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Research on the application of residual networks considering attention mechanism in concrete curing robot

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ABSTRACT

Manual curing after concrete pouring is mainly divided into two methods: plastic film curing and water spray curing, both of which have shortcomings, such as high working intensity and intense subjectivity. Current intelligent curing methods mainly focus on establishing intelligent water spray curing systems according to site needs and have poor versatility. There are currently no relevant intelligent curing measures for plastic film curing after concrete pouring. To solve the above problems, we designed and developed a concrete curing robot system based on the com-puter vision technique, including the concrete curing robot body and a corresponding control terminal, which realizes the intelligent operation of concrete plastic film curing and water spray curing. Through the classification model based on the improved ResNet-18 concrete curing surface image, the robot can make scientific judgments and decisions on the water spray curing independently. After the research and development of the robot were completed, we tested and verified the feasibility of the concrete curing robot system design at the project of Tianjin Lingang Hospital. This paper provides new ideas and technical schemes for intelligent and automatic control of concrete curing, especially for plastic film curing and water spray curing. It has essential scientific and practical significance for concrete curing, especially large-volume concrete curing.

1. Introduction

Concrete curing is the critical link to increasing the strength of concrete after pouring, and its quality has an important influence on the strength and impermeability of concrete. Concrete curing means artificially manufacturing or controlling specific temperature and humidity conditions to ensure normal hardening and strength growth of newly cast concrete under cement hydration reaction. When the curing environment does not satisfy the reaction conditions, such as high temperature and low humidity after concrete pouring, it will lead to excessive water evaporation in concrete, large shrinkage deformation, and dry shrinkage cracks, which will affect its strength. Therefore, curing after concrete pouring is very important. As shown in Fig. 1, concrete curing methods in concrete engineering are mainly divided into two categories: plastic film curing and water spray curing currently. Plastic film curing is the artificial laying of the curing film on the concrete structure or component, which is used to maintain the humidity environment on the surface and inside of concrete to promote the hydration effect of concrete. Water spray curing keeps the concrete surface wet by spraying water regularly. The disadvantages of traditional concrete curing work are apparent, such as the adverse working environment for concrete curing, high intensity of manual curing, long continuous working time of workers, strong subjectivity, excessive waste of film and water resources, etc.

In recent years, the rapid development of robotics technology has provided a new scheme for construction intelligence in the construction industry. Robots have radically changed the traditional industrial production mode and profoundly influenced human social life. In the 1980s, Shimizu Corporation of Japan developed the world's first construction robot, replacing manual refractory material spraying. Subsequently, construction robots rapidly rose, and more and more countries began to increase research and development and put them into use. In 2007, the Italian Polytechnic University of Marche developed a lightweight robot device for colorful interior wall painting (Naticchia et al., 2007); In 2015, Australia Fastrick Robotics developed the automatic robot bricklaying system HadrianX (Dakhli and Lafhaj, 2017); In 2016, Build

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Robotics of the United States produced a bulldozer capable of fully automatic driving (Bogue, 2018); In 2017, Chiba University of Technology in Japan developed the "T-i ROBO Rebar" automatic rebar binding robot (Yan et al., 2018); In 2018, Nanyang Polytechnic University of Singapore developed a robot called Quica Bot for quality inspection and evaluation (MX3D. Case Study Bridgecraft: Amsterdam, 2020); In 2020, MX3D in the Netherlands developed a robot system combining 3D printing technology with metal (Li and Jiang, 2018); In China, Xiang et al. (Zheng and Ma, 2019)designed a robot system for automatic plastering and leveling according to the state of the wall surface; Zhang et al. (Wang et al., 2019) designed a robot system for automatically stacking cement bags; Wang et al. (2020) of Hong Kong Polytechnic University designed a construction waste recycling robot; Wang et al. (Ghareeb, 2021)designed a garbage sorting and recycling robot for onsite demolition and construction; In 2019, Guangdong Bozhilin Corporation successively developed several construction robots (Bright Dream Robotics, 2017), including ground leveling robots, indoor spray robots and floor grinding robots, which significantly promoted the development of construction robots in China. With human beings' continuous exploration and innovation in robotics technology, it is an inevitable choice for the development of the science and technology era to use increasingly mature robotics technology to participate in building production. Using construction robots to assist or replace human beings in construction work helps human beings to stay away from the enormous work intensity and the dangerous working environment caused by construction, which significantly facilitates human production and life.

However, the application research of construction robots in concrete curing is not rich. The existing research on intelligent concrete curing can be mainly divided into two major parts: automatic testing of concrete test blocks and intelligent concrete spraying systems in actual engineering sites. In the area of automatic testing of concrete test blocks, it is already possible to achieve highly automated control of the entire process of concrete test blocks from storage, maintenance, measurement, testing, sample retention, and waste disposal, making the entire testing process more compact and efficient. In the area of intelligent concrete spraying systems, the automatic spray curing technology developed by Yuan Wei (Yuan et al., 2023) sets the regular curing function, improves the construction effect of high-rise structures, and evidently improves the water saving of the project; Wei Zhao (Zhao and Wei, 2019) developed a set of concrete spraying curing device and verified that the curing system has noticeable effects of spraying and moisturizing, reducing the generation of cracks and ensuring the construction quality of concrete in the application of concrete curing on the side wall of Hanwangling station of Changsha metro line 4; Lo King Chi (King Chi et al., 2021) examined an IoT-based concrete curing control system based on sensor technologies invented for monitoring and controlling the moisture content of hardening concrete to the levels appropriate for good quality hardened concrete. However, most intelligent concrete curing technologies are automatic spray curing systems, which are not universal to concrete curing tasks under various engineering conditions, and intelligent curing technology does not involve intelligent plastic film curing. Compared to industries such as communication, chips, new energy, and aerospace, which are now developing towards intelligence, digitization, and modernization, the construction industry, mainly concrete curing tasks, still rely heavily on manual labor.

