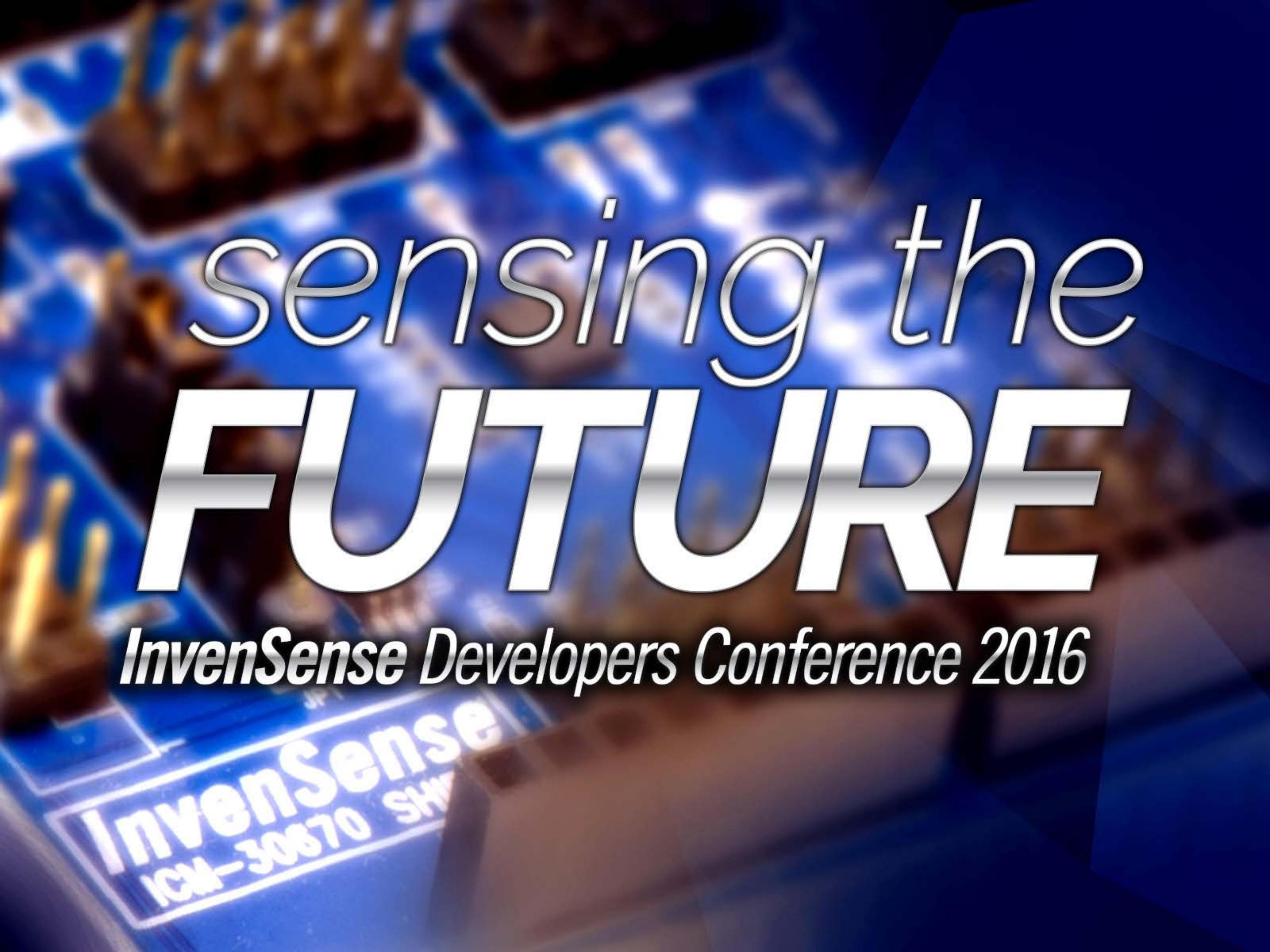
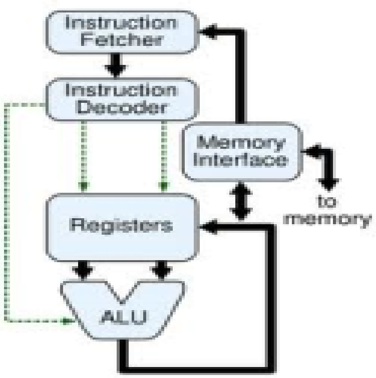

sensing the
FUTURE
InvenSense Developers Conference 2016
InvenSense

Motion Sensor SW Stack

Tracking Motion is a Complex Science!

Sensor Selection and System Integration

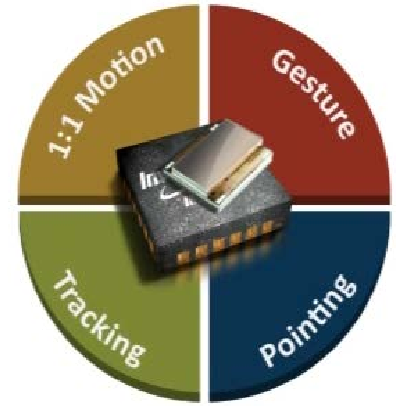
Sensor Calibration



Fusion

$$\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} v'_x \\ v'_y \\ v'_z \end{pmatrix}$$

Quaternion
Euler Angle
Rotation Matrix
…
Attitude
Orientation
Gravity Vector
Body Coordinate
World Coordinate
Linear Acceleration
Angular Velocity
Heading
Magnetic North
True North
Motion Monitor
… etc.



Minimize the limitations of each individual sensor

Provide better Motion tracking

Application specific SW stacks

sensing the FUTURE

Hide complex math; deliver customer tangible functionality

- Enable customers to focus on product differentiation
- Ease of integration
- App specific required performance
  - Accuracy, Power consumption, Data rate, Latency
- SW can run on one or combination of platforms
  - IC, device, mobile, cloud

HMD/VR

INVN Inside HMD/VR

Microsoft HoloLens

Oculus/Facebook

HTC Vive

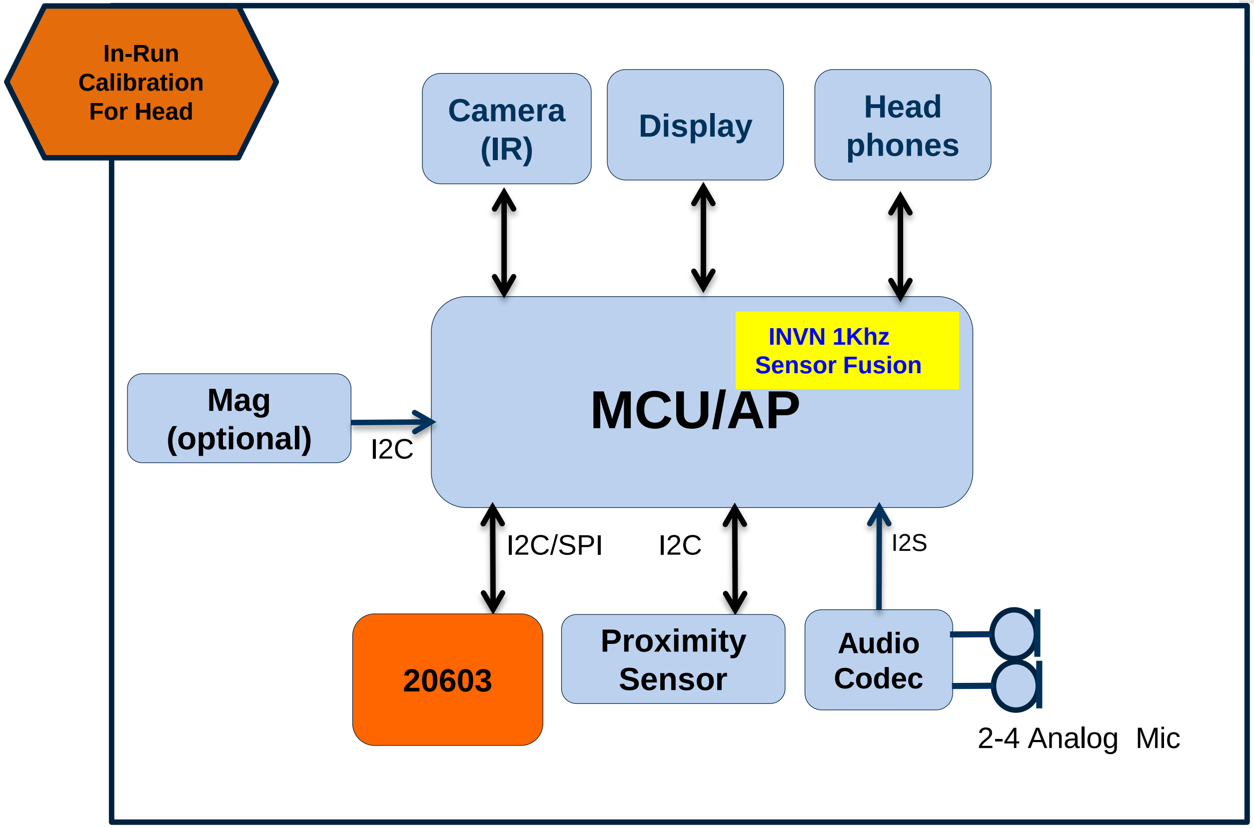
Key sensor Requirements

- Good sensor, cal and fusion performance
- High date rate
- Low latency

20603 in HMD

Head Tracking/Orientation

Calibration of Gyro



20603 Key Features

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Sensor Specs

- Gyroscope FSR: ±2000dps
- Accelerometer FSR: ±16g
- 1 KHz gyro/accel/fusion output
- VDD: 1.71V to 3.45V
- FIFO: 1Kbytes
- SPI: 10MHz SPI
- I2C: 400kHz (Host Interface)
- AUX I2C: Not Supported
- INT pins: 1
- Package: 3x3x0.75mm MAX 16-pins LGA

