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Using Imagery to Identify Abandoned Property in Public Spaces

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Overview

Generally, the present disclosure is directed to identifying private property that has been illegally dumped or stored for a prolonged period without use. In particular, in some implementations, the systems and methods of the present disclosure can include or otherwise leverage one or more machine-learned models to predict whether an item has been abandoned in a public right-of-way based on imagery of the item and record of public right-of-way.

Example Figures

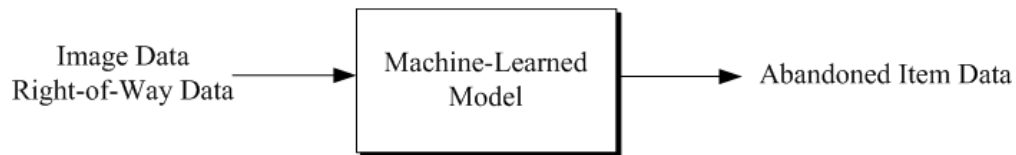


Figure 1

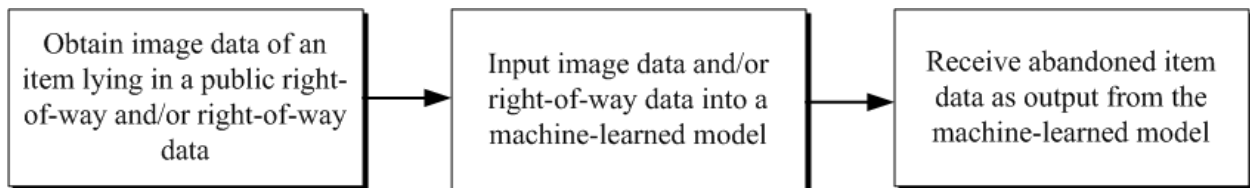


Figure 6

Introduction

Many municipalities have a need to remove abandoned property, e.g. vehicles, trash receptacles, etc., from public spaces, such as parks, roads, public right-of-way areas, etc. Unfortunately, it is often not easy to distinguish between long-abandoned property and in-use property, such as a parked vehicle which may need a parking ticket but is not necessarily abandoned. What is needed is a system to identify property which has been abandoned in a public space.

Summary

Generally, the present disclosure is directed to identifying private property that has been illegally dumped or stored for a prolonged period without use. In particular, in some implementations, the systems and methods of the present disclosure can include or otherwise leverage one or more machine-learned models to predict whether an item has been abandoned in a public right-of-way based on imagery of the item and record of public right-of-way.

A computing system can be provided that can employ a machine-learned model to predict whether an object lying in a public space, such as in a public right-of-way, has been illegally dumped or stored, and/or abandoned. The system can, in some embodiments, provide this information to the group responsible for maintaining the public space, such as a local government or park owner.

The model can use imagery of the object, such as ground-based, satellite, aerial, LiDAR data, or other forms of imagery. The imagery can be aggregated over time, such as over the course of a day, week, month, year, or other suitable time frame. For example, the presence of an

object in a public right-of-way area in only one satellite image may simply indicate, for example, illegal parking or temporary storage of the object. If the same object appears in the image for a year, however, it may be abandoned.

In some embodiments, the model can analyze characteristics of the object, such as a vehicle registry expiration date extracted from the imagery, or a state of wear as depicted by the imagery. For example, if vehicle registry information extracted from an image indicates that a vehicle has a registration expiration date that significantly predates the image, such as a registration that expired in 1995 while the image was taken in 2017, the vehicle may be abandoned.

Information about known events, e.g., construction, in some embodiments in addition to or alternatively to object recognition and/or localization algorithms, can additionally be used in some embodiments to avoid flagging, for example, scaffolding or construction equipment. For example, if it is determined the public right-of-way area is under construction and a road paver is found in a satellite image on the right-of-way area, the road paver may not be determined to be abandoned. Even if construction information is not considered, the model may recognize the presence of a road paver and predict it is not abandoned regardless.

The model can additionally and/or alternatively receive data descriptive of a record of public right-of-way as input data. For example, the record may be a mask overlaying a satellite image, or may be a two-dimensional space laid out in coordinates, among other formats. For example, the record can indicate a geographic space which is reserved for the public right-of-way. The model can be trained to limit its analysis of the imagery to those portions of the

imagery that depict the geographic space that is public right-of-way, thereby improving privacy. Alternatively or additionally, the imagery can be preprocessed to remove any portions of the imagery that do not correspond to the public right-of-way.

In some embodiments, the input data can include a record of whether the area is prone to illegal dumping. For instance, in some embodiments the prediction from the model can be weighted based on past infractions in the area. For example, if an area is known for illegal dumping, the model may predict that an object is abandoned if the object is present in images over a relatively smaller time interval, or may extend the time interval for an area not known for illegal dumping or abandonment of objects.

The model can output predictions about abandoned items included in the imagery. For example, the model can output a bounding box that indicates the location within provided imagery of abandoned items within the public right-of-way. As another example, the model can provide a confidence value descriptive of a level of confidence in marking a certain item as abandoned. As another example, the model can predict for how long the item has been abandoned at its current location.

The model can be trained on imagery labeled with known instances of abandoned items. As one example, the machine-learned model can be an artificial neural network, such as, for example, a recurrent neural network.

Thus, the system can identify and/or assist in the removal of abandoned items within a public space, such as in a public right-of-way. This can help the group responsible for managing the public space keep the space free of unwanted objects without accidentally removing an in-use

item.

