Mobileye Under the Hood

Prof. Amnon Shashua
President & CEO

CES 2022
2021 in Numbers

<table>
<thead>
<tr>
<th>New design wins with 30+ OEMs</th>
<th>Pipeline volume of new design wins (compared to 37M in 2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>50M</td>
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</table>

Record figure

<table>
<thead>
<tr>
<th>Vehicle models launched in 2021 with Mobileye inside</th>
<th>Revenue in 2021 40% YoY</th>
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</thead>
<tbody>
<tr>
<td>188</td>
<td>1.4B</td>
</tr>
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</table>

2021 in Numbers

- Industry-first L3 (as CV provider) Honda
- 120° 8MP highest resolution ADAS BMW
- First cloud-enhanced ADAS using REM maps Volkswagen
- Industry-first 8MP surround system (11 cameras) Zeekr

EyeQ Shipped

<table>
<thead>
<tr>
<th>Year</th>
<th>EyeQ Shipped</th>
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<tbody>
<tr>
<td>2014</td>
<td>2.7</td>
</tr>
<tr>
<td>2015</td>
<td>4.4</td>
</tr>
<tr>
<td>2016</td>
<td>6</td>
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<td>2017</td>
<td>8.7</td>
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<tr>
<td>2018</td>
<td>12.4</td>
</tr>
<tr>
<td>2019</td>
<td>17.5</td>
</tr>
<tr>
<td>2020</td>
<td>19.3</td>
</tr>
<tr>
<td>2021</td>
<td>28.1</td>
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100M EYEQ SHIPPED TO DATE

Vehicle models launched in 2021 with Mobileye inside

- Industry-first L3 (as CV provider) Honda
- 120° 8MP highest resolution ADAS BMW
- First cloud-enhanced ADAS using REM maps Volkswagen
- Industry-first 8MP surround system (11 cameras) Zeekr
The Mobileye Database
Believed to be the largest driving database in the industry

Data:
- 200PB
  premise-On + cloud (AWS)
  Reference numbers: Intel (238), Israeli governmental services (5), Israel’s biggest insurance company (2)

Compute:
- 500K PEAK CPU CORES (parallel)
  All based on spot instance
  10x more than SkyScanner

- 16M CLIPS
  25 years of driving

- 50M MONTHLY RUNS
  100PB being processed every month on 500K hours of driving
Mobileye Strategy

The fundamentals of Mobileye’s strategy, as we outlined back in 2017:

**REM™ MAPPING**
- Crowdsourced AV-maps
- Cloud-based enhancements for ADAS

**TRUE REDUNDANCY™**
- Computer vision that powers the Sense-Plan-Act cycle end-to-end
- Radar/Lidar sensing for redundancy

**RSS SAFETY MODEL**
- Formal safety guarantees
- Very lean compute for Driving Policy

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On a Formal Model of Safe and Scalable Self-driving Cars

Shai Shalev-Shwartz, Sluked Shammah, Amnon Shashua
Mobileye, 2017
Mobileye Strategy

True Redundancy, REM, and RSS are the building blocks for:

**LEVEL 2+**

- Premium ADAS
  - Driven by camera-only subsystem - full ODD at low cost
  - REM - cloud enhancements for Pilot functions and geographic scalability
  - RSS-based driving policy allows for lean compute

**LEVEL 3 / 4**

- Conditional autonomy / full self-driving
  - True Redundancy paves the way for high MTBF
  - REM enables scale
  - RSS provides formal safety guarantees and a regulatory framework
  - Radars / Lidars assets depend on the desired ODD
Where we are today:

**SuperVision™**
- Productizing CV subsystem for hands-free L2+
- Radar/ Lidar subsystem is complete
- Unveiled our Robotaxi with the unified configuration at IAA, on the road 2022

**IEEE 2846 working group**
- Chaired by Intel-Mobileye with 30+ leading industry players
- The final version of the standard is to be published by the end of Q1
- Very lean Driving Policy enables L2+ at scale

**REM™ MAPPING**
- We built the largest crowdsourcing fleet for mapping- 25M km collected daily
- Fully functional for L2+: “Drive everywhere”
- AV test vehicles deployed in many cities based on REM maps
  (NYC, Detroit, Tokyo, Paris, Munich, Israel)

