HUMANIZING THE DIGITAL EXPERIENCE

TDK Developers Conference 2018

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Inertial-Assisted Positioning for Autonomous Vehicles

Contributing to fault-tolerant ADAS

TDK Developers Conference
September 17-18, 2018
Santa Clara Marriott

Agenda

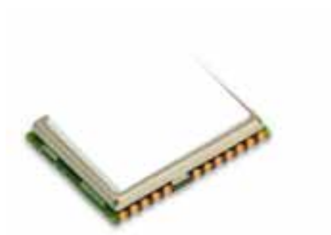
- Introduction
- Problem Statement and Technology Gaps
- Overview of Advanced Driver-Assistance Systems (ADAS) and Technologies
- Walkthrough of Current ADAS Solutions
- Forthcoming Localization Sensor Improvements
  - RTK GNSS
  - High-performance IMUs
  - ADAS-quality inertial dead reckoning
- Summary

Who we are

- A worldwide leader in automotive and consumer-grade MEMS inertial sensors
- 100+ man-years investment in inertial navigation system (INS) software
- INS software shipping in >50 million OEM systems worldwide

Vehicle Telematics

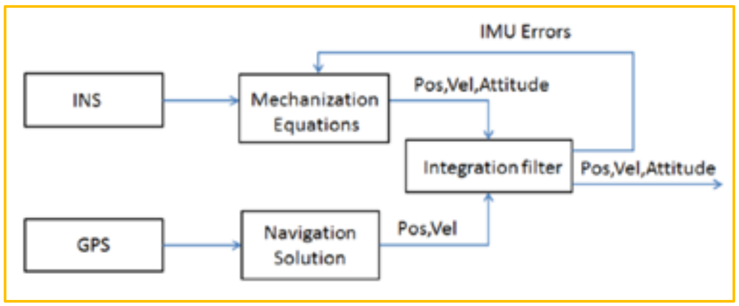
Smartphone Navigation



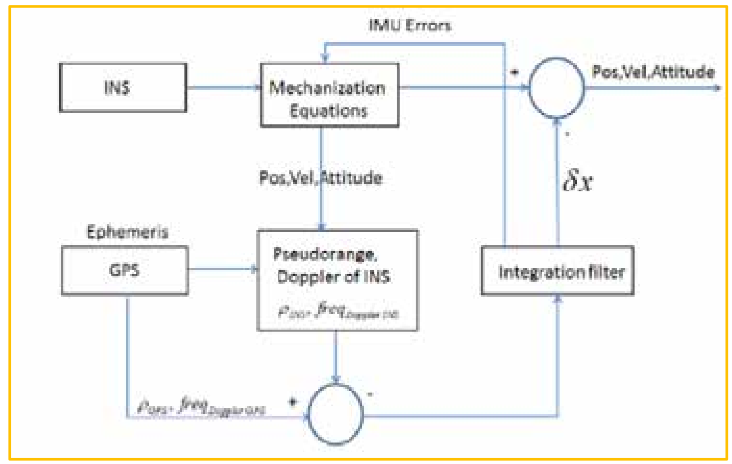
GNSS/DR Modules

Inertial Navigation System (INS) Internal Architecture

Loosely Coupled (LC)



Tightly Coupled (TC)



Inertial-Assisted Positioning in Vehicles

Today

Fluid, continuous "blue dot" user experience during turn-by-turn navigation (non-safety)

Position drift error: 1-10% of distance traveled

Forthcoming ADAS Applications

Autonomous vehicle positioning and fault-tolerance (safety)

