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Modular technology in the AutonomouStuff Lincoln MKZ

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The Ford-manufactured MKZ has drive-by-wire technology for various systems

Fit for purpose

Nick Flaherty reports on the mix-and-match approach to technology components that are the hallmark of this autonomous car

Building a self-driving car is hard, but building one where all the components can be swapped out, changed around and generally modified, is even harder. That is the challenge Bobby Hambrick set himself and his company, AutonomouStuff (AS). The company provides sensors, hardware and software for self-driving car projects, but Hambrick has put all of these together in a standard Lincoln MKZ sedan to fit all the different technologies together.

That has required the development of a wide range of software, including machine learning, and the company aims to demonstrate a driverless car performing many of the tasks required for SAE Level 4 autonomy by the end of this year. At Level 4, a passenger can still take control of the steering wheel, accelerator and brake, rather than the fully autonomous Level 5 that has no user controls.

But this is only one part of the project. The technology has deliberately been developed to be transferred to other vehicles including the Ford Fusion, an electric golf cart-like street-legal called Polaris Gem, or a petrol-engined off-road buggy platform called the Ranger.

That requires a whole new software architecture to support flexibility in the types of sensors used, where they are positioned around the vehicle and how they communicate. It gives many more options to engineers researching and developing new approaches to autonomous systems, but the technology had to be designed from the ground up.

The MKZ is manufactured by Ford, and has drive-by-wire technology for steering, brake and throttle connected via the CAN bus that runs throughout the vehicle to link all the electrical systems. The hybrid combines a 2 litre four-cylinder Atkinson-cycle engine with the hybrid powertrain from the Ford Fusion. The electric motor produces a total of 188 hp (142 kW) and includes an EV mode that allows the car to travel short distances on electricity alone at speeds of up to 47 mph.

AS modifies the car by adding laser, camera and radar sensors, a drive-by-wire interface and a compute engine

The MKZ's front bumper is fitted with two 16-layer laser scanners

to control the steering, braking and throttle via the CAN network. Without the drive-by-wire interface, the CAN control messages are not readily available to anyone who buys the vehicle.

Laser sensors

The MKZ has two types of laser sensor around the vehicle. Hambrick says, "Lidar is one sensor modality for perception, and we use a variety for research. We use the Velodyne 64-layer Lidar sensor to get a 360° field of view [FOV] for mapping, and we have developed some Lidar localisation algorithms so we can localise ourselves to know where the car is within its environment.

"The 64-layer sensor gives more than 2.2 million points of data per second, and we collect that from the roof. There are trade-offs though – it's a big spinning system, so for a production version you would not use that."

The Velodyne HDL-64E sensor has an effective range of 120 m around the vehicle. The returning data, known as the point cloud, is fed back as time-stamped packets via an Ethernet link.

> The Velodyne 64-layer Lidar sensor gives more than 2.2 million points of data per second, and we collect that from the roof

This data includes distance, angle and intensity values of the reflection of the laser, and is integrated with data from the IMU and GPS satellite navigation system. Structures in the point cloud such as stop signs and intersections are identified and tagged with the location to produce a base map.

AS also uses the smaller, 16-layer HDL-16E sensor for obstacle detection and tracking. The company has built its own Lidar processing system for recognising objects such as pedestrians and tracking their distance from the car, their direction of travel and speed, and this is handled in the compute engine.

These 16-layer rotating laser sensors are placed on the two front corners. "This is very similar to where Ford puts them, but our system is flexible and this is not yet locked down owing to continuous r&d," says Hambrick. The sensors could also be placed on the roof or the front bumper; all that would need to change is an offset value in the middleware.

Sensors are installed in the MKZ using 3D-printed mounts

The offset uses a precise measurement in reference to the centre of the rear axle, and the coordinate transformation happens in the middleware.

That is essential to the modular approach, as it allows the mounting of the sensors to be moved easily. The mounts are 3D printed to fit in different locations.

