Yisheng Lv, Editor

The Autonomous Vehicles and Electronics Lab

EDITOR'S NOTE

Please send your proposal on profiling research activities of your or other ITS research groups and labs for the "ITS Research Labs" column to Yisheng Lv at yisheng.lv@ ia.ac.cn.

The Korea Advanced Institute of Science and Technology (KAIST) was established in 1971 as a research-oriented university by the government of South Korea. KAIST currently leads the R&D of innovative technologies in South Korea with its 646 faculty members and 10,793 students, the majority of whom are graduate students. The five colleges at KAIST are equipped with state-of-the-art facilities, enabling KAIST-affiliated research groups to conduct cutting-edge research in almost all science and engineering fields, one of which is intelligent systems.

The Autonomous Vehicle and Electronics Laboratory (AVE Lab), directed by Associate Prof. Seung-Hyun Kong, is affiliated with the Graduate School of Green Transportation at KAIST (see Figure 1). The AVE Lab was established in 2010 with the mission to advance knowledge and technologies for autonomous driving systems and contribute to industry partners.

To achieve these goals, AVE Lab currently conducts research in three major areas: end-to-end autonomous driving systems, robust perception systems, and advanced positioning, with supporting research facilities such as two autonomous driving cars complete with state-of-the-art sensor suites and four deep learning servers, each of which is equipped with four RTX 3090 GPUs. The autonomous driving car of the AVE Lab won first prize of the Presidential Award for an autonomous driving challenge hosted by the Korean government. Thus far, the AVE Lab has collaborated with multiple strategic partners from both government and industry in their research projects, such as the Ministry of Science and Technology, the National Research Foundation, Hyundai Motors, LG, SK Telecom, Korea Telecom, and many more.

Research Activities

Autonomous Vehicles

Recent scientific breakthroughs in the field of artificial intelligence and vehicular technology have made the two emerging technologies ready for transfer from the controlled environment of the laboratory to a practical real-world environment, potentially making substantial contributions to the lives of millions of people around the world. One of the major applications combining the two fields is the autonomous vehicle system, by which vehicles can navigate without a driver to a destination under ever-changing road environments while obeying all traffic rules. Autonomous vehicles are proven to be useful in numerous areas, from

QUICK FACTS

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Established: 2010

Research focus: End-to-end Autonomous Driving Systems, Robust Perception Systems, Advanced Positioning Systems

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robot taxis for commuters, to autonomous truck platoons for efficient logistics chains.

As autonomous vehicles are gradually becoming more embedded in our daily lives, safety concerns are being raised. For example, accidents related to vehicles with partial autopilot capabilities are often highlighted by international media. Therefore, in the autonomous vehicle research, safety must be assigned the highest priority, meaning that these systems must be highly adaptive and robust, even in completely new environments.

Sim2Real Technology

Deep neural networks have demonstrated promising results for various tasks and conditions. A key aspect of the excellent performance of deep neural networks is availability of huge data sets. Unfortunately, acquiring data for both common and unexpected scenarios from the real world is often expensive, impractical, and sometimes dangerous. Driving simulation technology provides some answers to this problem as simulations can be run multiple times without any significant consequences. However, naively transferring simulation-based learned policies into the real-world domain may not be effective due to differences in data distributions, a problem called *distribution shift*.

The AVE Lab has developed a Sim2Real (see Figure 2) technique to avoid the distribution shift problem when applying policies learned in a simulation to the real world. The Sim2Real approach transforms input images, either from the real world or a simulation, into an intermediate domain (for example, a segmentation one), where real or simulation images can have the same distribution. A policy network for autonomous driving can then be trained using representations in the intermediate domain. As a result, the Sim2Real technique enables potentially infinite amounts of simulation data to train deep neural networks without suffering from the distribution shift problem.

End-to-End Autonomous Driving Systems

In general, an autonomous driving system must decide a driving maneuver

FIG 1 The Autonomous Vehicles Team of the AVE Lab with two autonomous driving cars.