1KHz Sensor Fusion Library

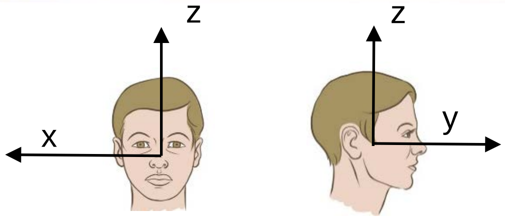
	20603 Requirements
Performance Targets*	Relative Heading Error Static - <1 Degree Relative Heading Error Dynamic - <3 Degree Pitch/Roll Error (6-axis) Static – <1 Degree Pitch/Roll Error (6-axis) Dynamic – <2.3 Degree

* Uniform Magnetic Field; Ambient Temp; Factory Cal assumed to be done

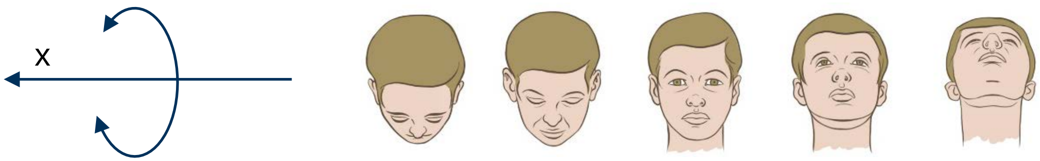
	System Requirements	Features Supported
Full Release	Algo: 15KB Driver 20603: 6.5KB Driver AKM09911: 7.5KB +Framework Overhead +Virtual Sensor	Raw/Cal Accel Raw/Cal Gyro Raw/Cal Mag GRV RV
Lite Release	Algo: 15KB Driver 20603: 6.5KB *Adding Mag manually will enable RV & Mag Cal	Raw/Cal Accel Raw/Cal Gyro GRV

HMD – Accelerometer / Mag Bias calibration

To calibrate accelerometer offset, we need:
- Diversity on Pitch and Roll
- Hold on each position for 1-2 sec



Roll: rotation around x

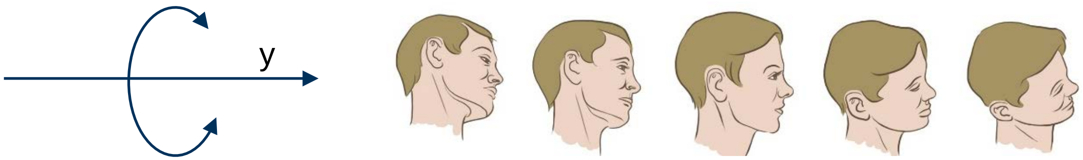


<u>To get the best calibration: faster time and smaller error</u>

1. With higher angles on Pitch and Roll

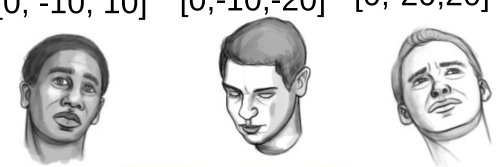
[Yaw, Pitch, Roll] [0,0,45] [0, 0,-45] [0, -45,0]

Pitch: rotation around y

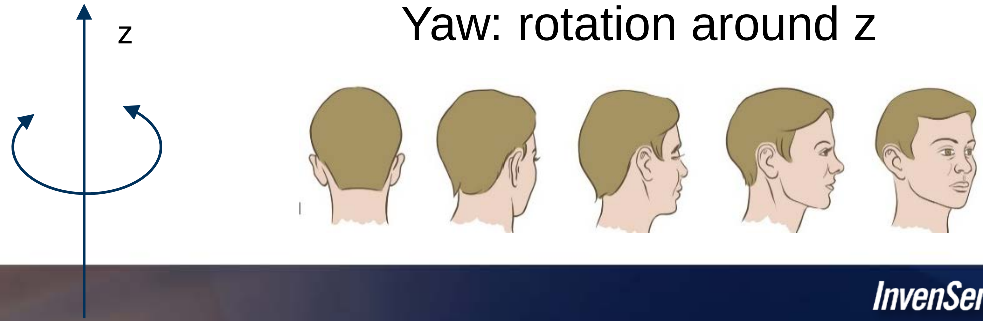


2. Diverse angles combination

[0, -10, 10] [0,-10,-20] [0,-20,20]



Yaw: rotation around z



Results –big initial biases (~100mg)

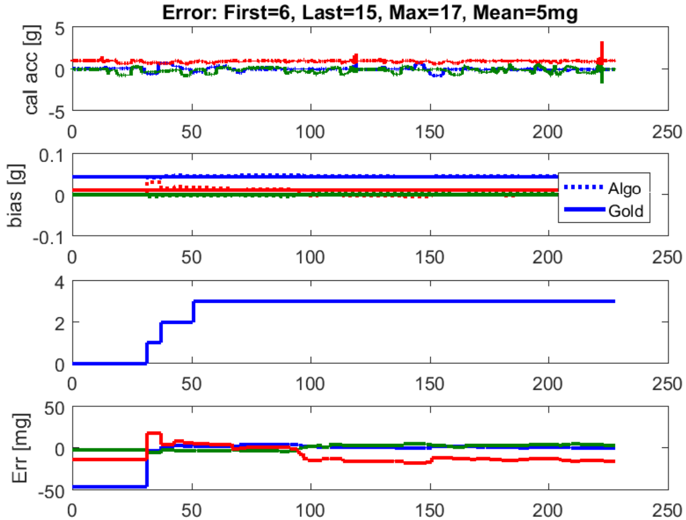
High Variation (in hand)	first estimated bias [g]	last estimated bias	Max Absolute Error [g]	Mean Absolut Error [g]
Session1_Run2_C3	0.005	0.003	0.005	0.002
Session1_Run3_C3	0.006	0.003	0.006	0.001
Session1_Run4_C3	0.005	0.006	0.006	0.004
Session1_Run5_C3	0.005	0.005	0.006	0.003
Session1_Run6_C3	0.006	0.004	0.007	0.002
Session2_Run1_C4	0.004	0.003	0.004	0.002
Session2_Run2_C4	0.001	0.003	0.003	0.002
Session3_Run1_C3	0.002	0.001	0.002	0.001
Session3_Run2_C3	0.003	0.001	0.004	0.001

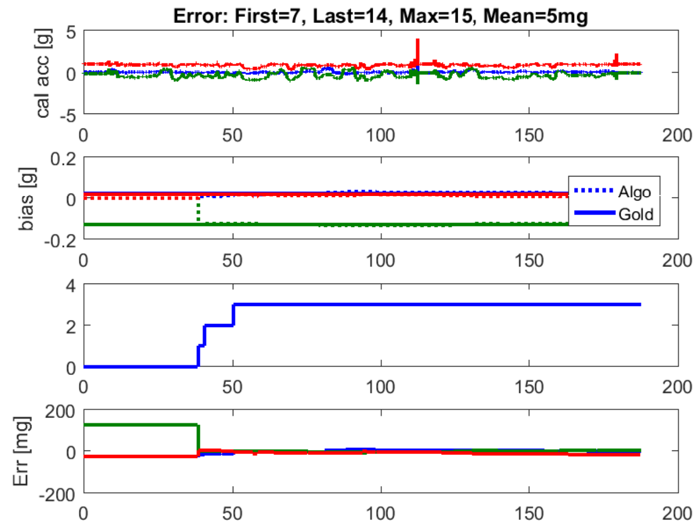
Low Variation (on head)	Error of first estimated bias [g]	Error of last estimated bias [g]	Max Absolute Error [g]	Mean Absolut Error [g]
Session1_Run2_C3	0.004	0.005	0.014	0.005
Session1_Run3_C3	0.003	0.005	0.006	0.002
Session1_Run4_C3	0.012	0.007	0.012	0.004
Session1_Run5_C3	0.010	0.016	0.016	0.006
Session1_Run6_C3	0.006	0.015	0.017	0.005
Session2_Run1_C4	0.007	0.014	0.015	0.005
Session2_Run2_C4	0.017	0.006	0.022	0.003
Session2_Run3_C4	0.038	0.009	0.038	0.004
Session2_Run4_C4	0.012	0.004	0.016	0.003

Average

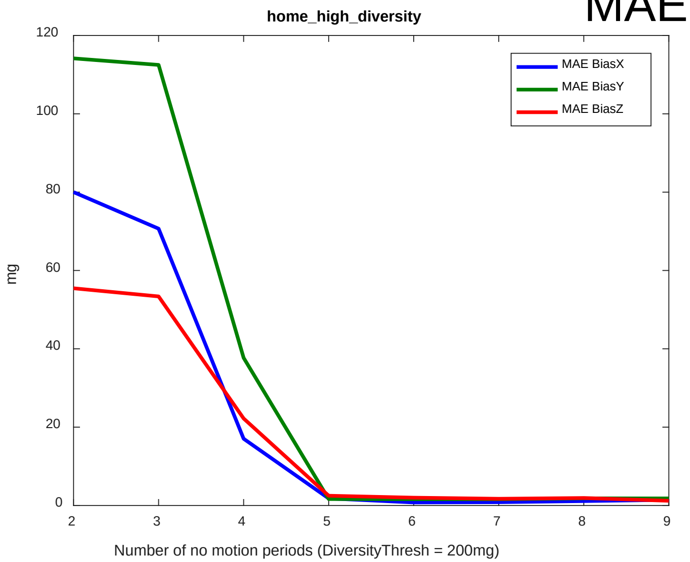
Use case	Error of first estimated bias [g]	Error of last estimated bias [g]	Max Absolute Error [g]	Mean Absolut Error [g]
In hand	0.004	0.003	0.005	0.002
On Head	0.011	0.009	0.016	0.004