Position drift error: 0.1-0.2% of distance traveled

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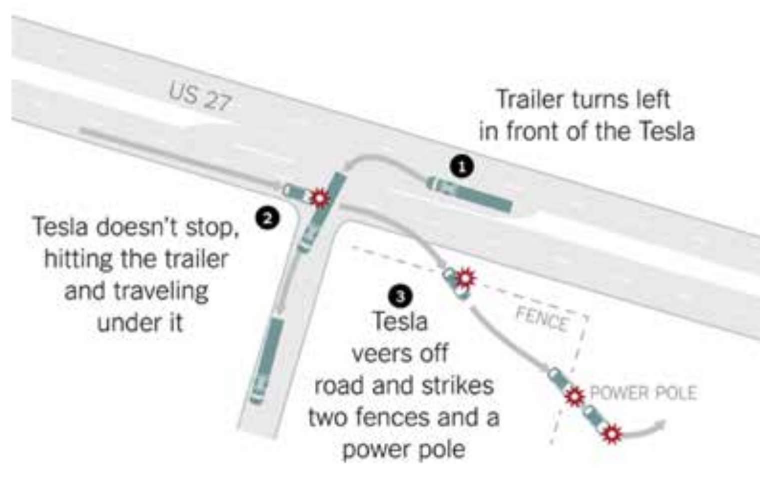
Problem: Today's ADAS Systems are Incomplete

Today's ADAS Solutions are Incomplete

- Excitement and "cool factor" need to come with proper consumer education about current limitations
- Robust and fault-tolerant ADAS system will also require high-precision RTK GNSS and affordable, yet near-tactical-grade IMUs that can deliver centimeter-level positioning.

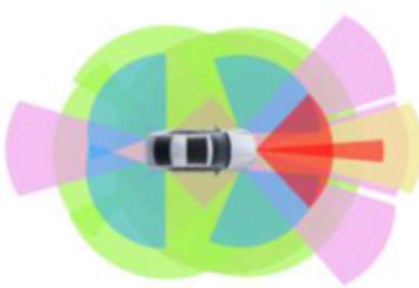


Automated Driving Levels & Sensor Evolution

- From IHS Markit

Fail-safe — Now-2020 — 2020-2024 — *Fail-operational*

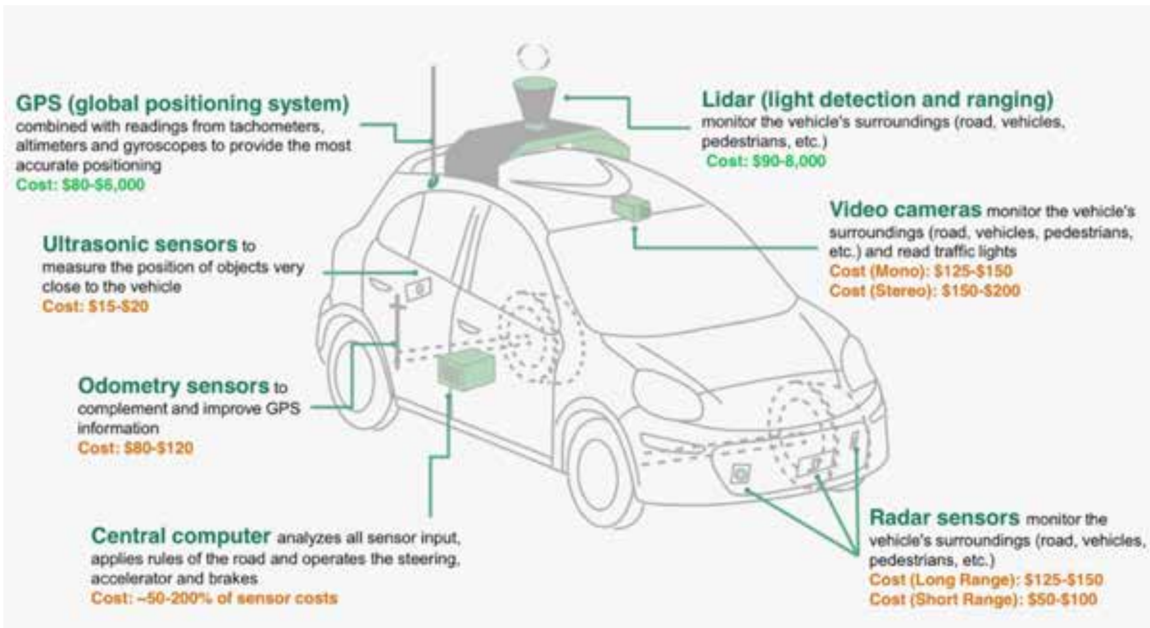
	L1	L2	L3	L4	L5
Automation level	Only driver assistance	**Partial** Automation	**Conditional Automation**	**High Automation**	**Full Automation**
System capability	Some driving modes	Some driving modes	Some driving modes	Some driving modes	**All driving modes**
Driving environment monitoring	Human Driver	Human Driver	**System**	**System**	**System**
Fallback responsibility of driving task	Human Driver	Human Driver	Human Driver	**System**	**System**



