase, during which it acts as system **110**, and for an inference phase, during which it acts as system **120**.

[0086] Training system **110** may comprise a processor system **111**, a storage **112**, and a communication interface **113**. Evaluating system **120** may comprise a processor system **121**, a storage **122**, and a communication interface **123**.

[0087] In the various embodiments of communication interfaces **113** and/or **123**, the communication interfaces may be selected from various alternatives. For example, the interface may be a network interface to a local or wide area network, e.g., the Internet, a storage interface to an internal or external data storage, an application interface (API), etc.

[0088] Storage **112** and **122** may be, e.g., electronic storage, magnetic storage, etc. The storage may comprise local storage, e.g., a local hard drive or electronic memory. Storage **112** and **122** may comprise non-local storage, e.g., cloud storage. In the latter case, storage **112** and **122** may comprise a storage interface to the non-local storage. Storage may comprise multiple discrete sub-storages together making up storage **112** and **122**.

[0089] Storage **112** and/or **122** may be non-transitory storage. For example, storage **112** and/or **122** may store data in the presence of power such as a volatile memory device, e.g., a Random Access Memory (RAM). For example, storage **112** and/or **122** may store data in the presence of power as well as outside the presence of power such as a non-volatile memory device, e.g., Flash memory. Storage may comprise a volatile writable part, say a RAM, a non-volatile writable part, e.g., Flash.

Storage may comprise a non-volatile non-writable part, e.g., ROM.

[0090] The systems **110** and **120** may communicate internally, with each other, with other systems, external storage, input devices, output devices, and/or one or more sensors over a computer network. The computer network may be an internet, an intranet, a LAN, a WLAN, a WAN, etc. The computer network may be the Internet. The systems **110** and **120** may comprise a connection interface which is arranged to communicate within system **100** or outside of system **100** as needed. For example, the connection interface may comprise a connector, e.g., a wired connector, e.g., an Ethernet connector, an optical connector, etc., or a wireless connector, e.g., an antenna, e.g., a Wi-Fi, 4G or 5G antenna.

[0091] The communication interface **113** may be used to send or receive digital data, e.g., to receive training data, and/or to send the trained neural network, e.g., the trained parameters thereof. The communication interface **123** may be used to send or receive digital data, e.g., to receive the trained network, to receive an input, and/or to send an output, or data derived from an output.

[0092] Training system **110** and evaluating system **120** may have a user interface, which may include conventional elements such as one or more buttons, a keyboard, display, touch screen, etc. The user interface may be arranged for accommodating user interaction for, e.g., initiating a training or an evaluating.

[0093] The execution of systems **110** and **120** may be implemented in a processor system. The systems **110** and **120** may comprise functional units to implement aspects of embodiments. The functional units may be part of the processor system. For example, functional units shown herein may be wholly or partially implemented in computer instructions that are stored in a storage of the system and executable by the processor system.

[0094] The processor system may comprise one or more processor circuits, e.g., microprocessors, CPUs, GPUs, etc. Systems **110** and **120** may comprise multiple processors. A processor circuit may be implemented in a distributed fashion, e.g., as multiple sub-processor circuits. For example, systems **110** and **120** may use cloud computing.

[0095] Typically, the training system **110** and the evaluating system **120** each comprise one or more microprocessors which execute appropriate software stored at the system; for example, that software may have been downloaded and/or stored in a corresponding memory, e.g., a volatile memory such as RAM or a non-volatile memory such as Flash.

[0096] Instead of using software to implement a function, the systems **110** and **120** may, in whole or in part, be implemented in programmable logic, e.g., as field-programmable gate array (FPGA). The systems may be implemented, in whole or in part, as a so-called application-specific integrated circuit (ASIC), e.g., an integrated circuit (IC) customized for their particular use. For example, the circuits may be implemented in CMOS, e.g., using a hardware description language such as Verilog, VHDL, etc. In particular, training system **110** and server **120** may comprise circuits, e.g., for cryptographic processing, and/or arithmetic processing.

[0097] In hybrid embodiments, functional units are implemented partially in hardware, e.g., as coprocessors, e.g., neural network coprocessors, and partially in software stored and executed on the system.

[0098] FIG. 3A schematically shows an example of an embodiment of multi-task neural network **300**. FIG. 3A shows one possible architecture for a multi-task neural network. The multi-task neural network is configured to receive an input **301**, also referred to as x , and to produce multiple outputs. Shown are outputs **331**, **332**, and **333**. The outputs are also referred to as $y_{sub.1}$, $y_{sub.2}$, . . . , $y_{sub.k}$. The number of outputs, that is, the number of tasks, could be two, or more than three, e.g., at least 4, at least 10, etc.

[0099] Accordingly, various outputs are computed for a single input. Note that input **301** typically comprises a mixture of input data types. For example, a single input may comprise one, or two, or more of: images, radar signals, lidar signals, ultrasound signals, etc., to produce the multiple outputs.

[0100] In the architecture shown in FIG. 3A, the multi-task neural network comprises a shared backbone **310** and multiple task-specific heads. Shown are task-specific heads **321**, **322** and **323**. Shared backbone **310** receives the input **301** and produces an intermediate result which is provided to each one of the task-specific heads. Each task-specific head computes one of the output of multi-task neural network **300**. The task-specific heads do not need to be of the same size, e.g., may have a different number of layers. For example, a head that produces an object segmentation or a depth map may have more layers than a layer that classifies an image.

[0101] The architecture of FIG. 3A is an example of hard parameter sharing, in which one or more network layers are shared across all tasks, in this case the lower-level layers. The network has multiple task-specific heads, each of which may comprise one or more layers, whose parameters are not shared. The shared layers capture and learn features that are common across the tasks, leveraging the underlying similarities. Meanwhile, the task-specific layers allow the model to fine-tune these shared features for their particular task.

[0102] Instead of one backbone **310** shared across all tasks a more complicated architecture is possible. For example, some layers may be shared across all tasks, while one or more other layers may be shared over a subset of the tasks. Such an architecture allows for a high degree of flexibility and adaptability, promoting further parameter efficiency

[0103] Instead of hard sharing of parameters, all or part of the shared parameters may be soft shared. In an embodiment using this approach, the model comprises a module, e.g., a neural network, for each individual task; the module having its own set of parameters. Part of the modules are soft shared parameters, e.g., parameters of certain layer(s), e.g., one or more lower layers of the modules. The modules are then regularized to encourage their shared parameters to be similar. This regularization allows the tasks to learn from each other without being forced to share the exact same feature representations. This may be achieved by adding a regularization term to the loss function, which penalizes the distance between the parameter matrices of the different tasks' modules.

