Today's LiDARs and GPUs Enable Ultra-accurate GPS-free Navigation with Affordable SLAM

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CEO, Co-Founder
Quanergy Systems, Inc.
Recent technology advances resulted in low cost, high performance:
- LiDARs
- GPUs
- IMUs

These new components enable affordable ADAS and autonomous driving systems

These advanced systems, installed on a network of vehicles, enable GPS-free navigation through SLAM

LiDAR: Light Detection And Ranging
IMU: Inertial Measurement Unit
ADAS: Advanced Driver Assistance Systems
SLAM: Simultaneous Localization and Mapping
Time of Flight LiDAR

- LiDAR stands for **Light Detection And Ranging**
- Measures **Time of Flight** (TOF), the round-trip travel time for a laser pulse reflected off obstacles
- Depth perception → **3D mapping**
- High-speed detection & processing → **real-time detection**
- Long **range**, high **accuracy**, works **day & night, rain or shine**
- Low-cost LiDARs benefit **Mapping** vehicles and **ADAS** today, **semi-autonomous** vehicles in the near future, and **fully autonomous** vehicles in the future
<table>
<thead>
<tr>
<th>NHTSA Level</th>
<th>SAE Level</th>
<th>SAE Name</th>
<th>SAE Narrative Definition</th>
<th>Execution of Steering and Acceleration/Deceleration</th>
<th>Monitoring of Driving Environment</th>
<th>Backup Performance of Dynamic Driving Task</th>
<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Non-Automated</td>
<td>The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Human driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Assisted</td>
<td>The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>Human driver and system</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some Driving modes</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Partial Automation</td>
<td>The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>System</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some Driving modes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automated driving system (“system”) monitors the driving environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Conditional Automation</td>
<td>The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>Human driver</td>
<td>Some Driving modes</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>High Automation</td>
<td>The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Some Driving modes</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Full Automation</td>
<td>The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>All driving modes</td>
</tr>
</tbody>
</table>

Source: Summary of SAE International’s Draft Levels of Automation for On-Road Vehicles (July 2013)
NHTSA - National Highway Traffic Safety Administration
SAE - Society of Automotive Engineers
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Why LiDAR

• LiDAR is the most reliable sensor for object detection
• LiDAR is more reliable than any existing sensing solution, including:
  – Radar (all types)
  – Video (all types, including IR)
  – Video + Radar
  – Video + Ultrasonic Sensors
  – Stereoscopic Cameras

LiDAR is the only acceptable technology for object detection in vehicles – technologies that detect 99 out of 100 objects would be acceptable if one accepts the consequences of failing to detect 1 out of 100 pedestrians or bikers

Brad Templeton, Robocars (& Google Car Consultant)
The Need for Low Cost LiDAR

LiDAR 3D sensors enable safety and efficiency in numerous applications unserved on mass scale due to cost, size, reliability.

Surveying

Automotive – Full Awareness

Safety – Monitoring, Security – Surveillance

Military – Driverless Vehicles

Maritime – Autonomous Vessels

Simultaneous Localization & Mapping

Industrial – Factory/Warehouse Automation

Automotive – Driver Assistance

Automotive – Autonomous Driving

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• Real-time object detection, tracking, identification and classification is important in ADAS and critical in Autonomous Vehicles

• Objects include vehicles, pedestrians, animals, road features (e.g., debris, speed bumps, potholes), infrastructure (e.g., bridges, curbs, street signs), etc.

• We are doing CUDA implementation of this capability on the Tegra K1 platform
Jetson TK1

• NVIDIA Jetson TK1 (Tegra K1 dev kit) was provided to Quanergy by Carlos Garcia-Sierra (thank you!)

