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Fuzzy Logic - Based control for autonomous vehicles in urban environments
(application description)

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Abstract. **Fuzzy logic is a mathematical approach used to model uncertainty in decision-making processes. Fuzzy logic has been widely applied in fields where uncertainties are encountered, such as automatic control, artificial intelligence, shape recognition system, robotics and other fields. Autonomous vehicles are vehicles that are able to move and function without the direct control of the driver. This paper shows how fuzzy logic makes decisions, what are the advantages and disadvantages of such a driving system in urban areas, the results of fuzzy logic "inference" and how fuzzy logic makes decisions instead of humans on the basis of forwarded information from the environment, and specifically the focus is on making decisions about speed and registering obstacles. These results are quite good, but it turns out that they still cannot completely replace humans, especially when it comes to some ethical issues.**

Keywords: Autonomous Vehicle, Fuzzy Logic, Obstacle detection

1. INTRODUCTION

In recent decades, the development of autonomous vehicles has become one of the greatest achievements in the field of transportation. This innovative technology opens up new perspectives for the future of transportation, especially in urban environments. Driving autonomous vehicles in urban environments is a complex challenge due to the presence of numerous variable factors such as traffic congestion, pedestrians, weather conditions, traffic signs and signaling. Fuzzy logic provides a suitable framework for driving autonomous vehicles in such complex environments. Basically, fuzzy logic relies on linguistic variables and inference rules to make decisions based on imprecise data [1]. This flexible and adaptive logic allows autonomous vehicles to behave according to changing conditions in urban environments. Using this logic, the aim is to make the autonomous vehicle as independent as possible from the driver and his need to react. The paper focuses on understanding the challenges of autonomous vehicles in urban environments and exploring ways in which fuzzy logic can solve these challenges. In the first part of the paper, the concept of fuzzy logic and its importance in the context of autonomous vehicles is explained. Also, the basics of fuzzy logic and how it can be applied in the management of autonomous vehicles are presented, with special reference to the urban environment. Safety and reliability of autonomous vehicles are also key aspects in this paper. The paper presents concrete examples of the application of fuzzy logic in driving autonomous vehicles in urban areas and how, with the help of this logic and other parts of the system, the vehicle makes a decision to change the speed or to notice the obstacles it encounters. The central place in the paper is occupied by fuzzy logic for the detection of obstacles and speed control in the urban environment, the description and application of fuzzy logic in this process, examples and results, and examples of the implementation made in the Python programming language.Through all these analyzes and examples, the goal is to understand how fuzzy logic can be useful in driving autonomous vehicles in urban environments. The utilization of fuzzy logic technology holds the potential to enhance driving safety, efficiency, and comfort in urban areas by enabling intelligent decision-making based on imprecise data. This technology paves the way for intelligent, autonomous transportation that can adapt driving to different situations and contribute to the sustainability and efficiency of urban transportation systems. The International Federations of Robotics concluded that there have been 19% increase in the use of robots in the vehicle industry with a statistics of 86 200 to 106 300 units in just a space of three years 2004 – 2007 [2], and today these percentages have increased significantly.

2. FUZZY LOGIC

Fuzzy logic is based on clear and precisely determined rules, and rests on set theory. It allows modeling complex systems with uncertain or unclear inputs and making reasonable decisions based on those inputs [3]. An element may or may not belong to a set. Sets have clearly defined boundaries. In fuzzy logic, the belonging of one element to a certain set is not precisely defined, but the belonging is measured in, say, percentages [4]. These membership measures, scaled, can take values from 0 to 1. We use very imprecise sentences every day and they are not useful in fuzzy logic, for this reason we have to give up the binary decision in which something is true or false or black or white and turn it all into fog and "gray color". This logic is very close to the human perception of many things in life. It finds its application in many areas, such as autonomous vehicles systems. Many similar situations that are not clearly separated, which are a mixture of several things, are present around us every day, and fuzzy logic measures the truth of each statement in percentages. Fuzzy sets are the basic elements with which we describe imprecision. A discrete set contains elements with the same properties, while a fuzzy set contains elements with similar properties. The essence is to form a program code that implements the knowledge of an expert about some processes [5]. This system can be seen as a black box in which certain outputs are formed based on the inputs based on the dependence of the input units and the relationships between them.