[0104] For example, the architecture shown in FIG. 3A may be adjusted by duplicating the backbone **310** for each task; obtaining three copies of backbone **310** one for each head. The three backbones are trained individually, but are regularized to be close to each other. Losses used for training each combination of backbone and head may still be weighted by a task weight according to an embodiment.

[0105] The embodiments shown herein focus on a backbone/task-specific head architecture with hard shared parameters. However, embodiment can be adjusted to other options, e.g., soft shared parameters.

[0106] The neural network may comprise a variety of neural network layers, e.g., one or more of attention layers, including self-attention layers, encoding layers, decoding layer, convolutional layers, normalization layers, activation layers, e.g., ReLu, and so on.

Inputs/Outputs

[0107] In an embodiment, the multi-task neural network input, e.g., input **301** comprises dimensional data obtained from a sensor, that is, data having one dimension or more. The dimensional data in the input may be one-dimensional, e.g., audio data, temperature data, pressure data, time sequence data, etc. The dimensional data in the input may be two-dimensional, e.g., image data, including visible light image data and infrared image data, radar signals, lidar signals, ultrasound signals, etc. The dimensional data in the input may be three-dimensional, e.g., volumetric data, such as medical imaging data from MRI or CT scans, 3D models, e.g., computer-aided design (CAD) models, and virtual reality environments. The dimensional data in the input may be four-dimensional, e.g., spatiotemporal data, which includes three spatial dimensions plus one time dimension, such as video data that captures movement over time, or 4D medical imaging that provides 3D spatial reconstruction over time. In an embodiment, input **301** may comprise, or comprise also, scalar data, e.g., zero-dimensional data, e.g., sensor measurements.

[0108] The input data may comprise multi-dimensional image data, e.g., to two-dimensional (2D), three-dimensional (3D) or four-dimensional (4D) images, acquired by various acquisition modalities such as, but not limited to, standard X-ray Imaging, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Ultrasound (US), Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT), and Nuclear Medicine (NM).

[0109] In an embodiment, the image data comprises one or more of: audio data, image data, video data, lidar data, radar data, infrared data, ultrasonic data, sensor data, temperature data, pressure data, electrophysiological recording, e.g., electrocardiogram (ecg), electroencephalography (eeg), and/or electromyography (emg) data.

[0110] The output data depends on the particular task. The output data may include the same gamut of data types as the input data. For example, the output may include dimensional data, such as indicated above. The output may include scalar data, e.g., a classification of the input. An output may be a binary value.

[0111] For example, in an embodiment, the input data comprises image data, and possibly additional data. The multi-task neural network may have one output that classifies an object in the image data, one output with estimated depth for the image data, e.g., a depth map, and one output that comprises an object segmentation for the image data. Having only two of these outputs, e.g., only the object segmentation and estimated depth, is possible. Having more outputs is also possible.

[0112] In an embodiment, the input data represents a real-world environment of a mechanical agent, e.g., a robot or vehicle, operating in the environment. The mechanical agent may operate autonomously or semi-autonomously. The multi-task neural network may be trained to infer a state of the environment and/or of the mechanical agent.

[0113] After training the multi-task neural network may be used to operate the mechanical agent. For example, an input obtained from one or more sensors, e.g., cameras, radar, vehicle sensors, and the like, representing the environment and/or the state of the vehicle is provided and multiple outputs are computed therefrom by evaluating the neural network for the input. A control function is derived from one or more of the multiple outputs of the multi-task neural network. The control function is to be executed by the mechanical agent interacting with the real-world environment. A control function may include: actuating the vehicle, e.g., accelerating, decelerating, emergency braking, changing course, etc.

[0114] In an embodiment, a semi-autonomous or autonomous vehicle, e.g., a car, comprises a multi-task neural network configured to receive as input various inputs for the purpose of environment perception, decision making, and control signal generation. The network receives dimensional data obtained from a sensor or a combination of two or more dimensional data obtained from multiple sensors. The inputs to the multi-task neural network include, but are not limited to, camera images, which provide visual information about the environment, such as road conditions, traffic signs, and obstacles, lidar data, and/or radar signals. The input may also include IMU (Inertial Measurement Unit) data for accurate positioning of the vehicle. The multiple outputs of the multi-task neural network may include, but are not limited to, object detection and classification, e.g., identifying and categorizing obstacles, vehicles, pedestrians, etc., lane detection, e.g., identifying lane boundaries for lane-keeping and lane-changing maneuvers, and distance estimation, e.g., assessing the proximity of objects, e.g., to maintain safe following distances. The network may produce vehicle dynamics predictions, such as the vehicle's potential future position and speed.

[0115] In an embodiment, the input comprises medical data, and the multiple outputs represent medical information derived from the medical input data. For example, tasks of the multi-task neural network may include: anatomical structure segmentation, such as, e.g., tumors, organs, and blood vessels; tumor detection and characterization, e.g., distinguishing between benign and malignant types based on imaging characteristics; functional analysis, e.g., evaluating the function of specific

organs or systems, for example, measuring blood flow in cardiac imaging or assessing metabolic activity in PET scans.

[0116] For example, in an embodiment the input comprises Cardiac Magnetic Resonance Imaging (Cardiac MRI). Tasks of the multi-task neural network may include: Cardiac Structure Segmentation, e.g., segmenting the heart into its major components, such as the left ventricle, right ventricle, myocardium (heart muscle), and the atria; Myocardial Tissue Characterization, e.g., Differentiating between healthy and diseased myocardial tissue, such as identifying areas of fibrosis or infarction; Function Analysis: Analyzing the functional aspects of the heart, such as ejection fraction, cardiac output, and myocardial strain, blood flow quantification, e.g., in the cardiac chambers; Detection of Cardiac Abnormalities, e.g., congenital heart defects, diseases, e.g., coronary artery disease.

[0117] FIG. 3B schematically shows an example of an embodiment of training multi-task neural network, e.g., neural network **300**.

[0118] To train the network a training set is obtained. The training set comprises multiple training pairs of a training input and corresponding multiple training outputs. FIG. 2 schematically shows an example of an embodiment of training set **200**. Set **200** comprises multiple training pairs of a training input and corresponding multiple training outputs. FIG. 2 shows two training pairs: pair **210** and pair **220**. Typically, a training data set will comprise many more training pairs, e.g., over more than 1000, or more than 10000, or more than 100000.