The application of computer vision technology has produced practical effects in many aspects currently, such as the measurement of structural displacement (Khuc et al., 2020), the evaluation of acceleration and vibration performance of pedestrian bridges under pedestrian load (Chuan-Zhi et al., 2020), the evaluation of concrete surface cracks (Liu et al., 2019), the monitoring of bolt looseness (Huynh et al., 2019), the identification of space-time distribution of vehicle weight (Zhou et al., 2020). The convolutional neural network is one of the representative models of computer vision technology and has been widely used in monitoring. For example, In 2019, Cao Vu Dung (2019) proposed a crack detection method based on deep fully convolutional network (FCN) for semantic segmentation on concrete crack images; In 2021, Pierclaudio SAVINO (Savino and Tondolo, 2021) proposed the model which can correctly classify images from real concrete surfaces of bridges, tunnels, and pavement, resulting in an effective alternative to the current visual inspection techniques; In 2022, Han Qinghua (Han et al., 2022a) proposed to achieve structural deformation measurement based on smartphones with the help of the convolutional neural network. In the same year, he (Han et al., 2022b) proposed to monitor steel structure cracks based on YOLO V3 and DeepLab V3+ models.

Based on the above problems and considering the two main characteristics of the non-fixed environment and curing work in the concrete curing process, this paper, based on the technology of robot control and computer vision, takes the curing links of plastic film curing after concrete pouring and water spray curing after the initial setting of concrete as the research objects, carries out a deep discussion on the curing standard of artificial spraying water by studying the curing principle and process of an artificial covering film. We designed and developed the concrete curing robot system, which can realize movement functions, the film covering and sprinkler curing, obstacle avoidance, etc. In terms of plastic film curing, this article proposes a new type of automated structure, which has been proven to be reasonable in its structural design through on-site testing; In terms of water spray curing, we combine computer vision technology and use the neural network to classify and judge the concrete curing situation. The robot can automatically control the water pump for operation based on the classification results.

2. Concrete curing robot system

2.1. Functional requirements for concrete curing robots

Considering the complexity of the working environment, in order to ensure that the concrete curing robot can work adequately in the

Fig. 1. Concrete curing methods: (**a**) Plastic film curing; (**b**) Water spray curing.

unconsolidated concrete surface environment, the robot should have a specific ability to cross obstacles and climb hills and trenches. According to technical requirements, the functional design of the concrete curing robot is as follows: plastic film curing function, vibration function, water spray curing function, intelligent detection function, and motion sensing function. The plastic film curing function refers to the robot should have the curing function of replacing the manual laying curing film on the concrete structure or component. Vibration function refers to that when the robot carries out plastic film curing, and it should have such functions as preventing damage and disturbance of the chassis to the surface of the concrete in the film covering area when the robot chassis travels to the concrete. The water spray curing function refers to that during the hardening process of concrete, and the robot replaces manual work to sprinkle the surface of the concrete to maintain the strength of the concrete structure. Intelligent detection function means that during the water spray curing, the robot should be able to determine whether the concrete surface needs the water spray curing or not and to control the water spray curing independently. Motion sensing function refers to the robot should have functions of image return of driving area, sensing of surrounding obstacles, and real-time display of body information in working operation.

2.2. Integral design scheme of concrete curing robot

To meet the functional requirements of the robot as mentioned above, we divided the concrete curing robot body into six modules, including the walking module, covering module, sprinkler module, suspension module, energy module, and induction module, as shown in Fig. 2.

2.2.1. Walking module selection

The walking module of the concrete curing robot is of great significance to the research of the whole system. Whether the robot adapts to the environment of working on the unset concrete surface determines its curing performance. Besides, the five modules of the covering module, the sprinkler module, the suspension module, the energy module, the induction module, and many parts can typically work only when built on the walking module.

The track-type mobile mechanism is shown in Fig. 3, and it has many advantages.

Fig. 3. Track-type mobile mechanism.

(1) The track-type chassis has a solid load-bearing capacity, large supporting area, and slight specific pressure to the ground, which is easy to achieve complex actions that wheeled robots cannot achieve, such as turning, climbing stairs, and crossing ditches, and is not easy to slip;
(2) The ground adaptability is strong, and the mobile performance in muddy areas and other complex roads is also better than wheeled and bionic leg robots;
(3) The turning radius is small, taking into account the complexity of dense, narrow areas, and turning in place can be realized;
(4) The track is generally made of flexible material with low vibration, low noise, significant ground adhesion, and slight damage to the road surface.

When selecting the mobile mechanism, full consideration should give to various possibilities of the working environment of the concrete curing robot, such as terrain environment and obstacles. To sum up, considering the working environment of the concrete curing robot designed in this paper, we adopt the track-type mobile mechanism as its walking module.

2.2.2. Driving mode selection

The driving modes of the walking mechanism at home and abroad mainly include gas, hydraulic, and electric drives. Advantages of electric drive: low energy consumption, high control accuracy, high

Fig. 2. Structure diagram of the concrete curing robot body and the control terminal.

transmission efficiency, and low noise; Advantages of gas drive: easy to obtain air as energy, green and environmental protection; It can respond quickly and reach the set speed and pressure in a short time. The disadvantages are that it is difficult to control accurately and noisy; Hydraulic transmission advantages: the hydraulic motor and pump body connect by flexible pipes, and the spatial layout is not limited; Large output torque; Small wear, and long service life. The disadvantages are that it is necessary to maintain the oil regularly and ensure that the oil is clean and free of impurities; High precision, high cost, and complex curing of hydraulic components; Considering the working environment, conditions of the concrete curing robot, and the advantages and disadvantages of the three driving modes, we adopted the electric drive as the driving mode.

2.2.3. Covering module design

This module is the core part of the concrete curing robot to realize the film covering operation. The covering module comprises two parts: the box of the film covering device and the vibration device. The primary size of the film covering device of the box is about 1350 mm × 350 mm × 580 mm (long × wide × High); the interior of the box is mainly composed of concrete curing film sleeve and drum structure, paddle structure, and corresponding servo motor, stop structure and corresponding electric push rod and electric cutting device. The variety of devices work together to realize a complete set of the film covering automation processes from film covering to film cutting to the next film covering as the robot chassis moves; The vibration device consists of a vibrating plate and a vibrating motor. When the film covering device is working, start the vibration device according to the construction operation requirements to level the marks caused by the robot chassis moving on the concrete surface.