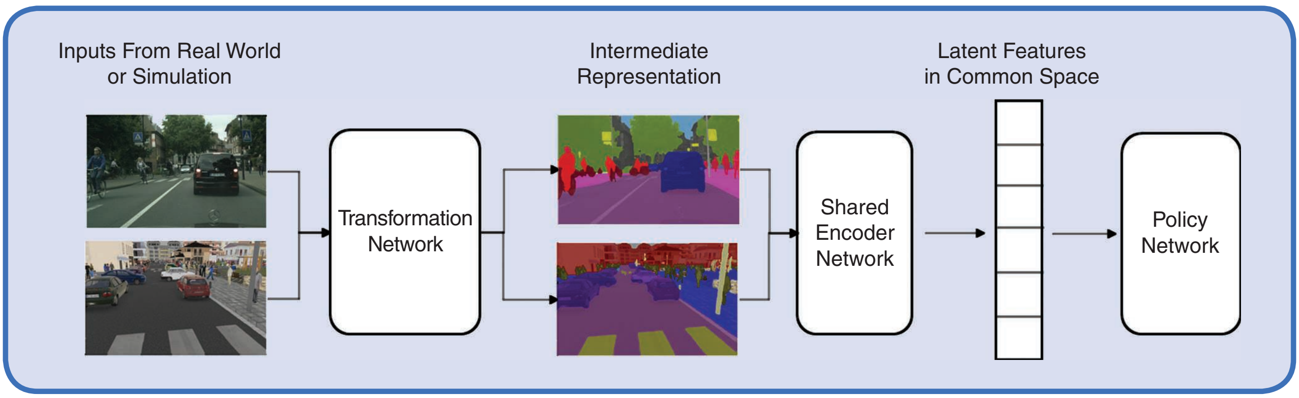

FIG 2 The AVE Lab's Sim2Real technology transforms inputs into intermediate representations before being encoded into a common latent space.

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based on numerous real-time computations with a large amount of complex, incoming data. The conventional modular-based architecture of autonomous driving systems links a large number of deep learning blocks in a structured manner to mimic the human decision-making process. However, due to its structured process, the modular-based architecture may not drive the vehicle appropriately in certain environments and in situations where experience is lacking.

To overcome the disadvantages of the conventional modular-based approach, AVE Lab is focusing on an end-to-end architecture (see Figure 3), where the autonomous driving system employs a single, or at most a few large neural networks, along with a hybrid learning algorithm using imitation learning (IL) and reinforcement learning (RL).

Provided with abundant driving data, autonomous driving systems trained with the IL approach can produce an expert driving policy by learning from human driver actions, thus supporting stable driving in normal scenarios. However, one major problem of the IL approach is its vulnerability to unexpected novel scenarios (UNSs), such as abnormal road shapes, unknown objects, and many unexperienced situations.

The AVE Lab is addressing the problems regarding UNSs using a hybrid learning algorithm where the IL-based driving policy is used as the baseline policy, with subsequent optimization using meta-RL. The hybrid learning scheme allows the meta-RL network to explore driving actions not available in the data set while maintaining quick network convergence, given that the baseline policy acts as strong prior knowledge. As such, the driving policy obtained from this additional optimization can be expected to be stable in normal driving conditions and robust in the case of UNSs.

In addition to environmental changes outside the vehicle, as in UNSs, autonomous driving systems may also experience control problems and unexpected vehicle dynamics due to perturbations such as a tire puncture or loss of traction. The occurrence of such a problem may result in a different action-state pair compared to the pairs experienced by the policy network. For example, in the presence of an anomaly such as a partially wet road, partial black ice, or a flat tire, an autonomous vehicle may lose balance and traction unexpectedly and experience an unconventional action-state pair such that simply applying the brake may result in an uncontrollable situation in only a few seconds. In such urgent cases, both handing over control to a human driver and relying on the current driving policy can be dangerous due to the inevitable delay and inappropriate control choices, respectively.

