An early-warning system for fire spreading by monitoring simple climate conditions and combining Cellular Automata with Digital Twins

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***Abstract*—The present study focuses on the monitoring of interior climate parameters of a building, aiming to provide better situational awareness towards heating efficiency and an early warning system in case of critical accidents, such as fire outbreaks. More specifically, in this paper, a digital twin platform of humidity and temperature conditions in a building interior is proposed, which also provides an early detection and warning in case of fire accidents. Furthermore, for the first time Cellular Automata and Digital Twins are combined to predict and simulate the fire spreading inside the building. The sensor data of temperature and humidity were acquired by an Arduino platform, which transmits the data to the command and control center. On the other hand, the building interior design, the visualization of the outcome to the operator and the simulation of fire spreading were built using the Processing software.**

***Index Terms*—digital twin, fire simulation, monitoring, early-warning, cellular automata**

I. Introduction

In recent decades, new construction techniques and insulating materials have been developed that significantly reduce heat loss in buildings. But still the majority of buildings are old and face serious problems in maintaining proper heating and humidity conditions, which increases the costs of living and may lead in long term corrosion of the building materials and health issues[1]. Advancements in technology and data management can contribute to provide a more efficient monitoring system of climate critical parameters of the interior of buildings such as temperature and humidity. Furthermore, these parameters may also initiate an early warning system for fire outbreaks and dispersion that can provide insight to safe evacuation scenarios. Digital twins, Internet of Things (IoT) and building information modelling (BIM) are widely used by the research community in order to propose an efficient and effective way of indoor parameters monitoring. In [2], a framework for an indoor safety management system is proposed, based on a digital twin, which exploits the Internet of Things (IoT), building information modelling (BIM), the Internet, and support vector machines (SVMs) to improve the level of indoor safety. The proposed system realizes the functions of the scene display of the operation status, danger warning and positioning, danger classification and level assessment, and danger handling suggestions (illegal invasion, overcrowding, fire). In [3], an illustration of machine-learning algorithms with multistage fire spread models is described. The algorithm presents the ground-based fire spread and possibility of secondary fires spreading if conditions are appropriate. The framework is designed to be used in digital twin technology aiming to provide useful information to first responders in real time. In [4], the integration of federated learning and digital twin for adoption in real-time and life-critical scenarios as well as for ease of governance in smart city applications is presented. Core applications, advantages, differences compared to already existing technology, potential and future use are depicted in this survey. In [5], a case study of AR systems in mechanical stress monitoring that can be used as input in a digital twin concept is also presented. The AR device is related to mechanical risk prevention for steel shelving breakdown, overheating risk prevention of electrical equipment, fire risk and emergency management due to overcrowding or critical emergency situations. In [6], a review to deepen the relation between the digital approach and safety issues is published. Findings show that digital twins have been tested and developed to support operators during normal and emergency conditions and to enhance their abilities to control safety levels. In [7], a scientific review was conducted of digital twins in disaster management and mitigation for infrastructure (IDPMI) plus a scientific framework of DT-IDPMI is programmed, that provides guidance to the integration of DT-IDPMI and identifies the challenges. In [8], the proposed model integrates the IoT, BIM and a security risk analysis method combining the a-priori algorithm and complex network. The paper focuses on the coupling analysis of security risk factors. However, when it comes to safety and fire outbreaks, besides of detecting the fire accidents, another important factor is to create an integrated system from the sensors to the analysis and decision support, which is also capable to predict the dispersion of fire to avoid and early prevent consequences such blocking possible emergency exits. In order to represent and predict this dispersion Cellular Automata (CA) modeling tool is deployed, which requires no large datasets for the learning procedure or high performance hardware to support complex deep learning architectures. CA exploit the interaction of neighboring components, using simple rules of evolution.