3. HOW DOES AN AUTONOMOUS VEHICLE WORK?

Driverless vehicles are getting closer to reality. Every major vehicle manufacturer has its own project related to autonomous driving. Some components are already in use today, such as self-parking, automatic braking or cruise control. Autonomous driving technology is not simple. They rely on sensors that collect information from the environment. They use various technologies, such as sensors, cameras, radars, GPS and artificial intelligence, to make real-time driving and navigation decisions. That information is then sent to a very powerful computer unit that processes it [6]. Extremely accurate maps and an internal GPS system are inserted into the computer memory. The sensors use ultraviolet and infrared rays. In addition to sensors, cameras and lidar (Light Detecting and Ranging) are also used to collect information. Lidar is an optical measuring instrument that uses 32 or 64 lasers to measure the distance between objects. This information is needed to create a virtual 3D map [7]. Sensors, cameras and lidar can "see" stationary and moving objects, such as people, animals, obstacles on the road, other vehicles, read traffic signs. The processor processes the data generated in this way, creates a visual image and combines it with preloaded maps.

3.1 Challenges for autonomous vehicles

There are many challenges of operating autonomous vehicles in urban environments and obstacles that these vehicles need to overcome without consequence. Traffic congestion is one of them because urban environments are often characterized by heavy traffic and congestion that can affect the speed of vehicle movement. Autonomous vehicles must be able to adapt to these conditions, making decisions about changing speed, avoiding obstacles and optimizing the path [8]. Then caution towards pedestrians and their unpredictable movements. It is necessary to identify pedestrians, predict their movement and adjust driving in order to ensure the safety of all road users. In this context, fuzzy logic can be useful in analyzing sensor data to identify pedestrians. Just as cars that require a driver and must obey traffic signs, traffic signs and signaling represent a special type of challenge for autonomous vehicles. Correctly interpreting and reacting to traffic signs and signaling is key to safe driving in urban environments. Fuzzy logic can be applied to model and interpret various traffic sign and signaling situations, allowing autonomous vehicles to recognize and properly respond to changes in those situations. Weather conditions, such as rain, snow or fog, can significantly affect driving conditions and require autonomous vehicle driving to be adjusted. Fuzzy logic can be applied to model the effect of weather conditions on vehicle performance and make decisions about optimal speed, braking or steering according to those conditions. Then the traffic flow in urban environments is often variable and unpredictable. Autonomous vehicles must be able to adapt to changes in traffic speed and density to maintain safety and efficiency. All these are challenges that an autonomous vehicle must successfully overcome.

3.2 Advantages and disadvantages of autonomous vehicles

It is almost difficult to talk about the balance between the advantages and disadvantages of such vehicles. One of the reasons is the raising of many ethical questions, so there are differences of opinion in the analysis of those questions. Perhaps the biggest advantage of autonomous vehicles is that you don't need any driving knowledge or a driver's license to own and operate one. Also, autonomous vehicles are programmed to follow traffic regulations and rules that will prevent human error. These vehicles are equipped with sensors that enable quick reactions in critical situations, which a person would not be able to do. Autonomous vehicles can use advanced algorithms for routing and path planning, optimizing traffic flow and reducing congestion. They can communicate with each other and synchronize their movements, thereby reducing road congestion and increasing the overall efficiency of the transportation system. On the other hand, sensor precision, software reliability and solving unpredictable traffic situations have not yet reached high accuracy. Vehicle automation may now be at a transitional level between partial and full automation, but in the coming years, cars will certainly be able to drive independently. Another disadvantage of these vehicles is setting the level of privacy, which is otherwise a huge problem nowadays. Autonomous vehicles generate large amounts of data about users' journeys, locations and habits. This raises issues of privacy and data security, as well as the need for adequate protection of user data. Autonomous vehicles require a high investment in the development, research and implementation of technologies. Currently, the costs of autonomous vehicles are high, making them inaccessible to a wide range of consumers. Also, maintenance and repairs of autonomous systems can also be expensive and demanding. As technology today leads to the loss of many jobs, driving autonomous vehicles can have a negative impact on jobs that are related to driving, such as taxi, truck or bus drivers.

4. FUZZY LOGIC FOR OBSTACLE DETECTION AND SPEED CONTROL IN AN URBAN ENVIRONMENT

In the previous part of the paper, it was shown how fuzzy logic is present in almost the complete system that was created for the functioning of an autonomous vehicle. In the rest of the paper, the emphasis is on the example of the programmer's implementation of fuzzy logic for the management of autonomous vehicles in urban areas. It is described how to build a system for detecting obstacles and making decisions about avoiding collisions, as well as about vehicle speed control.