- Perception sensors:
  - Camera
  - Radar
  - Lidar
  - Ultrasonic
  - IR Camera
- Localization sensors:
  - IMU
  - Odometer
  - Barometer
  - Magnetometer
  - GNSS
- HD maps

Autonomous Driving Sensor Technologies

- Most new technologies are for "relative" positioning and object avoidance (perception system)
- MEMS inertial are being driven to provide better performance for DR applications (short outages)



Pros/Cons Summary of Various Sensors

Sensor	Lidar	Radar	IR Camera	Normal Camera
Advantages	- Accurate depth measurement - Inherently 3D so it can identify real objects from photos - Higher resolution than radar - Can identify shapes based on contrast in reflectivity (e.g. lane markings)	- Range and speed are direct measurements - Depth Sensor - Cheap and already exists in vehicles - Works well in poor weather conditions (fog, dust, rain and snow) - LRR high range, velocity and AOA resolution. Wider bandwidth and hence higher object resolution.	- Works perfectly at night even with oncoming headlights - Very reliable in identifying living objects - Can identify living things from statues - Works well in poor weather conditions - Not affected by sudden changes in lighting conditions (such as going in-out of tunnel)	- Height resolution - Color information useful for identifying objects - Cheap - Necessary for perception and object classification - Exist in all cars nowadays
Disadvantages	- It can't work in poor weather conditions such as snow, rain, dust, and mist. - Expensive (price coming down hugely with solid state LIDAR) - Lower resolution than camera - Can't differentiate between statues and real living objects	- Very low resolution for MRR-SRR. - Can't differentiate between statues and real living things - Can have problem with wood and painted plastic. - Can't always correctly identify objects leading to false positives.	- Degraded performance at high ambient temperatures (daytime summer in hot countries) - Low resolution compared with normal cameras - Higher price than normal cameras but lower than lidar	- Poor performance at night especially with oncoming headlights - Poor performance at poor weather conditions - Temporary blind at sudden change in lighting conditions (e.g. tunnels) - Can't differentiate between photos and real objects

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A Look Into Today's L2/L3 ADAS Systems

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Tesla (L2 Autonomy)

- Requires hands on wheel
- Not restricted to freeway; but no detection of stop signs or traffic lights
- No lidar

https://www.youtube.com/watch?feature=oembed&v=pqmdc9YoFVY
https://www.youtube.com/watch?feature=oembed&v=-2ml6sjk_8c

Cadillac Super Cruise

- Hands-free, highway-only
- Operates only on divided highways w/on and off ramps
- Sensors monitor eyes to make sure attention is on the road
- Lidar-mapped 130,000 miles of freeway for HD maps (5cm accuracy)