In general, CA is a very elegant parallel computational tool started by John von Neumann [9] and Konrad Zuse [10]. CA are models of physical systems, where space and time are discrete and interactions are local. They achieve that because they combine the use of memory (CA cell state) and processing unit (CA local rule) in a CA cell. They can capture the essential features of systems, where global behavior comes of the collective effect of simple components, which interact locally. In addition, they can process complex boundary and initial conditions. These characteristics are very convenient so as to describe algorithms and particularly to simulate the dynamics of a phenomenon like fire spreading [11,12]. In general a CA requires:

1) A regular lattice of cells covering a portion of d-dimensional space;
2) A set $C(\vec{r},t) = (C_1(\vec{r},t), C_2(\vec{r},t), ..., C_m(\vec{r},t))$ of variables attached to each site $\vec{r}$ of the lattice giving the local state of each cell at the time $t = 0, 1, 2, ...$;
3) A rule $R = (R_1, R_2, ..., R_m)$ which specifies the time evolution of the states $C(\vec{r},t)$ in the following way: $C_j(\vec{r}, t+1) = R_j(C(\vec{r},t), C(\vec{r}+\vec{\delta}_1, t), C(\vec{r}+\vec{\delta}_2, t), ..., C(\vec{r}+\vec{\delta}_q, t))$, where $\vec{r}+\vec{\delta}_k$ designate the cells belonging to a given neighbourhood of cell $\vec{r}$.

The state of the a cell at time step (t+1) is computed according to R. R is a function of the state of this cell at time step (t) and the states of the cells in its neighborhood at time step (t).

The type and size of the neighborhood is a very important parameter that greatly affects the performance of the model for CA. The neighborhood of a cell is the spatial region in which the cell needs to search and with which is interacting. For one dimensional CAs, a cell is connected to n local neighbors on either side. N is referred as the radius. Thus, each cell has 2n + 1 neighbors. For two-dimensional CAs, there are two types of neighborhoods that are the most known and used in the majority of scientific works. The Von Neumann neighborhood, which consists of a central cell (the one which is to be updated) and its four geographical neighbors north, west, south and east. The Moore neighborhood contains, in addition, second nearest neighbors northeast, north-west, south-east and south-west. There also extended versions of Von Neumann and Moore neighborhoods, which use additional cells as neighbors, but they have to be chosen carefully, because they increase the amount of spatial complexity.

As it happens in every physical system, the cells' activity happens simultaneously. So, the same clock exist for all the cells and the change of their internal state happens simultaneously. This fully distinctive dynamic system, created by Von Neumann, are known as CA. CA can capture the essential features of systems where global behavior arises from the collective effect of simple components which interact locally. CA have sufficient expressive dynamics to represent phenomena of arbitrary complexity [13]. In this paper, CA are exploited and combined for the first with a Digital Twin in order to simulate fire spreading inside an area of a building by continuously monitoring humidity and temperature conditions. This integrated system provides all the necessary components and features from the actual sensors that are installed in the building to the visualization of the information, early-warning and decision support via the digital twin. This is achieved using the minimum amount of computational resources due to low complexity of inherent CA design. In Section II the approach, the methodology and the results are described also highlighting the contribution of this work. Finally, in Section III the conclusions are presented.

II. Method, Contribution and Results

This paper describes a digital twin solution that provides four different features. The first one is the deployment of the sensing platform for humidity and temperature in a specific area of a building. The second one is the visualization of all these information received from the sensors to a user-friendly graphical interface, which keeps the operator updated about the environmental conditions. The third one is the combination of all the received data in order to provide early-warning and inform in real-time the user about a fire accident that outbreaks somewhere inside the building. Furthermore, upon user's decision, the system is able to predict and visualize the expansion of the fire inside the building taking under consideration the position of the initially detected fire, the expansion of the heat wave and the values of temperature and humidity that are received from sensors installed in the physical twin. So the main contribution of this work is a digital twin system that integrates sensing and monitoring tools of indoor climate conditions and incorporates advanced modelling methods to provide early-warning during a fire accident in real-time and using low computational resources and power that make it ideal for embedded applications (Fig.1).

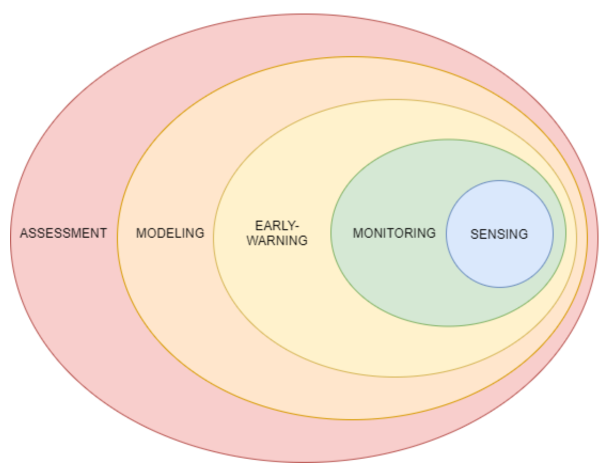

Fig. 1. Integrated features in proposed solution.

