LiDAR **Giant**

by Lindsay Brooke

100 competitors want to eat his lunch, but Velodyne president Mike Jellen aims to maintain leadership in this fast-moving, trillion-dollar technology space.

In a word-association game that begins with "lidar companies," the first response is likely to be "Velodyne." The Silicon Valley-based pioneer in 3D light-detection-and-ranging sensors, whose groundbreaking 64-laser, 360° field-of-view technology famously helped win the 2007 DARPA Urban Challenge for self-driving vehicles, is currently shipping seven sensor models to hundreds of mobility-industry customers for testing and for limited commercial use. The annual production rate from the company's San Jose plant today, in tens-of-thousands of units, is just the tip of an impending tidal wave.

"We're moving fast through a period of intense fleet testing into the initial ramp-ups for true automotive-scale, high-volume production—both for the retail ADAS as well as for on-demand mobility fleets," explains Mike Jellen, Velodyne Lidar's president and chief commercial officer. "Most current volume goes into [SAE] Level 4 developments. A significant portion of new-vehicle activity is on ADAS safety systems. We see an opportunity for sustained unit-volume growth occurring 2019 through 2025."

Velodyne Lidar

Trio of Velodyne's latest lidars to show their relative size (from left)—the range leader VLS-128, the 32-channel Ultra Puck VLP-32C, and the compact, solid-state Velarray. A Velarray also appears on the cover of this magazine, held by Mike Jellen.

While lidar's high-definition 3D mapping capability represents a separate market for Velodyne, automated and autonomous vehicles (AVs) remain "the dominant force—a trillion-dollar market opportunity," Jellen tells SAE's *Autonomous Vehicle Engineering*. "We'd like each of the billion vehicles on the world's roads to have two to four lidar sensors—maybe $1000 of sensors per vehicle—and see the trillion-dollar opportunity emerge."

OEMs may bring suppliers even greater delight: Aptiv uses nine lidar units in its BMW-based AV demonstration vehicle.

To prepare for the gold rush, Velodyne Lidar has been steadily growing its engineering, scientific and technical resources. The company, founded by CEO David Hall in 2006 (see sidebar), now has over 500 full-time employees at five facilities around the world.

Ford and Baidu are among its high-profile investors, and the company also has a cooperation with Mercedes.

Velodyne's core IP portfolio includes embedded software and algorithms, and detectors, as well as ASICs—application-specific integrated circuits that are custom engineered for mobility lidars. All are strategically developed in-house.

This dense point-cloud street scene represents up to 9.6 million points per second. It was generated by Velodyne's most advanced 3D lidar sensor, the VLS-128 introduced in 2018. Engineered specifically for AV use, the 128-channel unit provides real-time data up to 0.1-degree vertical and horizontal resolution with up to 300-m range and 360° surround view.

Higher resolution, lower cost

The latest fruits of this focus debuted at the 2018 CES and have been in customer evaluation. The VLS-128, which Jellen anointed "the best lidar sensor on the planet," succeeds the company's classic DARPA-winning HDL-64 seen spinning atop many prototype AVs. Nearly one-third smaller and lighter than its predecessor, with twice the lasers (channels), the VLS-128 is claimed to deliver ten times better resolution. This greatly improves object identification and detection within a 360° field of view (FOV).

Velodyne claims the new lidar, with range up to 300 m (984 ft) can be used directly for object detection without additional sensor fusion. It was designed for automated assembly that includes a proprietary laser-alignment process.

Also appearing was the Velarray, a fixed-laser, solid-state sensor with 200-m (656-ft) range. Designed with a compact form factor for more natural integration into vehicle bodywork of both ADAS-enabled SAE Level 2 automated-driving vehicles, as well as SAE Level 4 and 5 autonomous vehicles, the Velarray's target price—"in the hundreds of dollars" at automotive scale—was equally big news.

And according to Jellen, development also is underway on integrated arrays that combine lidar and other sensor modalities including camera—"both in direct fulfillment efforts to customers as well as internal R&D."

Velodyne plans a regional approach to global lidar production, with manufacturing facilities to serve customers directly in North America, China and Europe. A range of vehicle-integration models depends on the vehicle market and use case.

"On the full-AV side, the leading companies will have in-house integration efforts," Jellen said. "Others will rely on Tier-1 partners, through whom Velodyne will support directly. For the ADAS safety market, Velodyne will support both through Tier 1 partners as well as through direct full solutions. Therefore we plan on a Tier 1/Tier 2 mix, as is the case today."

100% Level 4 market penetration

Occasionally dubbed "the 800-pound gorilla" of the mobility-lidar market, Velodyne currently sits atop a burgeoning technology space that, by some counts, includes nearly 100 players of varying strengths and prospects. Some new competitors include ex-Velodyne staff—typical cherry-picking activity in a high-growth industry.