[0119] FIG. 2 shows inputs, shown are: inputs **211** and input **221**. Note that a single input may comprise multiple different data types, e.g., multiple camera images, in addition to radar and/or lidar data. For each input, the expected output for each task of the multi-task neural network is provided. For example, given the input data **211**, the outputs **212**, **213** and **214** are expected; given the input data **221**, the outputs **222**, **223** and **224** are expected;

[0120] For example, using the architecture of FIG. 3A, the task specific heads **321**, **322** and **323** are expected to produce 212, 213 and 214 respectively, if backbone **310** receives input **301**.

[0121] Typically, each training pair comprises one input, and one output for each task. This is not necessary. Some training pairs may comprise a training input, yet may comprise a training output for fewer than all tasks. Embodiments herein assume all training pairs are full training pairs, however an embodiment may be adjusted by computing losses and task weights only for outputs present in a training pair.

[0122] During training, an iterating is made over the training set. To train on a training pair of the training set, the multi-task neural network is evaluated for the training input in the training pair. For example, given input **301**, one may obtain outputs **331**, **332**, and **333**. Typically, during training not all outputs will be correct. Accordingly, for each output a loss may be computed. Each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs. Various conventional loss functions may be used for this purpose.

[0123] For instance, for a task of object detection in a camera images, the loss function may be the cross-entropy loss for classifying the types of objects, e.g., vehicles, pedestrians, etc. A task of distance estimation to objects, e.g., using the same camera images as input, may use a mean squared error (MSE) loss function, to quantify the difference between the predicted distances and the true distances.

[0124] Accordingly, the input **301** gives rise to (in this example) three outputs **331**, **332**, **333**, and three corresponding losses: loss **341**, loss **342**, and loss **343**, respectively. To balance the learning of the three tasks, task weights are computed to weight the losses. For example, a weighted loss unit **370** may weigh the individual losses, e.g., losses **341-343**, using task weights **361-363**. A learning unit **380** then uses the weighted losses to train the neural network. The training may use a conventional training algorithm, e.g., back propagation or one of its variants. For example, the training may train each of the heads using the corresponding weighted loss. The training preferably

includes training the backbone **310**, e.g., as part of training each of the task heads.

Task Weights

[0125] Using the individual losses a raw task weights unit **350** may compute raw task weights from the multiple individual losses. The inventors found that applying a normalization function to the raw task weights improves the training.

[0126] Typically, the raw task weights are computed only from the individual losses, but this is not necessary, further factors may be taken into account. For example, additional factors that may be taken into account to compute the raw task weight may include one or more of: Task Importance, e.g., the relative importance of each task can be a factor. For example, in a semi-autonomous vehicle scenario, the task of detecting pedestrians may be assigned a higher importance than lane detection; Data imbalance. For example, if one task has more training data than another, the training may be adjusted to give more emphasis to a task with less data.

[0127] Computing task weights may use any conventional method of computing raw task weights. The inventors found that one particularly advantageous method of computing task weights is to use the inverse of the losses. This has the effect of scaling the losses to a constant. For example, given individual losses ($L_{sub.1}$, $L_{sub.2}$, . . . , $L_{sub.k}$) for the obtained multiple outputs of the multi-task neural network, the raw task weights ($\omega_{sub.1}$, $\omega_{sub.2}$, . . . , $\omega_{sub.k}$), may be computed as $\omega_{sub.i} = \gamma / L_{sub.i}$, for all i and a fixed positive scalar γ , e.g., $\gamma = 1$.

[0128] To obtain the task weights from the raw task weights a normalization function is applied, e.g., $(\omega_{sub.1}, \omega_{sub.2}, \dots, \omega_{sub.k}).\text{fwdarw.Normalize}(\omega_{sub.1}, \omega_{sub.2}, \dots, \omega_{sub.k})$. In an embodiment, the normalization function is a probability distribution function; the outputs of the normalization function being numbers from **0** to **1**, that sum to 1. For example, the normalization function may be SoftMax, Temperature-Scaled SoftMax [38], soft-margin SoftMax, Taylor SoftMax [40], or any combination thereof.

[0129] Note that, although the task weights are computed from the individual losses, the task weights are not taken into account for computing gradients, apart from the scaling. This may be implemented by applying a so-called stop gradient operator to the multiple task weights.

Batching

[0130] In an embodiment, the iteration over the training set is batched. A batch of training input and output pairs may be collected from the training data. The same, partially trained, multi-task neural network may be evaluated for the training data in the batch. The parameters of the multi-task neural network may be adjusted based on the aggregated computed individual losses weighted by the task weights. The adjusted multi-task neural network may then be used for the next training batch. Various batch sizes may be used, e.g., at least 2, at least 16, at least 32, etc. A batch size of 1 corresponds to updating after each training pair.

[0131] For example, the following pseudocode could be used

[0132] FOR each batch i DO

[0133] Get the current state of the neural network: NN_i

[0134] Select a batch of training inputs (e.g., inputs **1** to **32**)

[0135] FOR each training input j in the batch DO

[0136] Compute the set of losses for input j using NN_i : $L_j = (L1_j, L2_j, \dots, Lk_j)$

[0137] End for

[0138] Calculate the average loss for each task: $L_{avg} = (L1_{avg},$

[0139] $L2_{avg}, \dots, Lk_{avg})$

[0140] Compute raw task weights from averaged loss: E.g., $Raw_Task_weights = (1/L1_{avg}, \dots, 1/Lk_{avg})$

[0141] Normalize raw task weights to obtain task weight. E.g.,

[0142] $Task_weights = \text{SoftMax}(Raw_Task_weights)$

[0143] Apply $Task_weights$ to L_{avg} to obtain loss for the batch and use it for backpropagation.

Thus updating the neural network state to NN_{i+1}

End for

[0144] Below several further optional refinements, details, and embodiments are illustrated. Some embodiments are further detailed using a mathematical notation.

[0145] In MTL, we aim to resolve K tasks for some input data point $x \in X$. For this, x is mapped to labels $\{y_{\text{sub.k}} \in \text{custom-character.sub.k}\}_{\text{sub.k} \in [1, K]}$ simultaneously using specific mappings $\{f_{\text{sub.k}}: X \rightarrow \text{custom-character.sub.k}\}$. We assume hard task-shared parameters θ in a hydra-like neural network architecture. This means all tasks receive the same intermediate feature $z = f(x; \theta)$ from the shared backbone and each task head yields output $f_{\text{sub.k}}(x) = f'_{\text{sub.k}}(z; \theta_{\text{sub.k}})$ with task-specific parameters $\theta_{\text{sub.k}}$. However, other architectures for multi-task neural network may be used instead.