Other laser sensors

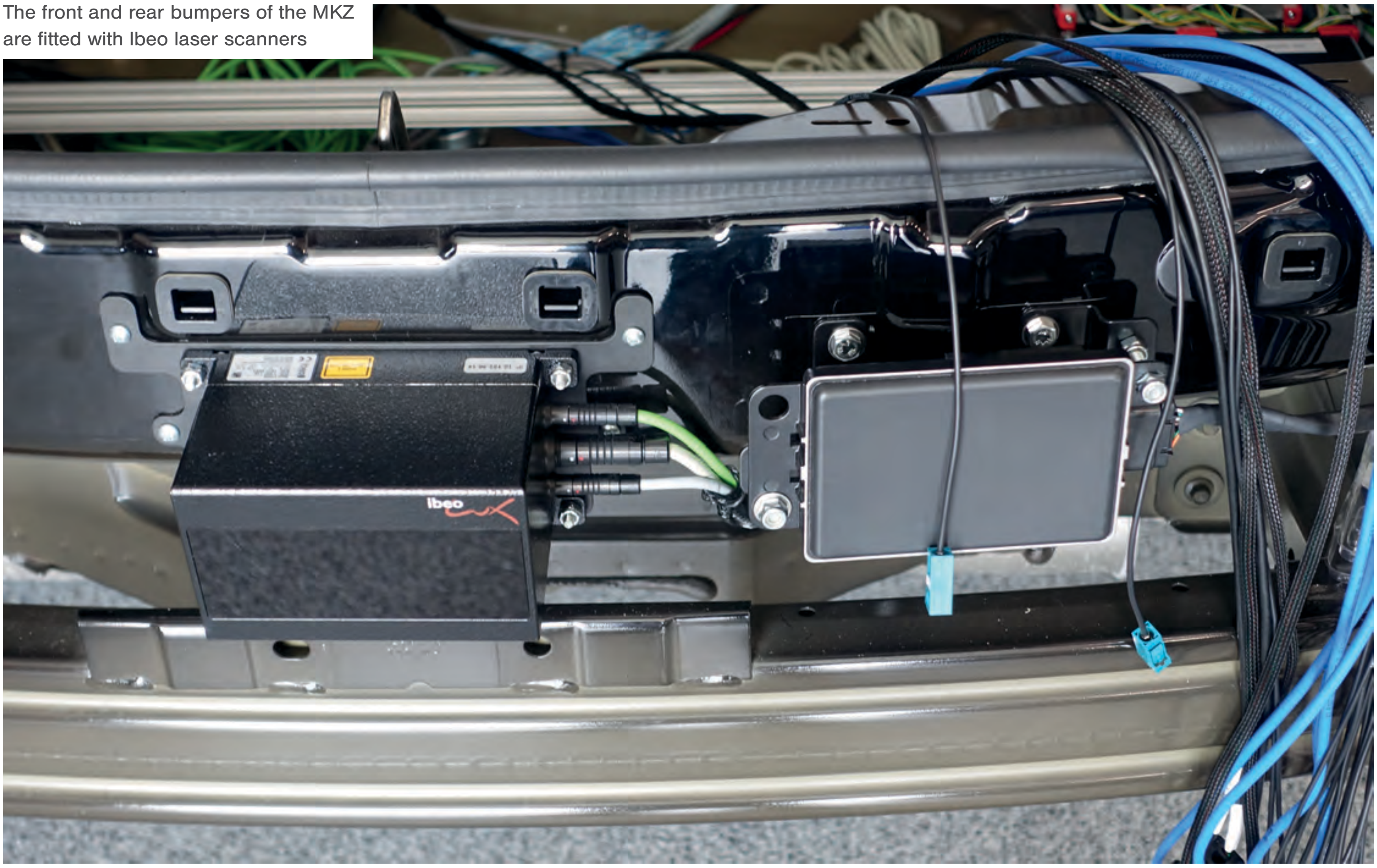
The AS MKZ also uses rotating laser sensors from Ibeo Automotive Systems for different functions.

"These have always been one of my favourites," says Hambrick. "You get a directionally focused beam with four layers and a 110° FOV, so it's a smaller amount of data than the Velodyne. We use them on the bumpers to cover the blind spot of the Velodyne on the roof."

These sensors have a narrower FOV than the Velodyne and a longer range, of 200 m, as well as integrated object tracking. Hambrick says, "We fuse the data from six of those around the car, and use that with the object tracking to fuse the data into one scan."