A DHT11 sensor is used for the first feature, which provides a digital output proportional to the temperature and humidity measured by the sensor. The DHT11 sensor's manufacturing technology ensures high reliability, excellent long-term stability, and a very fast response time. This sensor is paired with an Arduino Uno, which is a micro-controller board based on the ATmega328P. It contains everything needed to support the micro-controller. In this work, Arduino receives the sensor's digital output data, converts them to humidity and temperature variables, and transmits them to the command and control for further analysis. More specifically, relative humidity is measured as a percentage or ratio of the amount of water vapor in a volume of air relative to a given temperature and the amount it can hold at that given temperature. This combination of DHT11 and Arduino is the system's sensing device and it can be installed anywhere in the building with sufficient power supply and network availability.

For the rest of the features, Processing [14] is used. Processing is a free graphical library and integrated development environment (IDE), which uses the Java language, with additional simplifications such as additional classes and aliased mathematical functions and operations. It also offers graphical user interface features for simplifying the compilation and execution stage and is the precursor to other projects including Arduino. So, the pairing of Arduino IDE, with Processing IDE is straightforward for a variety of applications. The graphical user interface is presented in Fig.2, where the operator can have a continuous watch of temperature and humidity levels of a given area in the building. Furthermore, a simple architectural top view of the indoors area is also provided to the left of the GUI, which also includes the position of the sensors and the fire extinguishers. A simple topology is presented for demonstration. The gray part represents the walls and inaccessible areas, where the fire cannot disperse. The black section of the topology represents the free area, in this case two merged corridors, in which the people can walk and the fire can expand. The green spots represent the position of the fire extinguishers and the blue one represent the position of the sensor. In addition, the operator can watch the exact relative humidity and temperature values, in a rate between 0 and 100 and Celsius scale respectively. Processing, receives the humidity and temperature values from Arduino via serial port. In Fig. 2, there are 3 fire extinguishers, one sensor and the temperature has 28.2 degrees Celsius and 56.2 % humidity. So there is no warning about any fire accident.

In Fig. 3, there is a reading from sensor number one that the temperature has 47.5 degrees Celsius and the humidity has fallen to 29.8 %. This is an indication of fire accident conditions and the blue spot becomes yellow to make visible the sensor that reports this accident. Simultaneously, a message in red is displayed at the bottom right side of the GUI warning the operators about the possible fire accident and the specific sensor that reports it, in case there are multiple sensors in the area.

The operator has the option to begin a simulation of fire spreading from the location that this sensor is placed. There are two buttons at the top of the GUI, the first one is to start the simulation and the second one is to finish the simulation. When

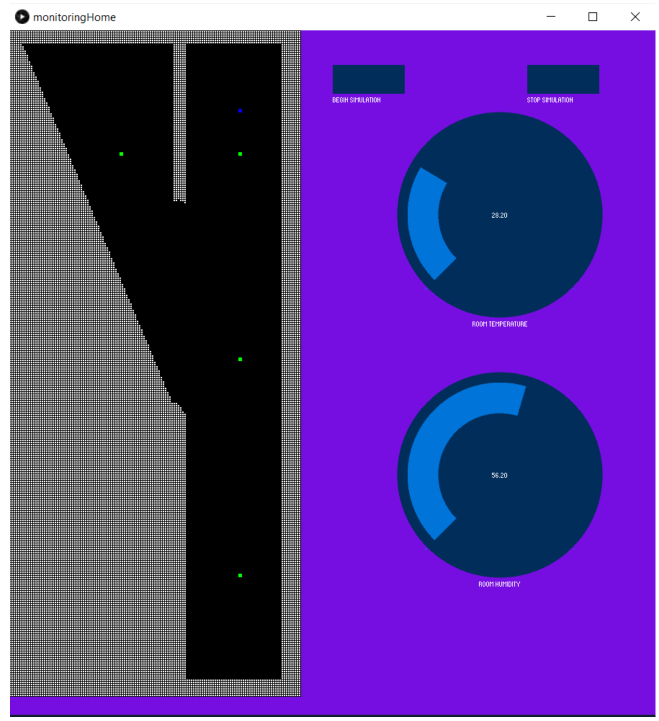

Fig. 2. Monitoring the climate conditions of the area without any warning about fire accident.