[0146] The network is trained by considering all tasks' losses $L_{\text{sub.k}}$. Naively summing up these losses typically leads to imbalanced learning as tasks, wherein a high loss magnitude might dominate the training. The goal is thus to find improved task weights $\omega_{\text{sub.k}}$, possibly dynamic task weights, for all tasks to optimize the loss $L = \sum_k \omega_{\text{sub.k}} L_{\text{sub.k}}$ in a way that all tasks benefit w.r.t. their final performance metrics.

[0147] Some embodiments are directed to training a multi-task neural network, wherein during training task weights are computed to weight individual losses. A normalization function is applied to normalize the task weights.

[0148] A first loss weighting method UW-O (Optimal Uncertainty Weighting) computes weights based on an analytical solution, instead of, e.g., learning weights using gradient descent as in UW. The UW-O method does not apply a normalizing function. A second loss weighting method UW-SO (Soft Optimal Uncertainty Weighting) normalizes the analytically optimal weights using a normalizing function. We will assume a softmax function, though other normalizing functions may be used.

UW-O: Analytical Solution

[0149] In the approach of [16] weights losses are based on task-specific aleatoric uncertainty. The exact weighting formula depends on the type of loss. For instance, for tasks with an L_y loss it can be derived by assuming a Laplace posterior distribution and identifying $\sigma_{\text{sub.k}}$ with the uncertainty of each task $k \in \text{custom-character}$, treating them as learnable parameters that are input independent

$$[00001] \quad L = \frac{1}{\sigma_k} L_k + \log \sigma_k \quad (1)$$

[0150] Here, $L_{\text{sub.k}}$ is the task-specific loss, e.g., a mean absolute error. Intuitively, the $\sigma_{\text{sub.k}}$ in the first term allows to down-weight difficult tasks by increasing the uncertainty represented by $\sigma_{\text{sub.k}}$. The second term acts as a regularizer and prohibits the trivial solution of $\sigma_{\text{sub.k}} \rightarrow \infty$.

[0151] Instead of learning σ , we derive the analytically optimal solution and show its derivation. For example, for $L_{\text{sub.i}}$ loss the objective for tasks with an $L_{\text{sub.1}}$ loss can be formulated as $\min_{\sigma} \sum_k \sigma_{\text{sub.k}} L_{\text{sub.k}}$, see, e.g., [16], where we minimize the UW loss function with respect to $\sigma_{\text{sub.k}}$. Taking the derivative and solving for σ_k results in an analytically optimal solution:

$$[00002] \quad \sigma_k = L_k \quad (2)$$

[0152] Replacing $\sigma_{\text{sub.k}}$ with its analytical solution $L_{\text{sub.k}}$ in the total loss function (Eq. 1) gives the following loss:

$$[00003] \quad L = \frac{1}{\text{sg}[L_k]} L_k + \log \text{sg}[L_k],$$

where we denote sg as the stopgradient operator to avoid zero gradients of the network updates.

Since we do not compute any gradient of the second part of the loss, we can simplify the term, such that

$$[00004] \quad L = \frac{1}{\text{sg}[L_k]} L_k \quad (3)$$

[0153] For example, UW-O performs better than [16] especially in applications when task losses

L.sub.k differ significantly in magnitude, as each loss is normalized by sg[L.sub.k], canceling out any large scale difference in individual losses L.sub.k. Furthermore, UW-O mitigates the initialization/inertia problem of approaches that learn task weights, such as in [16], or [21].

[0154] UW-O does not include a normalization function. An example of computer-implemented method (400) for training a multi-task neural network using UW-O is the following method:

[0155] A computer-implemented method (400) for training a multi-task neural network, the multi-task neural network being configured to receive an input (x) and to produce multiple outputs (y.sub.1, y.sub.2, . . . , y.sub.k), the multi-task neural network input comprising dimensional data obtained from a sensor, the method comprising [0156] obtaining (410) a training set, the training set comprising multiple training pairs of a training input and corresponding multiple training outputs, [0157] iterating (420) over the training set, comprising, for a training pair of the training set [0158] evaluating (421) the multi-task neural network for the training input in the training pair, thus obtaining multiple outputs of the multi-task neural network, [0159] computing (422) multiple individual losses (L.sub.1, L.sub.2, . . . , L.sub.k) for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, [0160] computing (423) task weights ($\omega_{\text{sub.1}}, \omega_{\text{sub.2}}, \dots, \omega_{\text{sub.k}}$), comprising computing task weights from the multiple individual losses, wherein the multiple task weights are chosen to scale [0161] the corresponding multiple individual losses to a constant (e.g., $\omega_{\text{sub.i}}L_{\text{sub.i}}=1$), [0162] adjusting (424) parameters of the multi-task neural network based on the computed individual losses weighted by the task weights.



[0163] UW-SO: Transformation of UW-O with normalization

[0164] Although an embodiment according to UW-O, e.g., as defined above performs well in some cases, e.g., scenarios with imbalanced losses, nevertheless, UW-O does not reliably outperform [16], or [21] across all datasets and architectures.

[0165] To challenge not only UW but even the high-performing Scalarization approach, we additionally propose UW-SO. Experimental results confirm the effectiveness of tuning task weights that sum to 1, e.g., by applying a normalization function. For example, the softmax function may be applied to UW-O (Eq. 3), yielding UW-SO:

$$[00005] \quad L = \frac{\exp(\frac{1}{\text{sg}[L_k]} / T)}{\sum_{j \in \text{Math}} \exp(\frac{1}{\text{sg}[L_j]} / T)} L_k, \quad (4)$$

[0166] UW-SO achieves strong results while overcoming the inherent computational cost dependency on the number of tasks of scalarization.

[0167] In formula (4) we denote T as the softmax temperature, with a higher value of T resulting in more evenly distributed task weights with  $\omega_{\text{sub.k}}=1$. Contrary to Scalarization which requires the tuning of  task weights, thus being infeasible for a large number of tasks, our novel method UW-SO requires only tuning of one hyperparameter T.

[0168] In this section, we provide more details on the analytically optimal derivation of the uncertainty-based task weights. Note that the analytical solution to UW, which we call UW-O, varies for different loss criteria (e.g., L.sub.2 and Cross-Entropy Loss yield a different constant in the denominator compared to L.sub.1). However, we simplify this by taking a unified formula (see Eq. 3) not depending on the kind of task. This reduces the implementation overhead. Empirically, we further saw improvements in the results due to the unification.

[0169] Nevertheless, we show the detailed derivation of UW-O for L.sub.1, L.sub.2, and Cross Entropy Loss in the following paragraphs.