The vehicle is equipped with sensors that collect data about the environment, including the distance to other vehicles, pedestrians, obstacles and traffic signs *(Figure 1)*. Fuzzy logic is used to process that data and make decisions based on a set of rules. For the implementation that was done, a work-generated dataset was used, with the parameters registered by the mentioned sensors. For this analysis, it is not important that the data are correct, but the emphasis is on fuzzy decision-making based on the transmitted information from sensors located on autonomous cars. Inputs are described using fuzzy sets. Fuzzy set A has a membership function (μ_A) where for each value x from the domain of the phase variable X, a membership to phase set A is assigned, which is a number in the range from 0 to 1 *(1)*.

$$\mu_A(x) : X \rightarrow [0,1] \qquad (1)$$

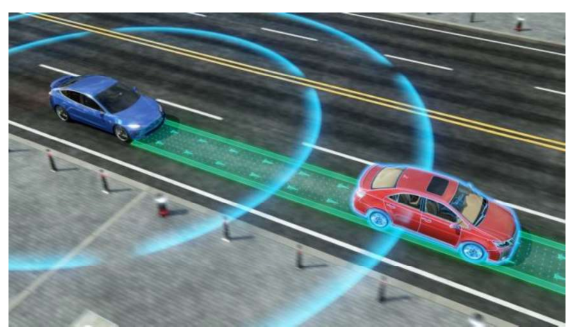

***Figure 1**: Display of data collection using sensors* [9]

The distance to the obstacle can have vague sets of "close", "moderately close" and "far". Then the rules are defined that connect these inputs with the outputs of the system. If the distance to the obstacle is "close" and the vehicle speed is "high", then a decision can be made to brake the vehicle to avoid a collision. After defining inputs, outputs and rules, a fuzzy logic inference process is used to make decisions. This process uses rules and input data to make inferences about how the vehicle should be operated in a given situation. Decisions can be made based on a combination of multiple inputs and rules using fuzzy logic methods, such as maximum or minimum. The principle of maximum is used to combine inputs when the highest value of the input is to be emphasized, while for minimum it is the opposite, the minimum value of the input is emphasized. After the decisions have been made, the outputs are translated back into concrete actions taken by the vehicle. In case the decision is to brake the vehicle, appropriate action is taken to stop the vehicle or reduce speed. All the decisions made are further sent through the system, where the vehicle is enabled to react quickly by executing the order that is the result of fuzzy reasoning.

Below *(Figure 2)* is shown the output of the Python code that enables the input of the parameters registered by the sensors. In order to demonstrate how fuzzy logic makes conclusions in the given example, only two variables were observed, speed and distance, and of course in practice for making a decision with a vehicle it is necessary to observe more factors that influence the decision making, which were mentioned earlier in the paper. From the graph *(Figure 2),* it is possible to estimate how far the input value for distance belongs to the set "close" or "far" by looking at the values on the Y-axis at the point where the X-axis is on that value. Similarly, how far the output value belongs to the "decrease" or "obstacle" set by looking at the values on the Y-axis. The colored/shaded part on the graph represents the intensity area of belonging to a certain set or the resulting set. This is one of the ways of forming fuzzy sets, where in further actions the belonging to the set of all the variables is observed. This part of the graph indicates how high or low a given membership value is for a given set. The colored part is useful because it allows to visually identify the area in which there is a certain value or range of values for the intensity of affiliation. In this way, it can be estimated to which category a certain value belongs based on the intensity of belonging in that area. Drawing a conclusion from the results discussed in this way is precisely the task of fuzzy logic.

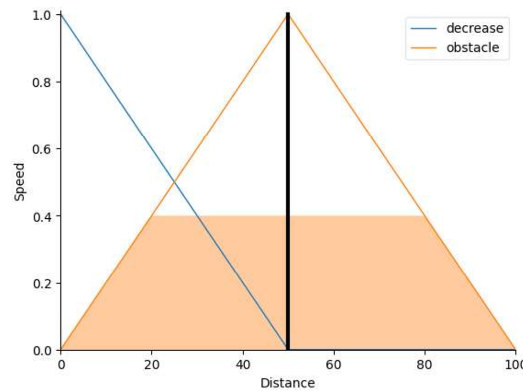

Figure 2*: Vehicle speed control graph*

The basic logic behind fuzzy-logic systems is the application of the operator's expert experience in designing a decision algorithm, whose input-output connections are represented by a collection of IF-THEN fuzzy rules that include fuzzy logic variables. In order to reach the final decision in the aforementioned analysis, this rule was used in the implementation as: IF the speed is low THEN set a high acceleration; which leads to the final decision on speed regulation. It is closely connected with fuzzy inference process which is formulated from fuzzy logic operators and fuzzy If-Then rules. To define consistency of given rules enables decision makers to select more important criteria. Researches on consistency for fuzzy control systems are still scarce [10]. By applying phase linguistic variables, the control rules phase and the approximate reasoning phase, it is possible to incorporate the operator's expert experience into the design of the control algorithm.