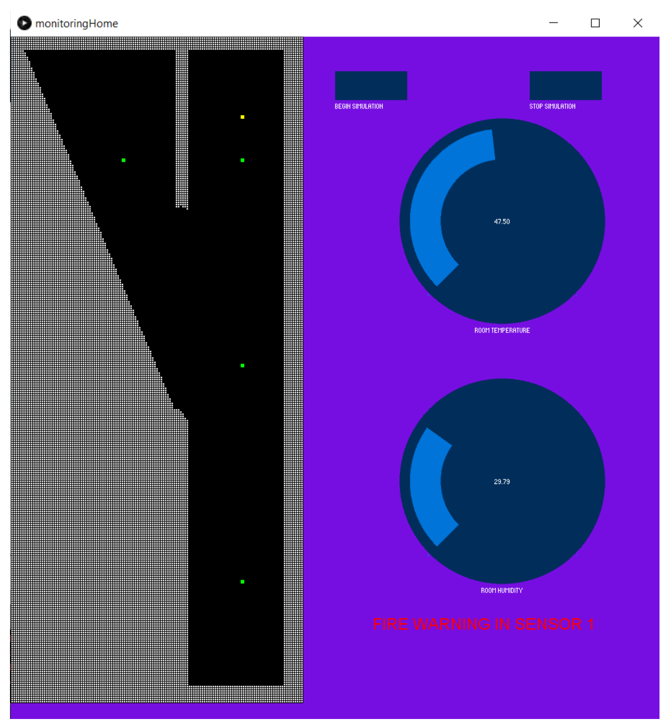

Fig. 3. Monitoring the climate conditions of the area with increased temperature and low humidity indicating fire accident. A warning in red is displayed at the bottom.

the operator chooses to start the simulation, the expansion of the fire towards the other areas of the corridors is depicted inside the top view at the left part of the GUI as red cells (Fig. 4).

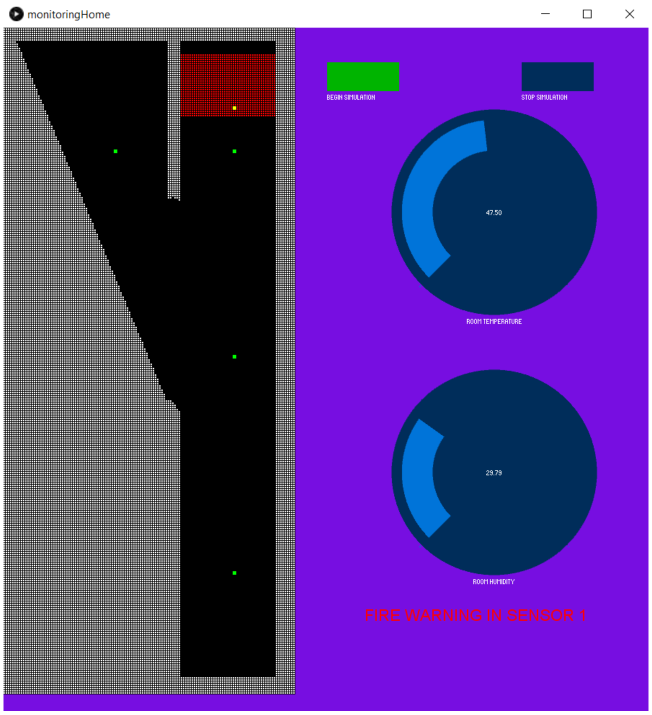

Fig. 4. The operator chooses to begin the simulation of the fire dispersion.

In order to simulate the spreading of fire with CA, the area is divided into a matrix of squares with identical areas and each square of the surface is represented by a CA cell. In this demonstration the lattice is 320 x 130 cells. They type of neighborhood that was used in this CA model is the Moore neighborhood, which means that we use the north, south, east, west, north-east,north-west,south-east, south-west neighbors. The state of the i, j cell at time t, defined as $C^t_{i\,j}$ is equal to the Eq.1.

$$C^t_{i\,j} = \{CellType_{i,j}, FireValue^t_{i,j}\} \quad (1)$$

CellType is a variable that can acquire four different values and indicates the type of the area represented by the corresponding (i, j) cell.