L1 Loss

[0170] In the case of regression tasks evaluated by the L.sub.i loss we define our likelihood as a Laplace distribution, thus, the objective is given as [16]

$$[00006] \quad \min_k \frac{1}{k} L_k + \log k, \quad (5)$$

[0171] where we minimize the UW loss function with respect to $\sigma_{\text{sub},k}$ with k representing the k -th task weighted by $\sigma_{\text{sub},k}$. Taking the derivative and solving for $\sigma_{\text{sub},k}$ results in an analytically optimal solution:

$$[00007] \quad \frac{\partial}{\partial \sigma_{\text{sub},k}} \frac{1}{\sigma_{\text{sub},k}} L_k + \log \sigma_{\text{sub},k} = -\frac{1}{\sigma_{\text{sub},k}^2} L_k + \frac{1}{\sigma_{\text{sub},k}} \quad (6) \quad -\frac{1}{\sigma_{\text{sub},k}^2} L_k + \frac{1}{\sigma_{\text{sub},k}} \stackrel{!}{=} 0 \quad (7) \quad \sigma_{\text{sub},k} = L_k \quad (8)$$

[0172] We assume $\sigma_{\text{sub},k}$ to be positive and therefore only allow for positive losses.

[0173] Replacing $\sigma_{\text{sub},k}$ with its analytical solution L_k in the total loss function gives the following loss:

$$[00008] \quad L_{\text{weighted}} = \frac{1}{\text{sg}[L_k]} L_k + \log(\text{sg}[L_k]), \quad (9)$$

[0174] where we denote sg as the stopgradient operator to avoid zero gradients of the network updates. Since we do not compute any gradient of the second part of the loss, we can simplify the term, such that

$$[00009] \quad L_{\text{weighted}} = \frac{1}{\text{sg}[L_k]} L_k. \quad (10)$$

[0175] To show that UW-O is indeed unaffected of loss scalings, we can assume task-specific weights $\omega_{\text{sub},k}$ in the loss function. However, these weights cancel out, making UW-O very effective for scenarios with highly imbalanced losses, as also our experiment show.

$$[00010] \quad L_{\text{weighted}} = \frac{1}{\omega_{\text{sub},k} \text{sg}[L_k]} L_k = \frac{1}{\text{sg}[L_k]} L_k \quad (11)$$

L2 Loss

[0176] The objective in UW for regression tasks with an L2 loss can be formulated as [16]

$$[00011] \quad \min_k \frac{1}{2} L_k + \log \sigma_{\text{sub},k}, \quad (12)$$

[0177] Consequently, our derivation and total loss again change:

$$[00012] \quad \frac{\partial}{\partial \sigma_{\text{sub},k}} \frac{1}{2} L_k + \log \sigma_{\text{sub},k} = -\frac{1}{\sigma_{\text{sub},k}^2} L_k + \frac{1}{\sigma_{\text{sub},k}} \quad (13) \quad -\frac{1}{\sigma_{\text{sub},k}^2} L_k + \frac{1}{\sigma_{\text{sub},k}} \stackrel{!}{=} 0 \quad (14) \quad \sigma_{\text{sub},k} = \pm \sqrt{L_k} \quad (15)$$

$$L_{\text{weighted}} = \frac{1}{2 \text{sg}[L_k]} L_k + \log \sqrt{\text{sg}[L_k]} \quad (16)$$

$$[00013] \quad L_{\text{weighted}} = \frac{1}{2 \text{sg}[L_k]} L_k. \quad (17)$$

Cross-Entropy Loss

[0178] The derivation for classification tasks evaluated by the cross-entropy loss looks as follows:

$$[00014] \quad \min_k \frac{1}{\sigma_{\text{sub},k}} L_k + \log \sigma_{\text{sub},k} \quad (18) \quad \frac{\partial}{\partial \sigma_{\text{sub},k}} \frac{1}{\sigma_{\text{sub},k}} L_k + \log \sigma_{\text{sub},k} = -\frac{L_k}{\sigma_{\text{sub},k}^2} + \frac{1}{\sigma_{\text{sub},k}} \quad (19)$$

$$-\frac{L_k}{\sigma_{\text{sub},k}^2} + \frac{1}{\sigma_{\text{sub},k}} \stackrel{!}{=} 0 \quad (20) \quad \sigma_{\text{sub},k} = \pm \sqrt{2 L_k} \quad (21) \quad L_{\text{weighted}} = \frac{1}{2 \text{sg}[L_k]} L_k \quad (22)$$

[0179] Surprisingly, it turns out, that in each of these cases, task weights are obtained that scale the corresponding multiple individual losses to a constant (e.g., $\omega_{\text{sub},i} L_{\text{sub},i} = 1$). Using these task weights directly works especially well in scenarios with highly imbalanced losses. However, in each of these scenarios, a normalization factor may be added to normalize the task weights.

Test Results

[0180] We compare our methods to the most common loss weighting approaches.

[0181] Datasets We use three common computer vision MTL datasets: two datasets for scene understanding—NYUv2 [27] and Cityscapes [8]—and a binary attribute dataset CelebA [23]. Both NYUv2 and Cityscapes comprise the tasks of semantic segmentation and depth estimation. The third task for NYUv2 is surface normals estimation. CelebA constitutes a 40-class binary classification problem.

[0182] Architectures For NYUv2, we use a SegNet [1] and ImageNet pretrained ResNet-50/ResNet-101 with a DeepLabHead. For Cityscapes, we use a SegNet and a DeepLabV3+ [5] network with pre-trained ResNet-50/ResNet-101 backbones. Single-task learning (STL) baselines are only trained with the SegNet. For CelebA, we use a ResNet-18, also for STL.

[0183] We train all architectures on a training data set and use early stopping to determine the

epoch with the best $\Delta_{\text{sub.m}}$ on the validation data. Further using a line search, for each method, we have tested different learning rates and weight decays to find the best combination with respect to the $\Delta_{\text{sub.m}}$ on the validation data. For this combination and the best epoch, the $\Delta_{\text{sub.m}}$ and task specific metrics on the test data is reported.

[0184] Metrics To compare models, we use the widely established $\Delta_{\text{sub.m}}$ -metric [24]. It measures the average relative performance gain of the multi-task model $M_{\text{sub.m}}$ w.r.t. a single-task baseline $M_{\text{sub.b}}$:

$$[00015] \quad m = \frac{1}{K} \cdot \text{Math}_{k=1}^K (-1)^{l_k} (M_{m,k} - M_{b,k}) / M_{b,k},$$

where $l_{\text{sub.k}}$ is 1 if a higher value is better for criterion $M_{\text{sub.k}}$, and $l_{\text{sub.k}}$ is 0 otherwise. For the $\Delta_{\text{sub.m}}$ metric, we further list the standard deviation.