2.2.4. Sprinkler module design

Considering that the water spray curing and plastic film curing need not be carried out simultaneously in the concrete curing operation, the sprinkler module and the covering module can be replaced. The main body of the sprinkler module comprises a sprinkler, a 25 L water tank, an electric pump, and other structures. The sprinkler is composed of a spray pipe with a length of 1 m and nozzles arranged on both sides of the spray pipe; The water tank and water pump are fixed on the robot walking module, and the outer part is equipped with a protective shell.

2.2.5. Energy module

Considering the energy demand characteristics of the concrete curing robot and the choice of driving mode, two 48 V 30 A H lithium batteries are configured to meet the multi-module energy demand of the concrete curing robot. This specification of the lithium battery can meet the functional requirements of the concrete curing robot for 3 h of operation and 8 h of standby. The battery is 300 mm × 300 mm × 150 mm, weighing about 15 kg.

2.2.6. Induction module

The induction module of the concrete curing robot is composed of multiple sensors installed on the vehicle body. A laser ranging sensor is used to realize the perception of dynamic/static obstacles in the working environment; The intelligent perception of concrete surface curing is realized by using the 1080 P industrial camera. The parameters of the industrial camera are shown in Table 1; During the water spray curing process, the water level sensor is installed inside the water tank to automatically alarm when the water level is lower than the operational water level.

The parameters of the concrete curing robot are shown in Table 2.

Table 1
Parameters of the industrial camera.

S/N	Item	Specification
1	Pixel size	3 μm * 3 μm
2	Resolution ratio	1080 P
3	Frame rate	30 frame/s
4	Power supply mode	USB bus power
5	Signal to Noise Ratio	39 dB
6	Minimum illumination	0.051 lux

2.3. Working process of concrete curing robot

The plastic film curing and the water spray curing process of the concrete curing robot are shown in Fig. 4, and the main steps are summarized as follows.

Step 1 Pull out the emergency stop button, press the power supply of the robot body, and then turn on the power supply of the remote control to start the concrete curing robot system. At this time, the system will power on the related modules and structures, then initialize the system parameters to ensure the system's normal start and signal connection between the modules.

Step 2 The control terminal transmits the control signal to the built-in STM32 controller of the robot through the 2.4 GHz WiFi network. The controller parses the command, converts the command information based on the CAN bus, and inputs it to the corresponding motors of each module to realize the respective functions. The airborne laser range finder is used for the perception and avoidance of obstacles during the driving process of the concrete curing robot.

Step 3 According to the needs of onsite concrete curing, replace the equipment carried by the suspension module of the concrete curing robot. That is, judge whether remote control personnel need plastic film curing or water spray curing according to the needs of onsite curing and replace the corresponding equipment. Move the concrete curing robot to the working area, and work according to the task requirements.

Plastic film curing: The working principle of mechanical plastic film curing is divided into the following eight actions, which correspond to the pictures in Fig. 5.

1. The suspension device puts the film covering device down, the roller structure is attached to the ground, and the film covering is carried out from left to right by the robot power;

Table 2
Parameters of concrete curing robot.

S/N	Item	Specification
1	Operating weight	About 145 kg
2	Chassis type	Track structure
3	Overall dimension	1350 × 350 * 580 mm (length × width * height), including film covering device
4	Maximum speed	≤1.5 m/s
5	Working hours	Rechargeable lithium battery, continuous walking ≥ 3 h
6	Load weight	≥50 kg
7	Climbing angle	≥30°
8	Maximum obstacle crossing	≤100 mm
9	Steering diameter	Turning in place
10	Standby time	≥8 h
11	Ambient temperature	Range - 20 °C∼+60 °C
12	Ambient relative humidity	5%–95% (no condensate)
13	Illumination light	Highlight LED light
14	Video	HD camera
15	Emergency stop	Emergency stop switch (snap to stop)
16	Voice Announcements	Broadcast the alarm and prompt information about the body