**TRUE REDUNDANCY™**
- SuperVision™- productizing CV subsystem for hands-free L2+
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The Largest Global Footprint in the AV Industry

ISRAEL

DETROIT

NYC

TOKYO

MUNICH

PARIS
AV driving in Paris
AV driving in Tokyo
Achievements

Where we are today:

<table>
<thead>
<tr>
<th>2017</th>
<th>2021</th>
<th>2025</th>
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<tbody>
<tr>
<td><strong>CLOUD-ENHANCED L2</strong></td>
<td><strong>LEVEL 3</strong></td>
<td><strong>LEVEL 4</strong></td>
</tr>
<tr>
<td>Volkswagen Travel Assist™ 2.5</td>
<td>Honda Legend, Japan only</td>
<td>Unveiled Robotaxi at IAA, on the road 2022</td>
</tr>
<tr>
<td>(powered by REM maps)</td>
<td>(computer vision)</td>
<td>Signed Robotaxi/AV shuttle/goods delivery</td>
</tr>
<tr>
<td>Next-generation Ford Blue Cruise™</td>
<td>BMW 7 Series, coming this year</td>
<td>deals</td>
</tr>
<tr>
<td>(powered by REM maps)</td>
<td>(computer vision)</td>
<td></td>
</tr>
<tr>
<td>SuperVision™- productizing CV</td>
<td></td>
<td>First design win for consumer L4 with</td>
</tr>
<tr>
<td>subsystem for hands-free L2+</td>
<td></td>
<td>Geely-Zeekr (SoP 2024)</td>
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2017 2021 2025
First Design Win
Consumer L4 Platform
Powered by 6 EyeQ®5 High
SoP early 2024
Where Does This Lead Us?

- **New category emerging:**
  - **L2+ Premium ADAS**
    + Surround sensing
    + Cloud-based enhancements - REM and OTA
    + Full Sense-Plan-Act cycle on a wide ODD range

- **Emerging 2022/2023:**
  - **L4 Robotaxi**
    + Geo-fenced
    + Cost - $X0,000

- **Emerging 2024/2025:**
  - **L4 Consumer AV**
    + Drives everywhere
    + Cost - <$5K
The autonomous mobility market may unfold in two forms:

**Robotaxi** (people and goods) → Waymo, Argo, Cruise, Aurora, etc.

**Consumer AV** → Tesla, Apple?

Where Does This Lead Us?

- **Consumer AV** → **Robotaxi**
  - PTO/TNCs buy AVs and just add the service layer on top.

- **Robotaxi** → **Consumer AV**
  - Geo scalability and consumer-level cost (<$5K BoM at scale) are “weak spots” for the Robotaxi companies.

- **Doing both is not just about hedging**
  - There are strong synergies between Robotaxi and Consumer AV.
  - Maximizing the learnings from Robotaxi operation can serve as a stepping stone for Consumer AV.
The Criteria for a Good Solution

**Capabilities**
- Wide self-driving ODD
- Human-like driving policy

**Robustness**
- High MTBF

**Efficiency**
- Cost (compute and sensors <$5K)
- Scale (drive everywhere)

**Definition**

**Mobileye’s approach**
- Full ODD from L2+ to L4
- What differentiates L2+ from L4 is MTBF, not ODD
- RSS (formal safety)
- True Redundancy:
  - Two separate sensing subsystems (CV, R/L)

Strong synergies between the building blocks in Mobileye’s approach

- Purpose-built SoC
- SW-defined imaging radar
- Lean Compute
- REM crowdsourcing mapping

Strong synergies between the building blocks in Mobileye’s approach
+ Purpose-built SoC
+ SW-defined imaging radar
+ Lean Compute
+ REM crowdsource mapping
The New Generation of EyeQ®
A Family of SoCs That Covers the Entire ADAS/AV Spectrum