[0185] Overall, UW-SO consistently performs best or second-best across all datasets and architectures w.r.t the $\Delta_{\text{sub.m}}$ metric.

[0186] NYUv2 On NYUv2, UW-SO achieves the best $\Delta_{\text{sub.m}}$ score when trained on the ResNet-50 and the second-best behind Scalarization when trained on either the SegNet or ResNet-101 (see Table 2). Both methods perform particularly well on the normal task, while still achieving strong results on the other two tasks. While UW-O slightly stays behind UW and IMTL-L on the SegNet, it is the third-best method on the ResNet architectures.

[0187] When comparing the three weighted losses for different MTO algorithms, we find that, interestingly, Scalarization and UW-SO result in comparable weighted losses, indicating that UW-SO finds a similar weighting scheme; though as a fraction of the computational cost.

[0188] Cityscapes We observe comparable results on Cityscapes: UW-SO shows the best performance when using one of the ResNet architectures and is only outperformed by Scalarization on SegNet. In contrast to NYUv2, the performance of Scalarization decreases for larger networks due to weak results on the difficult and highly sensitive relative depth error. While an even more fine-grained search of task-weights might yield better results, we argue that our weight search with step size going down to 0.02 was performed adequately well to keep the computational cost feasible.

[0189] CelebA Considering a more challenging setup with 40 tasks, UW-SO is clearly exceeding the performance of all other methods with a $\Delta_{\text{sub.m}}$ score of -4.0 and an average error of 8.95 (see Table below). In contrast to the other two datasets, we did not include Scalarization due to the infeasibility of performing a grid search over 40 task weights. While we tried to run **50** different random weight combinations, we were not able to beat the EW performance and thus omit to report these results. Furthermore, GLS is also not reported as the losses diverge due to numerical instabilities for a large number of tasks. In contrast to our previous results on the other datasets, EW, RLW, and DWA show a strong performance on CelebA compared to UW and IMTL-L. We attribute this observation to UW and IMTL-L being prone to overfitting on a subset of tasks, as indicated by how early the validation $\Delta_{\text{sub.m}}$ score reaches its minimum (e.g., epoch **6** for UW). We analyze the overfitting behavior of UW in comparison to UW-SO later in this section. As indicated by the negative $\Delta_{\text{sub.m}}$ score, one achieves a positive transfer by training on multiple tasks simultaneously and using an appropriate MTO. Examining the task-level performance to verify that the enhanced average performance of UW-SO is not solely attributable to a limited set of tasks, it is noteworthy that UW-SO surpasses UW/UW-O/IMTL-L/RLW/EW/DWA in **34/34/31/27/24/24** out of 40 tasks.

TABLE-US-00001 Method Avg Err ↓ Ep $\Delta_{\text{sub.m}}$ % ↓ STL 9.24 EW 9.00 33.2 -2.4 ± 0.4 RLW 9.01 54.4 -2.5 ± 0.6 DWA 9.01 39.2 -2.5 ± 0.7 IMTL-L 9.18 5.0 -1.2 ± 0.9 UW 9.26 6.0 -0.1 ± 0.7 UW-O 9.30 15.4 -0.6 ± 0.7 UW-SO 8.95 61.2 -4.0 ± 0.2

[0190] Test data results on CelebA with ResNet-18. We show the average test error (**5** runs) over all 40 tasks. The chosen softmax temperature for UW-SO is $T=100$. We exclude GLS and Scalarization due to infeasibility, see details in the text.

[0191] FIG. 4A schematically shows an example of weight ratio development for an embodiment

of training a multi-task neural network. The horizontal axis shows the number of Epochs. The vertical axis shows Bald Weight Ratio. Shown are Uncertainty Weighting **411** (UW), Soft Optimal Uncertainty Weighting **412** (UW-SO), and Equal Weighting **413** (EW)

[0192] FIG. **4B** schematically shows an example of loss development for an embodiment of training a multi-task neural network. The horizontal axis shows the number of Epochs. The vertical axis in FIG. **4B** shows Bald Loss. Shown are Uncertainty Weighting Train **421** (UW Train), Uncertainty Weighting Test **422** (UW Test), Soft Optimal Uncertainty Weighting Train **423** (UW-SO Train), Soft Optimal Uncertainty Weighting Test **424** (US-SO Test).

[0193] FIGS. **4A** and **4B** show a comparison of weight ratio and loss development of UW and UW-SO for the Bald task of CelebA. While UW shows superior training performance caused by putting a high weight on the task, it fails to generalize to unseen data, as evident in the increasing test loss. UW-SO puts less weight on the task and alleviates the overfitting.

[0194] FIG. **5** schematically shows an example of performance for different choices of T in an embodiment. The horizontal axis shows Temperature T . The vertical axis shows $\Delta_{\text{sub.m}}$ on the validation data. The figure shows the performance of UW-SO for different choices of T . The figure shows a clear, reasonably flat minimum for Cityscapes that eases the optimization of T .

[0195] The UW-SO approach has a strong performance, but one needs to tune the single hyperparameter T . In FIG. **5**, we show how the performance changes when the temperature T is tuned for Cityscapes with a SegNet. The best run was achieved for $T=20$, but values close to it are also performing well. We conducted a line search for T in steps of 5 and further with a step size of 2 around the optimum. We conclude that it is possible with acceptable tuning effort to find a good value for T .

[0196] FIG. **6A** schematically shows an example of task weight development for the segmentation task in an embodiment. FIG. **6B** schematically shows an example of task weight development for the depth task in an embodiment. FIG. **6C** schematically shows an example of task weight development for the normal task in an embodiment. In all three figures, the horizontal axis shows the epoch, and the vertical axis shows the task weight. The figures show: Scalar **611**, Equal Weighting **612**, Uncertainty Weighting **613**, Geometric Loss Strategy **614**, Impartial Multi-Task Learning **615**, Optimal Uncertainty Weighting **616**, Soft Optimal Uncertainty Weighting **617**.

[0197] Comparing the task weights throughout the training process using various weighting methods provides better understanding of the respective weighting principles of each MTO approach. FIGS. **6A-6C** exemplarily shows the weights for the 3 tasks of the NYUv2 dataset using the SegNet.

[0198] Besides the similarity of Scalarization and UW-SO, we can also observe that UW-O and IMTL-L show a fairly similar task weight development. While IMTL-L develops the weights rather smoothly due to the small gradient updates, UW-O shows more fluctuation and jitters around IMTL-L.