The raw data is fed from the six sensors – three on the front bumper and three on the back – to an Ethernet switch and then to an ECU from Ibeo that acts as a fusion engine. This combines the raw data from the sensors and identifies objects in the point cloud, the output being both the objects and the raw data.

This provides detection and tracking of other road users with detailed information on the position, motion and shape of surrounding road users as well as static background objects. It detects cars, trucks, bikes and pedestrians, and provides estimated uncertainties for each object.



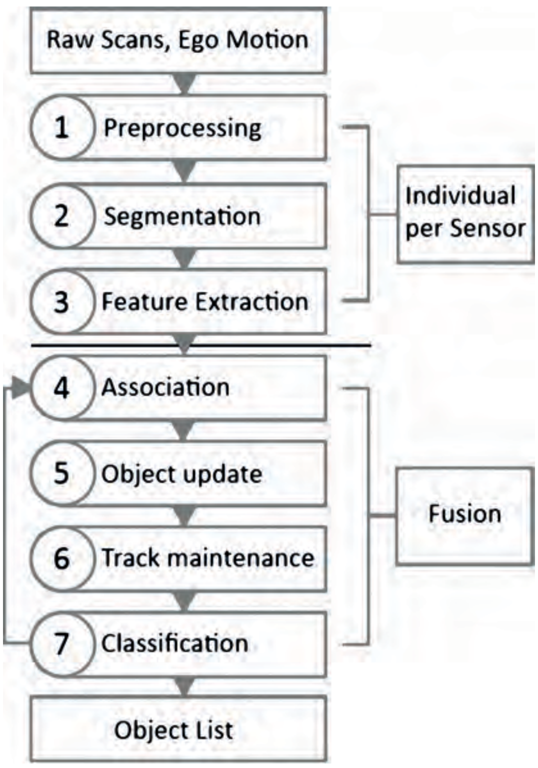
The front and rear bumpers of the MKZ are fitted with Ibeo laser scanners

The laser sensors on the bumpers give a beam with four layers; we use them to cover the blind spot of the Velodyne on the roof

"Ibeo has a clearly defined API document to read the messages via an interface, and we look at both the raw data and object data," says Hambrick. The distance and angular resolution data are used to offset camera and radar data.

Three steps are performed in the sensor. Pre-processing filters out invalid scan points – that is, points such as rain or ground, which are highly unlikely to be objects; then the clustered point clouds that might belong to an individual object are identified in

The Ibeo laser scanners have object detection software built in



A camera from Mobileye handles lane detection on the highway

Key suppliers

Laser scanners: Velodyne
Laser scanners: Ibeo
Camera: Mobileye (now Intel)
Cameras: Point Grey
Radar: Delphi
GPS: Novatel
IMU: KVH
Compute engine: Neousys Technology/in-house
Storage systems: Quantum
Operating system: ROS
Operating system: Ubuntu Linux
CAN by-wire interface module: Dataspeed

the segmentation step; and then these features are extracted from the overall point cloud.

There are four steps that are handled by the fusion engine. In the Association step, the identified segments are matched with their corresponding object, and the position and motion of the objects between each scan are updated based on an Interacting Multiple Model.

In the Track Maintenance step, the plausibility of whether certain segments belong to the same object, based on the orientation and yaw rate of the object, is checked. A decision is then made to either merge or split objects based on their behaviour or appearance. For example, if there are two objects following each other with the same velocity and distance, they could be a truck with a trailer, so they can be merged into one object.

The Classification step applies a 'track before detect' mechanism. That means an object is tracked for as many scans as necessary until the object is clearly identified. In this step, the objects also receive a label such as car, truck, bike or pedestrian.

These objects from the fusion engine are then integrated into pathfinder software as the fourth step.

> We get the raw detection data out of the radar, which needs to be filtered and processed, and this gives a lot of reflectivity data

Cameras

The AS research platform uses two visible-light cameras. Infrared is not needed as the laser sensors operate well at night.

Mounted in the front windscreen to provide lane modelling information and object tracking and classification is a Mobileye 660 single-lens camera. The lane modelling is used for highway driving to determine lane quality, for example how clear the solid, double solid or dotted lines are on the road. It uses the reflectivity of the lane marker to calibrate how well the camera is working, on a scale from zero to three.