Detailed Description

As described above, the present disclosure is directed to identifying private property that has been illegally dumped or stored for a prolonged period without use. In particular, in some implementations, the systems and methods of the present disclosure can include or otherwise leverage one or more machine-learned models to predict whether an item has been abandoned based on imagery of the item and record of public right-of-way.

Figure 1 depicts a block diagram of an example machine-learned model according to example implementations of the present disclosure. As illustrated in Figure 1, in some implementations, the machine-learned model is trained to receive input data of one or more types and, in response, provide output data of one or more types. Thus, Figure 1 illustrates the machine-learned model performing inference.

In some implementations, the input data can include one or more features that are associated with an instance or an example. In some implementations, the one or more features associated with the instance or example can be organized into a feature vector. In some implementations, the output data can include one or more predictions. Predictions can also be referred to as inferences. Thus, given features associated with a particular instance, the machine-learned model can output a prediction for such instance based on the features.

The machine-learned model can be or include one or more of various different types of machine-learned models. In particular, in some implementations, the machine-learned model can perform classification, regression, clustering, anomaly detection, recommendation generation,

and/or other tasks.

In some implementations, the machine-learned model can perform various types of classification based on the input data. For example, the machine-learned model can perform binary classification or multiclass classification. In binary classification, the output data can include a classification of the input data into one of two different classes. In multiclass classification, the output data can include a classification of the input data into one (or more) of more than two classes. The classifications can be single label or multi-label.

In some implementations, the machine-learned model can perform discrete categorical classification in which the input data is simply classified into one or more classes or categories.

In some implementations, the machine-learned model can perform classification in which the machine-learned model provides, for each of one or more classes, a numerical value descriptive of a degree to which it is believed that the input data should be classified into the corresponding class. In some instances, the numerical values provided by the machine-learned model can be referred to as “confidence scores” that are indicative of a respective confidence associated with classification of the input into the respective class. In some implementations, the confidence scores can be compared to one or more thresholds to render a discrete categorical prediction. In some implementations, only a certain number of classes (e.g., one) with the relatively largest confidence scores can be selected to render a discrete categorical prediction.

In some implementations, the machine-learned model can provide a probabilistic classification. For example, the machine-learned model can be able to predict, given a sample input, a probability distribution over a set of classes. Thus, rather than outputting only the most

likely class to which the sample input should belong, the machine-learned model can output, for each class, a probability that the sample input belongs to such class. In some implementations, the probability distribution over all possible classes can sum to one. In some implementations, a softmax function or layer can be used to squash a set of real values respectively associated with the possible classes to a set of real values in the range (0, 1) that sum to one.

In some implementations, the probabilities provided by the probability distribution can be compared to one or more thresholds to render a discrete categorical prediction. In some implementations, only a certain number of classes (e.g., one) with the relatively largest predicted probability can be selected to render a discrete categorical prediction.

In some implementations in which the machine-learned model performs classification, the machine-learned model can be trained using supervised learning techniques. For example, the machine-learned model can be trained on a training dataset that includes training examples labeled as belonging (or not belonging) to one or more classes. Further details regarding supervised training techniques are provided below.

In some implementations, the machine-learned model can perform regression to provide output data in the form of a continuous numeric value. The continuous numeric value can correspond to any number of different metrics or numeric representations, including, for example, currency values, scores, or other numeric representations. As examples, the machine-learned model can perform linear regression, polynomial regression, or nonlinear regression. As examples, the machine-learned model can perform simple regression or multiple regression. As described above, in some implementations, a softmax function or layer can be used to squash a

set of real values respectively associated with a two or more possible classes to a set of real values in the range (0, 1) that sum to one.

In some implementations, the machine-learned model can perform various types of clustering. For example, the machine-learned model can identify one or more previously-defined clusters to which the input data most likely corresponds. As another example, the machine-learned model can identify one or more clusters within the input data. That is, in instances in which the input data includes multiple objects, documents, or other entities, the machine-learned model can sort the multiple entities included in the input data into a number of clusters. In some implementations in which the machine-learned model performs clustering, the machine-learned model can be trained using unsupervised learning techniques.

In some implementations, the machine-learned model can perform anomaly detection or outlier detection. For example, the machine-learned model can identify input data that does not conform to an expected pattern or other characteristic (e.g., as previously observed from previous input data). As examples, the anomaly detection can be used for fraud detection or system failure detection.

In some implementations, the machine-learned model can provide output data in the form of one or more recommendations. For example, the machine-learned model can be included in a recommendation system or engine. As an example, given input data that describes previous outcomes for certain entities (e.g., a score, ranking, or rating indicative of an amount of success or enjoyment), the machine-learned model can output a suggestion or recommendation of one or more additional entities that, based on the previous outcomes, are expected to have a desired

outcome (e.g., elicit a score, ranking, or rating indicative of success or enjoyment). As one example, given input data descriptive of a number of products purchased or rated highly by a user, a recommendation system can output a suggestion or recommendation of an additional product that the user might enjoy or wish to purchase.

In some implementations, the machine-learned model can act as an agent within an environment. For example, the machine-learned model can be trained using reinforcement learning, which will be discussed in further detail below.

In some implementations, the machine-learned model can be a parametric model while, in other implementations, the machine-learned model can be a non-parametric model. In some implementations, the machine-learned model can be a linear model while, in other implementations, the machine-learned model can be a non-linear model.

