Indoor navigation & positioning

For autonomous vehicles, robots, drones, forklifts, VR and humans

Review and comparison of indoor positioning technologies and methods with focus on industrial applications

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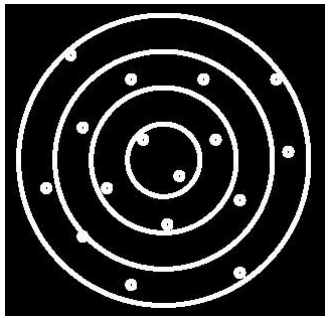
robotics

Problem to solve

- **GPS does not work indoor:**
  1. no direct view to satellites
  2. location precision is measured in meters rather than in centimeters (required indoor)
- Other indoor navigation systems - UWB, Bluetooth beacons, odometry, magnitometers, WiFi RSSI, laser triangulation, optical, etc. - have their **own serious limitations** – usually, either precision, or price, or size
- <u>Without precise and timely knowledge of location, autonomous navigation is impossible</u>



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Terminology

- **AoA** Angle of Arrival
- **AoD** Angle of Departure
- **AR** Augmented Reality
- **BLE** Bluetooth Low Energy
- **GNSS** Global Navigation Satellite System (GPS, GLONASS, Galileo, Beidou. Michibiki
- **GPS** Global Positioning System
- **IA** Inverse Architecture (Marvelmind Robotics)
- **ILS** Indoor Localization System
- **IP67** Ingress Protection
- **IPS** Indoor Positioning System
- **IMU** Inertial Measurement Unit
- **LIDAR** Light Detection and Ranging
- **LoS** Line-of-sight
- **MEMS** Micro-Electro-Mechanical Systems
- **NIA** Non-Inverse Architecture
- **Non-LoS** Non-line-of-sight
- **RSSI** Received Signal Strength Indicator
- **RTLS** Real-time Locating Systems
- **TDoA** Time Difference of Arrival
- **TDMA** Time Division Multiple Access
- **ToA** Time of Arrival
- **UWB** Ultra Wideband
- **VR** Virtual Reality
- **ZigBee** Wireless mesh network standard

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Types of indoor positioning methods

- **Trilateration** – time of flight
  - GPS
  - UWB
  - Marvelmind Robotics' Indoor "GPS"
- **RSSI-based**
  - BLE (Bluetooth Low Energy)
  - WiFi
  - ZigBee
- **Triangulation**
  - LIDARs
- **Mixed**
  - BLE + angle of arrival (AoA)
- **Odometry**
- **Inertial**
  - Inexpensive MEMS IMU vs. laser IMU
- **Optical**
  - QR codes
  - Stargazers
  - Optical flow
  - Motion capture
- **Sensor fusion**
  - IMU+ultrasonic
    - Drift vs. jumps
    - Location update rate
- **Other types and exotic**
  - Li-Fi
  - RFID
  - Magnetic

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No methods or RTLS good for all

Too many contradicting requirements. Users must choose:

- Update rate
  - Update on request vs. 100-400Hz for VR/AR
- IP67 and Ex requirements
- Price
- Power consumption and battery lifetime
- Weight
- Size
- Tolerance to particular types of interferences (radio, light, sound)
- Location vs. Location+Direction
- Embedded IMU
- Data communication to and from mobile beacons