The autonomous driving system of the AVE Lab addresses this problem in two steps: 1) detecting the occurrence

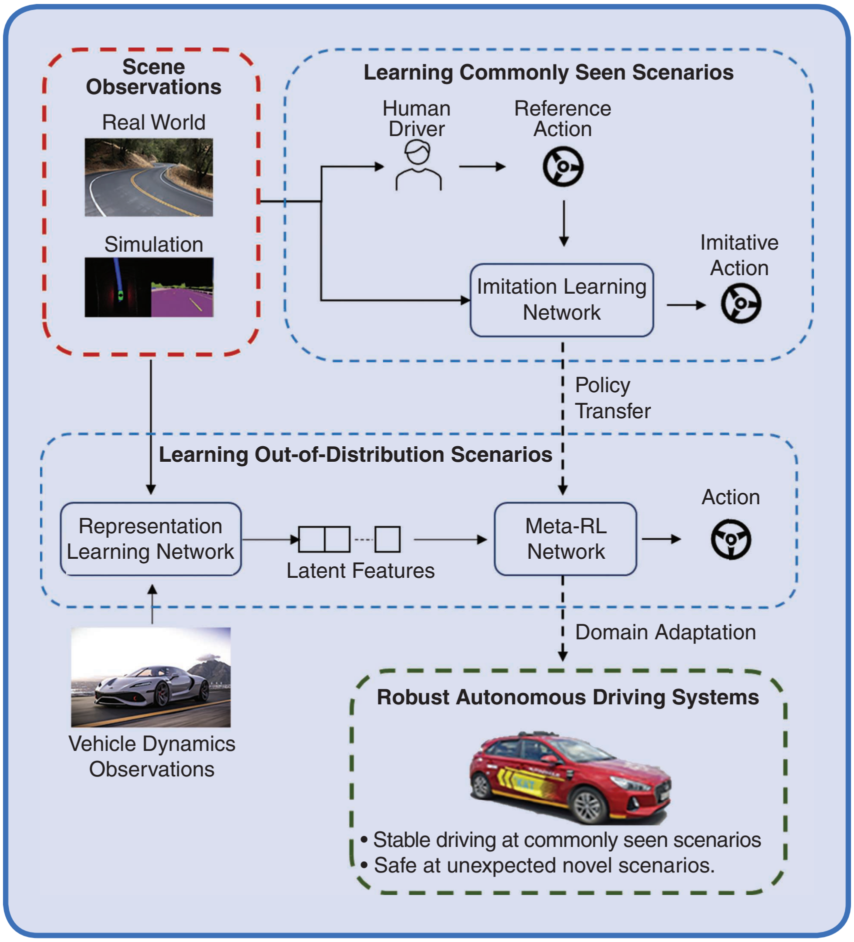

FIG 3 The end-to-end autonomous driving system.

of a control anomaly using a discriminator network and 2) figuring out the abnormal state-action relationship instantly to develop an appropriate control policy to cope with the anomaly using meta learning and model predictive control.

The AVE Lab has developed a Sim2Real technique to avoid the distribution shift problem when applying policies learned in a simulation to the real world.

Robust Perception Systems

Parallel to end-to-end autonomous driving system research, another major research direction of AVE Lab focuses on robust perception systems, specifically for perception under harsh driving conditions. An accurate perception system is an essential aspect of autonomous driving as the subsequent motion planning and vehicle control processes depend on sensing of the surrounding environment. Accurate and reliable perception in all environments requires perception techniques robust to noise and capable of inferring semantic information from a limited number of measurements.

With the powerful capability of deep neural networks as function approximators and the availability of vast numbers of samples for training, many state-of-the-art deep learning schemes are able to deliver reliable perception results under normal driving conditions. However, most of those techniques are for red, green, blue camera images, which have inherent weaknesses, such as a lack of depth information and vulnerability to low and harsh lighting conditions, making these methods incapable of guaranteeing the safety of autonomous driving.

To compensate for the shortcomings of camera sensors, AVE Lab studies robust perception systems using active sensors, e.g., lidar and 4D radio detection and ranging. The active sensors are robust to lighting conditions, and their measurements can be projected into a bird's-eye-view image without severe distortion, a characteristic that is often useful for motion planning.

Lane Detection With Lidar

One of their recent works is on a lane-detection algorithm for lidar (see Figure 4). For this work, the AVE Lab built the world's first public lidar lane-detection data set consisting of more than 15,000 point cloud frames with labels of up to six lanes per frame. The data set contains various road conditions, such as daytime, nighttime, and urban road lanes with occlusion as well as highways. The AVE Lab is planning to release their development tools to further accelerate advancements in the field of lidar lane detection, allowing researchers around the world to produce more lidar lane data sets.