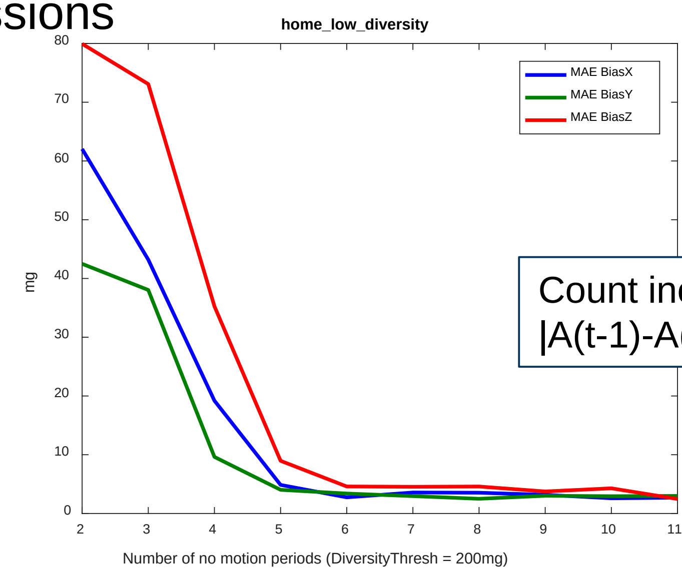
Results - convergence





MAE over all sessions





Count increase only if |A(t-1)-A(t)|>200mg

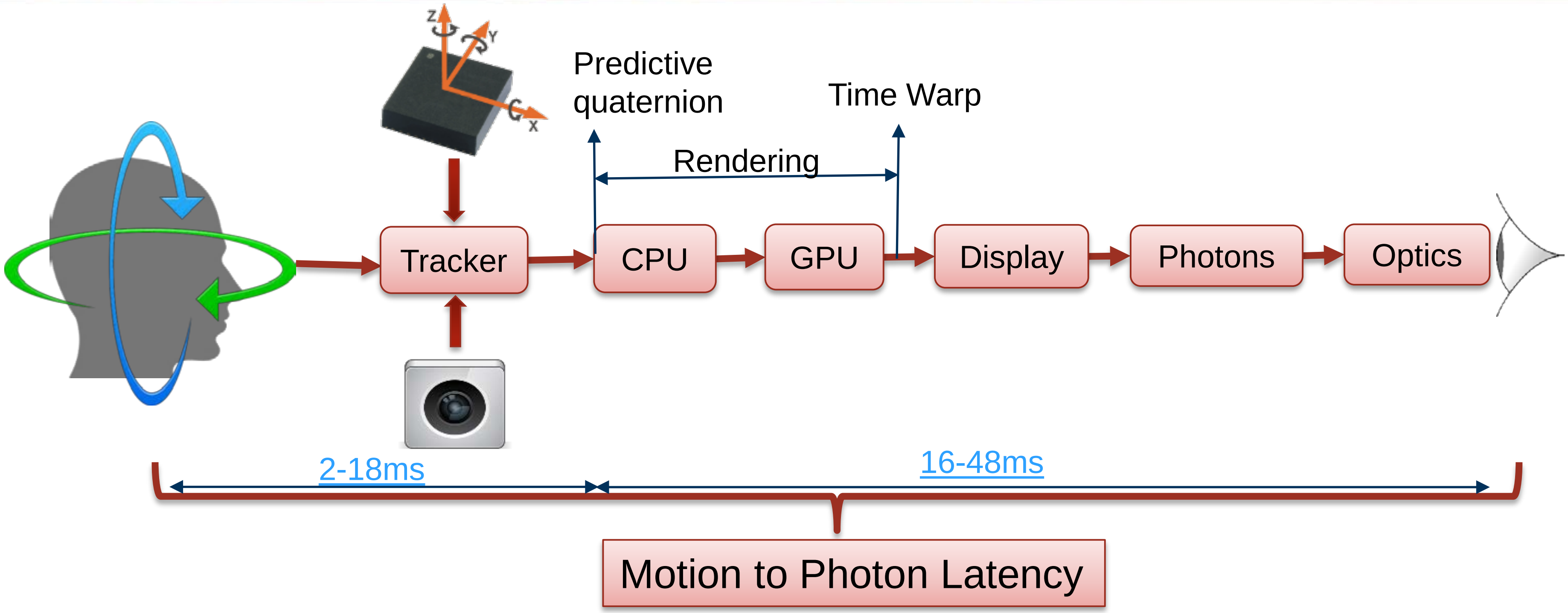
Compass calibration – Uniform mag field

High Variation (in hand)	Error of first estimated bias [uT]	Error of last estimated bias [uT]	Max Absolute Error [uT]	Mean Absolut Error [uT]
Session1_Run1_C3	1.0	0.3	1.0	0.2
Session1_Run2_C3	2.1	1.0	2.1	0.5
Session1_Run3_C3	1.3	2.1	2.1	0.8
Session1_Run4_C3	1.6	1.3	1.9	0.8
Session1_Run5_C3	0.7	1.0	1.2	0.7
Session1_Run6_C3	2.2	0.3	2.2	0.5
Session2_Run1_C4	2.7	0.2	2.7	0.3
Session2_Run2_C4	1.4	0.6	1.5	0.2
Session3_Run1_C3	0.8	0.1	0.8	0.2
Session3_Run2_C3	0.3	0.1	0.7	0.2

Low Variation (on head)	Error of first estimated bias [uT]	Error of last estimated bias [uT]	Max Absolute Error [uT]	Mean Absolut Error [uT]
Session1_Run1_C3	4.3	3.1	4.9	1.7
Session1_Run2_C3	2.1	2.4	2.8	1.4
Session1_Run3_C3	1.0	1.7	1.8	0.8
Session1_Run4_C3	4.2	2.6	4.2	1.8
Session1_Run5_C3	3.4	1.4	3.4	1.3
Session1_Run6_C3	1.3	1.1	2.3	0.8
Session2_Run1_C4	2.2	2.6	2.7	1.1
Session2_Run2_C4	2.2	2.3	3.4	1.1
Session2_Run3_C4	5.3	2.8	5.7	1.1
Session2_Run4_C4	3.4	1.8	3.4	1.3

Average	Error of first estimated bias [uT]	Error of last estimated bias [uT]	Max Absolute Error [uT]	Mean Absolut Error [uT]
Low Variation	2.9	2.2	3.5	1.2
High Variation	1.4	0.7	1.6	0.5

Motion to photon latency (accuracy)

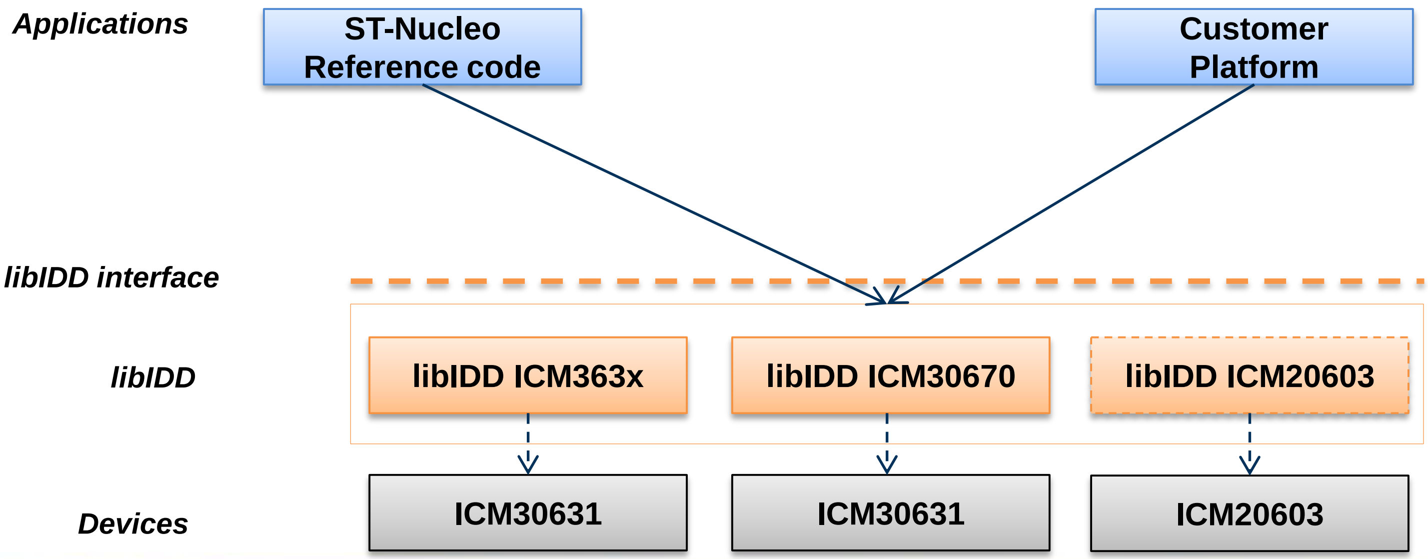


- **Motion to photon Latency:** [2] Difference in person's expectation to what is displayed
  - **Issue:** Disorientation and nausea attributing to motion sickness
  - **Solutions**:
    - **Lower latency in Motion detection & Sensor fusion**
    - **Predictive quaternion**
    - Higher frame rate (Faster rendering)
    - OLED display for faster refresh rate

Predictive quaternion – available as SW update with 20603 in Dec

Easy SW Integration with libIDD

- libIDD (InvenSense Device Driver library)
  - collection of drivers for InvenSense devices, used on eMD platforms and more
  - unified/abstract APIs to control/retrieve data from InvenSense devices (like SoC, smart/DMP sensors, dumb sensors, etc.), including 3063x/20603
  - customers/developers can port libIDD example code from our ST-Nucleo reference platform into target system seamlessly