• TK1 is computer-on-a-board with K1 processor, 2GB RAM, 16GB eMMC storage, and:
  - Half mini-PCIE slot
  - Gigabit Ethernet
  - SD card connector
  - HDMI port
  - Mic and Line jacks
  - 1 micro USB 2.0 port
  - 1 USB 3.0 port
  - SATA data port
  - 4MByte boot flash
  - Expansion port for UART, GPIO, DP/LVDS signals

• Jetson TK1 board has NVIDIA’s ARM Cortex-A15 4-Plus-1 quad-core processor with Kepler graphics and 192 CUDA cores

• TK1 supports the CUDA 6.0 developer tool suite; it provides tools for app developers to take advantage of the Tegra K1 features, and for hardware makers to test the platform for chip selection
The Mark VIII: 8-Beam LiDAR

Designs focus simultaneously on cost, performance, size, and reliability
Gen 1: mechanical LiDAR (Mark VIII)
Gen 2: solid state LiDAR

19 Patents Pending

- Lasers that see farther are spaced closer to maintain resolution at distance
- Some beams are pointed skyward to prevent blind spots in the event of pitch or roll
# Mark VIII Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser Class</strong></td>
<td>Class 1 (eye safe)</td>
</tr>
<tr>
<td><strong>Laser Wavelength</strong></td>
<td>905 nm</td>
</tr>
<tr>
<td><strong>Measurement Technique</strong></td>
<td>Time of Flight (TOF)</td>
</tr>
<tr>
<td><strong>Measurement Range</strong></td>
<td>300 m at 80% reflectivity, 100 m at 10% reflectivity</td>
</tr>
<tr>
<td><strong>Range Accuracy</strong></td>
<td>1.5 cm</td>
</tr>
<tr>
<td><strong>Angular Resolution</strong></td>
<td>0.1°</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td>17.5 cm at 100 m</td>
</tr>
<tr>
<td><strong>Sensors</strong></td>
<td>8 laser/detector pairs, 3-axis accelerometer</td>
</tr>
<tr>
<td><strong>Field of View (FOV)</strong></td>
<td>Horizontal: 360°, Vertical: 20° (+3°/-17°)</td>
</tr>
<tr>
<td><strong>Frame Rate (Update Frequency)</strong></td>
<td>10-30 Hz</td>
</tr>
<tr>
<td><strong>Operating Temperature</strong></td>
<td>-40°C to +85°C (-40°F to +185°F)</td>
</tr>
<tr>
<td><strong>Storage Temperature</strong></td>
<td>-40°C to +105°C (-40°F to +220°F)</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>20 W</td>
</tr>
<tr>
<td><strong>Operating Voltage</strong></td>
<td>9-32 VDC</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>1 kg</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>3.5” diameter x 3” height</td>
</tr>
<tr>
<td><strong>Shock</strong></td>
<td>500 m/sec² amplitude, 11 msec duration</td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
<td>5 Hz to 2000 Hz, 3 G&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td><strong>Environmental Protection</strong></td>
<td>IP69K – NEMA* rating for dust &amp; water ingress protection</td>
</tr>
<tr>
<td><strong>Functional Safety</strong></td>
<td>ISO 26262 – Road Vehicle Functional Safety</td>
</tr>
<tr>
<td><strong>Stress Resistance</strong></td>
<td>AEC-Q100 – Critical Stress Test for Automotive ICs</td>
</tr>
<tr>
<td><strong>Laser Safety</strong></td>
<td>ANSI Z136.1 – American National Standard for Safe Use of Lasers</td>
</tr>
<tr>
<td><strong>Laser Product Safety</strong></td>
<td>IEC 60825 – European Standard for Safety of Laser Products</td>
</tr>
<tr>
<td><strong>Military System Safety</strong></td>
<td>MIL-STD-882E – System Safety (for Military Applications only)</td>
</tr>
<tr>
<td><strong>Data Output Connection</strong></td>
<td>1 Gbps Ethernet</td>
</tr>
<tr>
<td><strong>UDP</strong> Packets**</td>
<td>Angle, Distance, Intensity, IMU, Status, Return Classification (solid vs. aerosol)</td>
</tr>
</tbody>
</table>

*NEMA: National Electrical Manufacturers Association  **User Datagram Protocol*
- For vehicles (0.8 reflectivity [standard in range reporting]), range is >400m
- For low reflectivity obstacles (0.1 reflectivity), range is 250m
The Mark VIII 8-beam LiDAR

Compact size, easy to integrate discreetly in various vehicle types
Mark VIII LiDAR
Mounting in Van

Small form factor allows easy fit in various locations on a vehicle
Mark VIII LiDAR
Mounting in Sports Car

Small form factor allows easy fit in sports cars without impacting aesthetics or aerodynamics
ADAS Ecosystem

Cloud Based Data Processing

Off-line Data Fusion Cloud Computing

Online Map Data Cloud Streaming

Telematics

Cellular Connectivity

Wi-Fi Connectivity

Map Data Generation

Safety Monitoring

On-Board Data Parsing

Sensor Layer

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**Point Cloud Fusion in the Cloud**

LiDAR point cloud data is pre-processed in the system, then post-processed and fused in the cloud, creating a continuously updated 3D map for SLAM.