The New Generation of EyeQ®

EyeQ®6 Light
- L1-L2 ADAS

EyeQ®6 High
- L2+ / L3 Premium ADAS

EyeQ®ULTRA
- L4 Full Self-Driving
The EyeQ® ULTRA

**AV-on-Chip:** A single SoC to power autonomous driving end-to-end

- Controlling the entire AV stack allows us to know precisely what is required from the AV’s onboard compute
- We first built an AV and only then designed an application-specific SoC for the AV
- EyeQ® ULTRA utilizes an array of four classes of Mobileye’s proprietary accelerators (64 in total), each built for a specific task:
  - **XNN**: Dedicated AI engine for DL neural network
  - **PMA**: Programmable CGRA
  - **VMP**: Multiple barrel-threaded CPU cores
  - **MPC**: Multiple barrel-threaded CPU cores

- Full support for co-hosting third-party applications by offering a complete SDK package and OpenCL environment

<table>
<thead>
<tr>
<th>5 nm</th>
<th>176 TOPS (INT8)</th>
<th>4.2 TFLOPS</th>
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**Additional Vitals**
- **CPU:** 12 RISC-V cores (12C24T)
- **GPU GFLOPS:** 256
- **ISP:** 2.4GPixel/s
- **Video Enc:** 2x H264/5 Enc 4K60, MJPEG
- **Power (SDP):** <100W

**ES:** Q4/2023 | **Volume production:** 2025
EyeQ® 6 High

The ultimate compute platform for Premium ADAS

- 3x more TOPS than an EyeQ5H with just 25% more power
- Advanced visualization capabilities for parking and UX applications supported by dedicated GPU, ISP, and a video enc.
- Will carry all premium ADAS tasks (next-gen SuperVision™)

Additional Vitals

CPU: MIPS64 (8C32T)
GPU (ARM) GFLOPS: 64
GFLOPS (OCL): 1000
ISP (ARM): 1.2GPix/s
Video Enc: MJPEG, Disp Out 4K60

ES: Q4/2022 | Volume production: 2024
EyeQ® 6 Light

The new work horse for all ADAS functions

+ The most power/performance/cost-efficient SoC we have ever built
+ Compared to EyeQ4M:
  + 45% smaller package
  + 450% more TOPS
  + Similar power consumption
+ One-box, behind windshield solution that can support CV+ localization to power L2+ functionalities
+ Committed deals for over 9M units

Additional Vitals

CPU: MIPS64 (2C8T)
GFLOPS (OCL): 720

7nm 5TOPS (INT8) 5ACC. CORES

ES: Q2/2021 | SOP: Q2/2023
Redefining Radars and LiDARs

+ Purpose-built SoC
+ SW-defined imaging radar
+ Lean Compute
+ REM crowdsourcing mapping
The Motivation Behind LiDAR and Radar Development

**2022 LiDAR/radar subsystem**
- ToF LiDAR - 360° coverage
- Advanced stock radars - 360° coverage

*Need both to build a sensing state*

**2025 LiDAR/radar subsystem**
- Front sector - 3-way redundancy
- Remaining FoV - 2-way redundancy of cameras + radars
- Massive cost reduction that will unlock consumer L4 at scale

*The enabler: **“Drive by” radar capabilities**
- Solving angular res., dynamic range, and side lobes effect*

Current radar-lidar subsystem configuration

Next gen radar-lidar subsystem:
- 360° radar cocoon
- 1 front facing LiDAR
SW-Defined Imaging Radar - Game-Changing Capabilities

Main attributes

+ Massive MIMO radar with **2,304 virtual channels** (48x48)
+ High angular and vertical res. - **0.5°x2°**
+ **100dB** dynamic range
+ **40dBc** azimuth sidelobe levels (SLL)
+ **20 FPS**, Multi-mode scanning (SRR, MRR, steerable LRR)
+ Digital signal processing for up to **500K PPS**

**LOCAL OSCILLATOR**

- Ultra low Phase Noise
- Assuring the system is not bounded by its internal noise

**4 TX CHANNELS**

- High TX power
- Can implement any waveform
- 6 Tx chips controlling 2 antennas = 48 Tx channels

**6 RX CHANNELS**

- High bit rate sampling (1 GHz/11 bits)
- Low noise figure
- 8 Rx chips = 48 Rx channels