Wearable Sensor Platform System Solutions

Activity/Context Solutions

6-axis "Smart" Sensor ICM-20648

Activity- Classifier B2S

Wearable FireFly™- ICM-30631/2

Activity

Statistics

Sensor Support

Gestures

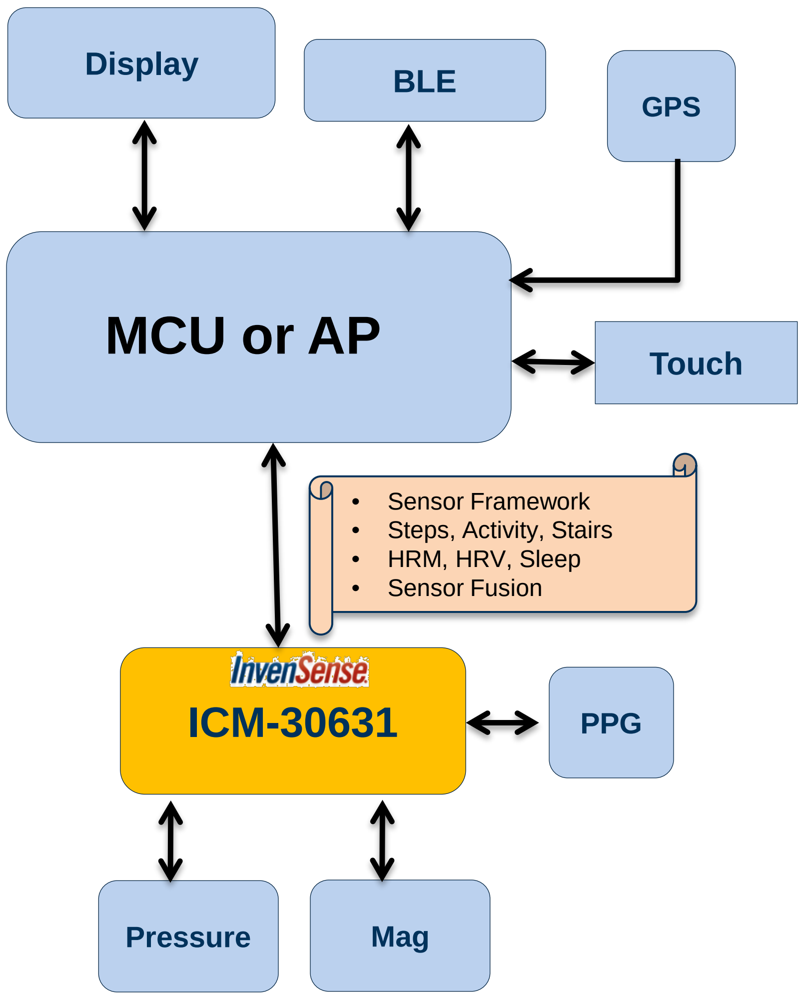
Power optimized self contained solutions
SW stack runs on Device

ICM-30631/32

sensing the FUTURE

- **Complete SW Stack "out of the box"**
  - Customer uses baseline features from INVN
  - Customer focus their SW resources on Differentiated Features of their product
- **Power**
  - ICM-30631
    - BAC – 172uA
- **Integration**
  - Sensor, MCU and SW from one Vendor

Smart Watch/ Fitness Tracker



30631/32 Feature Set

sensing the FUTURE

Category	SW Feature	ICM-30631	ICM-30632
Hardware Sensor	Accelerometer	Yes	Yes
	Gyro	Yes	Yes
	Pressure (BMP280)	Yes	**No**
	Mag (AKM09911)	**No**	Yes
	Proximity (CM36671)	**No**	Yes
	PPG (PAH8001/2, ADPD174, PPS960)	Yes	**No**
Fitness/ Wellness Feature	Walk,Run, Bike,Still, (Pedometer)	Yes	Yes
	Walk/Run Step Counter	Yes	Yes
	Walk/Run Time Accrual	Yes	Yes
	Stand/Sit Time Accrual	Yes	Yes
	Sedentary Reminder	Yes	Yes
	HRM Motion Correction	Yes	**No**
	Heart Rate Variation (HRV)		
	Sleep Analysis (Manual Entry)	Yes	Yes
	Calorie Counter (Activity)	Yes	Yes
	Distance (walk/run)	Yes	Yes
	Floor Climbed Counter (& BMP280)	Yes	**No**
Gestures	Shake	Yes	Yes
	DoubleTap (with B2S first)	Yes	Yes
	B2S	Yes	Yes
Android Sensors	Android Fusion: Gravity, Linear Accel, Orientation (RV, GRV, GEOMAG)	GRV only	Yes

No = Not Supported
Yes = Part of Default 3063x Image

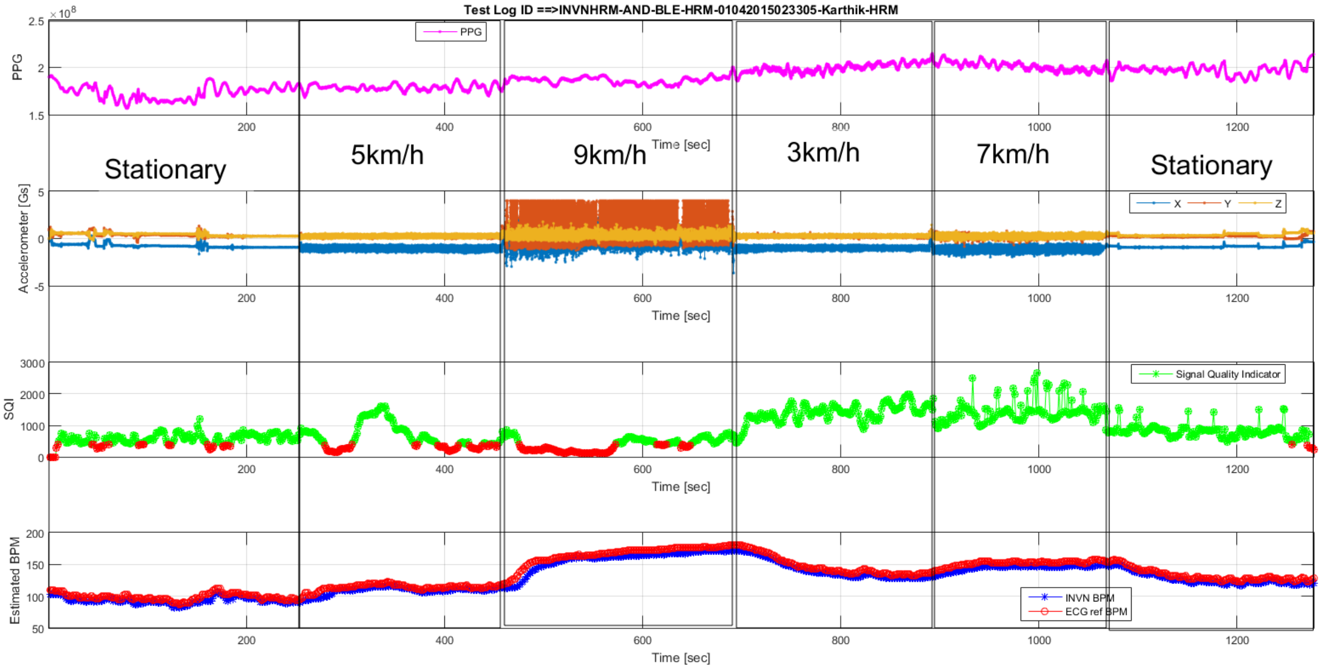
30632-4.1.0 Feature accuracy

sensing the FUTURE

Features	Metric	4.1.0 Typ Performances
Pedometer (Normal Continuous Walk/Run)	Absolute Error	Walk: **5 %** Run: **6 %**
Distance (Requires User height Input)	Absolute Error	Walk: **< 10 %** Run: **< 15%**
BAC	Detection rate	Still: **79 %** Walk: **93 %** Run: **83 %** Bike: **92 %**
Sit/Stand (+BAC)	Detection rate	Sit: **82 %** Stand: **89 %**
Bring To See	Detection rate	sedentary position: **85 %** walking/running: **75 %**
Shake *two half-rotations of the wrist in Look at screen position*	Detection rate	sedentary position: **90 %**
Double Tap *in Look at Screen position*	Detection rate	sedentary position: **85 %** walking/running: **80 %**

PPG Motion Correction Solution

sensing the FUTURE



PPG Sensors Supported

PAH8001
PAH8002

PPS960
(includes AFE4404)

ADPD174

HRM Algo	MIPS	Size		HRM Tracking Performance [bpm 1σ]		
		Code	Data	Stationary	Walking	Running
InvenSense (Cortex M4 Lib)	1	15KB	17KB	±3	±4	±6

InvenSense HRM Algo vs. Android Wear

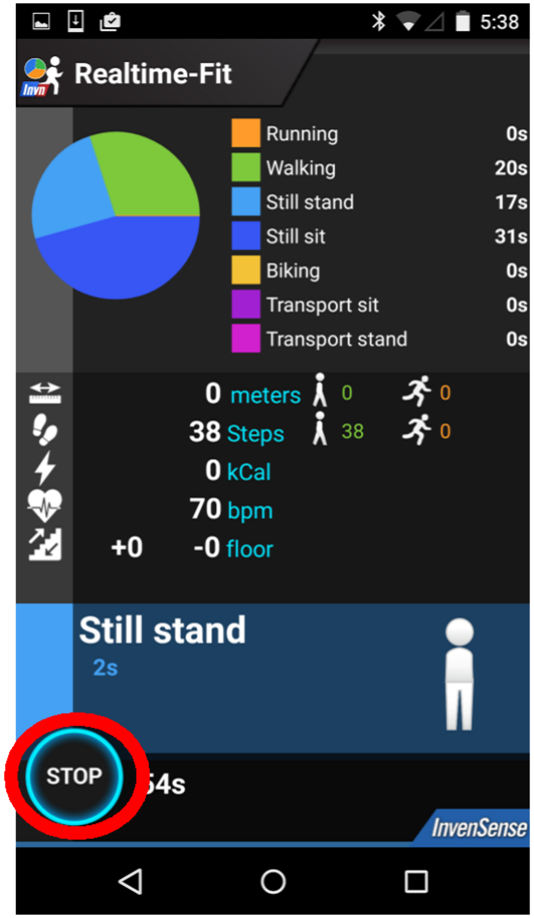
sensing the FUTURE

- HRM engine bpm performance summary
  - Results based on 118 data logs known to have good PPG signal quality