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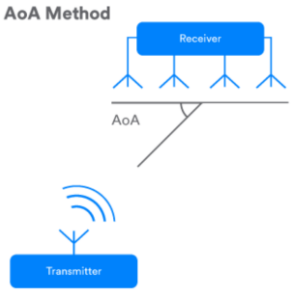
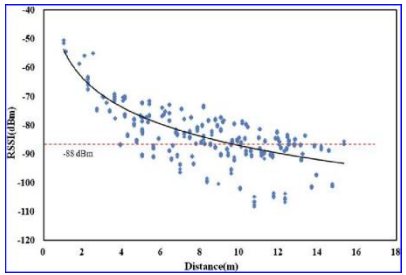
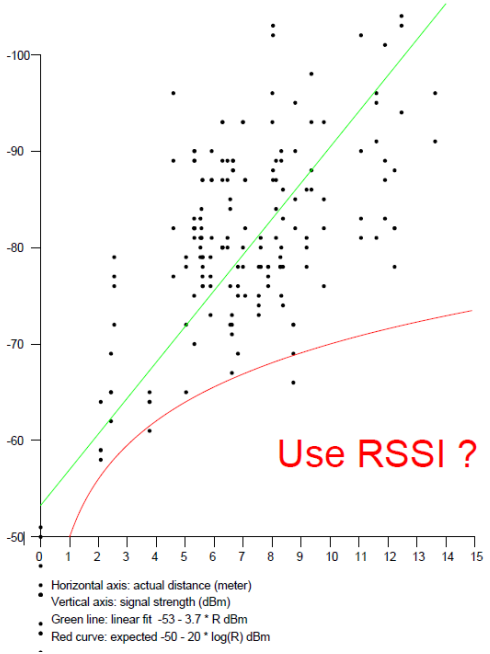
RSSI-based RTLS imprecise by design

- WiFi, BLE (Bluetooth), ZigBee, LoRa – not designed for positioning, but can be used in many cases with technology related limitations
- **Signal strength (RSSI) easily deviates 10x times over the course of 1m**
- Fingerprint Database and need for calibration – time and efforts
- Additional improvements:
  - Averaging => but leads to more latency and shorter battery lifetime
  - Mathematical models => limits applicability
- Angle of Arrival (AoA) and Angle of Departure (AoD)
  - Combination of imprecise RSSI + angles => up to 3 times better precision
  - Multiple antennas => larger size, larger cost, limitations of applicability







https://people.csail.mit.edu/bkph/ftmrtt_intro

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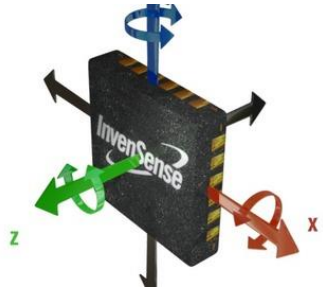
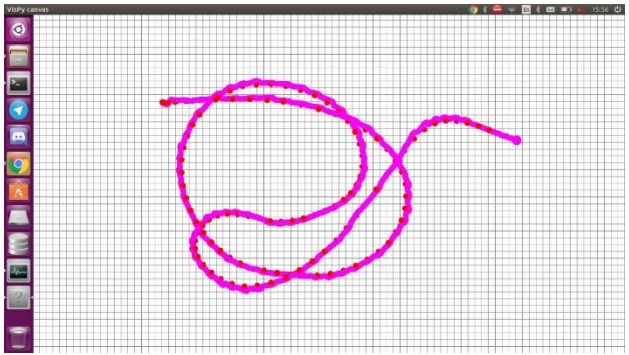
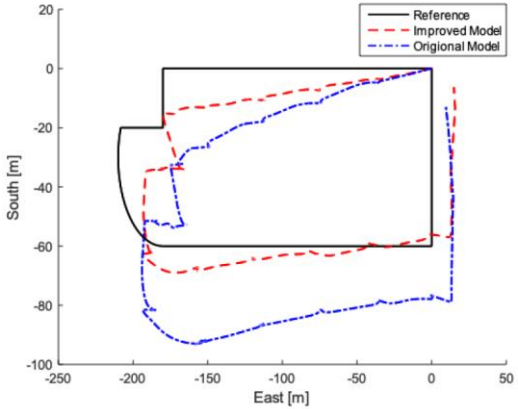
IMU-based RTLS drifts a lot



- IMU (inertial measurement unit) – usually, 3D accelerometer + 3D gyroscope. Often, additionally, 3D magnetometer
- Magnetometers work poorly indoor – don't rely on them
- Pure IMU indoor RTLS can't really perform for long time period (more than seconds) due to **very-very high drift of double integration of accelerometer data**
- Still, they can be sufficiently precise depending on the types of IMU units (laser-based IMU vs. MEMS IMUs) and required precision (cm vs. km) – fraction of seconds to small seconds. Need constant drift elimination by external systems
- Pedestrian Dead Reckoning algorithms and different flavors of them
- IMU+Ultrasonic sensor fusion of Marvelmind Robotics