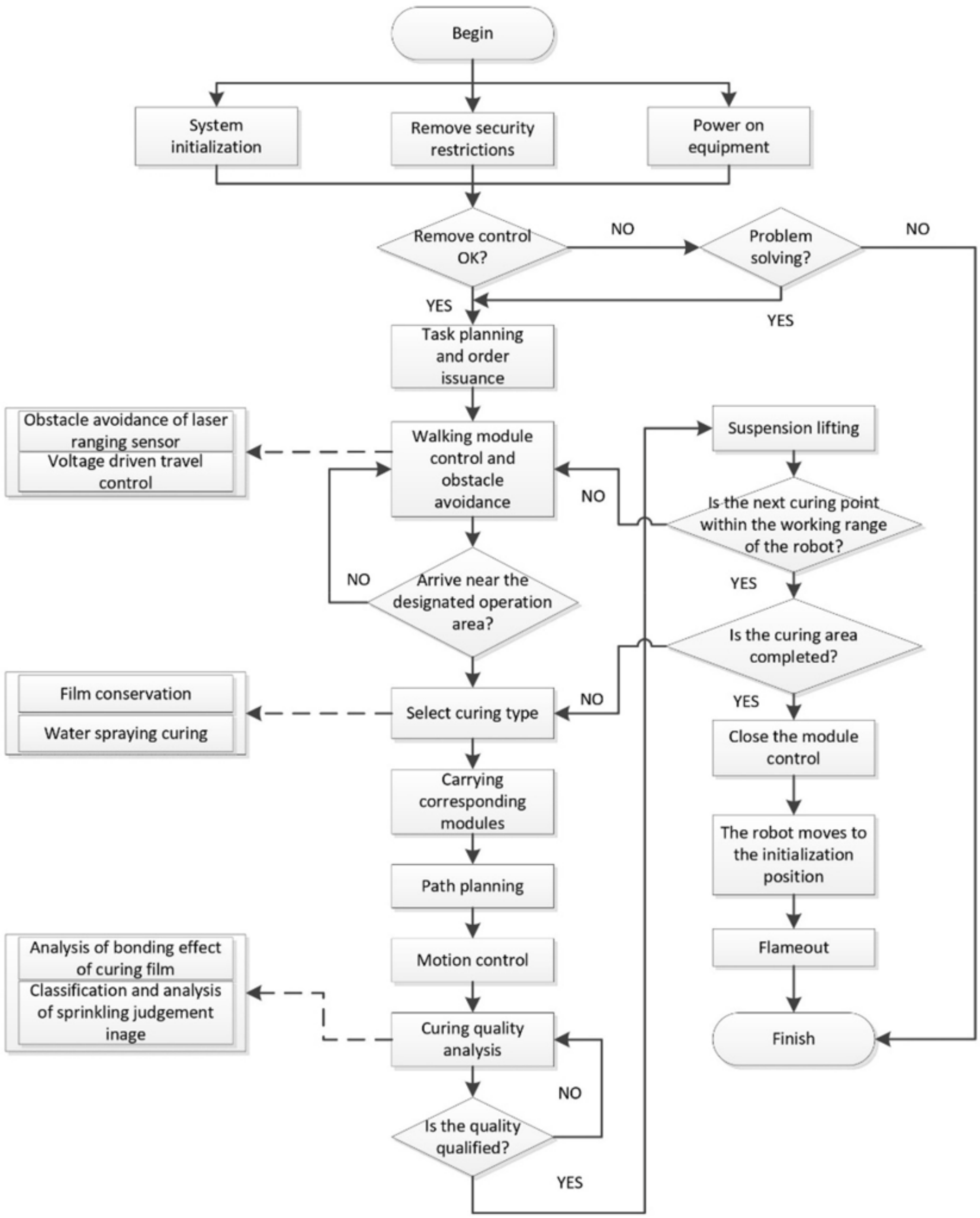

Fig. 4. Working process of concrete curing robot.

2. When the curing film needs to be cut off, the film covering device shall be lifted by the suspension device;
3. Turn the coaxial paddle from the first state to the second state to hang the curing film;
4. The electric push rod pushes the stop device against the curing film to the roller structure;
5. The electric cutting wire moves forward to cut the film;
6. When it is necessary to cover the film again, put the film-covering device down through the suspension device, and the large roller is again attached to the ground;
7. The stop device and electric cutting wire are retracted to the initial position;
8. Start the second film covering work.

Water spray curing: After replacing the covering module carried by the suspension device with the sprinkler module, open the water tank opening from the blue shell of the concrete curing robot, and fill it with a proper amount of water to complete the preparation for the robot water spray curing. After being cured with plastic film curing until the initial setting of the concrete, the strength of the concrete has reached the requirements for carrying the robot and remote control personnel, then control the robot to drive to the area to be cured. When observing the video returned by the camera, switch the watering mode to the intelligent water spray curing mode. See Chapter 3 for the intelligent recognition model of surface images. The neural network model deployed inside the robot automatically divides the images into three categories according to the camera's returned images: the fully cured area, the incompletely cured area, and the uncured area. When the uncured and incompletely cured areas are judged, the water pump is automatically controlled to spray water for curing; When it is judged that the area has been fully cured, the water pump will be automatically controlled to shut down to stop the watering and curing operation. Suppose the site

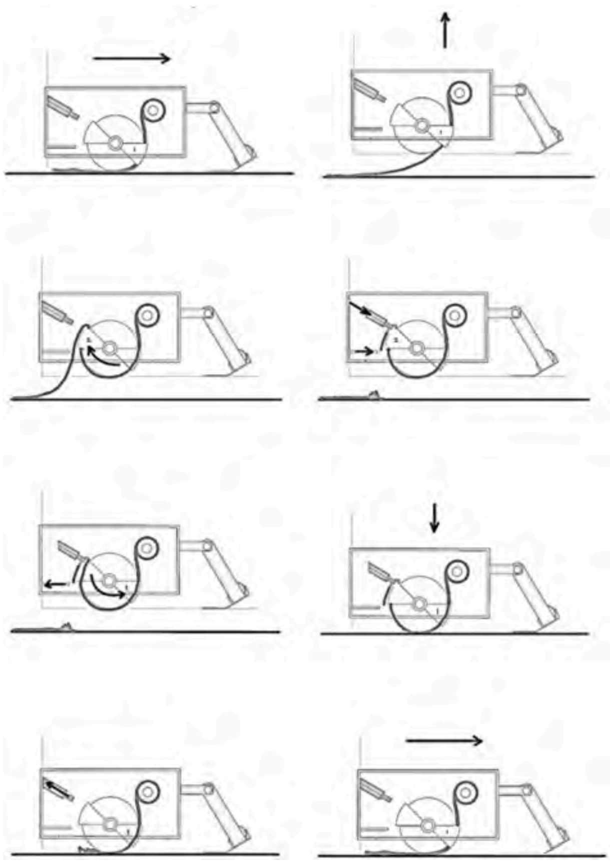

Fig. 5. Working principle of film covering structure.

environment is complex, and the effect of the intelligent recognition algorithm model is not ideal. In that case, the remote controller can be switched to manual water spray curing mode, and the operator can judge whether the area needs water spray curing according to the returned image on the remote controller and control the water pump to operate. Robot water spray curing is shown in Fig. 6.

3. Image recognition algorithm of concrete surface curing based on improved residual network

3.1. The ResNet18-CBAM model

According to the Guide to Curing Concrete (Reported by ACI Committee 308) (ACI-COMMITTEE 308R, 2008), the water spray curing can be roughly divided into two methods: one is to determine the evaporation rate, and curing can be carried out when the water evaporation rate exceeds 1.0 kg/m2/h; Secondly, during the curing period, workers should sprinkle water regularly every day to keep the concrete surface moist. For method one, its limitations and accuracy are clearly stated in the code. It strictly stipulates the measurement height of indicators such as temperature, humidity, and wind speed. And others have proven through experiments that the measurement error of evaporation rate is between ±25%–50%. Therefore, there is currently no effective method to accurately determine the evaporation rate on construction sites (non laboratory environments). Curing the construction site based on the evaporation rate is a time-consuming and costly task. Most concrete curing operations are based on whether the concrete surface is moist for curing currently.

Fig. 6. Robot water spray curing.

In the traditional water spray curing process, the concrete surface curing depends on the concrete curing staff to evaluate the concrete surface image characteristics, which has an intense subjectivity. And human's subjectivity leads to problems such as uneven watering area and waste of water resources. For this reason, this paper proposes a computer vision technology based on the improved ResNet-18 (HE et al., 2016) model to realize the classification and recognition of concrete surface curing by the robot and to control the water pump to spray water for curing.