As described above, the machine-learned model can be or include one or more of various different types of machine-learned models. Examples of such different types of machine-learned models are provided below for illustration. One or more of the example models described below can be used (e.g., combined) to provide the output data in response to the input data. Additional models beyond the example models provided below can be used as well.

In some implementations, the machine-learned model can be or include one or more classifier models such as, for example, linear classification models; quadratic classification models; etc.

In some implementations, the machine-learned model can be or include one or more regression models such as, for example, simple linear regression models; multiple linear

regression models; logistic regression models; stepwise regression models; multivariate adaptive regression splines; locally estimated scatterplot smoothing models; etc.

In some implementations, the machine-learned model can be or include one or more decision tree-based models such as, for example, classification and/or regression trees; iterative dichotomiser 3 decision trees; C4.5 decision trees; chi-squared automatic interaction detection decision trees; decision stumps; conditional decision trees; etc.

In some implementations, the machine-learned model can be or include one or more kernel machines. In some implementations, the machine-learned model can be or include one or more support vector machines.

In some implementations, the machine-learned model can be or include one or more instance-based learning models such as, for example, learning vector quantization models; self-organizing map models; locally weighted learning models; etc.

In some implementations, the machine-learned model can be or include one or more nearest neighbor models such as, for example, k-nearest neighbor classifications models; k-nearest neighbors regression models; etc.

In some implementations, the machine-learned model can be or include one or more Bayesian models such as, for example, naïve Bayes models; Gaussian naïve Bayes models; multinomial naïve Bayes models; averaged one-dependence estimators; Bayesian networks; Bayesian belief networks; hidden Markov models; etc.

In some implementations, the machine-learned model can be or include one or more artificial neural networks (also referred to simply as neural networks). A neural network can

include a group of connected nodes, which also can be referred to as neurons or perceptrons. A neural network can be organized into one or more layers. Neural networks that include multiple layers can be referred to as “deep” networks. A deep network can include an input layer, an output layer, and one or more hidden layers positioned between the input layer and the output layer. The nodes of the neural network can be connected or non-fully connected.

In some implementations, the machine-learned model can be or include one or more feed forward neural networks. In feed forward networks, the connections between nodes do not form a cycle. For example, each connection can connect a node from an earlier layer to a node from a later layer.

In some instances, the machine-learned model can be or include one or more recurrent neural networks. In some instances, at least some of the nodes of a recurrent neural network can form a cycle. Recurrent neural networks can be especially useful for processing input data that is sequential in nature. In particular, in some instances, a recurrent neural network can pass or retain information from a previous portion of the input data sequence to a subsequent portion of the input data sequence through the use of recurrent or directed cyclical node connections.

As one example, sequential input data can include time-series data (e.g., sensor data versus time or imagery captured at different times). For example, a recurrent neural network can analyze sensor data versus time to detect or predict a swipe direction, to perform handwriting recognition, etc. As another example, sequential input data can include words in a sentence (e.g., for natural language processing, speech detection or processing, etc.); notes in a musical composition; sequential actions taken by a user (e.g., to detect or predict sequential application

usage); sequential object states; etc.

Example recurrent neural networks include long short-term (LSTM) recurrent neural networks; gated recurrent units; bi-direction recurrent neural networks; continuous time recurrent neural networks; neural history compressors; echo state networks; Elman networks; Jordan networks; recursive neural networks; Hopfield networks; fully recurrent networks; sequence-to-sequence configurations; etc.

In some implementations, the machine-learned model can be or include one or more convolutional neural networks. In some instances, a convolutional neural network can include one or more convolutional layers that perform convolutions over input data using learned filters. Filters can also be referred to as kernels. Convolutional neural networks can be especially useful for vision problems such as when the input data includes imagery such as still images or video. However, convolutional neural networks can also be applied for natural language processing.

In some implementations, the machine-learned model can be or include one or more generative networks such as, for example, generative adversarial networks. Generative networks can be used to generate new data such as new images or other content.

In some implementations, the machine-learned model can be or include an autoencoder. In some instances, the aim of an autoencoder is to learn a representation (e.g., a lower-dimensional encoding) for a set of data, typically for the purpose of dimensionality reduction. For example, in some instances, an autoencoder can seek to encode the input data and then provide output data that reconstructs the input data from the encoding. Recently, the autoencoder concept has become more widely used for learning generative models of data. In some instances,

the autoencoder can include additional losses beyond reconstructing the input data.

In some implementations, the machine-learned model can be or include one or more other forms of artificial neural networks such as, for example, deep Boltzmann machines; deep belief networks; stacked autoencoders; etc. Any of the neural networks described herein can be combined (e.g., stacked) to form more complex networks.

In some implementations, one or more neural networks can be used to provide an embedding based on the input data. For example, the embedding can be a representation of knowledge abstracted from the input data into one or more learned dimensions. In some instances, embeddings can be a useful source for identifying related entities. In some instances embeddings can be extracted from the output of the network, while in other instances embeddings can be extracted from any hidden node or layer of the network (e.g., a close to final but not final layer of the network). Embeddings can be useful for performing auto suggest next video, product suggestion, entity or object recognition, etc. In some instances, embeddings be useful inputs for downstream models. For example, embeddings can be useful to generalize input data (e.g., search queries) for a downstream model or processing system.

In some implementations, the machine-learned model can include one or more clustering models such as, for example, k-means clustering models; k-medians clustering models; expectation maximization models; hierarchical clustering models; etc.