Along with this data set, the AVE Lab developed a novel lidar lane-detection network based on global feature correlators (GFCs), i.e., Vision Transformer and MLP-Mixer, and segmentation heads that take full advantage of the unique characteristics of lane-line features in point clouds. Compared to traditional convolutional neural network-based lane-detection networks, the developed GFC-based network is more robust to feature sparsity and more appropriate given the global characteristics of lane features in a point cloud. The GFC-based lane-detection network shows overall state-of-the-art performance, with an F1 score of 82.1.

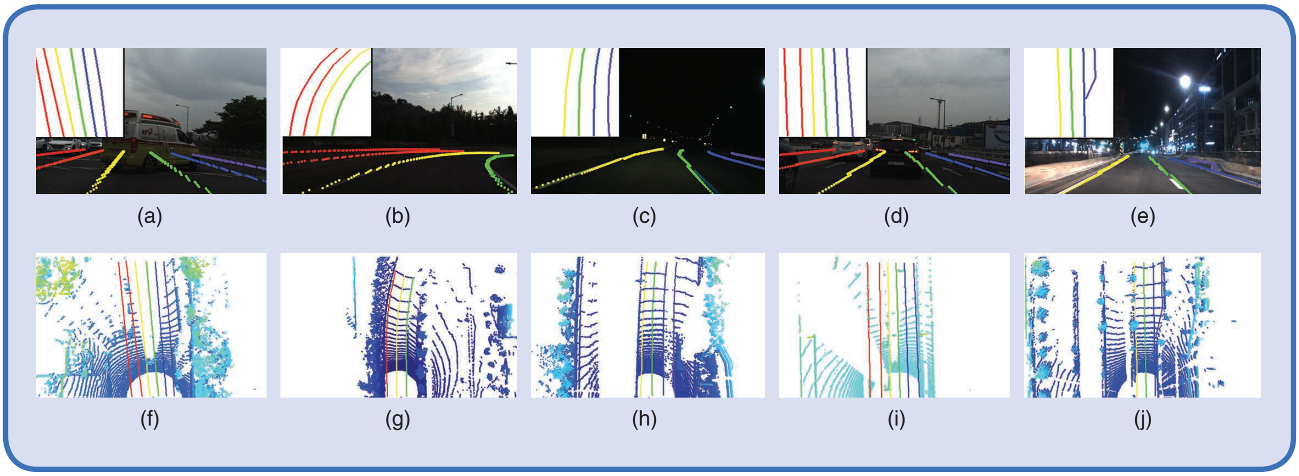

FIG 4 The inference results of the AVE Lab's lidar lane-detection network in different driving conditions. (a) Occlusion (day), (b) sharp curve (day), (c) gentle curve (night), (d) occlusion (day), and (e) merging (night). (f)–(j) The inferenced lane lines in lidar.

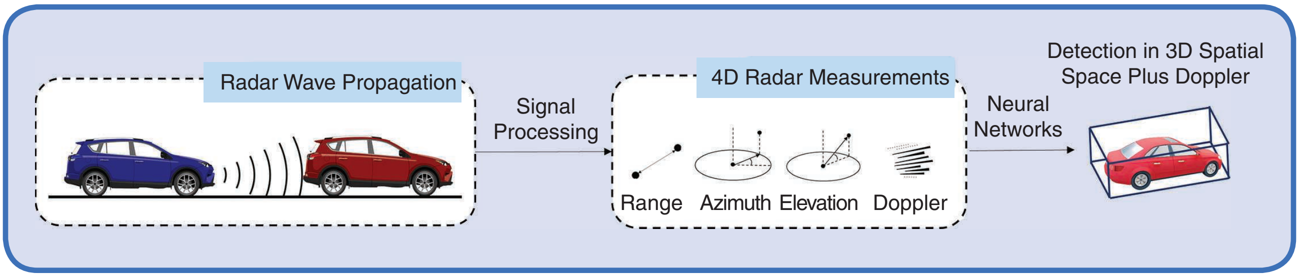

FIG 5 Object detection with 4D radar. In addition to the range, azimuth, and Doppler measurements seen in conventional radar, 4D radar produces additional elevation measurements, enabling object detection in 3D spatial space.

