

A Survey of XAI Methods and Use Cases with Autonomous Vehicles

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Abstract—Artificial intelligence and, especially, machine learning have gained notoriety in recent years due to the influx in ways that they impact people’s lives. AI/ML can replace and supplement human experts and provide automation in ways like never before, such as medical diagnosis, smart home technology, and autonomous vehicles. With new roles like these so close to the personal lives of the general public, there has been growing concern from political and technological leaders about putting too much trust in the automated decision-making process of AI/ML systems or about the biases that they can learn through the training process. The internals of some AI/ML methods are inherently difficult to interpret, e.g. deep neural networks. The combination of the societal interest in making AI/ML systems more accountable combined with the difficult-to-interpret nature of some decision systems has brought about a new field of research frequently referred to as explainable artificial intelligence, or XAI. There is currently sparse literature on the overlap between XAI and autonomous vehicles. In this survey, the relationship between the demand for and value provided by XAI is explored, and we align those use cases with the various backgrounds of engineers, consumers, and auditors of autonomous vehicle technology.

I. INTRODUCTION

A. History and Concepts

Machine learning and artificial intelligence (AI/ML) have gained mainstream attention as consumer products featuring these technologies permeate into everyday life. Healthcare, transportation, supply chains, stock markets, social media, national security, genetic engineering, political science, and smart homes are all applying AI/ML to make faster, more accurate decisions and to automate tasks that previously required a human expert [add citations here]. As a wider audience is exposed to AI/ML, new questions are on the tips of people’s tongues, like “what is the difference between artificial intelligence and machine learning?” and “do I need to be worried about computers making decisions that directly impact my health, security, and privacy?”.

Artificial intelligence is a broad term with an amorphous definition that changes over time, but machine learning can be more explicitly defined: machine learning is the algorithmic processing of training data to create a computer program that can be used for repeatable tasks, such as making decisions or extracting insights from data. In this sense, the computer can said to be “learning” by looking at existing data and by creating a model that can be applied to new data. While the term “machine learning” has been added to the English lexicon only recently, the foundation of machine learning was paved as far back as the 19th century. Linear regression has its roots in

the work of mathematicians Legendre and Gausse in the early 1800s [add citation], and even the hot topic of training neural networks was published in the 1970s [1]. The catalyst for bringing these methods to the forefront of modern methods of AI and automation is the combination of the broad availability of data and powerful data centers of compute resources to actually perform large scale AI/ML activity. Despite “AI” being directly in the name of XAI, the field is typically more focused on so-called “black box” machine learning models, such as deep neural networks.

Deep learning is a relatively new branch of machine learning methods based off the older concept of neural networks. Thanks to advancement in GPU technology, the training of deeper, more complex neural networks has become affordable and available to common individuals, such as researchers, hobbyists, and data science professionals. These deep neural networks (DNN) excel at optimizing the relationship between input and output variables from the training data without any input from a human expert describing rules or conditions. This process of training a DNN inevitably creates a model whose internals are not able to be understood via human inspection. While the internals of the model are opaque, the optimized relationship that the model learned from the training data is able to quickly make decisions without ever having received any direct rules or instructions, making it ideal in situations like computer vision and natural language processing where explicit rules are difficult to define.

Through progress and controversy, artificial intelligence and machine learning are interfacing with more people in more ways every year, and there is a general awareness being raised about the legitimate concerns of the trustworthiness and accountability of these technologies. Medical diagnosis, autonomous vehicles, and national security are just a few examples of ways in which machine learning can directly impact the health and well being of individuals’ lives. XAI is a new tool in the frontier of establishing traceable, trustworthy, and accountable decision systems.

*** This section should likely have something about autonomous vehicles in society ***

B. Organization of Paper

This paper is organized into the following sections.

- *Background:* Specifically, what are existing methods of XAI? Also, there are existing literature surveys with their own perspectives.
- *Use Cases:* Methods of XAI can be used to benefit users with a wide variety of backgrounds. We identify

four general use cases for data scientists, consumers, and auditors of AI/ML systems.