https://www.youtube.com/watch?feature=oembed&v=_rxW68ADldI

Audi Traffic Jam Pilot “Conditional” L3

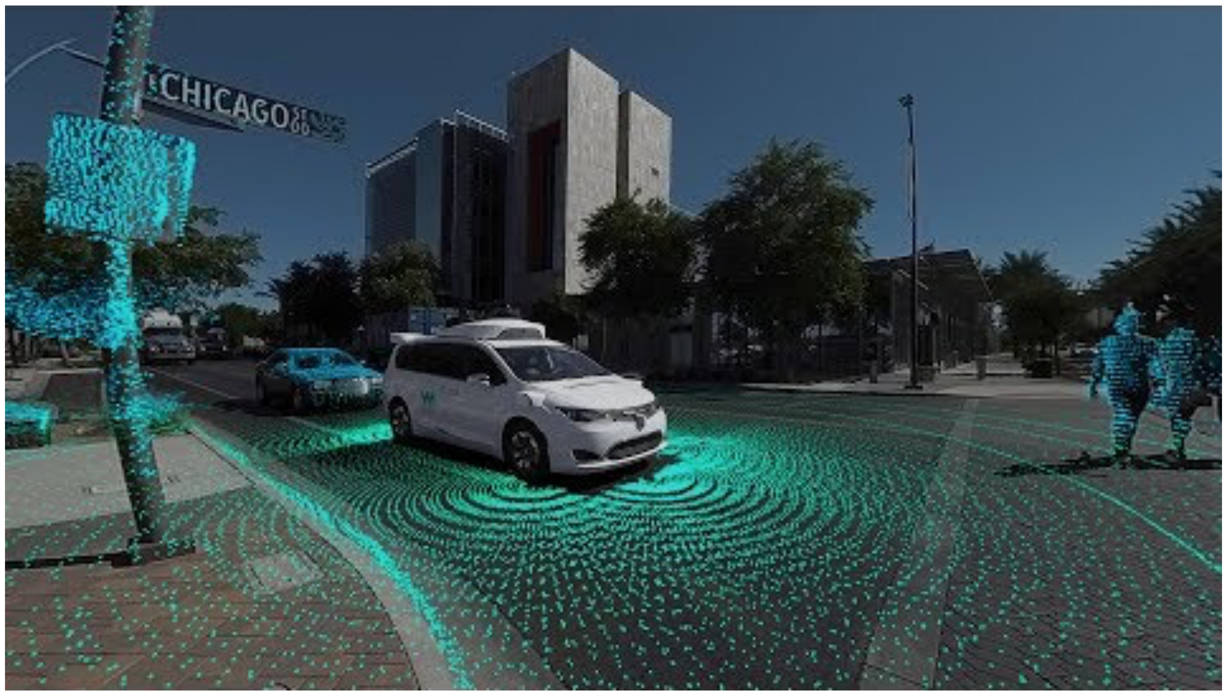
- World’s First production lidar scanner in a high-volume passenger car
- 37 MPH (60KM/hr) limit on freeway
- Limted-access, divided highways only
- Hands off, eyes off under pre-defined circumstances
- Hands on, eyes on L2 for US (adaptive cruise w/steering)
- Must be in-traffic in front and sides
- No traffic lights or pedestrians
- 10 second warning for driver to take over

https://www.youtube.com/watch?feature=oembed&v=nUlK6fpveXg

Waymo

- Lidar, Radar, cameras, HD maps
- AI and deep learning: Human behavior modeling

WAYMO



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Missing Piece #1: High-Accuracy GNSS

Absolute Position, Time and Velocity

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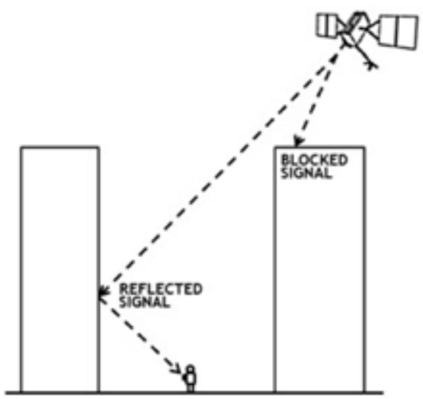
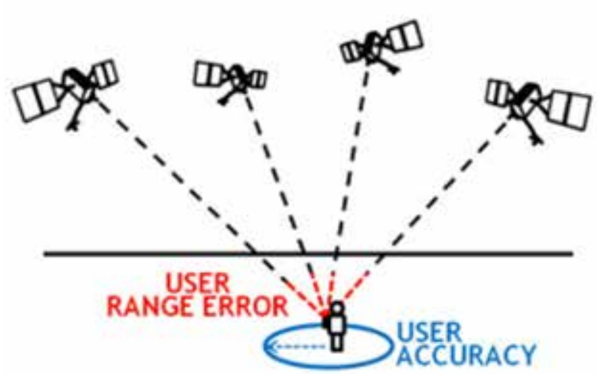
Standard GNSS Not Sufficient for Autonomous Vehicles