**MAIN RADAR PROCESSING UNIT**

- 11 TOPS SoC
- State-of-the-art signal processing
- High BW RF samples interface
Separating objects in dense traffic
Construction area and path delimiters detection
Object detection in a noisy environment (metal fence, tunnel)
Tracking a motorcycle in dense traffic off-boresight
RESEARCH THEORY 1:
Can EyeC Radar output be presented like LiDAR?
Can EyeC Radar output be presented like LiDAR?
Can we train a network to create camera-like video based on our Imaging Radar point Cloud?
Building the Best-in-Class FMCW LiDAR

Main attributes

+ Best point density (600pt/deg^2, over 2M discrete 4D PPS over 1000 lines/sec)
+ Doppler content provides objects velocity and heading without dependencies on multi-frame tracking/registration
+ Long range (300m, over 200m for 10% refl)
+ Higher immunity (no sun or retro-reflectors impairments)
+ Price target under $1000 (design for manufacturability)

GoldBox- optical head enabling 90 vertical lines per scan

LiPRO- the worlds first-ever multi-channels FMCW LiDAR processor SoC

- Multi-channel FMCW HW Accelerators handling up to 50GSPS
- 16 DSP cores enabling additional processing flexibility
- 4 CPU cores for scanner control, host Interface, maintenance, etc.
- 2 safety islands for FuSa and eye safety monitoring
What We Have Covered So Far

Game-changing developments going forward:

- AV-on-Chip
- SW-defined imaging radar becomes a heavy lifter in the self-driving architecture
- Front FMCW LiDAR, yielding tri-fold redundancy in the front sector
Lean Compute enabled by RSS Driving Policy Methodology

+ Purpose-built SoC
+ SW-defined imaging radar
+ Lean Compute
+ REM crowdsourcing mapping
Sense / Plan / Act Methodology

**Sense**
Perception of the environment.
Building a world model of the vehicle’s surroundings: where we are, other road users, obstacles, traffic lights...

**Plan (Driving Policy)**
Decision making
“What would happen if” type of reasoning

**Act**
Execute the plan (Control):
transform speed and curvature commands to pedals and steering wheel commands
About Driving Policy

Definition:

**Sensing state**
The sensing state contains our location, static obstacles, lane semantics, traffic lights, kinematic state of other road users, etc.

**Action**
The desired action is the speed and curvature of the car.

Why it is hard?

- No “Ground Truth”
- Actions may have a long-term effect
- Close-loop: actions affect other road users
- Must handle uncertainties about the future
Driving Policy — Existing Approaches

- Monte-Carlo Tree Search (MCTS)
- Markov Decision Process (MDP)

Quality of search vs. Compute:
- Brute force
- MCTS
- MDP

Realism of assumptions:
- MDP: Assumes the future behavior of all road users is fixed and known
- MCTS: Assumes the policy of all road users is known
- Brute force: No assumptions
Our Approach - RSS

A formal model for safety, that provides mathematical formalization for the AV’s driving policy to never cause an accident.

The Method

01. Defining reasonable boundaries on the behavior of other road users.

02. Within the boundaries specified by RSS, one must always assume the worst-case behavior of other agents.

03. The boundaries capture the common sense of reasonable assumptions that human drivers make.

04. Any action beyond the defined boundaries is not reasonable to assume.

On a Formal Model of Safe and Scalable Self-driving Cars
Shai Shalev-Shwartz, Shaked Shammah, Amnon Shashua
Mobileye, 2017

Abstract

In recent years, car makers and tech companies have been racing towards self-driving cars. It seems that the main parameter in this race is who will have the first car on the road. The goal of this paper is to add to the equation two additional crucial parameters. The first is the formalization of safety assurance — what are the technical requirements that non-self-driving cars must satisfy, and how can we verify these requirements. The second parameter is scalability — engineering solutions that lead to unlimited costs will not scale to millions of cars, which will push solutions in this field into more academic venues, and drive the entire field into a “winner of marathon driving.” In the first part of the paper we propose a write-once, integrate-and-verify, mathematical model for safety assurance, which we call Responsibility-Sensitive Safety (RSS). In the second part we describe a design of a system that adheres to our safety assurance requirements and is scalable to millions of cars.