[0199] FIG. **7** schematically shows an example of an embodiment of a method **400** for training a multi-task neural network. The multi-task neural network being configured to receive an input (x) and to produce multiple outputs ($y_{\text{sub.1}}$, $y_{\text{sub.2}}$, \dots , $y_{\text{sub.k}}$), the multi-task neural network input comprising dimensional data obtained from a sensor. Method **400** may be computer implemented and comprises [0200] obtaining (**410**) a training set, the training set comprising multiple training pairs of a training input and corresponding multiple training outputs, [0201] iterating (**420**) over the training set, comprising, for a training pair of the training set [0202] evaluating (**421**) the multi-task neural network for the training input in the training pair, thus obtaining multiple outputs of the multi-task neural network, [0203] computing (**422**) multiple individual losses ($L_{\text{sub.1}}$, $L_{\text{sub.2}}$, \dots , $L_{\text{sub.k}}$) for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, [0204] computing (**423**) task weights ($\omega_{\text{sub.1}}$, $\omega_{\text{sub.2}}$, \dots , $\omega_{\text{sub.k}}$), comprising computing raw task weights from

the multiple individual losses, and applying a normalization function to the raw task weights, [0205] adjusting (424) parameters of the multi-task neural network based on the computed individual losses weighted by the task weights.

[0206] In an embodiment, the method may comprise a training phase and an inference phase. In the training phase, multi-task neural network is trained, e.g., as described herein. In the inference phase, the trained multi-task neural network is used. For example, the inference phase may comprise receiving an input (x), and applying the trained multi-task neural network to the input, thus obtaining the corresponding multiple outputs of the multi-task neural network.

[0207] For example, the inference phase may be performed in or for a mechanical agent. The input data may represent a real-world environment of a mechanical agent, e.g., a robot or vehicle, operating in the environment. The multi-task neural network may be trained to infer a state of the environment and/or of the mechanical agent, the inference phase comprising [0208] deriving a control function of the mechanical agent from one or more of the multiple outputs of the multi-task neural network, which control function is to be executed by the mechanical agent interacting with the real-world environment.

[0209] For example, the machine learning method may be computer implemented methods. For example, accessing training data, and/or receiving input data may be done using a communication interface, e.g., an electronic interface, a network interface, a memory interface, etc. For example, storing or retrieving parameters may be done from an electronic storage, e.g., a memory, a hard drive, etc., e.g., parameters of the networks. For example, applying a neural network to data of the training data, and/or adjusting the stored parameters to train the network may be done using an electronic computing device, e.g., a computer.

[0210] The neural networks, either during training and/or during applying may have multiple layers, which may include, e.g., convolutional layers and the like. For example, the neural network may have at least 2, 5, 10, 15, 20 or 40 hidden layers, or more, etc. The number of neurons in the neural network may, e.g., be at least 10, 100, 1000, 10000, 100000, 1000000, or more, etc.

[0211] Many different ways of executing the method are possible, as will be apparent to a person skilled in the art. For example, the order of the steps can be performed in the shown order, but the order of the steps can be varied or some steps may be executed in parallel. Moreover, in between steps other method steps may be inserted. The inserted steps may represent refinements of the method such as described herein, or may be unrelated to the method. For example, some steps may be executed, at least partially, in parallel. Moreover, a given step may not have finished completely before a next step is started.

[0212] Embodiments of the method may be executed using software, which comprises instructions for causing a processor system to perform method according to an embodiment, e.g., method 400. Software may only include those steps taken by a particular sub-entity of the system. The software may be stored in a suitable storage medium, such as a hard disk, a floppy, a memory, an optical disc, etc. The software may be sent as a signal along a wire, or wireless, or using a data network, e.g., the Internet. The software may be made available for download and/or for remote usage on a server. Embodiments of the method may be executed using a bitstream arranged to configure programmable logic, e.g., a field-programmable gate array (FPGA), to perform the method.

[0213] It will be appreciated that the presently disclosed subject matter also extends to computer programs, particularly computer programs on or in a carrier, adapted for putting the presently disclosed subject matter into practice. The program may be in the form of source code, object code, a code intermediate source, and object code such as partially compiled form, or in any other form suitable for use in the implementation of an embodiment of the method. An embodiment relating to a computer program product comprises computer executable instructions corresponding to each of the processing steps of at least one of the methods set forth. These instructions may be subdivided into subroutines and/or be stored in one or more files that may be linked statically or dynamically. Another embodiment relating to a computer program product comprises computer executable

instructions corresponding to each of the devices, units and/or parts of at least one of the systems and/or products set forth.

[0214] FIG. 8A shows a computer readable medium **1000** having a writable part **1010**, and a computer readable medium **1001** also having a writable part. Computer readable medium **1000** is shown in the form of an optically readable medium. Computer readable medium **1001** is shown in the form of an electronic memory, in this case a memory card. Computer readable medium **1000** and **1001** may store data **1020** wherein the data may indicate instructions, which when executed by a processor system, cause a processor system to perform an embodiment of a method of training and/or evaluating a multi-task neural network, according to an embodiment. The computer program **1020** may be embodied on the computer readable medium **1000** as physical marks or by magnetization of the computer readable medium **1000**. However, any other suitable embodiment is possible as well. Furthermore, it will be appreciated that, although the computer readable medium **1000** is shown here as an optical disc, the computer readable medium **1000** may be any suitable computer readable medium, such as a hard disk, solid state memory, flash memory, etc., and may be non-recordable or recordable. The computer program **1020** comprises instructions for causing a processor system to perform said method of training and/or evaluating a multi-task neural network.

[0215] FIG. 8B shows in a schematic representation of a processor system **1140** according to an embodiment. The processor system may be configured for a method of training and/or evaluating a multi-task neural network. The processor system comprises one or more integrated circuits **1110**. The architecture of the one or more integrated circuits **1110** is schematically shown in FIG. 8B. Circuit **1110** comprises a processing unit **1120**, e.g., a CPU, for running computer program components to execute a method according to an embodiment and/or implement its modules or units. Circuit **1110** comprises a memory **1122** for storing programming code, data, etc. Part of memory **1122** may be read-only. Circuit **1110** may comprise a communication element **1126**, e.g., an antenna, connectors or both, and the like. Circuit **1110** may comprise a dedicated integrated circuit **1124** for performing part or all of the processing defined in the method. Processor **1120**, memory **1122**, dedicated IC **1124** and communication element **1126** may be connected to each other via an interconnect **1130**, say a bus. The processor system **1110** may be arranged for contact and/or contact-less communication, using an antenna and/or connectors, respectively.