- *Alignment with Autonomous Vehicles:* The perspectives of both engineers and consumers of autonomous vehicles (AV) are considered as the relationship between XAI and AV are explored.
- *Challenges:* XAI is a relatively young field, lacking formality, and there are several legitimate criticisms against it. It is important to recognize the shortcomings of XAI and assess the current feasibility and progress in overcoming its obstacles.
- *Conclusion and Future Research:* A summary of the alignment between XAI and AV is presented along with an outline of how identified obstacles may be approached in the future.

II. BACKGROUND

XAI is the interpretation and explanation of machine learning models. In order to go further, the concepts of "interpretation" and "explanation" warrant a more formal definition:

- an **interpretation** is the mapping of an abstract concept (e.g. a predicted class) into a domain that the human can make sense of, and
- an **explanation** is the collection of features of the interpretable domain, that have contributed for a given example to produce a decision (e.g. classification or regression) [2].

Interpretations can be presented in the form of a heat map layer on an image, as natural language generated to either describe a decision or to describe a boundary of what a model can or cannot do, or as an easier-to-explain model, such as a decision tree. An explanation is the relationship between a human-interpretable concept, such as words or shapes, and some aspect of a machine learning model, such as how or why a decision was made. There is ambiguity and a lack of formality around the concept of an explanation that is discussed further in V *Challenges in XAI*.

Some trained ML models may have easier-to-explain internals than others. Decision trees are a common example of an explainable ML model. The output of the decision tree can be directly traced back to identify the values of specific features that lead the model to its decision. On the other hand, the internals of DNNs, by default, are opaque and are not directly interpretable. Any node in the output layer of a neural network has many inputs with many weights, each of which may have many more inputs with many weights. The value of a single input feature can propagate through potentially every node in a neural network, making it challenging to isolate the contribution of the value of a single feature in the decision of the model. In addition to the challenge in tracing a single feature through the a DNN, a single feature, such as the pixel in an image, may not have an isolated interpretation for humans to understand. In that sense, the relevancy of an isolated input feature may not have meaning or value from a human's perspective. Other difficult-to-explain machine learning models include support vector machines (SVM), random forests, and Gaussian belief networks.

There are various methods of XAI that can be applied in machine learning, both during or after the training of the ML model. *A priori* methods are those in which a traditionally black box model can be constructed in such a way that it either is easier to explain with other methods or can generate an explanation alongside its traditional output. Examples of generated explanations include using a LSTM DNN alongside a CNN to generate natural language explanations [3] or embedding prototypes of outputs classes directly in the CNN [4]. *A posteriori* methods of XAI include visualizations techniques such as Deep Taylor decomposition and Layer-wise Relevance Propagation to generate heat maps that can be over-layed on the original input to help identify patterns in the relevancy of input features, such as highlighting shapes or regions that either supported or detracted from the network's decision.

In this section, methods of XAI are organized into the types of artifacts that are generated: visualization, verbalization, data provenance, and model induction.

A. Visualization Techniques

1) *LRP:* Layer-wise relevance propagation (LRP) is an a posteriori method of generating heat maps, or saliency maps, to highlight the positive and, sometimes, negative relevancy of input features in the output layer, or decision, of a DNN. LRP is functionally a backward pass of the output layer back through the neural network to the input layer. At its core, LRP is not a mathematical function but a set of constraints that defines properties of the relationship between layers in a DNN. Data scientists can substitute existing or new activation functions to apply different highlight with different levels of sensitivity the relationship between the input and output layers of the DNN.

The heat maps generated by LRP are not limited to image inputs. Researchers have applied heat maps generated by LRP to natural language, genetic sequences, and 3D models of molecules [2].