The camera includes the EyeQ2 image processing chip that provides real-time image processing for detecting lanes, vehicles and pedestrians, measuring the dynamic distances between the vehicle and road objects. This object data is fed back via the CAN bus to the compute engine.

There are some limitations with this system. For example, an exit from the highway appears as a turn in the road.

"Not all of our automation software operates on a predefined map, so we are doing everything in real time, and that can affect how the highway automation works," Hambrick says. "You can use additional camera algorithms to detect or pre-map the road, and tag it to compensate for this, and we supplement the output with our own algorithm to produce a reference image."

The MKZ also uses cameras from Point Grey, with image processing algorithms from AS and an Ethernet output back to the compute engine. This is used to provide a reference image that can be superimposed on top of the Lidar point cloud to check that the two sets of data match.

One of the cameras is placed near a front window pillar to monitor a lane, while one in the back of the car provides a reference image for the laser scanners when changing lanes.

AS is also working on its own camera-based lane modelling algorithms that would provide longer range and a wider FOV than the Mobileye system.

Radar

There are five Delphi ESR 76 GHz radar sensors on the MKZ to provide object detection. One is mounted on the centre of the front bumper and has a range of up to 175 m with a narrow FOV of 10°, or a wider FOV of 45° but a shorter range of 60 m. Then there are 70 m range sensors on each corner of the vehicle with a 150° FOV to cover any blind spots and detect any cross-traffic.

The front radar is used in the highway scenario to track a car in front, where you only need to know what's in the lane ahead and in the next lane. The side detection radars on the bumpers need a focused beam but the FOV covers the blind spots and overlaps with the front sensor to give a 360° 'radar bubble' around the car.

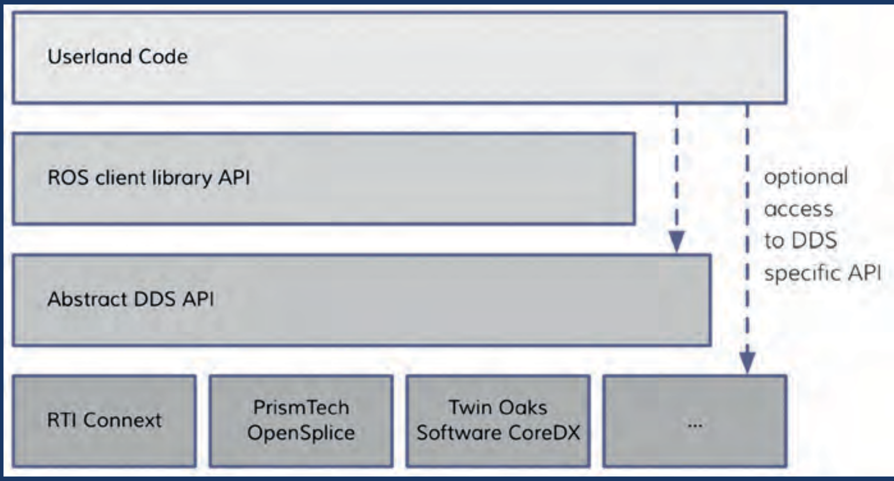
"The idea is to have multiple sensor FOV with multiple modalities," says Hambrick. The radar sensors use both Ethernet and CAN. "We get the raw detection data out of the radar, which requires filtering and processing, and this gives a lot of reflectivity data, like a point cloud.

"Then there is track data, which is the grouping of the detections. For example, you may get ten detections on the back of a car but the track will turn it into one detection point," he says.

"We use both but fuse the higher level output of different sensors such as the object data from the Lidar and the

Publish/subscribe

The DDS interface is well-defined to allow middleware such as ROS to provide modular services



The publish/subscribe software architecture is based around sending messages rather than streams of data. The system consists of nodes performing different functions: some will be a publisher, sending out messages, while others will subscribe to these broadcasts.

The publisher doesn't need to know who is subscribing to its message stream. This allows a scalable system to be built where new functions – nodes – can be easily added without having to rewrite the whole system.

The Data Distribution Service (DDS) is an end-to-end middleware that uses a publish/subscribe architecture for real-time control systems. This is an industry standard managed by the Object Management Group, who also developed other high-level design protocols.