EasyShare

Fully embedded, visually concealed sensors are not as critical for commercial autonomous shuttles (EasyShare's EZ10 shown) as they are for private vehicles, but operators will still want a seamless look. The France-based AV maker recently launched limited public-roads service in California.

David Hall: From subwoofers to spinning lidars

CEO David Hall

Velodyne founder and CEO David Hall has been an inventor his entire life, following the footsteps of his father and grandfather. After earning a mechanical engineering degree from Case Western University in 1974, Hall ran a specialized machine-tool shop in Boston where he developed medical equipment and invented a hand-held tachometer that is still sold today.

An interest in high-end audio prompted Hall to launch Velodyne Acoustics in 1983. That business created a new product category: servo-driven subwoofers. His custom-sensing, real-time DSP signal analysis updated the sound 16,000 times per second within these devices, millions of which have been sold. The innovation helped give rise to the home theater market.

Robotics development and successful participation in the televised *Robot Wars* and *BattleBots* competitions followed. Then came the 2004-2007 DARPA Challenges, aimed at making trucks drive by themselves through a grueling desert course. For Hall it was a perfect fit—and the genesis of 3D automotive lidar.

Unsatisfied with the limited 2D images of the stereo camera his team used in the 2004 event, Hall invented a spinning LiDAR to produce real-time 360° FOV, 3D maps of the surroundings. Whereas no team had previously been able to complete the Challenge, in 2007 six out of the seven finishers had Hall's Velodyne lidar atop their vehicles.

–LB

"Given the potential, it's not surprising we see a large number of companies and approaches coming in to attempt to serve this vast opportunity," he said. "Different companies are targeting different solutions at different times, though there has been a lot of repackaging of approaches that are 30, 40 years old. A number of these companies are taking advantage of the hype on lidar, and of the significant investment flowing into the space."

AV engineers widely consider lidar to be an essential sensor (in combination with cameras and radars) for SAE Level 4 and 5 "full-autonomous" operation, and of high value in Level 3 automated driving. Employing a pulsed laser to measure variable distances, lidar is used for creating and updating 3D maps that enable real-time, 3-centimeter-level precision in vehicle location as well as providing fail-safe sensor redundancy.

The high-def maps allow the on-board processors to "continually compare and get a sense of static and dynamics and know exactly its position in space regardless of GPS or IMU [inertial measurement unit] performance," Jellen said. "This greatly simplifies the real-time perception challenge."

Jellen, an electrical and software engineer, joined Velodyne in 2015 with 20 years' industry experience in robotics and automation. He expects the first major commercial lidar applications to be in autonomous shuttles and delivery vehicles running a geofenced route. Pilot-fleet use is well underway.

"You'll continue to see quarter-over-quarter growth with [AV shuttle] companies such as Navya, EasyMile and Baidu Apollo," whose new shuttle program in China was recently announced.

For the retail vehicle market, Jellen expects eventual 100% market penetration for lidar for SAE Level 4 driving. "I do not see another type of sensor that fills in for its capability," he asserted. And companies choosing a "true Level 3" system—hands-off/mind-off highway operation—are including lidar to provide Level 4 functionality in that operating mode, rather than risk relying on the driver to be the backup.

Velodyne Lidar

Cost, size, power consumption

The explosion of lidar start-ups has tended to classify companies by a particular sensor approach, such as

solid state. Velodyne is researching "dozens" of models beyond its current portfolio, Jellen said. The goal is to offer different beam-steering methodologies (including solid-state sensors), and both wide and narrow FOV types to serve various use cases. "The right tool with the right maturity for a given product line is how we do it," he explained.

Narrow FOV is typically 120 degrees or less; wide is 180° or more. For one sensor placed on one location in the vehicle, being able to "see" a clear 180-degree sweep helps to solve some of the more daunting driving scenarios, such as identifying black tire-chunk debris in the road while approaching a 'T' intersection at speed.

Unit cost reduction and package efficiency—creating a form factor that can be integrated invisibly into a vehicle's exterior skin—are the two greatest challenges related to lidar in 2018, vehicle development engineers tell *AVE*. According to Jellen, cost performance requires two things: volume, and ASICS. Velodyne's "base" 16-channel unit, the VLP-16 Puck with 100-meter range, can be had for about $4000 for low-volume orders in 2018—far less than the $70,000 price tag of the old HDL-64 and has the ability to be priced competitively for high-volume automotive customers.