2) *Activation maximization:* Activation maximization is an a posteriori method for generating an input for a model that maximizes the activation of a specific output neuron[5], such as a class label. In theory, the input that maximizes the output would be some sort of ideal or target input, but in practice, the input that maximizes the activation of a neuron may not resemble other similar training samples. Further literature searching needs to be done in this area to identify cases in which valuable relationships were discovered via AM.

3) *Prototypes in CNNs:* Thus far in research, the concept of building a CNN with a prototype layer has been applied in image classification tasks. A prototype is essentially an image of one of the target labels of the classifier. The prototype image can either be a subset of an image from the training data or it can be images of the subject class from outside of the training data. When the prototype layer is constructed from subsets of training images, the theory is that each prototype represents some interpretable, defining characteristic of the class, such as a color pattern on a bird or the shape of ears on a bear.

Once a CNN has been constructed using a prototype layer, a data scientist can inspect the activation of various prototypes

from that layer to gain insights into the importance of those characteristics in the CNN's decision.

B. Verbalization of Explanations

1) *Generating explanation in parallel*: Verbalization of CNN decisions [3]

2) *Counterfactual explanations*: An introduction of counterfactual explanations as a method of explaining decisions without interpreting "black box" internals [6]

3) *Rule-based decision systems*: While rule-based decision systems may not be the result of a machine learning method of training, these rule-based systems excel at verbal explanations. Soar is a good example of this.

C. Data Provenance

While other methods of XAI mostly focus on interpreting or explaining a model's decision based on evaluating new input, data provenance can explain how a model was created or how the training data relates to a decision. Applying the principles of data provenance to the development of ML models establishes transparent data lineage throughout the life cycle of the data. Being able to trace the history of the data provides benefit particularly for data scientists and auditors of ML systems. Data scientists can develop ML models more collaboratively when they are able to log and share the various steps that have been applied in their workflows and their results, and auditors may analyze the history of the data to help identify potential issues with bias or discrimination. If an opportunity to reduce bias or discrimination is discovered, then having a healthy lineage of the data should help data scientists in reducing effort in training a new model by exercising lessons learned and observations from previous development.

The taxonomy of concepts of data provenance may be high-level or even vague at times, but the core concepts lend themselves well to practical usage, such as the modeling, capturing, and persisting metadata [7]. There exist many tools for generic data provenance activities, like managing the overhead and the scaling of metadata capture [8] or capturing data lineage by wrapping ETL pipelines [9]; however, there are also software tools that are establishing themselves as ML-centric by integrating directly with existing ML libraries or offering their own libraries for common ML activity. MLflow is a python library that provides metadata logging and collaboration features by integrating with common ML libraries, including Tensorflow, scikit-learn, Spark ML, and PyTorch [10]. H2O.ai is a platform that focuses more inter-language operability by providing python, scala, R, and java APIs for their data provenance platform which includes libraries for feature extraction, dimension reduction, classification, and other common activities for training models [11]. Software tools and libraries for machine learning are becoming more accessible to wider audiences of data scientists, and there is industry demand for data provenance solutions that support heterogeneous machine learning platforms [12].

D. Model Induction

Model induction is the creation of a more explainable model, such as a decision tree, from a black box model, such as a DNN. Model induction can be limited by the domain of the features. For example, decision trees of pixel patterns in a computer vision model may not provide additional interpretability.

E. Existing Surveys in XAI

Although XAI is a relatively young field of research, appearing in publications circa 2016, there are at least hundreds of publications on the topic along with accompanying literature surveys that draw from the breadth of research. Surveys vary in their perspective of XAI, the methods used to categorize literature, and the scope of methods that they cover.

Hohman et al. conduct a thorough literature search of visualization techniques of XAI [13]. The authors' perspective begins with an analysis of the taxonomy of questions that can be asked of machine learning models. The visualization techniques are labeled with various helpful metadata, such as what type of visualization is produced, if the XAI method is a priori or a posteriori, and more. This metadata on the visualization techniques allows the reader to easily map the various visualization techniques to the questions that they can answer.