The proposal of the residual neural network is a landmark event. Before the emergence of ResNet, the convolutional neural network had a degradation phenomenon; that is, with the increase of the network depth, the accuracy of the network did not improve significantly or even decrease. The VGGNet (Simonyan and Zisserman, 2014) proposed in 2014 has a maximum of 19 layers, while the ResNet proposed in 2015 has 152 layers. The depth of neural networks has been improved by leaps and bounds in only one year. ResNet adopts the idea of residual learning and "shortcut connection" in the network structure, which significantly alleviates the problem of network degradation. "Shortcut connection" superimposes the input data x and the convolution data F (x), making its mapping relationship H (x) = F (x) + x. The structure of the residual block is shown in Fig. 7. This structure makes the feature information of different layers can be transferred to each other, and the problem of gradient disappearance has been alleviated to some extent.

ResNet can realize the balance of training speed and network depth, especially the ResNet-18, which has moderate network layers and fast convergence speed and is widely used in classification and other tasks. For example, Petrov Dimitar (Dimitar et al., 2020) developed an anthropomorphic convolutional neural network (CNN) classifier, based on the ResNet18 deep learning network and validated it for task based image quality evaluation of digital breast tomosynthesis (DBT) using a structured phantom with non-spiculated mass simulating lesions; Huang Bo (Bo et al., 2022) proposed a new classification and identification method for different grades of aluminum scrap based on the ResNet18 network model, which improved the identification efficiency and reduced the equipment cost; Li Ma (Ma et al., 2023) proposed an improved ResNet-18-based multi-plant disease recognition method that

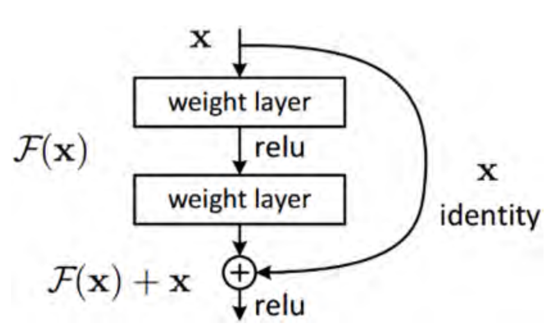

Fig. 7. Residual connection.

combined the characteristics of plant diseases. Considering that the model needs to be deployed to the concrete curing robot development board for operation, and because of the relatively small scale and high real-time requirements of the classification task of concrete surface dry and wet curing, ResNet-18 is selected as the backbone network in this paper to ensure the feature extraction ability and make the network have faster training and reasoning speed. In addition, because of the problems that may exist in the identification of curing conditions, such as the scattered or small area of the cured area and the area to be cured, the Convolutional Block Attention Module (CBAM) (WOO et al., 2018) is introduced to strengthen the attention of the network to the wet and dry areas of the concrete surface, effectively extract different curing degrees and features to improve the accuracy. At the same time, to reduce the training parameters and improve the training speed of the model, random pruning branches are introduced to preprocess the training data set to optimize the network further. Through image preprocessing, the input image size of the improved ResNet-18 model is 224 × 224. The ResNet18-CBAM model structure is shown in Fig. 8.

3.2. Model training and evaluation

In the field of concrete curing, there is no open-source image data set of concrete surface curing. Therefore, this paper divides the surface images of concrete at different curing periods into three categories to build the image data set of concrete surface curing: the fully cured area, the incompletely cured area, and the uncured area. The fully cured area refers to the area that the concrete surface in this area is completely wet and has been watered for curing; The incompletely cured area refers to only a portion of the area that has been watered for curing; The uncured area refers to the area that is completely dry and has not been watered for curing. The classification criteria are based on the dry area of the concrete surface. Images of the three types of the concrete surface curing situations are shown in Fig. 9 below.

The number of images of each category is 2046, 2057, and 2055, a total of 6158 images. This paper randomly divides the data set into training and validation data sets according to the ratio of 0.9:0.1. The setting and meaning of network hyper-parameters are shown in Table 3.

With the increase of training iteration rounds, the accuracy curve of the model gradually rises and finally converges, while the loss function curve gradually decreases and finally converges. After analysis, the ResNet18-CBAM model has no over-fitting phenomenon. Compared with the original ResNet18, the ResNet18-CBAM the accuracy of validation samples and the loss function curve perform better. The accuracy and loss function of the ResNet18-CBAM model on the test set is 94.56% and 0.011. Fig. 10 shows the training accuracy and loss function change curve of ResNet18-CBAM and ResNet18 during model training.

To verify the effectiveness of the ResNet18-CBAM model, a comparative experiment was conducted between the ResNet18-CBAM model and ResNet18. We take the pictures to be detected that does not overlap with the training set and the verification set, and expand it to a total of 577 pieces as the test set through the data set pre-processing steps. Under the same training dataset and running environment, evaluate the model from three aspects: validation accuracy, test accuracy, and average detection time. The experimental comparison results of different classification models are shown in Table 4.

The experimental results show that the ResNet18-CBAM model performs better than the original ResNet18 model in the concrete curing surface dataset, and the performance improvement effect of the improved model is significant.

Confusion matrix (LIU et al., 2021) is one of the important indicators for evaluating image classification models. In order to objectively evaluate the recognition accuracy of the model for each current situation and improve the readability of the model confusion matrix, we also select test sets for statistics. The result of confusion matrix is shown in Figs. 11 and 12.

In Figs. 11 and 12, the vertical axis represents the true labels of the image to be classified, the horizontal axis represents the model prediction labels, the right side shows the distribution of prediction accuracy thermal map, the main diagonal represents the number of samples correctly predicted by the model, and the darker the color, the higher the accuracy. From Fig. 12, it can be seen that the recall rate of the uncured area is the lowest, at 85.492%. The reason for the analysis is that there are no significant characteristics and the model makes it difficult to identify. The fully cured area and the incompletely cured area have more obvious features, with the highest model recall rates of 89.005% and 93.264%, respectively.