It is written in an 'interface description language' that is defined by the OMG for message definition and serialisation. A distributed discovery system allows any two DDS programs, also called nodes, to communicate without the need for a central tool. One node broadcasts the availability of data, and another then subscribes to that output.

That makes the system more fault tolerant and flexible than a typical operating system, and DDS has been used in large military systems, flight controllers and space systems with commercial implementations developed by companies such as RTI, PrismTech and TwinOaks Software. Volkswagen's research labs for example has an agreement with RTI to use DDS technology, and space agency NASA uses the Robot Operating System (ROS 2.0) on top of DDS.

The benefits of end-to-end middleware such as DDS are that there is much less code to maintain, and the behaviour and exact specifications of the middleware have already been documented. DDS has recommended-use cases and a software API so that developers can work with it at different levels.

A drawback of using end-to-end middleware though is that an operating system such as ROS must work within that existing design. If the design did not target a relevant-use case or is not flexible, it might be necessary to work around the design – defeating the object of using it in the first place.

Point Grey cameras monitor objects around the vehicle

object tracking of the Mobileye camera."

According to Joe Buckner, director of engineering at AutonomouStuff, "We are talking over CAN to the radar. The sensors have an Ethernet interface but we are finding that CAN is more than sufficient."

There are ultrasound sensors on the vehicle, but these are not part of the system. Hambrick says, "We are not focusing on parking, but if you want to do a parking algorithm you would combine ultrasound with laser scanners."

Navigation

AS has worked with Novatel to develop kits that combine GPS navigation with an IMU to provide data when GPS is not available. The kit uses a 1750 fibre optic gyroscope from KVH, whose output is tightly coupled to the GPS system.

The GPS is accurate down to 2 cm when used with an RTK base station, where a 900 MHz or 2.4 GHz radio is used to send correction data. Using radio telemetry restricts where the vehicle can be used, so there are other methods of localisation being used in parallel, says Hambrick. Another option is to use Novatel correction data from the Terrastar satellite, which provides accuracy to an average of 10 cm.

A differential GPS antenna is mounted on the roof.

Compute engine

The heart of the autonomous car is the compute engine. AS has worked with Neousys Technology to specify its own engine for the MKZ, which is called the Nebula.

This combines a 4 GHz Intel Skylake Core i7-6700 quad-core processor with 16 Gbytes of DDR4 memory and the six Gigabit Ethernet connections that are needed for the sensors into a 240 x 225 x 110 mm footprint. However, the key to the system is the Nvidia GeForce GTX 1050 graphics card, which provides 768 graphics processing units (GPUs).

This is one option, according to Hambrick. "We work with many other compute platforms depending on the specific project. If we were to plan to use a number of cameras and radars to implement deep learning algorithms then we would use a different platform that may include an Nvidia DrivePX," he says.

An innovative thermal design helps to dissipate the heat generated by the GPU card so that the compute engine can operate reliably at 60 C with 100% GPU loading.

The Nebula has 16 channels of isolated digital I/O, but that is not being used. "We don't really have a use for the digital I/O at this point," says Buckner.

The main storage is a 128 Gbyte solid-state disk with a thermal sensor, and the box accommodates two 2.5 in SATA hard disk drives with RAID 0/1 support for basic data storage.

Storage

Data storage is actually a major issue for such a system. With tens of millions of data points generated every second by the sensors, storing the raw data in such a way that it can be used by researchers is often overlooked. If hundreds of USB sticks have to be used to transfer data from the car to the lab, the data is never going to be examined.

As a result, AS has added an I/O card with a Fibre Channel optical link to offload data to an array of hard drives, the capacity of which can be configured by the customer.

The storage systems, from Quantum, are designed for high-performance computing applications, but AS has integrated eight of them in a RAID array, each running at 500 Mbit/s, into the MKZ. Each one has 768 Tbytes of storage for a total of 1.8 Pbytes, which allows six uploads of the complete car systems data before the data needs to be migrated.

An external Ethernet connection can be used to access the data directly from the array or via the Nebula, and there is software that helps tag, retrieve and sort through the data. "The cost per terabyte is much less by using this system compared with traditional IT methods. You want everyone to have access to the data via a remote server anywhere in the world," says Hambrick. "That's often overlooked until it is too late."