Test Definitions	Mean Absolute Error (MAE) [bpm]		Standard Deviation (σ) of Residuals [bpm]		Percent of Values within ±10bpm [%]	
	Android Specs	InvenSense	Android Specs	InvenSense	Android Specs	InvenSense
Sedentary Heart Rate	< 5.00	2	< 8.00	4.5	> 90	97.2
Indoor Walking	< 5.00	3.4	< 8.00	6.1	> 85	92.9
Running	< 7.50	4.1	< 8.00	7.4	> 80	90.8
Biking	<7.50	TBD	<8.00	TBD	> 80	TBD
Elliptical	N/A	2.6	N/A	5.2	N/A	95.1
Combined	N/A	3.8	N/A	5.2	N/A	91.9

* Working on Biking Database

SW Feature Evaluation Platform: MIO Msport Band

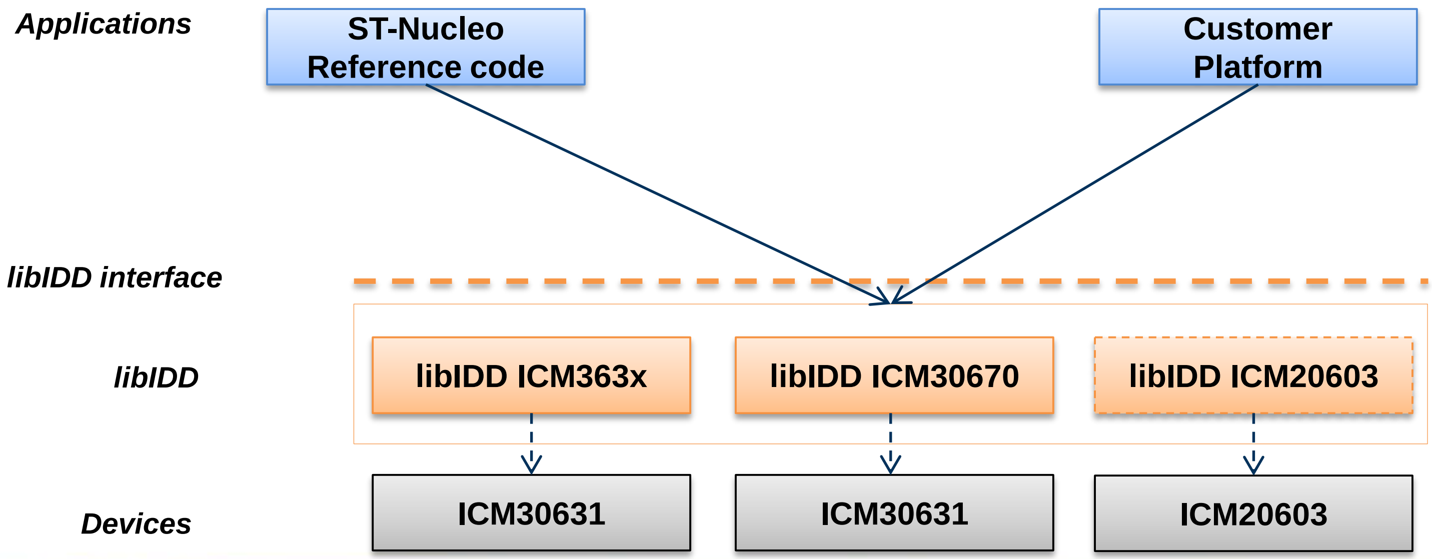


- Msport MIO Band
  - Evaluate all features of 3063x
  - Collect Sensor Data Logs
  - Contact CPM for unit

Easy SW Integration with libIDD

sensing the FUTURE

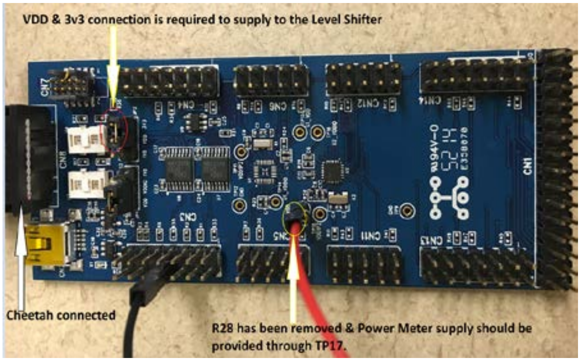
- libIDD (InvenSense Device Driver library)
  - collection of drivers for InvenSense devices, used on eMD platforms and more
  - unified/abstract APIs to control/retrieve data from InvenSense devices (like SoC, smart/DMP sensors, dumb sensors, etc.), including 3063x/20603
  - customers/developers can port libIDD example code from our ST-Nucleo reference platform into target system seamlessly



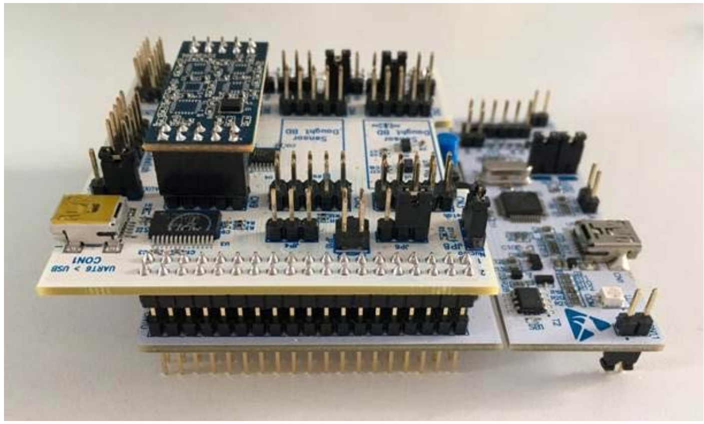
InvenSense

Evaluation Platforms

- SDK Platform for Field Eval
  - Host is emulated on a PC
  - SW Integration/Bring-up
  - Basic feature checkout/evaluation (not requiring form-factor).
  - Data Logging
  - Sensor debug/integration
    - Mag
    - Prox
    - Pressure
    - PPG
  - Power Measurements



- Nucleo Platform for Field Eval
  - Same as SDK, plus the capability to verify/integrate LibIDD functionality on a commonly used MCU
    - Host is the MCU
  - Host functions on a MCU



Coursa Sports

GPS is a Wearable Battery Killer

Problem 1: GPS usage kills battery life

Fitbit Surge:
- 7 day Battery life on standby
- 5hr GPS Battery life

Apple Watch 2:
- 10 hour battery life in workout mode without GPS
- 5 hour battery life in workout mode with GPS

Android Fitness Apps
- 4-6hr Battery Life w/ GPS

Many early smartwatches didn't include GPS due to power drain

Users not happy with this easy solution due to accuracy sacrifice

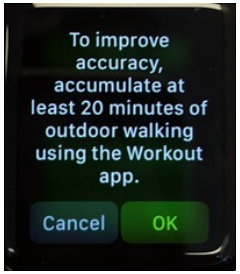
Better Solution: Use <u>less</u> GPS

- Duty cycle GPS and bridge outages with sensors
  - Distance, speed and trajectory using less GPS
  - Minimize time using GPS, thus minimize battery drain

Accuracy: GPS or Sensors?

Problem 2: poor accuracy on wearables

- Sensors drift over time
- GPS not accurate enough on wearables
  - Small antenna
  - Attenuation from body
  - Arm swinging
  - Lack of assistance data to watch GPS