Montavon et al. present a far more focused literature search on a specific method of visualization in XAI and how it has been applied by other researchers, which domains, and to what ends [2]. For a large portion of the paper, the method of Layer-wise Relevance Propagation (LRP) is broken down into its core mathematical principles so and trace those principles through a conceptual CNN to demonstrate how LRP may be applied to generate heat maps of input features to understand feature relevancy. The authors provide examples of LRP being applied in domains such as computer vision, genetic engineering, and chemistry.

The approach of Abdul et al. is to plot the relationship of topics around the interpretation and explanation of machine learning through the use of network graph visualizations [14]. This contribution to the surveying of XAI literature provides a much needed compass since the terminology in XAI, and even the name of the field itself, is still evolving rapidly. We can also observe the relationship of topics in XAI as they weave through such domains as psychology, human-computer interaction, and the sociological aspects of accountability and fairness.

Guidotti et al. take a more broad approach to XAI methods by analyzing to what type of ML models have researchers been applying explanation methods, what were the interpretable domains of their inputs (e.g. images, natural language), and what methods of explanation were applied [15]. In this survey, a unique amount of attention was paid to methods of rule or model extraction, in which data scientists can extract a decision tree model or natural language rules as approximations of the original ML model.

Adadi et al. also take look at the methods of XAI as a whole and describe considerable detail on the non-visualization

methods of XAI [16]. In addition to their discussion on the taxonomy of XAI methods, this survey tracks the history of the terminology around XAI, exposing the burgeoning growth of the field and providing insight on the demands being placed on the field. The authors classify the value provided by XAI into four different areas: explain to justify, explain to control, explain to improve, and explain to discover.

In some sense, the abundance of literature in such a short period of time speaks to the demand for further research in the field and to the wide-held interest across people of many backgrounds. Time will tell if XAI can deliver the value that people seek or, maybe, if societal impressions of AI/ML will evolve to no longer be concerned with the inner workings of machine learning.

III. USE CASES

Various methods of XAI have been laid out in the previous section, but the question still remains of how do these methods provide value to scientists, consumers, or society at large. Here, we explore the various users who interface with XAI and what value is provided.

A. As a data scientist, I can use the explanation of a model's decisions to identify opportunities to improve the training data set and make the model more robust

This use case takes an *a posteriori* approach to identifying opportunities to improve a model's performance. In current literature, the XAI methods involved are commonly visualization techniques, but other methods are still applicable. Due to the subjective nature of interpretation methods like visualization of relevant features, any action in improving the training of a model requires a human expert to analyze the explanation for potential weaknesses in the model's decision process.

In one example of improving a model through the identification of relevant features, a group of researchers used a Fisher Vector classifier on the PASCAL VOC 2007 data set [17]. After applying LRP to as a tool in explaining the classifier's decisions, it was apparent that the copyright watermark on images of horses was highly relevant in the Fisher Vector model. The researchers then removed the copyright watermark before retraining the model, and future decisions considered the horse and its surroundings as more relevant features.

- Liu et al focus on interpreting the decisions of a model used to identify cyber security threats [18]. The researchers interpret the model's decisions that failed to successfully label threats. The interpretations help the researchers identify how to generate specific perturbations in the training data that improve the training of the model against previously misidentified threats. The accuracy of the model improves.
- LAMP is a tool that can trace the decision of a trained model to the importance that individual samples had on that decision. [19]

B. As a potential consumer of an AI/ML product, such as an autonomous vehicle or virtual assistant, an explanation of how the product is making its decisions will improve my trust in the product

The psychological study of the trustworthiness of AI systems is as old as AI itself. There are lots of concepts here; check out some of Mueller's work on XAI (big paper in Mendeley). The two papers in the outline here are great examples, but it would be good to tie it back into HCI/HMI/psychology of AI systems, right? I think there are actually quite a few papers like that in Mendeley, too, in the "XAI & AV" directory.