http://arxiv.org/abs/1708.06374
RSS Standardization and Government Efforts

**IEEE Workgroup to Define a Formal Model for AV Safety Chaired by Intel-Mobileye**
- Workgroup consists of 30 leading industry players
- Publication of final version - Q1, 2022
- This standard will provide governments the framework for setting the acceptable safety/usefulness balance

**ISO/TR 4804:2020**
- World’s first ISO Technical Specification defining a Safe-By-Design Automated Driving System
- RSS featured as a key element to implementing a safe Driving Policy

**U.S. Department of Transportation**

- US DOT Seeking public comment on the development of a framework for Automated Driving System (ADS) Safety
- RSS cited and recognized as a “Notable Effort Under Consideration” as an Engineering Measure for Safety

**Law Commission**

**AV Consultation, Proposing a Regulatory Framework for AV’s in UK**
- RSS proposed as a way to define “how safe is safe enough” by defining a “does not cause a fault”
- RSS featured as a way to define “road craft” - a safety envelope around the AV defined by safe distances
Our Approach - RSS

By using induction and analytical calculations, the RSS couples all plausible futures into the present. This yields efficiency, realism, quality, and explainability.

Instead of “Predictions” we Construct “intentions” of other agents:

- Those “intentions” control parameters of the “reasonable assumptions”
- Yields a “human-like” behavior
- We use deep learning to construct intentions
Our Approach - RSS

- Monte-Carlo Tree Search (MCTS)
- Markov Decision Process (MDP)
- Brute force
- RSS-based driving policy

Quality of search:
- X Brute force
- X MDP
- RSS-based driving policy

Realism of assumptions:
- X MDP
- X MCTS
- RSS-based driving policy
More on Mobileye’s Lean Driving Policy
From our CTO, Prof. Shai Shalev-Shwartz

Search: “Mobileye’s Lean Driving Policy”
Advancements in REM Mapping

- Purpose-built SoC
- SW-defined imaging radar
- Lean Compute
- REM crowdsourced mapping
Volkswagen
Travel Assist 2.5

The first L2+ system to widely use Mobileye’s REM technology
Cloud-enhanced lane-centering in challenging scenarios
Traffic light-to-lane association based on REM map
Europe REM RoadBook Coverage

- 2.5 million km
- Generated fully automatically in the cloud in less than a week
km harvested in 2021

- Q1: 247M
- Q2: 470M
- Q3: 1541M
- Q4: 1750M
The Richness of REM AV Maps

Main attributes of REM AV maps provided in any road type, as we revealed last CES:

- Drivable paths
- Road edge
- Traffic light and Traffic sign to lane association
- Yield and priority
- Crosswalks and crosswalks relevancy
- Stopping points and stop lines
- Common speed per lane
Advancements in REM Development

In 2021, we have added new features to REM maps, all based on crowd knowledge:

- **Construction Area Live Map**
- **Crowd Turn Indicators**
  
  Determining where to apply the Turn indicators through crowdsourcing for true “Human-like” behaviour of the AV.

In 12 out of 15 samples, turn indicator engaged.
Advancements in REM Development

In 2021, we have added new features to REM maps, all based on crowd knowledge:

**Speed bumps**
Enables smooth control in urban and rural areas.

**Legal speed**
Lane Level Legal Speed Limit Indication
Accounting for Explicit Speed Limit Signs, Implicit Speed Limit Signs and Road Type Classification.
Advancements in REM Development

Enriching the map by adding Semantic Lane Types:

- Public transportation lanes
  Also relevant for L2+ applications

- Toll areas

- Road type
  Refining policy parameters accordingly
  (e.g., pedestrian on a highway vs. deep urban)
Summary

The building blocks we have built:

01 Redefine the future of ADAS with REM mapping and CV subsystem

02 The right engineering design to achieve the needed MTBF and unlock MaaS

03 AV-on-chip and SW-defined imaging radar redefine the future of consumer L4
Thank You

Mobileye Under the Hood
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