[0216] For example, in an embodiment, processor system **1140**, e.g., the neural network training device and/or neural network evaluation device may comprise a processor circuit and a memory circuit, the processor being arranged to execute software stored in the memory circuit. For example, the processor circuit may be an Intel Core i7 processor, ARM Cortex-R8, etc. The memory circuit may be an ROM circuit, or a non-volatile memory, e.g., a flash memory. The memory circuit may be a volatile memory, e.g., an SRAM memory. In the latter case, the device may comprise a non-volatile software interface, e.g., a hard drive, a network interface, etc., arranged for providing the software.

[0217] Memory **1122** may be considered to be “non-transitory machine-readable media.” As used herein, the term “non-transitory” will be understood to exclude transitory signals but to include all forms of storage, including both volatile and non-volatile memories.

[0218] While device **1100** is shown as including one of each described component, the various components may be duplicated in various embodiments. For example, the processor **1120** may include multiple microprocessors that are configured to independently execute the methods described herein or are configured to perform steps or subroutines of the methods described herein such that the multiple processors cooperate to achieve the functionality described herein. Further, where the device **1100** is implemented in a cloud computing system, the various hardware components may belong to separate physical systems. For example, the processor **1120** may include a first processor in a first server and a second processor in a second server.

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Claims

1. A computer-implemented method for training a multi-task neural network, the multi-task neural network being configured to receive an input and to produce multiple outputs, the multi-task neural network input including dimensional data obtained from a sensor, the method comprising the following steps: obtaining a training set, the training set including multiple training pairs of a training input and corresponding multiple training outputs; and iterating over the training set, including, for each training pair of the training set: evaluating the multi-task neural network for the training input in the training pair, to obtain multiple outputs of the multi-task neural network, computing multiple individual losses for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, computing task weights, including computing raw task weights from the multiple individual losses, and applying a normalization function to the raw task weights, and adjusting parameters of the multi-task neural network based on the computed individual losses weighted by the task weights.
2. The training method as recited in claim 1, wherein the normalization function is a probability distribution function.
3. The training method as recited in claim 1, wherein the normalization function includes at least one of: SoftMax, Temperature-Scaled SoftMax, soft-margin SoftMax, Taylor SoftMax.
4. The training method as recited in claim 1, wherein the multiple task weights are chosen to scale the corresponding multiple individual losses to a constant.
5. The training method as recited in claim 1, wherein a stop gradient operator is applied to the multiple task weights.
6. The training method as recited in claim 1, wherein the iterations over the training set are batched, the multiple individual losses being computed for a batch of training pairs and averaged to obtained batched individual losses, the raw task weights being computed from the batched individual losses.
7. The training method as recited in claim 1, wherein the training input includes at least image data, and wherein: at least one of the multiple training outputs classify an object in the image data,

and/or at least one of the multiple training outputs comprise estimated depth for the image data, and/or at least one of the multiple training outputs comprise an object segmentation for the image data.

8. The training method as recited in claim 1, wherein the training input represents a real-world environment of a mechanical agent operating in the environment, the multi-task neural network being trained to infer a state of the environment and/or of the mechanical agent.

9. The training method as recited in claim 7, wherein the image data includes one or more of: audio data, image data, video data, lidar data, radar data, infrared data, ultrasonic data, sensor data, temperature data, pressure data, electrophysiological recording.

10. The training method as recited in claim 1, wherein the multi-task neural network includes a shared backbone and multiple task-specific heads, the shared backbone being configured to receive the input, the multiple task-specific heads receiving an output of the shared backbone, each one of the multiple outputs being produced by a corresponding one of the multiple task-specific heads.

11. A method for a multi-task neural network, comprising a training phase and an inference phase, wherein: the training phase includes performing a training method for training the multi-task neural network, the multi-task neural network being configured to receive an input and to produce multiple outputs, the multi-task neural network input including dimensional data obtained from a sensor, the training method including the following steps: obtaining a training set, the training set including multiple training pairs of a training input and corresponding multiple training outputs; and iterating over the training set, including, for each training pair of the training set: evaluating the multi-task neural network for the training input in the training pair, to obtain multiple outputs of the multi-task neural network, computing multiple individual losses for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, computing task weights, including computing raw task weights from the multiple individual losses, and applying a normalization function to the raw task weights, and adjusting parameters of the multi-task neural network based on the computed individual losses weighted by the task weights; and the inference phase includes receiving an input, and applying the trained multi-task neural network to the input, to obtaining corresponding multiple outputs of the multi-task neural network.

12. The method as recited in claim 11, wherein the input data represents a real-world environment of a mechanical agent, operating in the environment, the multi-task neural network being trained to infer a state of the environment and/or of the mechanical agent, the inference phase including: deriving a control function of the mechanical agent from one or more of the multiple outputs of the multi-task neural network, the control function configured to be executed by the mechanical agent interacting with the real-world environment.

13. A system comprising: one or more processors; and one or more storage devices storing instructions that, when executed by the one or more processors, cause the one or more processors to perform operations for a method for training a multi-task neural network, the multi-task neural network being configured to receive an input and to produce multiple outputs, the multi-task neural network input including dimensional data obtained from a sensor, the method comprising the following steps: obtaining a training set, the training set including multiple training pairs of a training input and corresponding multiple training outputs; and iterating over the training set, including, for each training pair of the training set: evaluating the multi-task neural network for the training input in the training pair, to obtain multiple outputs of the multi-task neural network, computing multiple individual losses for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, computing task weights, including computing raw task weights from the multiple individual losses, and applying a normalization function to the raw task weights, and adjusting

parameters of the multi-task neural network based on the computed individual losses weighted by the task weights.

14. A non-transitory computer storage medium encoded with instructions that, when executed by one or more computers, cause the one or more computers to perform a method for training a multi-task neural network, the multi-task neural network being configured to receive an input and to produce multiple outputs, the multi-task neural network input including dimensional data obtained from a sensor, the method comprising the following steps: obtaining a training set, the training set including multiple training pairs of a training input and corresponding multiple training outputs; and iterating over the training set, including, for each training pair of the training set: evaluating the multi-task neural network for the training input in the training pair, to obtain multiple outputs of the multi-task neural network, computing multiple individual losses for the obtained multiple outputs of the multi-task neural network, each individual loss of the multiple individual losses indicating a difference between the output of the multi-task neural network and the corresponding training outputs of the multiple training outputs, computing task weights, including computing raw task weights from the multiple individual losses, and applying a normalization function to the raw task weights, and adjusting parameters of the multi-task neural network based on the computed individual losses weighted by the task weights.