Reference
GPS from Gear S2

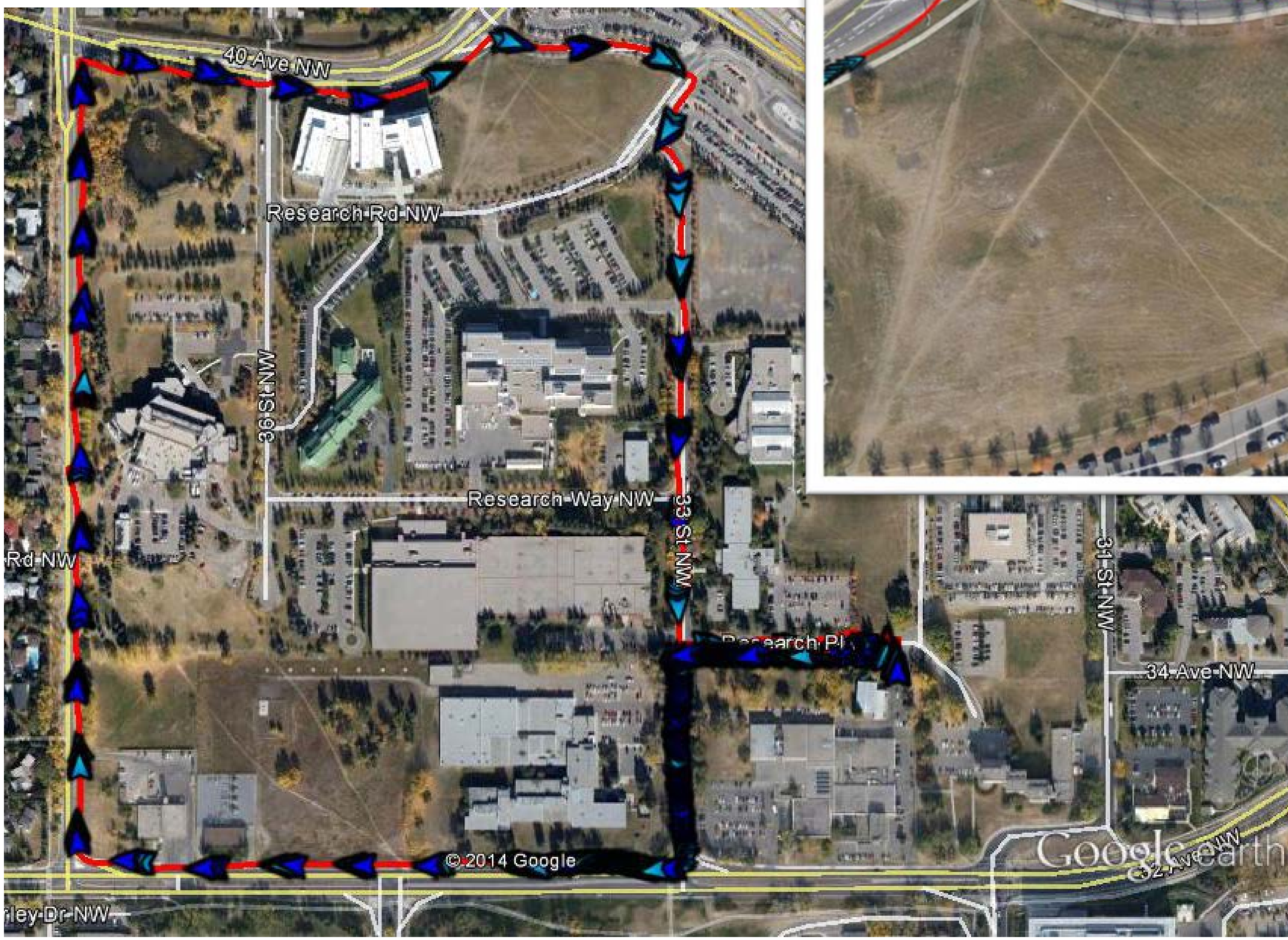
Solution: Combine GPS + sensors

- Improves accuracy of multipath GPS by filtering
- GPS can correct PDR sensor drift or offset errors (e.g. position drifts, stride length bias)

GNSS Duty Cycling Concept

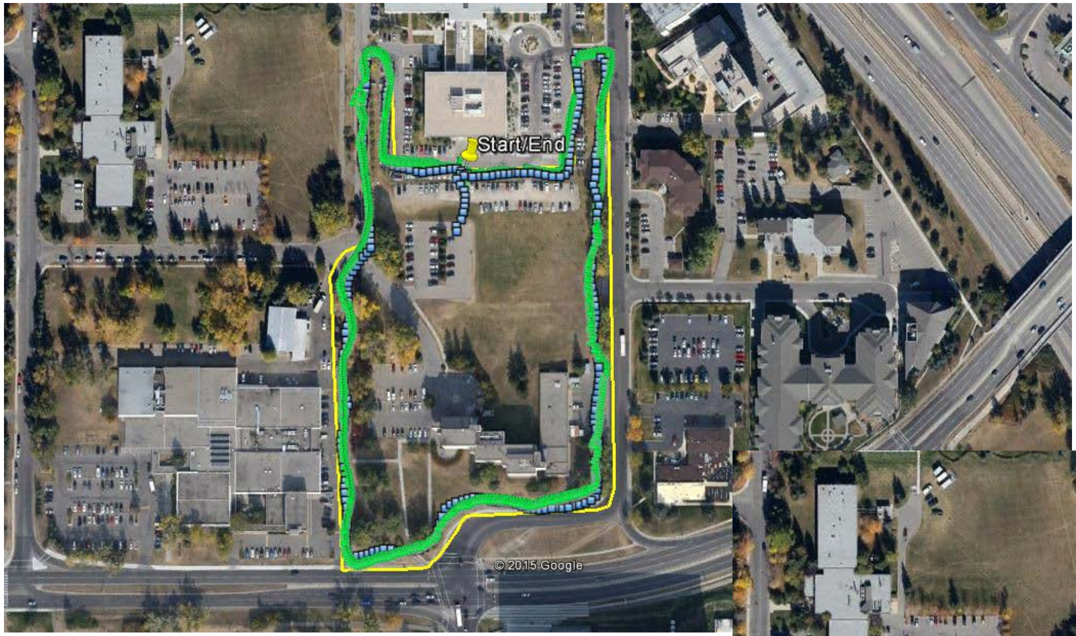
Sensing Everything

Power Savings
- Using 25% of GNSS



Position Performance:
- Distance: same as GNSS
- Horizontal: 3-4 m

Coursa Sports vs Strava vs Reference



Reference
Strava
Coursa Sports

GPS used for Coursa Sports

<u>Conclusion</u>
Coursa Sports can deliver the same accuracy as Strava (who uses 100% GPS) but with only 25% GPS

Reference
Coursa Sports

Apple Watch 2 Benchmark

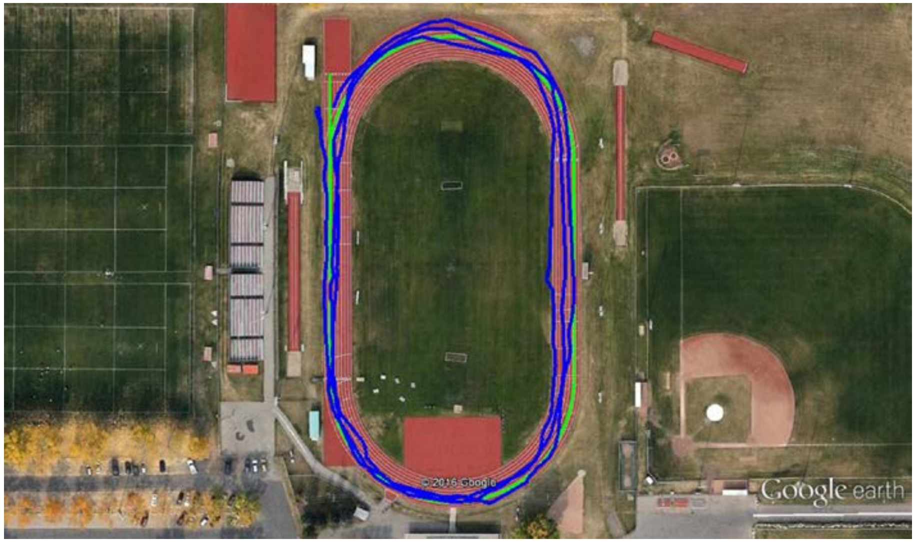
- Apple Watch 2 released in September 2016
  - Focus is on fitness tracking
  - Walk, run, bike, swim
- Apple Watch 2 validates Coursa Sports use case
  - Speed/pace & distance provided in real-time
  - Route provided after finishing an exercise session and only displayed on the iPhone
- Apple Watch 2 sets Performance Bar for Android/Others
  - Quality GPS implementation on a watch
  - Distance & route accuracy

Example 1: Coursa Sports Performance Mode vs Strava in Open Sky

sensing the FUTURE

- Below example shows ‘Performance Mode’ of operation on a Moto 360 watch
  - GNSS on all the time for Strava in blue and Coursa Sports in red
  - Coursa Sports route is more accurate than GNSS on all the time, even in open sky when GNSS is performing at its best
  - Strava distance travelled error = 7.9%
  - Coursa Sports distance travelled error = 2.2%

Strava with GNSS on all the time



Coursa Sports

Distance Benchmark Set by Apple

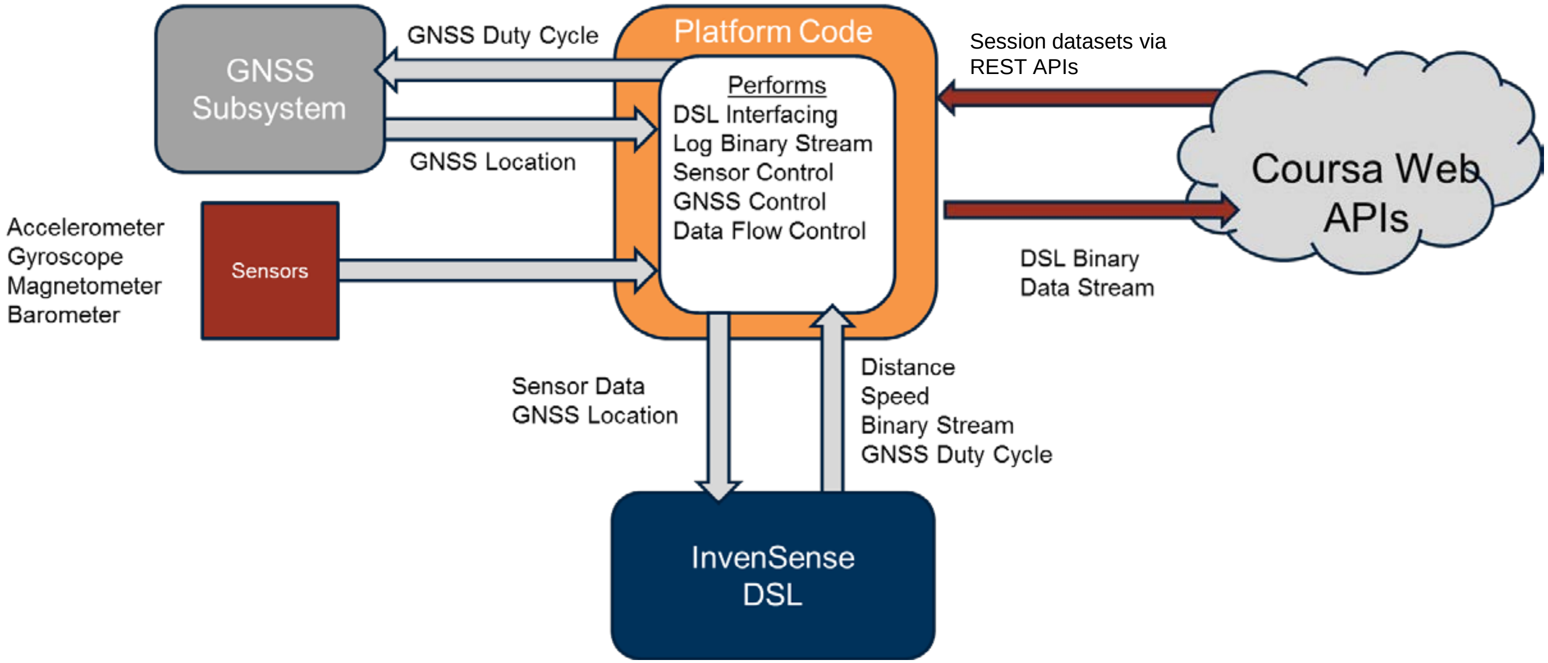
- Accuracy benchmarking of Coursa Sports performed using several Android devices