FireValue represents the value of heat when the fire is spreading from the initial point of outburst. For the expansion of the fire, we make use of the discrete diffusion equation based on Cellular Automata, which is a variation of the CA diffusion equations that are also used to describe effectively similar phenomena [15,16].

First we initialize the parameters. The cell of the sensor, where the fire is detected in the topology takes the initial *FireValue* = 10000. The parameters for the discrete diffusion equations are declared in Table I.

Then, an iterative execution of the diffusion equation gives the values of $FireValue^t_{i\,j}$ for all the free cells in the grid.

TABLE I
PARAMETER VALUES FOR THE DISCRETE DIFFUSION EQUATION FOR FIRE EXPANSION.

cp1	cp2	cp3
0.1	0.1	1

This spreading of fire is depicted in the GUI in red color and gives the operator an estimation of the path that the fire will follow inside the building.

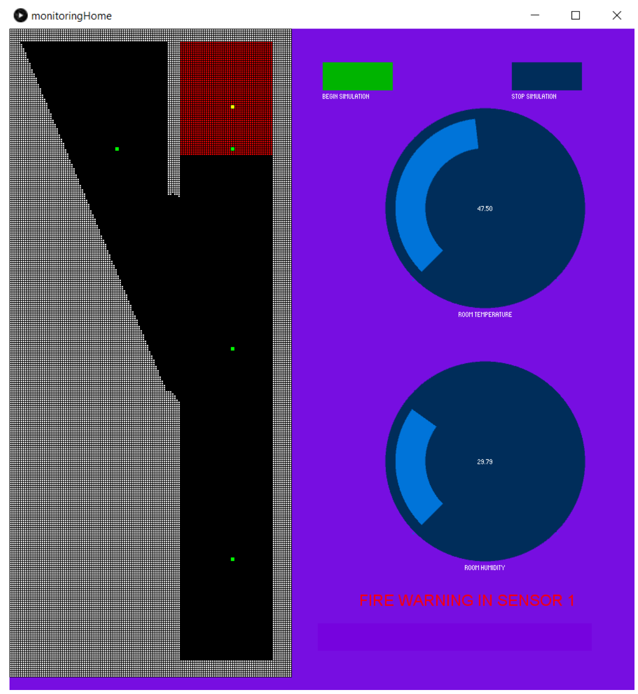

Fig. 5. The fire dispersion reaches the first fire extinguisher.

The simulation also predicts the sequence of the following extinguishers that will be reached by the fire wave. This is depicted in Fig. 6, where the simulation predicts that the fire will reach first extinguisher number two and then the extinguisher number 3. (Fig. 7).

The operator has the option anytime to stop the simulation of the fire expansion and resume at the specific point that it was left (Fig. 8).

The system is tuned to transmit data from the sensors every five seconds. Due to CA inherent simplicity in design without using any complex architectures, the entire simulation can be executed in milliseconds, but for better visualization to the operator this time is reduced so each time step of execution runs every 50 milliseconds. The computational resources of this system is extremely low in terms of processing power and memory and can also be executed in older hardware of workstations or embedded devices that support Java.

III. Conclusion

In this study we proposed a digital twin system capable of providing a situational awareness of the climate conditions

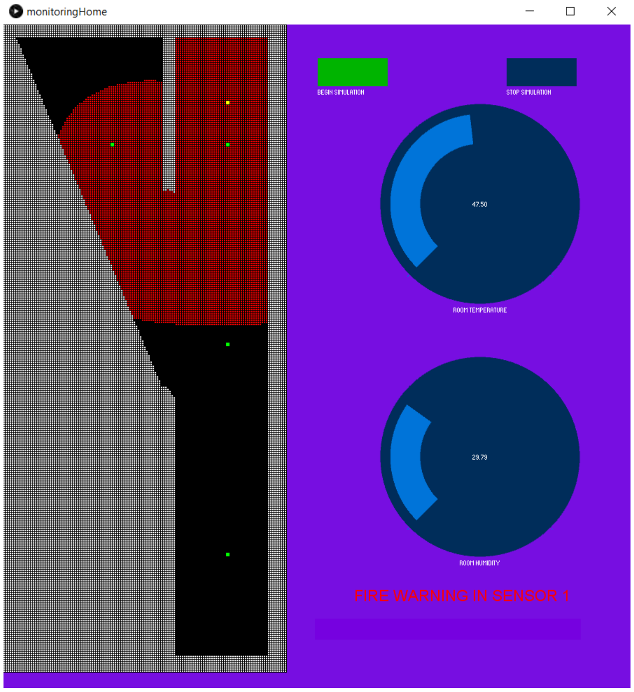

Fig. 6. The fire dispersion reaches the second extinguisher.