In some implementations, the machine-learned model can perform one or more dimensionality reduction techniques such as, for example, principal component analysis; kernel principal component analysis; graph-based kernel principal component analysis; principal

component regression; partial least squares regression; Sammon mapping; multidimensional scaling; projection pursuit; linear discriminant analysis; mixture discriminant analysis; quadratic discriminant analysis; generalized discriminant analysis; flexible discriminant analysis; autoencoding; etc.

In some implementations, the machine-learned model can perform or be subjected to one or more reinforcement learning techniques such as Markov decision processes; dynamic programming; Q functions or Q-learning; value function approaches; deep Q-networks; differentiable neural computers; asynchronous advantage actor-critics; deterministic policy gradient; etc.

In some implementations, the machine-learned model can be an autoregressive model. In some instances, an autoregressive model can specify that the output data depends linearly on its own previous values and on a stochastic term. In some instances, an autoregressive model can take the form of a stochastic difference equation. One example autoregressive model is WaveNet, which is a generative model for raw audio.

In some implementations, the machine-learned model can include or form part of a multiple model ensemble. As one example, bootstrap aggregating can be performed, which can also be referred to as “bagging.” In bootstrap aggregating, a training dataset is split into a number of subsets (e.g., through random sampling with replacement) and a plurality of models are respectively trained on the number of subsets. At inference time, respective outputs of the plurality of models can be combined (e.g., through averaging, voting, or other techniques) and used as the output of the ensemble.

One example model ensemble is a random forest, which can also be referred to as a random decision forest. Random forests are an ensemble learning method for classification, regression, and other tasks. Random forests are generated by producing a plurality of decision trees at training time. In some instances, at inference time, the class that is the mode of the classes (classification) or the mean prediction (regression) of the individual trees can be used as the output of the forest. Random decision forests can correct for decision trees' tendency to overfit their training set.

Another example ensemble technique is stacking, which can, in some instances, be referred to as stacked generalization. Stacking includes training a combiner model to blend or otherwise combine the predictions of several other machine-learned models. Thus, a plurality of machine-learned models (e.g., of same or different type) can be trained based on training data. In addition, a combiner model can be trained to take the predictions from the other machine-learned models as inputs and, in response, produce a final inference or prediction. In some instances, a single-layer logistic regression model can be used as the combiner model.

Another example ensemble technique is boosting. Boosting can include incrementally building an ensemble by iteratively training weak models and then adding to a final strong model. For example, in some instances, each new model can be trained to emphasize the training examples that previous models misinterpreted (e.g., misclassified). For example, a weight associated with each of such misinterpreted examples can be increased. One common implementation of boosting is AdaBoost, which can also be referred to as Adaptive Boosting. Other example boosting techniques include LPBoost; TotalBoost; BrownBoost; xgboost;

MadaBoost, LogitBoost, gradient boosting; etc.

Furthermore, any of the models described above (e.g., regression models and artificial neural networks) can be combined to form an ensemble. As an example, an ensemble can include a top level machine-learned model or a heuristic function to combine and/or weight the outputs of the models that form the ensemble.

In some implementations, multiple machine-learned models (e.g., that form an ensemble) can be linked and trained jointly (e.g., through backpropagation of errors sequentially through the model ensemble). However, in some implementations, only a subset (e.g., one) of the jointly trained models is used for inference.

In some implementations, the machine-learned model can be used to preprocess the input data for subsequent input into another model. For example, the machine-learned model can perform dimensionality reduction techniques and embeddings (e.g., matrix factorization, principal components analysis, singular value decomposition, word2vec/GLOVE, and/or related approaches); clustering; and even classification and regression for downstream consumption. Many of these techniques have been discussed above and will be further discussed below.

Referring again to Figure 1, and as discussed above, the machine-learned model can be trained or otherwise configured to receive the input data and, in response, provide the output data. The input data can include different types, forms, or variations of input data. As examples, in various implementations, the input data can include imagery of an object and record of public right-of-way. The imagery of the object can be one or more of various types of imagery, such as ground-based, satellite, aerial, LiDAR data, or other forms of imagery. The imagery can be

aggregated over time, such as over the course of a day, week, month, year, or other suitable time frame. In some embodiments, the input data can additionally include data about the object extracted from the imagery, such as a vehicle registry expiration date extracted from the imagery, or a state of wear as depicted by the imagery. Information about known events, e.g., construction, in some embodiments in addition to or alternatively to object recognition and/or localization algorithms, can additionally be used in some embodiments to avoid flagging, for example, scaffolding or construction equipment.

The model can additionally and/or alternatively receive data descriptive of a record of public right-of-way as input data. For example, the record may be a mask overlaying a satellite image, or may be a two-dimensional space laid out in coordinates, among other formats. For example, the record can indicate a geographic space which is reserved for the public right-of-way. The model can be trained to limit its analysis of the imagery to those portions of the imagery that depict the geographic space that is public right-of-way, thereby improving privacy. Alternatively or additionally, the imagery can be preprocessed to remove any portions of the imagery that do not correspond to the public right-of-way.

In some embodiments, the input data can include a record of whether the area is prone to illegal dumping. For instance, in some embodiments the prediction from the model can be weighted based on past infractions in the area. In some implementations, the machine-learned model can receive and use the input data in its raw form. In some implementations, the raw input data can be preprocessed. Thus, in addition or alternatively to the raw input data, the machine-learned model can receive and use the preprocessed input data.

In some implementations, preprocessing the input data can include extracting one or more additional features from the raw input data. For example, feature extraction techniques can be applied to the input data to generate one or more new, additional features. Example feature extraction techniques include edge detection; corner detection; blob detection; ridge detection; scale-invariant feature transform; motion detection; optical flow; Hough transform; etc.