- Human subjects are asked about how much they trust a classifier before and after its explanations are made available [20]. The image of a dog was misclassified as a wolf via an intentionally bad model, and a small set of human subjects trusted the classifier more after it was revealed that snow was apparently a feature rather than the shape, size, or color of the animal.
- Decisions from autonomous vehicles and advanced driver assistance systems (ADAS) may be explained using XAI methods to answer the questions "How?" and "Why?". Koo et al measure both the emotional impact and impact in making safer decisions when drivers are provided answers to these questions [21]

C. As a provider of an AI/ML product, I am responsible for providing an explanation for how my product makes its decisions in the case of being the subject of scrutiny, legal or otherwise

While legislation such as the EU's General Data Protection Regulation's "right to explanation" faces legitimate criticism about its scope and ability to be enforced [?], there exist non-legal reasons as well for providers of AI/ML products to provide explanations for their systems' decisions. Products and services infused with machine learning, such as autonomous vehicles, face challenges in establishing trust with consumers, and a product that has the ability to provide human-interpretable explanations for its decisions may gain a market advantage over its competitors. Autonomous vehicles and vehicles with ADAS from Tesla, Google, and GM Cruise have been involved with numerous traffic incidents, ranging from trivial to fatal [22] [23] [24] [25]. There also exist an ethical directive to identify discriminatory bias in ML systems. For example, in the criminal justice system, judges and parole boards may apply predictive models as tools in making their decisions, but racial discrimination has been uncovered in such tools [26] [27].

- Human subjects conduct fictitious banking scenarios, both with and without discrimination-aware data mining (DADM) tools [28]. The accuracy and presence of discrimination in decisions was compared across tools.
- A magazine article describes the GDPR's "right to explanation" and includes a survey of research in identifying and rectifying discrimination [29]

IV. ALIGNMENT WITH AUTONOMOUS VEHICLES

Machine learning is all up in autonomous vehicles. It is used in the perception tasks such as segmentation of entities from sensor data. Machine learning is also used in the decision layer of the autonomous vehicle that chooses the safest route to the destination. Where ever there is machine learning, there is an opportunity to apply XAI.

The three use cases defined in III each can be applied in the context of autonomous vehicles. The development process of the ML systems in the vehicle can be strengthened by data provenance techniques that improve collaboration or also by using explanations to identify opportunities to improve predictive models. Potential consumers of autonomous vehicles may feel safer when the vehicle can provide verbal explanations of the decisions that it is making. And automakers may be inclined or, potentially, required to be able to provide explanations to legal or auditory queries for the decisions made by their autonomous systems.

There is existing research in the field of applying XAI methods in the space of autonomous vehicles, but there is much uncertainty in the scope of the relationship between these two areas. Legal responsibilities are sometimes unclear or poorly defined for autonomous vehicle manufacturers, and the relationship between humans and AI systems is ever evolving. It is important for researchers to forge ahead on incorporating XAI concepts in autonomous vehicles before the demand arises, not in response to it.

A. Existing Research

In one study, research subjects participated in a driving simulator in which the vehicle had a semi-autonomous feature that would initiate hard braking events in the case of an unforeseen obstacle in the path of the vehicle [21]. Researchers programmed the simulator to provide different types of verbal explanations for the hard brake events. Survey responses from the research subjects showed that drivers had not only more positive emotional responses when more descriptive explanations were provided by the semi-autonomous system, but there was also measurably safer driving habits observed by the drivers when they received rich explanations that described not only how the vehicle was behaving but also why it was choosing those behaviors.