Jellen's projection of $1000 for a four-unit vehicle array highlights Velodyne's drive toward an aggressive unit-cost target, at volume. That is one of the missions, along with performance and package efficiency, of the new ASIC-enabled Velarray sensor. The first-gen Velarray unit measures 125 x 50 x 55 mm (roughly 5 x 2 x 2 in.), a dimension that OEM stylists and vehicle-integration teams will find easier to incorporate all around the vehicle.

"Having to package lidars inside aero-style blisters around the body may be acceptable for mail trucks or

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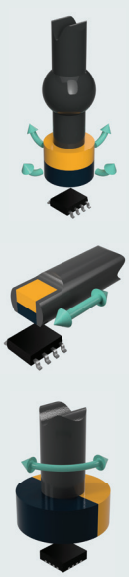

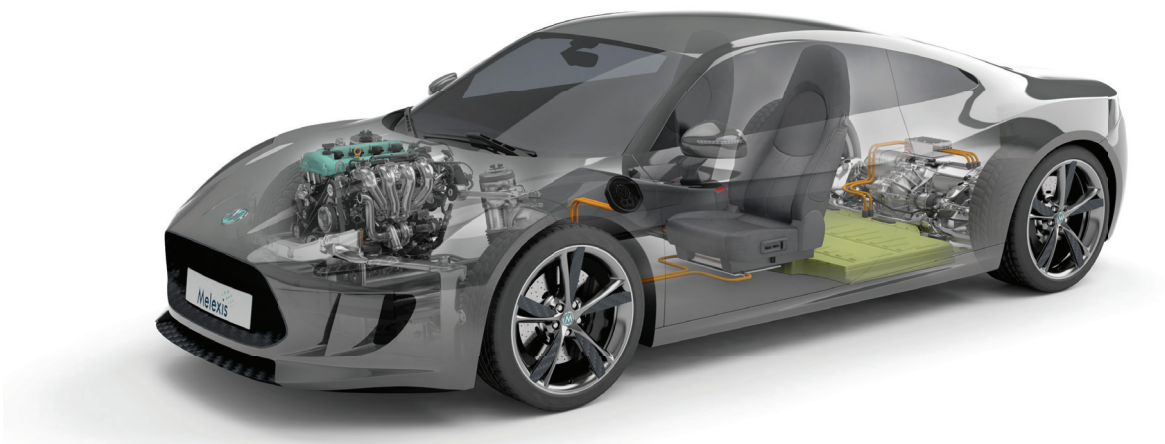

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I do not see another type of sensor that fills in for lidar's capability [for Level 4 driving].—**Mike Jellen**

Ford Fusion AV demonstrator wears a rooftop sensor array designed to resemble a cargo rack, plus stalk-mounted Velodyne Puck lidars on the A pillars.

Ford

robo-taxis, but not for private vehicles," a body-structures engineer tells *AVE*. Jellen explains that the challenge of perception is "you 'see' the environment much better, and with higher reliability, with a higher vertical sensor position within the vehicle. A retail vehicle that contemplates automatic emergency braking and limited Level 2-plus functionality may contemplate locating sensors in the bumpers."

But in the quest for true Level 3 eyes-off, mind-off functionality, "you need the sensors to effectively 'see' at or above the human-eye [vertical height] level."

Velodyne's ASICs development also is helping engineers manage power-hungry ADAS sensor arrays. "They [ASICs] are enabling real-time logic and 'intelligence' at very low power consumption," Jellen explained. "You'll continue to see Velodyne sensors become more intelligent, with some ability to off-load the high-power host systems in the AVs today. As they off-load some of that responsibility, the power consumption required for the host will be reduced."

Toward that goal, he cited demonstrations of 'slamming' within the Velodyne lidar using less than 1 watt of power. The term—simultaneous localization and mapping—refers to the algorithmic challenge of localizing (i.e. finding the position/orientation of) a sensor with respect to its surroundings, while simultaneously mapping the structure of that environment. A noteworthy achievement.

"It helps reduce power consumption and the integration costs of complex systems, which are clearly targets set by the industry," Jellen said.

Mission-critical tech

Adding engineering muscle to the fast-expanding team, Velodyne has ongoing recruiting efforts at the major universities and within industry. "We're looking for strong engineers across the various disciplines including electrical, embedded software, optical engineering, advanced packaging, and quality," Jellen reports. The real 3D lidar discipline, he admits, is a fairly new space, "so we look for people with experience in the laser and optical industries."

And as Velodyne diversifies, its leadership realizes the importance of maintaining the entrepreneurial spirit and flexibility created by founder Hall. That, of course, can be easier said than done.

"There is a police-reported vehicle accident in the U.S. every five seconds; 500 people are lost per day in China. These are crazy statistics," Jellen says. "We need sensors that deliver true functionality into new vehicles as quickly as possible. We're united under the mission of bringing life-saving technology to the masses." ■