In some implementations, the extracted features can include or be derived from transformations of the input data into other domains and/or dimensions. As an example, the extracted features can include or be derived from transformations of the input data into the frequency domain. For example, wavelet transformations and/or fast Fourier transforms can be performed on the input data to generate additional features.

In some implementations, the extracted features can include statistics calculated from the input data or certain portions or dimensions of the input data. Example statistics include the mode, mean, maximum, minimum, or other metrics of the input data or portions thereof.

In some implementations, as described above, the input data can be sequential in nature. In some instances, the sequential input data can be generated by sampling or otherwise segmenting a stream of input data. As one example, frames can be extracted from a video. In some implementations, sequential data can be made non-sequential through summarization.

As another example preprocessing technique, portions of the input data can be imputed. For example, additional synthetic input data can be generated through interpolation and/or extrapolation.

As another example preprocessing technique, some or all of the input data can be scaled,

standardized, normalized, generalized, and/or regularized. Example regularization techniques include ridge regression; least absolute shrinkage and selection operator (LASSO); elastic net; least-angle regression; cross-validation; L1 regularization; L2 regularization; etc. As one example, some or all of the input data can be normalized by subtracting the mean across a given dimension's feature values from each individual feature value and then dividing by the standard deviation or other metric.

As another example preprocessing technique, some or all of the input data can be quantized or discretized. As yet another example, qualitative features or variables included in the input data can be converted to quantitative features or variables. For example, one hot encoding can be performed.

In some implementations, dimensionality reduction techniques can be applied to the input data prior to input into the machine-learned model. Several examples of dimensionality reduction techniques are provided above, including, for example, principal component analysis; kernel principal component analysis; graph-based kernel principal component analysis; principal component regression; partial least squares regression; Sammon mapping; multidimensional scaling; projection pursuit; linear discriminant analysis; mixture discriminant analysis; quadratic discriminant analysis; generalized discriminant analysis; flexible discriminant analysis; autoencoding; etc.

In some implementations, during training, the input data can be intentionally deformed in any number of ways to increase model robustness, generalization, or other qualities. Example techniques to deform the input data include adding noise; changing color, shade, or hue;

magnification; segmentation; amplification; etc.

Referring again to Figure 1, in response to receipt of the input data, the machine-learned model can provide the output data. The output data can include different types, forms, or variations of output data. As examples, in various implementations, the output data can include a prediction of whether an object has been illegally dumped or stored, or otherwise abandoned. For example, the prediction can indicate that an object such as a vehicle has been abandoned as opposed to simply parked, including being parked within a public right-of-way, for a short time with the owner's intent to return to the vehicle.

As discussed above, in some implementations, the output data can include various types of classification data (e.g., binary classification, multiclass classification, single label, multi-label, discrete classification, regressive classification, probabilistic classification, etc.) or can include various types of regressive data (e.g., linear regression, polynomial regression, nonlinear regression, simple regression, multiple regression, etc.). In other instances, the output data can include clustering data, anomaly detection data, recommendation data, or any of the other forms of output data discussed above.

In some implementations, the output data can influence downstream processes or decision making. As one example, in some implementations, the output data can be interpreted and/or acted upon by a rules-based regulator.

Thus, the present disclosure provides systems and methods that include or otherwise leverage one or more machine-learned models to predict whether an item has been abandoned based on imagery of the item and record of public right-of-way. Any of the different types or

forms of input data described above can be combined with any of the different types or forms of machine-learned models described above to provide any of the different types or forms of output data described above.

The systems and methods of the present disclosure can be implemented by or otherwise executed on one or more computing devices. Example computing devices include user computing devices (e.g., laptops, desktops, and mobile computing devices such as tablets, smartphones, wearable computing devices, etc.); embedded computing devices (e.g., devices embedded within a vehicle, camera, image sensor, industrial machine, satellite, gaming console or controller, or home appliance such as a refrigerator, thermostat, energy meter, home energy manager, smart home assistant, etc.); server computing devices (e.g., database servers, parameter servers, file servers, mail servers, print servers, web servers, game servers, application servers, etc.); dedicated, specialized model processing or training devices; virtual computing devices; other computing devices or computing infrastructure; or combinations thereof.

Thus, in some implementations, the machine-learned model can be stored at and/or implemented locally by an embedded device or a user computing device such as a mobile device. Output data obtained through local implementation of the machine-learned model at the embedded device or the user computing device can be used to improve performance of the embedded device or the user computing device (e.g., an application implemented by the embedded device or the user computing device). As one example, Figure 2 illustrates a block diagram of an example computing device that stores and implements a machine-learned model locally.

In other implementations, the machine-learned model can be stored at and/or implemented by a server computing device. In some instances, output data obtained through implementation of the machine-learned model at the server computing device can be used to improve other server tasks or can be used by other non-user devices to improve services performed by or for such other non-user devices. For example, the output data can improve other downstream processes performed by the server computing device for a user computing device or embedded computing device. In other instances, output data obtained through implementation of the machine-learned model at the server computing device can be sent to and used by a user computing device, an embedded computing device, or some other client device. For example, the server computing device can be said to perform machine learning as a service. As one example, Figure 3 illustrates a block diagram of an example client computing device that can communicate over a network with an example server computing system that includes a machine-learned model.

In yet other implementations, different respective portions of the machine-learned model can be stored at and/or implemented by some combination of a user computing device; an embedded computing device; a server computing device; etc.