<table>
<thead>
<tr>
<th>Vehicle Side</th>
<th>Server Side</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware:</strong></td>
<td><strong>Hardware:</strong></td>
</tr>
<tr>
<td>- NVIDIA Tegra K1 integrated CUDA GPU and CPU coprocessor</td>
<td>- Scalable cloud storage and processing using a web service such as AWS (Amazon Web Services) and leveraging free data transfers between AWS modules</td>
</tr>
<tr>
<td><strong>Software:</strong></td>
<td>- Expandable storage cluster using service such as Amazon S3 for saving raw and processed data and serving data to both end users and internal processing routines</td>
</tr>
<tr>
<td>- Onboard software performing real time sensor data pre-processing, vehicle localization, sensor fusion (with GPS and IMU data), scene segmentation, object identification, tracking and classification, scenario analysis and preemptive safety modeling</td>
<td>- On-demand HPC (High Performance Compute) cluster such as Amazon EC2 using NVIDIA CUDA GPUs for highly parallelized raw point cloud fusion, multi dataset co-registration, filtering, scene segmentation &amp; classification, and dataset down-sampling</td>
</tr>
<tr>
<td>- Written in C++ and employing extensions/customizations of the PCL (Point Cloud Library)</td>
<td><strong>Software:</strong></td>
</tr>
<tr>
<td></td>
<td>- Scalable Hadoop instance on cluster such as EC2</td>
</tr>
<tr>
<td></td>
<td>- Customized C++ fusion algorithms employing HPC API wrappers, OpenCL, and PCL</td>
</tr>
<tr>
<td></td>
<td>- External-facing API for use of final 3D map</td>
</tr>
</tbody>
</table>

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Quanergy ADAS Components

• Sensor modules
  – 8-beam Quanergy LiDAR (typically 1 or 2 units)
  – GNSS (Global Navigation Satellite System) receiver
  – IMU (Inertial Measurement Unit), includes accelerometer & gyroscope
  – Wheel encoder (optional)
  – Video camera (optional)
  – Ultrasonic sensors (optional)
  – RADAR (optional for long-haul vehicles)

• Processing and communication modules
  – TEGRA K1 processor
  – Ethernet controller
  – Cell modem
  – Wi-Fi controller
  – Data storage
  – HMI (Human Machine Interface) e.g., onboard display, audio, buzzer

• Balance of System (BOS)
  – Power supply
  – Enclosure
  – Cabling
  – Mounting hardware
ADAS System Schematic

LiDAR Sensor Layer

Quanergy LiDAR Sensor
- Optics
- TOF Receiver
- Laser Driver
- Encoder
- HV Converter
- PMU

Data Fusion & Analysis Layer

Complementary Sensors:
- GPS/GNSS
- IMU
- Cell/Wi-Fi
- Wheel encoder*
- Radar*
- Ultrasonic*
- Video camera*

Data Fusion Module: Object Detection, Tracking, Identification, Classification
- CAN Bus Interface
- Passive Warning Codes & Active Vehicle Control Commands
- Vehicle Information, OBD-II: velocity, accelerator and brake pedal positions, etc.

NVIDIA TEGRA K1 Processor
- 100W Power Supply
- Gigabit Ethernet Switch
- LiDAR Data

Active Safety Control
- Pre-crash braking
- Adaptive cruise control
- Lane maintenance
- Traffic jam/intersection assist
- Autonomous driving

Vehicle CAN Bus

Passive Warning Systems
- Visual Cues – Head-up Display (HUD)
- Tactile Cues – vibrating seat / steering wheel
- Auditory Cues – beeps, vocal commands

Vehicle Power Supply
Quanergy LiDAR Use in Truck ADAS

- 1 or 2 LiDAR sensors secured to vehicle (side or roof mount)
- LiDAR sends pulsed laser light in 360° swath
- Data is relayed to a central processor for data fusion, object recognition, scenario analysis and decision making
- Passive ADAS: data is sent to HMI in cabin (audio, visual and/or tactile feedback)
- Active ADAS: system interfaces to ECU and takes action when driver does not react in time
- Autonomous Vehicle (AV): AI takes over, with driver or driverless
**Conventional ADAS Sensors:**