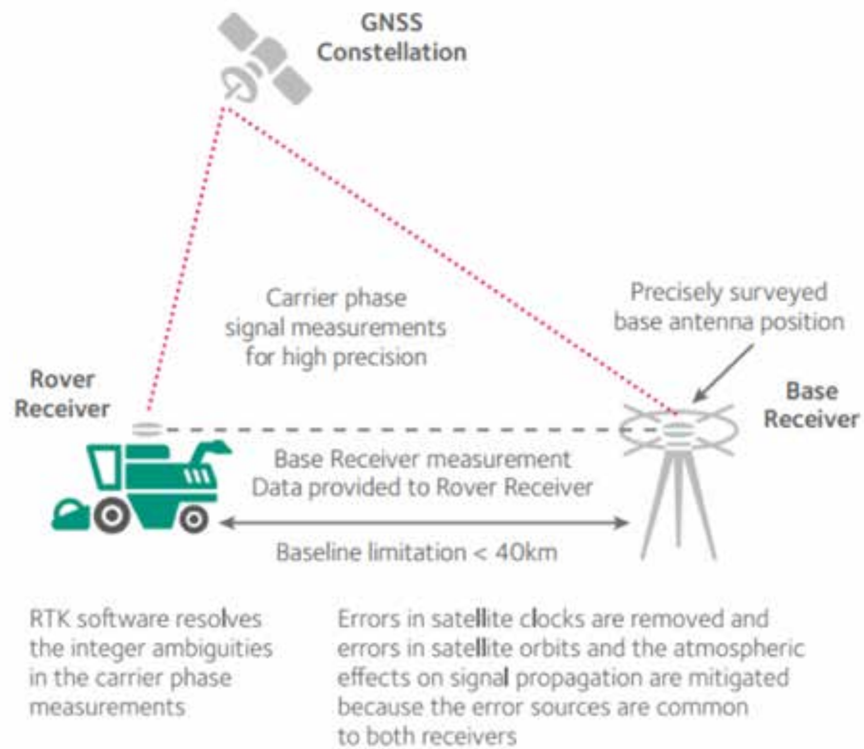


4.9m (16ft.): Average accuracy of GPS-enabled smartphones

Courtesy: gps.gov & ion.org

RTK-GNSS: Up to 1cm accuracy

- Network-based corrections for base station infrastructure



Courtesy: Novatel

RTK-GNSS TTFF

Time to First Fix (TTFF) Specifications[8]

Hot Start[9]	Cold Start[10]	Re-acquisition[11]
< 5 s	< 60 s	< 2 s

[8] In open sky and strong signals conditions.
[9] Hot Start is the time taken by the receiver to achieve a standard position fix after a brief outage. For example, the time taken to fix a position for a car that is exiting a long tunnel. This can also be simulated by a simple RF on/off test with outages between 30 and 50 seconds.
[10] Cold Start is the time taken by the receiver to achieve a standard position fix after a prolonged outage. For example, the time taken to achieve a position fix for a car that has been parked overnight in a garage and once it sees the sky view for the first time.
[11] Re-acquisition is defined as the time taken to re-acquire position lock after brief moment of outage. For example, a car traveling under a freeway/highway overpass. This can also be simulated by a simple RF on/off test with outages between 1 and 5 seconds.

Courtesy: Swift Navigation

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Missing Piece #2: High-Accuracy, Affordable IMU and Inertial-Assisted Positioning

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Why are high-precision IMUs required for ADAS

- Fault-tolerance during other ADAS system failure or uncertainty
  - IMU alone can position vehicle with 30cm accuracy for short time periods (10sec) to safely brake or pull a vehicle over

CAMERA	LIDAR	RADAR	GPS (RTK) Odometer	HD Maps
DEPTH + AMBIGUITY	WEATHER GEOMETRY	LOW RES + REFLECTIONS	URBAN CANYON	OUT OF DATE

- Attitude reference (orientation of the vehicle relative to the direction of travel)
  - Independent reference for LIDAR/cameras

- Improved RTK-GNSS precision and reacquisition

- High-rate position reference: 100Hz position data to image processing algorithms