Computing devices can perform graph processing techniques or other machine learning techniques using one or more machine learning platforms, frameworks, and/or libraries, such as, for example, TensorFlow, Caffe/Caffe2, Theano, Torch/PyTorch, MXnet, CNTK, etc.

Computing devices can be distributed at different physical locations and connected via one or more networks. Distributed computing devices can operate according to sequential

computing architectures, parallel computing architectures, or combinations thereof. In one example, distributed computing devices can be controlled or guided through use of a parameter server.

In some implementations, multiple instances of the machine-learned model can be parallelized to provide increased processing throughput. For example, the multiple instances of the machine-learned model can be parallelized on a single processing device or computing device or parallelized across multiple processing devices or computing devices.

Each computing device that implements the machine-learned model or other aspects of the present disclosure can include a number of hardware components that enable performance of the techniques described herein. For example, each computing device can include one or more memory devices that store some or all of the machine-learned model. For example, the machine-learned model can be a structured numerical representation that is stored in memory. The one or more memory devices can also include instructions for implementing the machine-learned model or performing other operations. Example memory devices include RAM, ROM, EEPROM, EPROM, flash memory devices, magnetic disks, etc., and combinations thereof.

Each computing device can also include one or more processing devices that implement some or all of the machine-learned model and/or perform other related operations. Example processing devices include one or more of: a central processing unit (CPU); a visual processing unit (VPU); a graphics processing unit (GPU); a tensor processing unit (TPU); a neural processing unit (NPU); a neural processing engine; a core of a CPU, VPU, GPU, TPU, NPU or other processing device; an application specific integrated circuit (ASIC); a field programmable

gate array (FPGA); a co-processor; a controller; or combinations of the processing devices described above. Processing devices can be embedded within other hardware components such as, for example, an image sensor, accelerometer, etc.

Hardware components (e.g., memory devices and/or processing devices) can be spread across multiple physically distributed computing devices and/or virtually distributed computing systems.

In some implementations, the machine-learned models described herein can be trained at a training computing system and then provided for storage and/or implementation at one or more computing devices, as described above. For example, a model trainer can be located at the training computing system. The training computing system can be included in or separate from the one or more computing devices that implement the machine-learned model. As one example, Figure 4 illustrates a block diagram of an example computing device in communication with an example training computing system that includes a model trainer.

In some implementations, the model can be trained in an offline fashion or an online fashion. In offline training (also known as batch learning), a model is trained on the entirety of a static set of training data. In online learning, the model is continuously trained (or re-trained) as new training data becomes available (e.g., while the model is used to perform inference).

In some implementations, the model trainer can perform centralized training of the machine-learned models (e.g., based on a centrally stored dataset). In other implementations, decentralized training techniques such as distributed training, federated learning, or the like can be used to train, update, or personalize the machine-learned models.

The machine-learned models described herein can be trained according to one or more of various different training types or techniques. For example, in some implementations, the machine-learned models can be trained using supervised learning, in which the machine-learned model is trained on a training dataset that includes instances or examples that have labels. The labels can be manually applied by experts, generated through crowd-sourcing, or provided by other techniques (e.g., by physics-based or complex mathematical models). In some implementations, if the user has provided consent, the training examples can be provided by the user computing device. In some implementations, this process can be referred to as personalizing the model.

As one example, Figure 5 illustrates a block diagram of an example training process in which a machine-learned model is trained on training data that includes example input data that has labels. Training processes other than the example process depicted in Figure 5 can be used as well.

In some implementations, training data can include examples of the input data that have been assigned labels that correspond to the output data. For instance, training data can include images of objects and records of public right-of-way labelled with whether the object has been abandoned or not. Training data can include images of objects aggregated over time, such as over several days, weeks, or months. For example, training data may include satellite imagery of a vehicle parked on the side of the road over the course of several weeks, and the vehicle may be labelled as abandoned. Training data may additionally and/or alternatively include satellite imagery of an area over the course of several weeks where only one image has a parked vehicle

present in the image. That parked vehicle and/or image may be labelled as not abandoned.

In some implementations, the machine-learned model can be trained by optimizing an objective function. For example, in some implementations, the objective function can be or include a loss function that compares (e.g., determines a difference between) output data generated by the model from the training data and labels (e.g., ground-truth labels) associated with the training data. For example, the loss function can evaluate a sum or mean of squared differences between the output data and the labels. As another example, the objective function can be or include a cost function that describes a cost of a certain outcome or output data. Other objective functions can include margin-based techniques such as, for example, triplet loss or maximum-margin training.

One or more of various optimization techniques can be performed to optimize the objective function. For example, the optimization technique(s) can minimize or maximize the objective function. Example optimization techniques include Hessian-based techniques and gradient-based techniques, such as, for example, coordinate descent; gradient descent (e.g., stochastic gradient descent); subgradient methods; etc. Other optimization techniques include black box optimization techniques and heuristics.

In some implementations, backward propagation of errors can be used in conjunction with an optimization technique (e.g., gradient based techniques) to train a model (e.g., a multi-layer model such as an artificial neural network). For example, an iterative cycle of propagation and model parameter (e.g., weights) update can be performed to train the model. Example backpropagation techniques include truncated backpropagation through time, Levenberg-

Marquardt backpropagation, etc.

In some implementations, the machine-learned models described herein can be trained using unsupervised learning techniques. Unsupervised learning can include inferring a function to describe hidden structure from unlabeled data. For example, a classification or categorization may not be included in the data. Unsupervised learning techniques can be used to produce machine-learned models capable of performing clustering, anomaly detection, learning latent variable models, or other tasks.