After the robot starts the intelligent water spray curing mode, it inputs images into the neural network every 30 frames for classification,

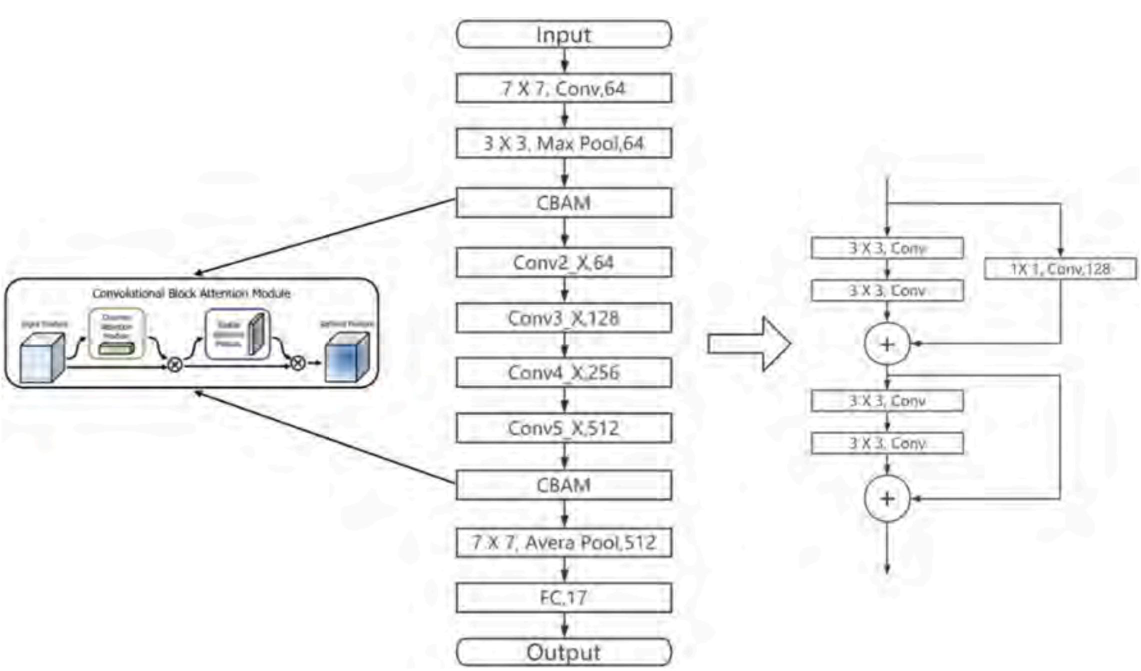

Fig. 8. Structure diagram of the ResNet18-CBAM model.

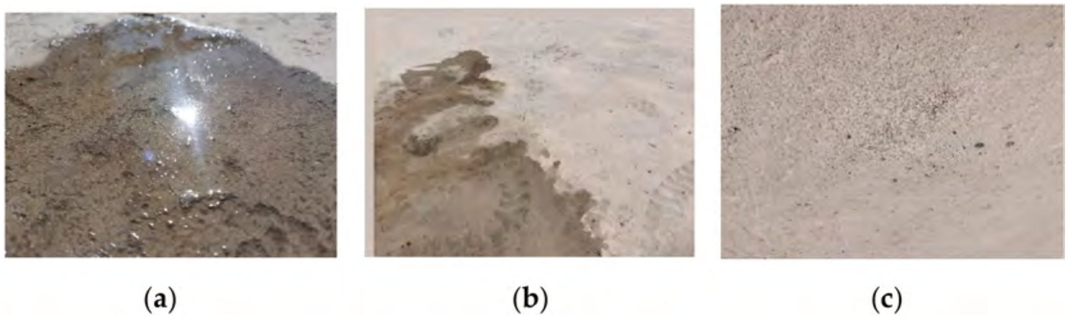

Fig. 9. Example of concrete curing category pictures: (**a**) The fully cured area; (**b**) The incompletely cured area; (**c**) The uncured area.

Table 3
Hyper-parameters setting.

Name	Setting	Meaning
BATCH_SIZE	16	Size of batch during training
LR	0.001	Initial learning rate
Optimizer	Adam	Algorithm for updating parameters
Loss function	CrossEntropyLoss	The degree of gap between performance prediction and actual data

carried out in the NVIDIA Jetson TX2 NX inside the robot. Finally, the classification results are transmitted to the robot control motherboard through the I/O port to decide whether to start the water pump. In the intelligent water spray curing mode, the robot operator only needs to drive the robot at a constant speed in the area to be maintained to achieve water spray curing. The images of the robot's water spray curing test are shown in Fig. 13. In Fig. 13, "close" indicates that the image is classified as the fully cured area, "open1" indicates that the image is classified as the uncured area by the improved ResNet-18 model and "open2" indicates that the image is classified as the incompletely cured area. The classification results all match the true labels. "FPS" represents the current real-time frame rate of video.

4. Engineering examples

Taking the concrete pouring and curing construction of Tianjin Port Free Trade Zone Lingang Hospital Project of China Construction Eighth Engineering Division Corp as an example, the concrete curing robot system and its module functions were tested on site. The Tianjin Port Free Trade Zone Port Hospital project has a total construction area of 86,525 m^2. The aboveground construction area is 62,325 m^2, including the complex medical building (3 floors of podium/14 floors of tower), scientific research building (5 floors), and infection building (3 floors). The structure is the frame-shear wall structure. The beam and column components are monolithic reinforced concrete structure, and the floor slab is 120 mm thick, which is the steel bar truss deck. The concrete curing task was located on the 11th floor of the tower of the medical complex building. The manual remote control carried out the onsite concrete curing. The engineering appearance of the concrete curing site and the physical object of the curing robot body are shown in Fig. 14.