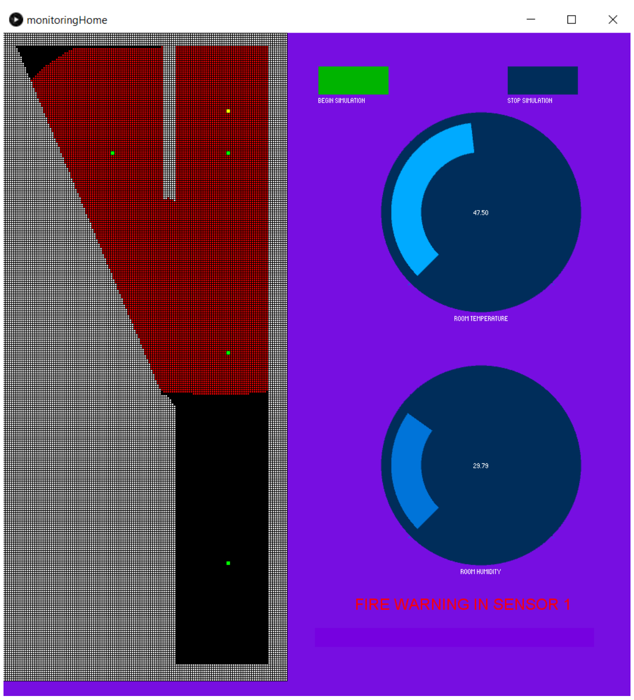

Fig. 7. The next extinguisher that the fire will reach is number three and this is also depicted to the operator.

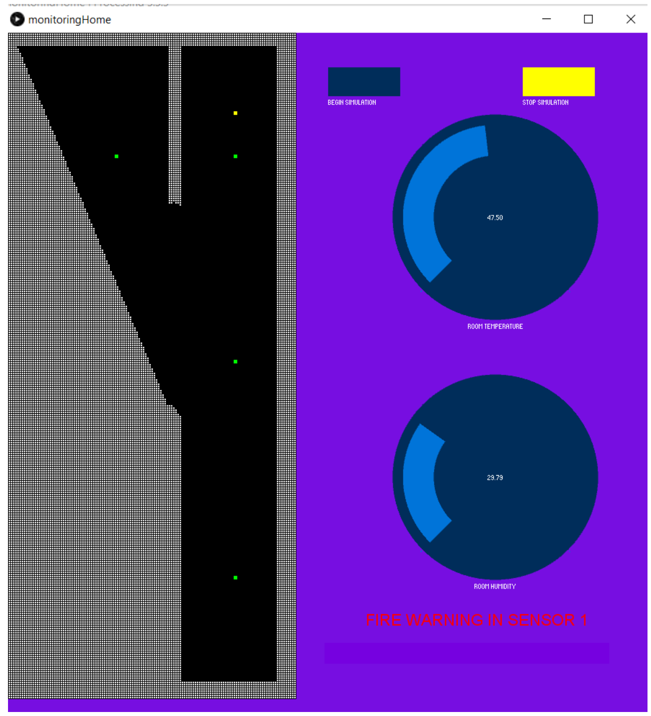

Fig. 8. The operator chooses to stop the simulation.

inside a building and more specific temperature and humidity. The system includes the deployment of a sensor platform capable to transmit the information to the main server. The main server receives all the data and visualize the information to the operator along with a simplistic architectural top view of the building's area that we are interested in. In case of abnormal temperature and humidity measures the system is capable to provide early-warning about a fire appearance in the building and simultaneously gives the operator the option to run a simulation of the spreading of fire towards other areas of the building. This simulation is based on CA, a powerful modelling tool that requires low computational resources and achieves high performance, without requiring any large datasets for training.

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