It is not uncommon for researchers to generate saliency maps of feature importance when doing computer vision tasks with deep neural networks. These feature saliency maps can overlay neatly over the original image to help developers of these decision systems to identify if the responses from the neural network are behaving as expected. Bojarski et al. developed a method of generating saliency maps called VisualBackProp [30] and apply it to an end-to-end autonomous driving system called PilotNet. PilotNet can decide steering wheel angles given input images, bypassing the need for an intermediate perception phase that identifies segmented objects in images before making decisions. VisualBackProp confirms that PilotNet is making decisions based on human-understandable features in the images, such as the boundaries

of the road, lane markers, and the boundaries of other vehicles on the road (see figure 1) [31].

Using visual explanations to explain the decisions of a trained model has multiple drawbacks which can be ameliorated with the emerging method of verbalization in XAI. While saliency maps may give insight into how a model is responding to a single input, both humans and autonomous systems make decisions based on information over time. Also, the interpretation of a visual explanation is subjective to the human audience; different observers may draw different or no insights from a single visual explanation. Kim et al. train a LSTM neural net on a dataset of images over time accompanied by human-labeled explanations of the current driving behavior [32]. The output layer of this trained model labels images over time with descriptive natural language of the driving behavior. Provided as input into this verbalization model are "attention" maps of regions in the images that are identified as important features. These regions of high and weak attention are generated from a CNN that is used to decide acceleration and course change behavior given input images. The objective of Kim et al. of explaining a limited set of automated behavior in an autonomous vehicle via visual explanations is similar to the work of Bojarski et al [31], but the concept is taken further by generating natural language responses to the feature relevances over time.

B. Gaps and Method Alignment

One of the most explicit use cases for applying XAI methods to the development of autonomous vehicles is in the support of researchers and engineers who are developing machine learning models, especially in the perception and decision systems of the autonomous vehicle. In III Use Cases, we identified examples of data scientists using explanations of non-intuitive, black-box ML models to improve how the models were trained and thus improve the performance of the models. While some researchers have applied XAI to CNNs that were used in an end-to-end system to decide steering angles [31], there was no published research found at the time of this writing on applying XAI towards the improvement of CNNs being applied in the perception system of autonomous vehicles for tasks such as object detection and object segmentation. Deep reinforcement learning is an emerging field for training the decision systems of autonomous vehicles [citation needed], and the resulting deep q-networks (DQNs) have not been explored for explaining their decisions onto a human-interpretable domain.

(Move this to section on legal/ethical obligations to explaining ML systems) Besides using explanations to discover opportunities to improve models, there is no published research on the application of data provenance as a tool to assist with the ML workflow of developers of autonomous vehicles by creating

How do we approach this section??? Potential idea: talk about each of the three use cases in turn, addressing which items in the background can be applied to that use case that haven't been done yet. *Demonstrate the need or value of doing so*. Another idea: walk through the applications of XAI



Fig. 1. Bojarski et al. generate saliency maps of input features in their end-to-end autonomous driving system [31]

in AV outlined in the second paragraph of the intro of this section

- There are a couple papers about the multimodal sensors in AV, the perception/decision architecture, and a survey of decision
- There are quite a few papers about establishing trust with automated systems, AI, and HCI. Is there a gap in establishing trust that has not been addressed in previous research?
- Might have to put the legal/auditory use case on the back burner...way out of scope for my expertise at this time.

V. CHALLENGES IN XAI

These challenges are important, but make sure to relate them back to the existing and proposed research in XAI/AV.

- Feature relevancy can be compromised by using a mask on the input that is virtually undetectable to the human eye [33].
- The concept of an explanation is subjective; there is no quantitative way of saying "yes, this decision is explained" or "no, this decision is not explained." [34]
- Due to the diverse audience of XAI, an explanation may be too technical or not technical enough to people of

different backgrounds.

- Private industry is rarely incentivized to expose algorithms and ML models to researchers [35].
- What exactly is the legal precedent of requiring explanations from ML systems? Is the GDPR's "right to explanation" even enforceable. [36]

VI. CONCLUSION AND FUTURE RESEARCH

Apply XAI to IV *Alignment with Autonomous Vehicles* and also identify V *Challenges in XAI* that may be worked towards.

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