According to the curing target of the project site was the concrete that had just been poured, the covering module was selected for the plastic film curing operation, which was carried out after the tower crane transported it to the designated working area. After the onsite workers had poured and vibrated the concrete, the concrete curing robot started the curing operation immediately. The robot drove backward into the area to be cured by remote control, and the suspension device descended to make the curing film carried on the film-covering device fully contact the concrete surface, then the curing film was rolled and paved under the traction of the robot. The curing process is shown in Fig. 15. After the completion of the long section of film covering, moved

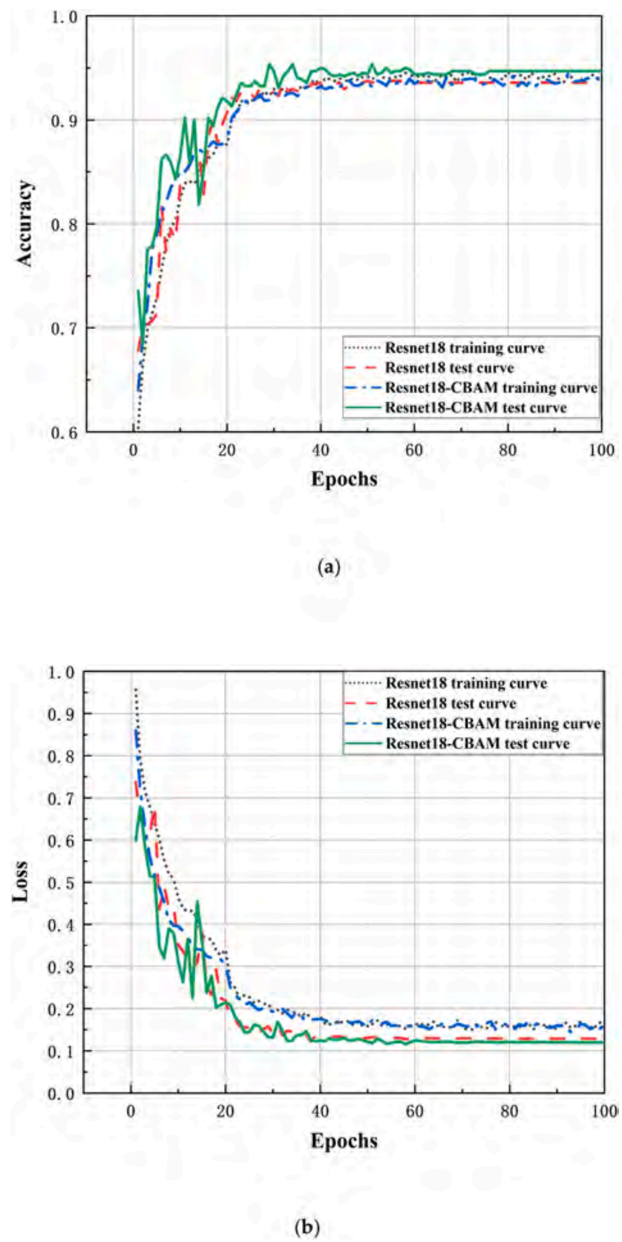

Fig. 10. Accuracy and loss function change curve during training: (**a**) Accuracy curve; (**b**) Loss function curve.

the three-gear switch SW3 of the control terminal was upward to start the film covering preset end procedure, and the suspension device was lifted to make the curing film at the end of the roller detach from the

Table 4
Performance comparison of different classification models.

Name	Epochs	Validation Accuracy	Test Accuracy	Average Detection
ResNet18-CBAM	100	94.56%	89.25%	2.19ms
ResNet18	100	92.57%	87.34%	2.08ms

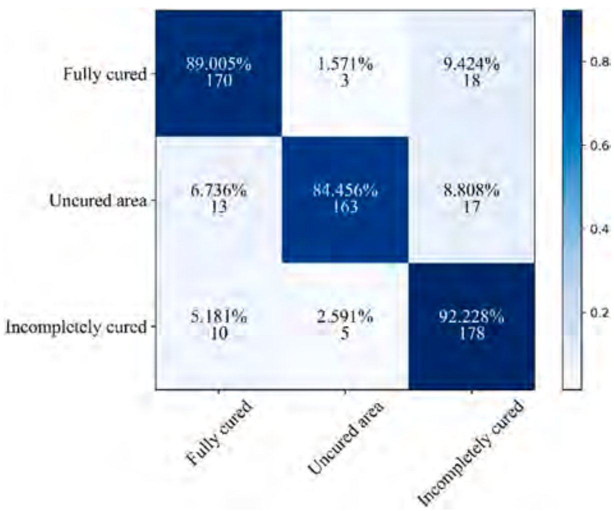

Fig. 11. Confusion matrix of based on ResNet18 model.

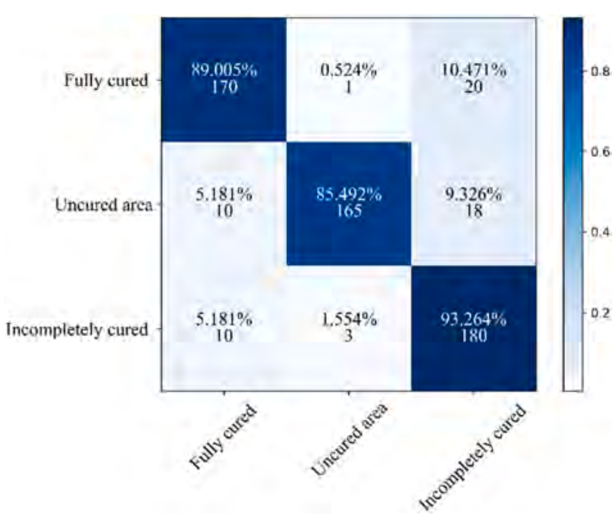

Fig. 12. Confusion matrix of based on ResNet18-CBAM model.

concrete surface, then the paddle was rotated and pushed into the structure to fix the end curing film on the roller, the electric heating wire was pushed forward smoothly and cut the curing film. Finally, the device's internal structure was restored to the initial state, and the robot drove away from the curing area to prepare for the next area curing operation.

After the completion of plastic film curing, we compared the curing effect with manual plastic film curing, which as shown in Fig. 16. According to the evaluation of experts and workers on site, the concrete surface was flat and free of the traces of the robot chassis rolling, and the curing film was tight, which meet the requirements of concrete plastic film curing construction. This test verified the rationality of the structural design of the covering module of the concrete curing robot system.

Compared with the traditional manual plastic film curing, the robot plastic film curing has two potential advantages.