**Long Range Radar**

Forward looking long range radar:
Most ADAS solutions require a long range, forward looking radar for high speed collision warnings.
Conventional ADAS Sensors: Ultrasonic Sensors

Ultrasonic Sensors – Impractical and poor performance:
- Impractical and expensive to mount so many sensors and to equip every trailer
- Sensors provide low quality data; a binary observation depending on presence of object, and short range
Radar Sensors – prohibitively expensive:
- Due to narrow field of view, 6-8 radar sensors are necessary to cover the area surrounding the vehicle
- Sensors provide medium quality data: capable of tracking stationary and moving objects; incapable of classifying objects, which can lead to false positive warnings and diminished driver trust
Typical Commercial ADAS

Volvo System Built by Delphi
Quanergy System: Configuration 1 – Side Mount

Video camera
Ultrasonic Sensor
50° RADAR Sensor
12° RADAR Sensor
LiDAR Sensor

Actual LiDAR range
10x longer (400 m)
Quanergy ADAS

Quanergy System: Configuration 2 – Roof Mount

Actual LiDAR range 10x longer (400 m)
Quanergy ADAS Safety Features

- **Front Collision Warning**
  - up to highway speeds, detection of moving & stationary objects

- **Blind Spot Detection**
  - comprehensive front and side coverage

- **Cross Traffic Monitoring**
  - for intersection crossings, tight turns, etc.

- **Object Detection, Tracking, Identification, Classification**
  - false alarms suppressed with high resolution under all conditions

- **Lane Assistance**
  - using robust road surface intensity readings, not video cameras

- **Scene Capture**
  - accurate capture of accident scenes, etc.

Features offered with 3D high-resolution mapping, 360° view, long range, and object recognition, at lower cost than today’s video & radar systems
Autonomous Vehicles

US Army: 600,000 non-combat vehicles self-driving by 2015

Tesla: Rolling out semi-autonomous technologies by 2017

Nissan: “Commercial self-driving Nissan cars in 2020”

Mercedes: “Commercial fully autonomous Mercedes cars in 2020”

Google: Developing commercial self-driving car systems
Driverless Cars Are Data Guzzlers
Wall Street Journal – March 23, 2014

One 8-beam Quanergy LiDAR sensor: 864,000 3D points/sec, 144 bytes of data per point → 1 Gbps Ethernet
Each 32-beam LiDAR sensor on Ford: 625,000 3D points/sec, 28 bytes of data per point → 100 Mbps Ethernet

Quanergy LiDAR sensor range: 400 m (1333 ft)
LiDAR sensor on Ford experimental car: 70 m (200 ft)
Benefits of Real Time 3D Map Data

Real time 3D maps deliver automatically:

- Actual local **weather** and **road quality** information
- Quantified **traffic observations** (speed, density, ...)
- **Lane-level traffic flow** measurements
- **cm-accurate** location of **accidents, obstacles, debris**
- **Lane-level street maps**
- **cm-accurate** position of **infrastructure** (road signs, ...)
- Full array of **LBS** (location based services)
- **Vehicle parameters** (speed, acceleration, braking patterns, gps coordinates, etc.) and **accurate factual accident recreation**
- Rich smart data needed for **autonomous vehicles**
- **And** the first **GPS-independent, cm-accurate localization** system on the planet
Centimeter-Accurate Localization with LIDAR

1. A centimeter-accurate, probabilistic 3D map is created from LIDAR, GPS, and IMU data using a computationally intensive simultaneous localization and mapping (SLAM) algorithm.

2. The map is loaded into a LIDAR equipped system, which combines real-time LIDAR data with a computationally efficient, localization algorithm to determine its location within the map with high accuracy.

3. The approach is robust even in dynamic environments.
In Summary

• Today’s mobile 3D mapping LiDARs are low cost and compact while delivering high performance and high reliability

• Advanced vehicular safety and navigation systems using LiDARs and GPUs with artificial intelligence deliver the most capable solution for real-time object detection, tracking, identification and classification

• Combining state of the art LiDARs and GPUs enables ultra-accurate GPS-free full-availability jam-proof centimeter-accurate navigation based on SLAM
Thank You

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