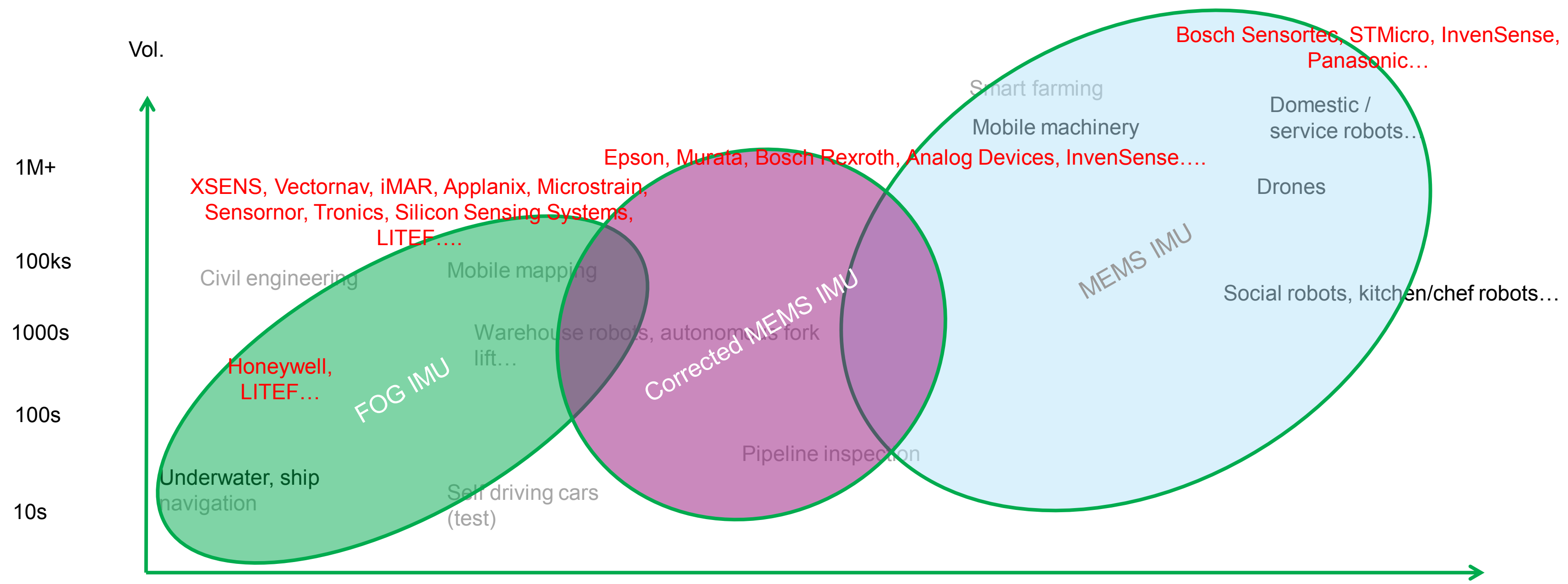
IMU Opportunity for Autonomous Driving (L3-L5)

Summary of autonomous driving

- Long term opportunity
- Begins 2022/2023 in few 1,000s (1–3 luxury car platforms)
- Reasonable volumes by 2030 (conservative estimate 2–3 million)
- Specifications not yet clearly defined
  - Is high performance sensor needed
  - Bias instability ranges from as much as 8°/h to as little as 0.01°/h
  - Dead reckoning will be part of sensor fusion concept
  - Inertial sensors will be augmented by cameras, radar, LIDAR, etc.
- Potential for performance devices
- Price point? Probably start high but tier 1s will need IMU costing as little as $10, $20?
- "Fail operational" mode requirement could drive price much higher, at least in beginning
  - What if camera, radar fail or sensor fusion is compromised (functional safety)
  - Over-engineer? Characterize sensor behavior in beginning
- Many players interested