4.1. Improve work efficiency

The application of robot in the large-scale concrete curing process can significantly improve the efficiency of construction work. Robot can automatically complete various processes based on preset programs and work for long periods without physical constraints, shortening the construction period. Considering that the shape of concrete pouring on the construction site is primarily rectangular, the expression formula for evaluating the efficiency of film covering work can be expressed as follows: (1)

$$T = n\frac{s}{v} + nt_1 + (n-1)t_2 \quad (1)$$

In the formula, T represents the total time of covering film; s represents the length of a single film covering, which is the film-covering length based on a 1 m wide concrete curing film in a single straight line process; n represents the number of film covering times is applied, that is, the number of times a single film-covering is used with a length of s; v represents the rate of covering film, which is the rate of single film-covering based on a 1 m wide concrete curing film; t_1 represents the preparation time for the film-covering process, which refers to the time from the end of a single film-covering to the start of film-cutting and other steps until the following film-covering preparation is completed; t_2 represents the turning time, which refers to the time used by the robot to adjust the direction of the body and continue the next stage of work after the completion of film-covering preparation. Some of the parameters are shown in Table 5 below:

By substituting the above evaluation parameters into equation (1), the expressions for the total time of robot film-covering T_1 and the total time of manual film-covering T_2 can be obtained, respectively, as shown below:

$$T_1 = n\frac{s}{1.2} + 50n + 15(n-1) \quad (2)$$

$$T_2 = n\frac{s}{0.6} + 5n + 3(n-1) \quad (3)$$

When the curing area is the same, the less the total film-covering time,

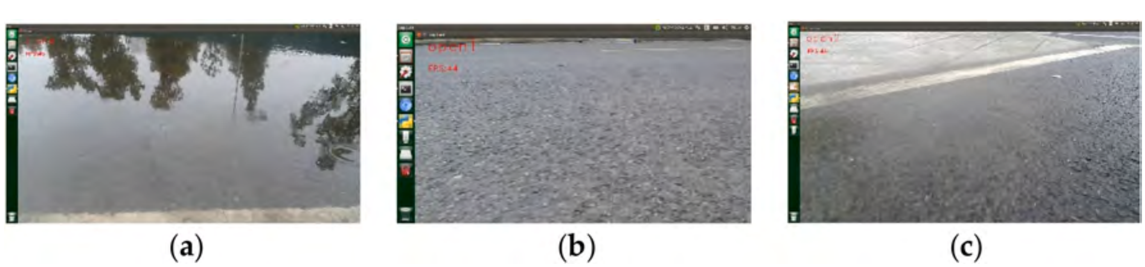

Fig. 13. The images of the robot's water spray curing test: (**a**) "close" image; (**b**) "open1" image; (**c**) "open2" image.

Fig. 14. Field test of concrete curing robot: (**a**) Engineering appearance of concrete curing site; (**b**) Concrete curing robot body.

Fig. 15. Robot plastic film curing operation.

the better the work efficiency. Therefore, subtracting equations (2) and (3) can obtain:

$$T_c = T_1 - T_2 = n\left(57 - \frac{s}{1.2}\right) - 12 \quad (4)$$

When $T_c < 0$, it indicates that the time required for robot film-covering is less than that for manual film-covering, and the efficiency of robot film-covering is higher than that of manual film-covering. From equation (4), it can be inferred that when $s \geq 54$, the efficiency of robot single film-covering gradually exceeds that of manual single film-covering. Moreover, when $s \geq 68.4$, regardless of the value of n, the efficiency of robot film-covering is higher than that of manual film-covering.

Therefore, in small areas with multiple obstacles and turns, manual film-covering still has advantages compared to robot film-covering due to its high flexibility. However, as the curing area expands, the characteristic of the curing speed of robots gradually becomes prominent. Moreover, with the continuous improvement of the robot curing function and the increasing proficiency of operators, T_1 And T_2 will gradually decrease. At the same time, manual film-covering will actually slow down the curing rate due to factors such as fatigue caused by the large working area. Therefore, in the task of large-area plastic film curing, the curing rate of the robot is much higher than that of manual curing.

4.2. Improve construction safety

The use of the robot reduces the time workers spend in contact with hazardous construction environments on the construction site, avoiding potential injuries that may occur to construction workers due to complex environments. The use of the robot makes the working environment on the construction site more humane, effectively reducing the incidence of work-related accidents and improving construction safety.

5. Conclusions

Aiming at the problems of high work intensity, intense subjectivity, and the existing concrete curing methods are not intelligent for the time being in the concrete curing field, this paper designs and develops a

Table 5
Evaluation parameters for film-covering efficiency.

S/N	Robot	Artificial
v	1.2 m/s	0.6 m/s
t_1	50 s	5 s
t_2	15 s	3 s

Fig. 16. Comparison of robot and manual curing operation effect: (**a**) The effect of robot plastic film curing; (**b**) The effect of manual plastic film curing.

concrete curing robot system, which takes the new intelligent plastic film curing scheme and automatic watering spray curing based on computer vision as the innovation points, then has been verified at the construction site, The following three achievements have been achieved.

1. The concrete curing robot system has been designed and developed, which includes the concrete curing robot body and its control terminal. Based on the new intelligent film-covering scheme, computer vision, and other technologies, the intelligent film-covering and watering spray curing after concrete pouring has been realized;
2. The concrete surface image classification model based on the improved ResNet-18 is constructed and deployed. The validation accuracy and test accuracy of the model converge to 94.56% and 89.25%, respectively, realizing the intelligent classification and recognition of the concrete surface image and providing the control basis for watering spray curing;
3. Field tests have verified that the concrete curing robot system can realize intelligent plastic film curing control, which solves the problems of manual evaluation of curing effect based on the naked eye, such as solid subjectivity and high work intensity, and effectively guarantees the quality of curing construction.

The research results of this paper provide a new technical solution for the intelligent curing of concrete after pouring, especially for plastic film curing and watering spray curing, and promote the intelligent and automatic development of concrete curing in engineering construction, especially for the mass concrete curing project, which has essential scientific research significance and engineering practice value. These tests still expose the problems of robots working in complex environments, such as cumbersome preparation during plastic film curing, inconvenient walking of the robot on construction sites, and path planning. In the future, it is necessary to continuously improve the related structures of the covering and sprinkler modules according to the different curing environments.

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CRediT authorship contribution statement

Jun Feng: Methodology, Data curation, Conceptualization. **Hongxue Jia:** Methodology, Investigation, Formal analysis, Conceptualization. **Hongbin Pei:** Methodology, Investigation, Formal analysis. **Haowei Zhai:** Writing – original draft, Methodology, Investigation, Data curation. **Jie Xu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Giuseppe Lacidogna:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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