4.1 Connection between fuzzy logic and deep learning

Connecting fuzzy logic and deep learning in the context of autonomous vehicles can bring numerous advantages and open up new opportunities. Fuzzy logic is used for high-level decision making, while deep learning is used for low-level object recognition. Fuzzy logic can be used to make decisions about how an autonomous vehicle should react in a given situation based on a higher level of abstraction, while deep learning can recognize objects in the environment such as vehicles, pedestrians or obstacles *(Figure 3).* Deep learning enables the creation of different models that will provide information and results that fuzzy logic can use later to make its decisions. These results are then used as inputs to fuzzy logic for decision making.

***Figure 3*: Example of a learning model** [11]

By combining fuzzy logic and deep learning, one can harness the strengths and versatility of both methodologies. In this context, deep learning can be used to improve object detection, recognize traffic signs and signals, and predict the movement of vehicles and pedestrians *(Figure 4)*. Fuzzy logic provides the ability to make decisions based on human knowledge and rules, while deep learning enables automatic learning of complex patterns and representations from large data sets. This combination can lead to improved performance and reliability of autonomous vehicles in urban environments. Also, this combination is excellent because it combines improvised human reactions and automatic reactions that deep learning models learn. The difference between static and dynamic environments in car object detection is another crucial aspect to consider. In car object detection, the term "static environment" refers to scenarios where the surrounding environment remains relatively unchanged over time. For instance, a parked car on a street or a car in a parking lot can be considered examples of objects in a static environment. In these cases, the primary challenge is accurately detecting and localizing the cars within the scene.On the other hand, a "dynamic environment" refers to scenarios where the surrounding environment is in constant flux.

Figure 4: Example of a learning model [12]

This can include situations such as cars moving on a busy road, where the positions and orientations of cars change rapidly. Detecting objects accurately in dynamic environments poses additional challenges due to motion blur, occlusions, and the need to track objects over time. In order to handle dynamic environments, advanced object detection algorithms incorporate motion modeling and tracking techniques. These techniques aim to predict the future location of objects based on their previous positions and motion patterns. By combining object detection with object tracking, autonomous navigation systems can handle dynamic environments more effectively. Furthermore, dynamic environments require real-time processing and decision-making capabilities to ensure the safe and efficient operation of autonomous vehicles. Processing speed becomes a critical factor in these scenarios, as the system needs to detect and respond to rapidly changing situations in a timely manner.

5. CONCLUSION

In this paper, the application of fuzzy logic in the context of the management of autonomous vehicles in urban environments was studied. The aim of the work is to show how fuzzy logic can be used in this area, then to point out the advantages and disadvantages of this type of transport. Fuzzy logic offers an effective approach for decision-making in the intricate situations that autonomous vehicles face in urban environments. Its connection with deep learning and artificial intelligence makes it a powerful tool for achieving safe and reliable control of autonomous vehicles. Deep learning can be combined with fuzzy logic to draw conclusions based on large amounts of data. This combination allows the autonomous vehicle to learn from experience and adapt to changing conditions in urban environments. It is important to note that the application of mathematics is key in fuzzy logic. Mathematical models and membership functions are used to describe and quantify uncertainty in data and decision making. Mathematical operations such as maximum and minimum are used to combine inputs and apply rules to produce output results. Fuzzy logic provides safety and reliability in the driving of autonomous vehicles, which is crucial for realizing more advanced and efficient transportation systems in urban areas. No one can yet predict when exactly automatic vehicles will take over. Software is powerless to answer driving dilemmas that are easy for humans and these are precisely the obstacles for which it is almost impossible to find a solution because this is the main difference between humans and robots. In the event that the vehicle cannot avoid a collision, is it better to hit a pedestrian or a tree on the side of the road? This significantly complicates the road to full automation of vehicles. Despite the advancements in automation levels, reaching level three, which involves conditional driving automation, remains a partial achievement. The ongoing progress, driven by a combination of fuzzy logic and artificial intelligence, has significantly contributed to this advancement. Whether autonomous vehicles with all their advantages and disadvantages will become part of everyday life is still an open question.

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