	Average Distance Errors w.r.t. Distance Travelled
Apple Watch 2 GPS on all the time, similar to Coursa Sports Performance Mode	3-4%
Android Phone GPS-only	8%
Coursa Sports Performance on Android (GPS on all the time)	4%
Coursa Sports Balanced on Android (50% duty cycle)	5%
Coursa Sports Low Power on Android (25% duty cycle)	7%

Power Comparison

- Apple Watch 2 can be used in workout mode for 5 hours with GPS ON and 10 hours with GPS OFF
  - 273 mAh battery
  - 27 mA/hour extra burn with GPS on
- Coursa Sports Low Power Mode uses about 25-30% GPS through duty cycling
  - Should extend battery life of Apple Watch 2 with GPS ON to about 8 hours delivering similar distance accuracy
- Coursa Sports Balanced Mode uses about 50% GPS through duty cycling
  - Should extend battery life of Apple Watch 2 with GPS ON to about 7 hours

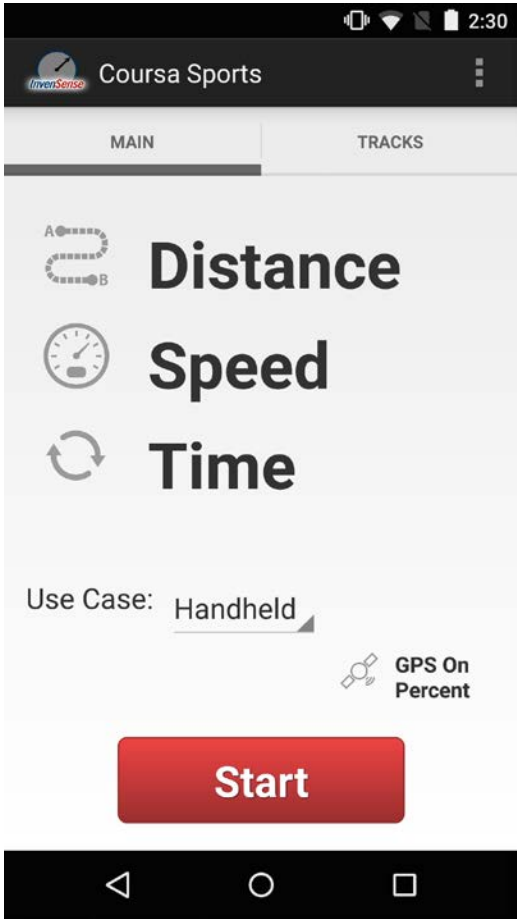
Coursa Sports Architecture

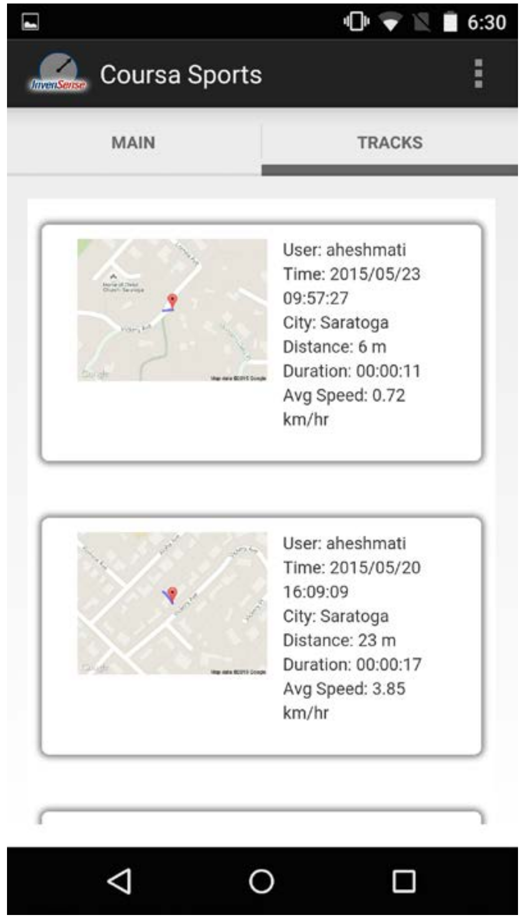


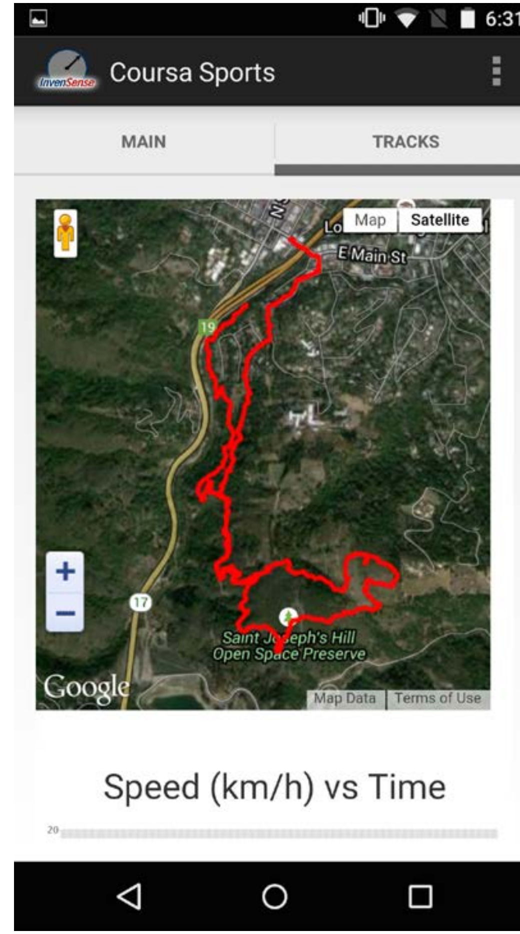
- Real time distance and speed computation is done on the device
- GNSS is duty cycled that leads to significant power savings on the device
- Route is calculated with 95%+ accuracy on Coursa Sports servers
- Session data processed by the Coursa Sports server is available via REST APIs

Coursa Sports Eval App

sensing the FUTURE





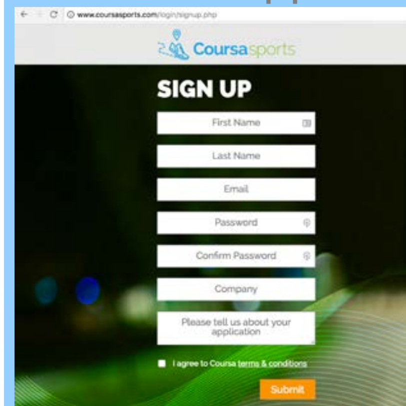


Eval app available for demo on Android, Android Wear and iOS devices

Coursa Sports Integration Lifecycle

sensing the FUTURE

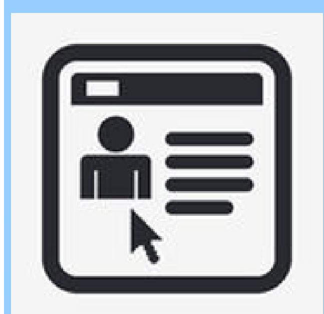
1] Request access to SDK & wait for approval



2] Login to download Android & iOS SDK

3] Integrate iOS & Android SDK using the <u>SDK key</u> granted to the account Verify <u>distance & speed</u>

4] Use unique user id's and upload data to the Coursa Sports servers



5] Use the <u>API key</u> to download <u>processed route</u> data from Coursa Sports servers

6] Test and verify implementation. Start Shipping!