In some implementations, the machine-learned models described herein can be trained using semi-supervised techniques which combine aspects of supervised learning and unsupervised learning.

In some implementations, the machine-learned models described herein can be trained or otherwise generated through evolutionary techniques or genetic algorithms.

In some implementations, the machine-learned models described herein can be trained using reinforcement learning. In reinforcement learning, an agent (e.g., model) can take actions in an environment and learn to maximize rewards and/or minimize penalties that result from such actions. Reinforcement learning can differ from the supervised learning problem in that correct input/output pairs are not presented, nor sub-optimal actions explicitly corrected.

In some implementations, one or more generalization techniques can be performed during training to improve the generalization of the machine-learned model. Generalization techniques can help reduce overfitting of the machine-learned model to the training data. Example generalization techniques include dropout techniques; weight decay techniques; batch

normalization; early stopping; subset selection; stepwise selection; etc.

In some implementations, the machine-learned models described herein can include or otherwise be impacted by a number of hyperparameters, such as, for example, learning rate, number of layers, number of nodes in each layer, number of leaves in a tree, number of clusters; etc. Hyperparameters can affect model performance. Hyperparameters can be hand selected or can be automatically selected through application of techniques such as, for example, grid search; black box optimization techniques (e.g., Bayesian optimization, random search, etc.); gradient-based optimization; etc. Example techniques and/or tools for performing automatic hyperparameter optimization include Hyperopt; Auto-WEKA; Spearmint; Metric Optimization Engine (MOE); etc.

In some implementations, various techniques can be used to optimize and/or adapt the learning rate when the model is trained. Example techniques and/or tools for performing learning rate optimization or adaptation include Adagrad; Adaptive Moment Estimation (ADAM); Adadelat; RMSprop; etc.

In some implementations, transfer learning techniques can be used to provide an initial model from which to begin training of the machine-learned models described herein.

In some implementations, the machine-learned models described herein can be included in different portions of computer-readable code on a computing device. In one example, the machine-learned model can be included in a particular application or program and used (e.g., exclusively) by such particular application or program. Thus, in one example, a computing device can include a number of applications and one or more of such applications can contain its

own respective machine learning library and machine-learned model(s).

In another example, the machine-learned models described herein can be included in an operating system of a computing device (e.g., in a central intelligence layer of an operating system) and can be called or otherwise used by one or more applications that interact with the operating system. In some implementations, each application can communicate with the central intelligence layer (and model(s) stored therein) using an application programming interface (API) (e.g., a common, public API across all applications).

In some implementations, the central intelligence layer can communicate with a central device data layer. The central device data layer can be a centralized repository of data for the computing device. The central device data layer can communicate with a number of other components of the computing device, such as, for example, one or more sensors, a context manager, a device state component, and/or additional components. In some implementations, the central device data layer can communicate with each device component using an API (e.g., a private API).

The technology discussed herein makes reference to servers, databases, software applications, and other computer-based systems, as well as actions taken and information sent to and from such systems. The inherent flexibility of computer-based systems allows for a great variety of possible configurations, combinations, and divisions of tasks and functionality between and among components. For instance, processes discussed herein can be implemented using a single device or component or multiple devices or components working in combination. Databases and applications can be implemented on a single system or distributed across multiple

systems. Distributed components can operate sequentially or in parallel.

In addition, the machine learning techniques described herein are readily interchangeable and combinable. Although certain example techniques have been described, many others exist and can be used in conjunction with aspects of the present disclosure.

Thus, while the present subject matter has been described in detail with respect to various specific example implementations, each example is provided by way of explanation, not limitation of the disclosure. One of ordinary skill in the art can readily make alterations to, variations of, and equivalents to such implementations. Accordingly, the subject disclosure does not preclude inclusion of such modifications, variations and/or additions to the present subject matter as would be readily apparent to one of ordinary skill in the art. For instance, features illustrated or described as part of one implementation can be used with another implementation to yield a still further implementation.

A brief overview of example machine-learned models and associated techniques has been provided by the present disclosure. For additional details, readers should review the following references: *Machine Learning A Probabilistic Perspective* (Murphy); *Rules of Machine Learning: Best Practices for ML Engineering* (Zinkevich); *Deep Learning* (Goodfellow); *Reinforcement Learning: An Introduction* (Sutton); and *Artificial Intelligence: A Modern Approach* (Norvig).