IMU Grade Landscape

IMU integrator and gyroscope supply chain

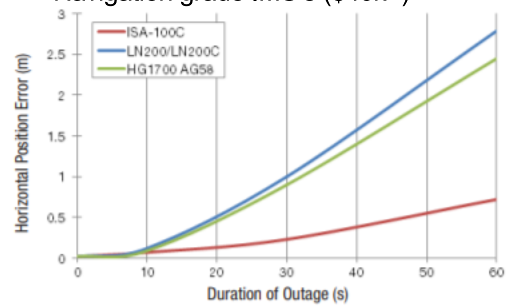


Source: IHS Markit

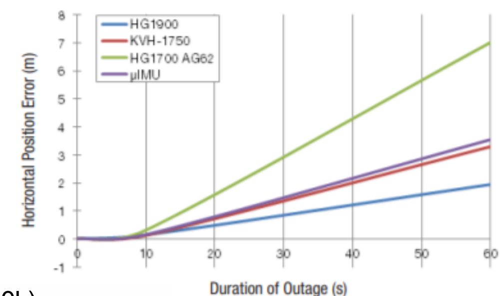
Today's RTK+INS Performance/Price

- High-grade IMU's on vehicles have nearly linear drift wrt time over short GNSS outages durations
- <30cm drift in 10 seconds
- 1-2m drift in 30 seconds

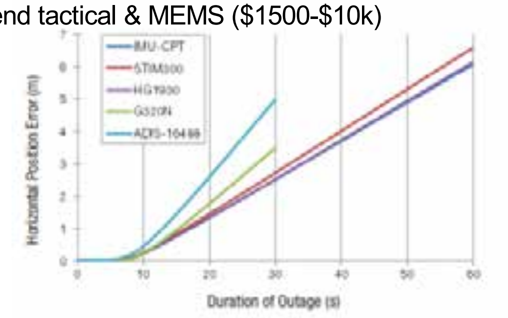
Navigation grade IMU's ($40k+)



Tactical grade IMU's ($15k-$40k)



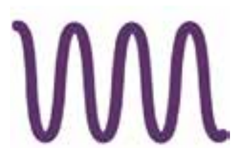
Low end tactical & MEMS ($1500-$10k)



IMU Performance Requirements for ADAS

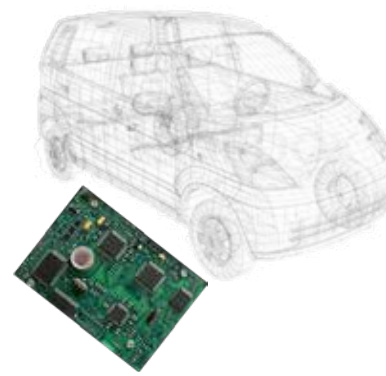
Gyroscope Performance	TYP	Units
In-run bias instability	<2	°/hr
Angular Random Walk	<0.1	°/√hr
Bias temperature coefficient	1	m°/sec/°C
Sensitivity temperature coefficient	<0.003	%/°C
Misalignment	<0.05	Degrees
g-sensitivity	<0.03	°/sec/*g*
Accelerometer Performance	TYP	Units
In-run bias Instability	<10	μg
Velocity Random Walk	<0.03	m/sec/√hr
Bias temperature coefficient	<0.07	*mg*/ ℃

ADAS INS Benefits & Requirements



100Hz high-rate position updates

30cm accuracy during GNSS or perception-challenged situations



Up to 10 degree vehicle mounting misalignment compensation

Reduced solution costs via high-volume consumer MEMS platform

Summary

- What's needed for a fault-tolerant, autonomous system:
  - A heck of a lot of software, algorithm and AI development
  - Ubiquitous HD maps
  - Centimeter-accurate RTK GNSS
  - Inertial dead-reckoning w/tactical-grade IMU
    - RTK+IMU is not a silver bullet, but it will be a key part of a fault tolerant system

- Reasons for ADAS-grade Inertial-assisted positioning
  - Improved fault tolerance
  - Reduce "grab the wheel scenarios"
    - Perception system uncertainty or unavailability
    - RTK-GNSS outage (e.g. underpass)
  - Enable more time for driver to grab the wheel
  - Enable autonomous safe stopping or roadside pullover in case of system failure

Thank You!