CAN

The CAN interface is used to link the Nebula engine to the vehicle. "That is really the only place we use CAN, with a USB-to-CAN converter or a PCI card in the PC for a direct CAN interface," says Buckner.

This connects to a CAN converter module from Dataspeed that translates messages from the middleware to CAN and receives the feedback. "Message latency has never caused us any pain in our control so we've never had to worry about that," Buckner says.

The Nebula compute engine uses an Intel Core-i7 processor and Nvidia graphics card

Power supply

Power is distributed via a 12 V harness to the individual sensors. "The power limitation isn't there unless you start talking about heavy server racks," says Buckner. "We have a 175 A inverter in the vehicle, and we have done studies on how much power the car is taking and how much extra is available.

"There's about 90 A drawn under normal conditions so we have 85 A to play with," he says. "That supports most of the sensors and a 1000 W server rack without voiding the warranty of the vehicle."

Software

The Nebula is preconfigured with Ubuntu Linux 16.04 LTS running on the Core-i7 processor and with the latest version of the Robot Operating System (ROS) acting as the middleware layer.

The middleware is the heart of the system, as it allows modules of software that are as independent as possible to work together in a scalable software architecture. ROS uses a publish/subscribe technology called DDS to link the different modules together (see sidebar: Publish/subscribe).

The idea is that high-level modules such as collision detection, image recognition or emergency braking can be like apps on a smartphone, and easily plugged into the middleware.

At the lowest level, there are separate software programs (called nodes in DDS) for controlling the steering, acceleration and braking that link to the by-wire CAN interface. These modules have an interface to ROS.

Similarly, there are ROS drivers for linking to the laser scanners, cameras, radars and the navigation system.

AS created an arbitrator software module within the ROS that decides which module to use at which time. There is a defined list of priorities that are dependent on the sensing data and the status of the car.

"Developing modular software is easier said than done," says Buckner. "Generally, if you take one piece out, it crumbles. The idea is that you can take out one piece and you lose only the functionality of that module but the rest of the system still functions."

The middleware knows which sensor the data is coming from via the port or USB channel, and makes it available in the ROS world. Then, any node that wants it subscribes to the data set or parts of the data set, such as the tracks or the visualisation data.

The apps have to be built to minimise their dependency on other modules and just use the lower level data sources. Each node has a standard defined set of messaging in and out like a typical API.

The modules currently handle:

- Lidar object detection – determining the ground plane and then identifying objects
- Highway autopilot module – this uses adaptive cruise control, a lane-keeping algorithm, intelligent lane change, a point of interest manager and more
- A shuttle module that allows the MKZ to be trained to follow a predetermined route. This has an option to increase the lateral acceleration limits so the vehicle can take curves faster.

These all make use of the underlying nodes for sensors, steering, acceleration and braking.

AS is working on another module for object classification from the camera images. This uses deep learning neural network algorithms running in the Nebula to identify cars and road signs.

This is still in the training and testing stage before running a live optimisation. The offline learning uses a System 76 Linux PC with the TensorFlow neural network software development kit to train the algorithm with over 36 Gbytes of image data. This will then be transferred to the Nebula for live testing.

The next step is to offer the modules as standalone software to allow customers to get up and running quickly. Every customer receives the throttle, brake and steering wheel command modules.

"We are finding that every customer has to build their own speed controllers, so we are releasing a product to allow customers to control the vehicle with a speed and curvature command," says Buckner.

The next module in development would then take in a series of waypoints, and output speed and curvature commands. "Then you have a module on top with a customer's path planning algorithm to produce a series of waypoints using what is seen in the lane model," he says.

The company

Bobby Hambrick formed AutonomouStuff (AS) shortly after the DARPA Urban Challenge in 2010, when he noticed a large gap in the industry's supply chain serving the growing interest in automated vehicles in various markets, including automotive, mining, military, agriculture, aerospace and academia.

He realised that robotics companies were finding it hard to gain access to the technology needed to solve their applications, so he set up AS to bring together the hardware and software components that engineers need. "I call this bringing together the world's best," says Hambrick.

The company has been part of the unmanned vehicle industry from its early days, bringing early systems to the autonomous track days that ran in 2016 in the US and the UK, as well as working with leading development teams around the world.