Figures

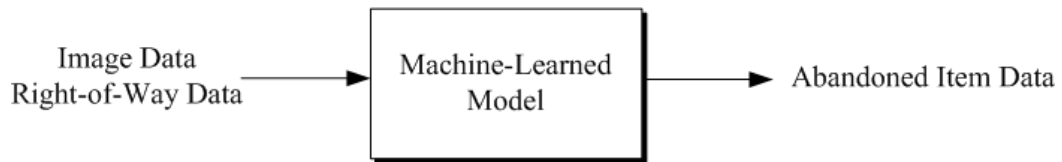


Figure 1

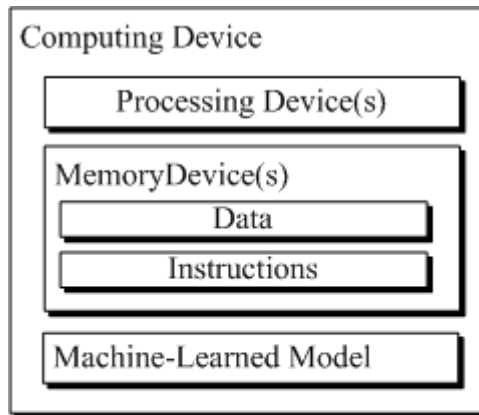


Figure 2

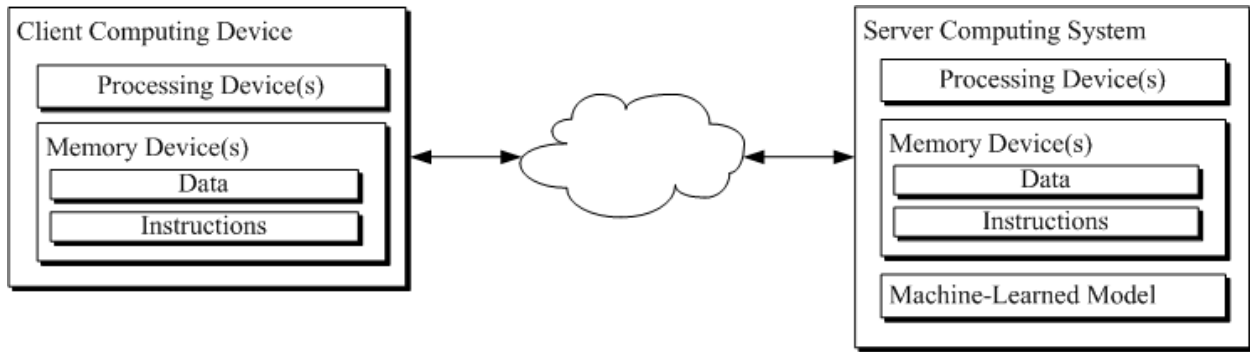


Figure 3

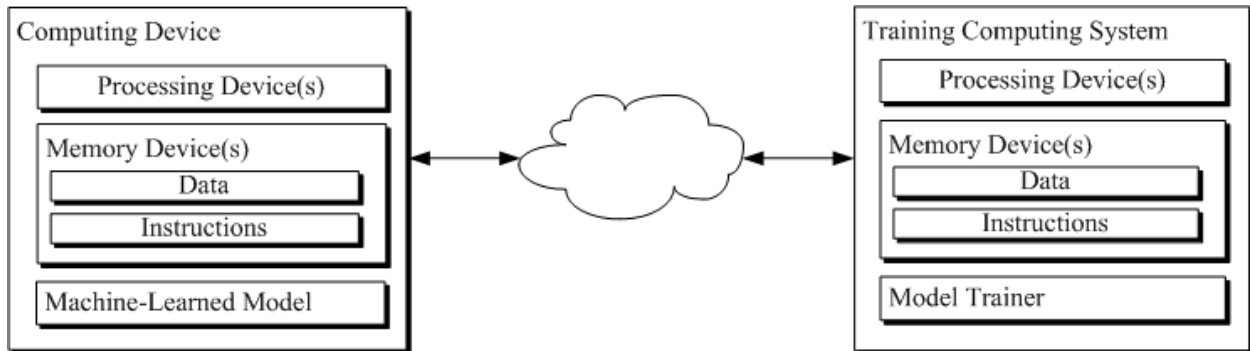


Figure 4

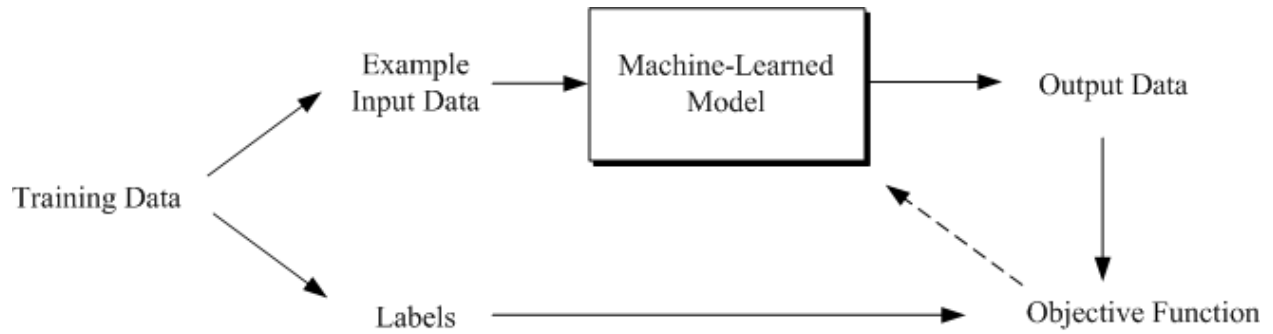


Figure 5

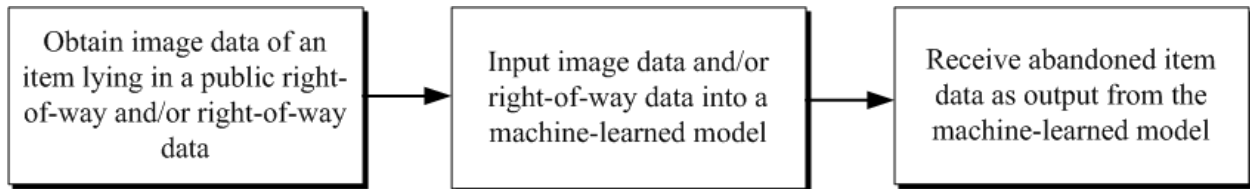


Figure 6