Moreover, the network performance at night stays firm with an F1 score of 82, indicating it is not affected by poor lighting conditions.

Object Detection With 4D Radar

Intuitively, using sensors with a longer wavelength would be useful for accurate measurements in harsh weather. One excellent alternative sensor for autonomous driving in harsh weather can be 4D radar, which produces 3D coordinates with velocity measurements of objects (see Figure 5). These 4D measurements give a strong benefit to the autonomous vehicles, and AVE Lab is developing one of the first object-detection networks for 4D radar.

However, there are challenges that need to be addressed regarding the development of a deep learning-based 3D object-detection network with 4D radar: efficient data labeling and the handling of sparse measurements of 4D radar. To create ground-truth data, the AVE Lab is developing an auto-labeling technique for 4D radar data using high-performance lidar object-detection networks. With careful calibration, detection results in the 3D lidar point cloud can be projected into the radar frame, resulting in accurate ground-truth proposals. At the same time, the AVE Lab is developing a novel 3D object-detection network that directly takes 4D radar data as input and produces highly accurate 3D object-detection results for all weather conditions (see Figure 6).

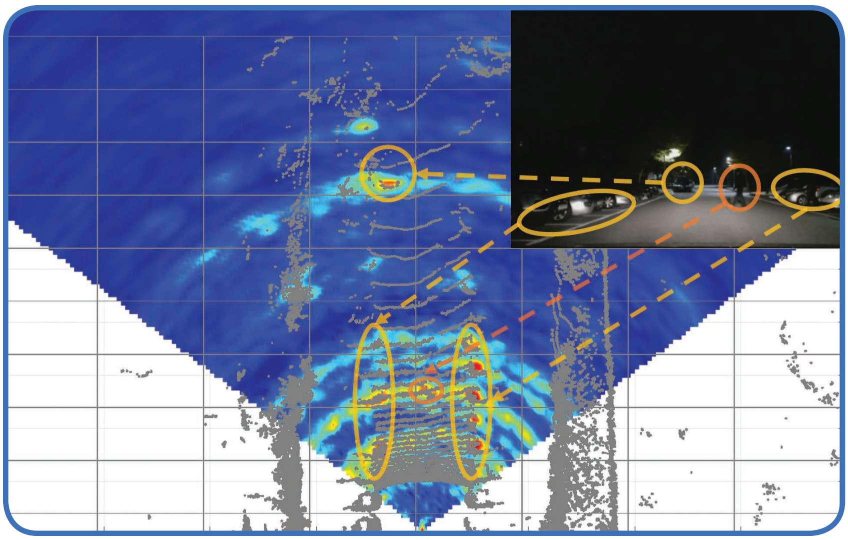

FIG 6 4D radar auto labeling with lidar supervision. The AVE Lab use their lidar object-detection network to generate object ground truths in radar coordinates after careful sensor calibration.

Advanced Positioning Systems

In addition to end-to-end autonomous driving and robust perception systems, AVE Lab has developed advanced positioning, localization, and navigation techniques. For example, map-based urban-assisted global navigation satellite systems methods have been commercialized in the mobile communication networks of SK Telecom and Korea Telecom in South Korea. The AVE Lab has developed a precise localization and navigation system using multisensors for very high-speed (>300 km/hr) express trains. Moreover, the AVE Lab is currently designing an advanced satellite navigation signal with a stepped-frequency binary offset carrier for the Korean Positioning Satellite system.

Autonomous Driving Systems in the Future

The aforementioned research directions of AVE Lab are closely interconnected and essential to the development of a Level-5 autonomous driving system. The robust perception and advanced localization systems allows autonomous vehicles to make the highly accurate observations required for end-to-end networks. In return, the end-to-end architecture with the hybrid IL and RL approach enables the autonomous vehicle to learn complex features of the surrounding environment and to be robust against UNSs and control anomalies. With advancements in these research areas, the AVE Lab expect a meaningful contribution to the commercialization of safe, autonomous driving systems in the near future, ultimately benefiting millions of people worldwide.

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