The Illinois-based company now provides sensors, engineering services and automated driving software to more than 2000 of the world's most advanced automated driving teams and research projects.

Future developments

Development of the AS platform can go in a number of different directions. The most immediate is to have the MKZ as a Level 4 autonomous system, driving on its own through an urban environment, onto a highway and off again.

"By the end of the year I want to be able to take a predetermined path through a town and drive autonomously through that route, while recognising and obeying road signs, then entering a highway and exiting it to show quasi-L4 autonomy," says Buckner. "We have all the different pieces and we are pulling them all together to do that in a clean boot.

"That means we learn that much more about how our customers are using what we have, and identify pieces of the software that we can commercialise, as it's a problem that everyone will need to solve. If we can allow customers to focus on what they do best, they will get there a lot faster and insert their technology into the modular software."

The modular nature of the design also applies to the hardware. AS is developing its own, purely electric vehicle platform based on the Gem, a small electric 'cart' manufactured by Polaris in the US. It has a top speed of 25 mph and can be configured with two, four or six seats. The Ranger, mentioned earlier, is an off-road version of the Gem.

AS has developed its own 'universal-by-wire' electronic interface for the Gem and the Ranger but it can also be used for all kinds of vehicles – the next target is trucks.

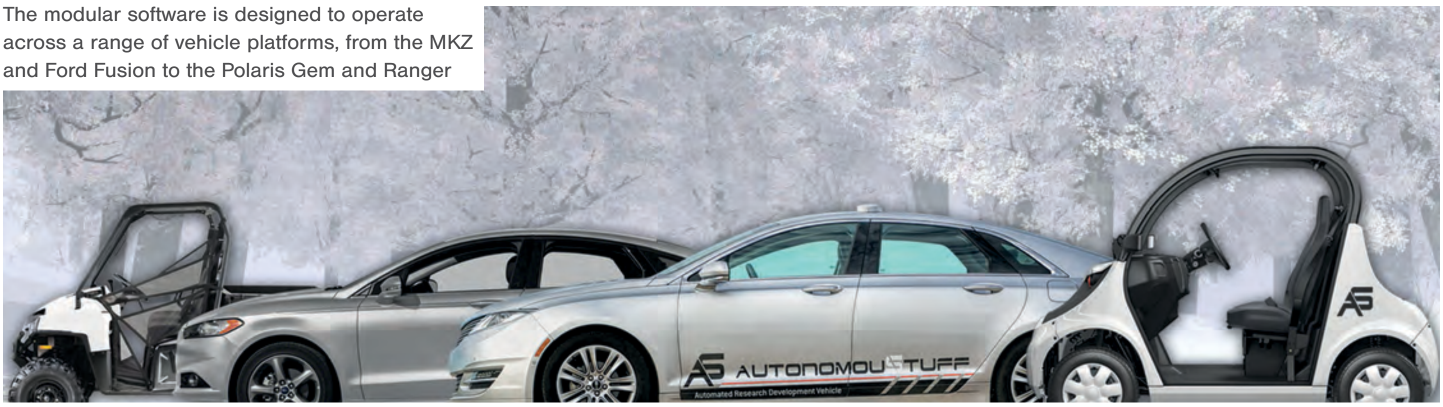
The aim is that customers can use the software for production systems. That will require some changes. "We are building the software for research but want a path to production, and ROS 2.0 provides that," says Hambrick.

That would remove tools such as the visualisation that combines the camera data with the laser point cloud, as this is not needed in a production system. The Ubuntu Linux would also be replaced by an automotive Linux being developed by the Yocto group, or other real-time operating systems with ROS running on top.

"There are also security concerns in running a production system in ROS that are still being defined," he said. "There is an abstraction interface, and you could rip out the ROS interface and replace it with something else," Hambrick says.

"You have the core software functionality and you could build your own proprietary message system to make it as difficult as possible for someone to reverse engineer."

Building a modular system where all the hardware and software works together reliably is a considerable challenge. It requires a middleware architecture that supports a modular and careful implementation of the sensors. All this allows researchers and developers to focus on their specific projects without having to build the underlying technology themselves. ◻



The modular software is designed to operate across a range of vehicle platforms, from the MKZ and Ford Fusion to the Polaris Gem and Ranger

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