Visit www.coursasports.com

Coursa retail
by InvenSense

Shopper Retargeting and Location Analytics for Brick and Mortar Retail

Use sensor data inside consumer smartphones to gather insights from shopper location history in retail stores

Improve in-store UX with realtime shopper and associate location

Coursa Concept

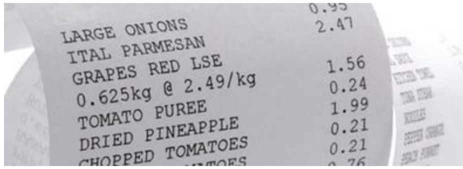
sensing the FUTURE

[Coursa Retail - Phase I]

InvenSense

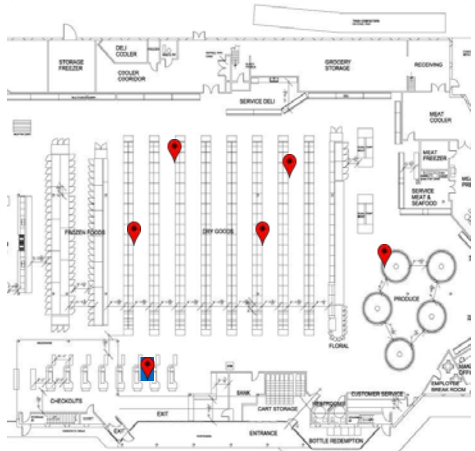
Fusion of Motion + POS + Maps

sensing the FUTURE



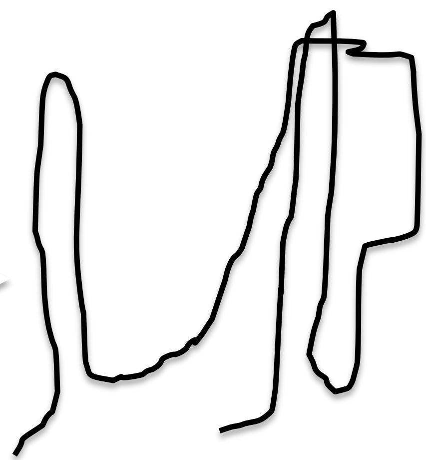
POS provides list of purchases+
Time at checkout

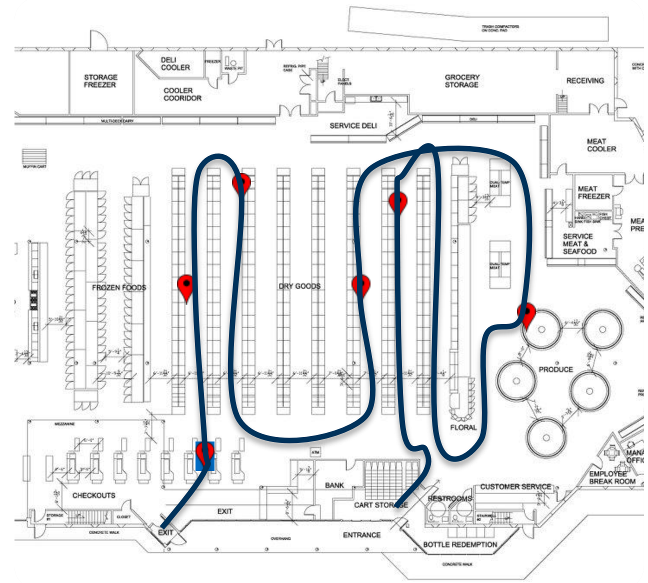
Store product locator



Location anchor points

Time tagged Sensor data collected in real-time - used to generate PDR either in real-time or post-mission





Best fit of PDR to anchor positions and optionally map matching delivers absolute position trace of user in physical space

InvenSense

No Costly Infrastructure

sensing the FUTURE

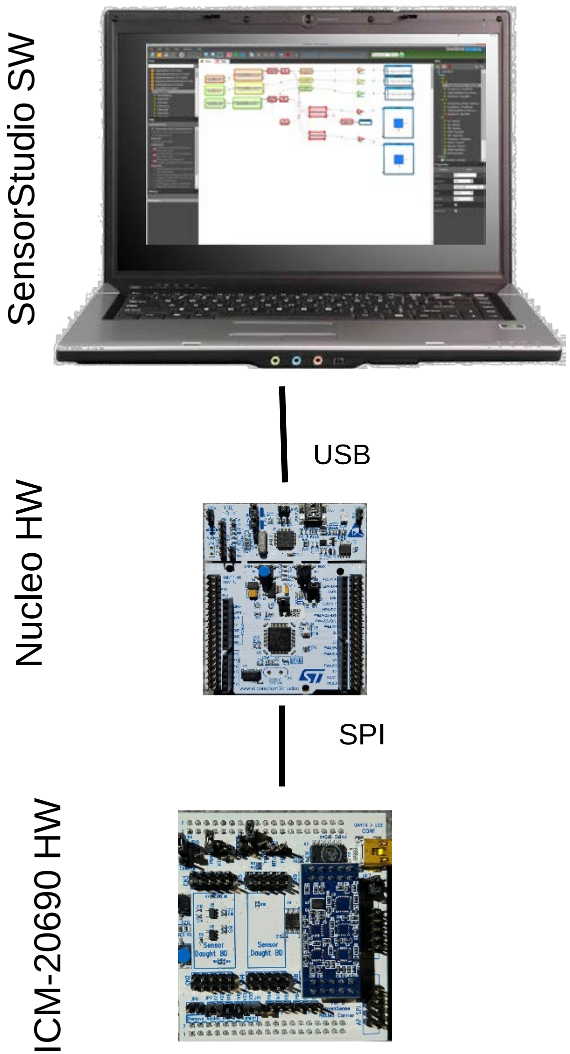
Coursa Retail gets you access to your valuable shopper and store insights without costly equipment purchases and installations. Coursa Retail also scales quickly across all of your stores by avoiding time-consuming per-store setup or site surveys.

- customer’s existing smartphones (iOS and Android)
- retail app w/ Coursa SDK
- One Bluetooth beacon per store entrance

- No expensive capital equipment (WiFi, video cameras, store-wide beacons)
- No access to the in-store data network required
- No per-store installation personnel required

DIY Algorithm Development

SensorStudio

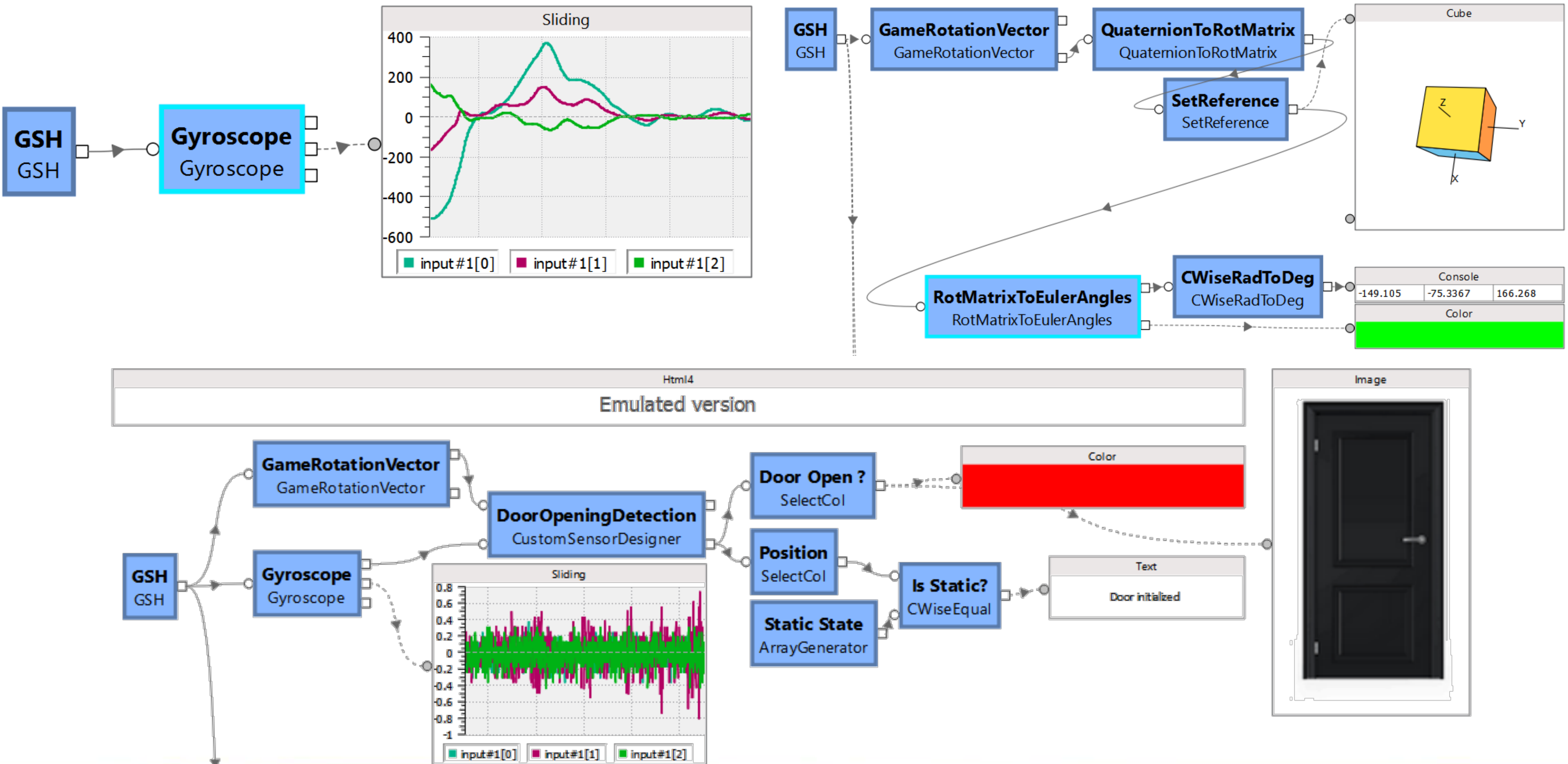


- High level of abstraction through visual programming
- Gain data insight through real time scientific visualizations
- Record & replay for a complete algo dev/validation cycle
- Creates compelling PoCs & demos in no time
- Expedite sensor-based custom product development without prior sensing knowledge

Visualize all signals Real-Time

sensing the FUTURE

- Visualize data at each stage
- Support InvenSense sensors & sensor fusion
- Facilitate development & integration of custom block of your own!



Conclusion

- Low cost high performance motion sensors are enabling broad set applications
- New algorithm innovation and SW solutions are key enablers for these applications
- Mass deployment of “sensor enabled” devices provides opportunity for crowd sourced remote sensing applications
- Future trend from fusion of previously disjoint data sources

Thank You