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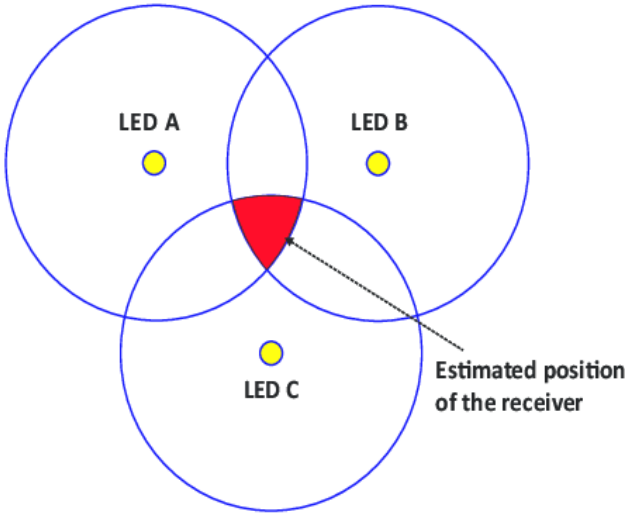
Trilateration can be very precise

- **Trilateration** ≠ triangulation
- Trilateration; measure distances from 3 or more known points and calculate location of mobile beacon. Usually, time of flight
- 1D, 2D, 3D, multilateration
- Examples of systems based on trilateration – time of flight:
  - **GPS** – radio waves 1.2GHz & 1.5GHz
  - **UWB** – ultra wideband radio waves (3..10GHz)
  - **Marvelmind Robotics' Indoor "GPS"** – ultrasound (20..60kHz) + radio in license-free ISM band (433MHz or 868/915MHz)
  - Light based trilateration RTLS – could exist
- Still uncertainty where the intersection point is – know-hows
- Timing and synchronization – know-hows
- Noise and interference
- Obstructions => use redundancy



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Precise RTLS must have line of sight

- Time of flight trilateration systems assumes that:
  - Distance measured precisely => Distance measured as speed*time => speed must be constant. But the signal propagation speed in air and in the wall are very different! Thus, you can rely on them any longer
- Non-line of sight precise RTLS are in fact, line of sight RTLS, but with transparent walls/obstructions:
  - Carton-like gypsum walls of many offices are radio transparent for UWB
  - “Breathable” cloth is transparent to Marvelmind Indoor “GPS” ultrasound
  - But!
    - Concrete walls of warehouses, palettes, metal shelves are radio non-transparent for UWB
    - Even sheet of paper is not transparent for ultrasound or LIDAR light

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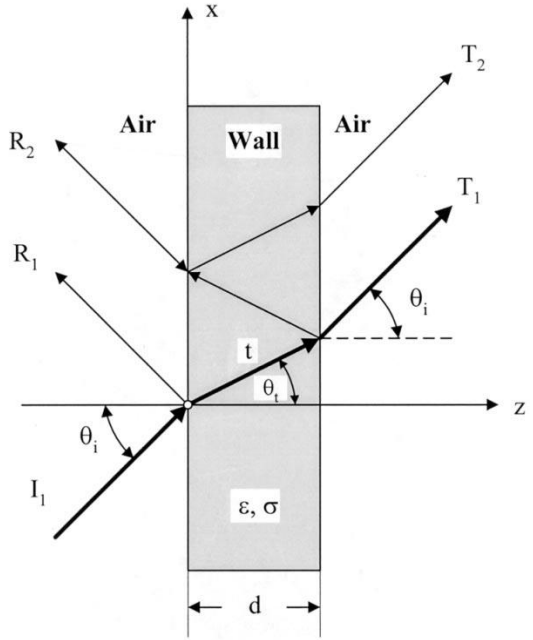
Line of sight is a must for precise industrial RTSL



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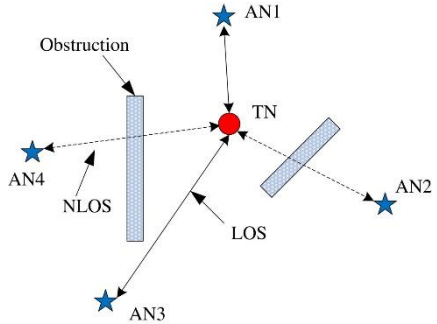
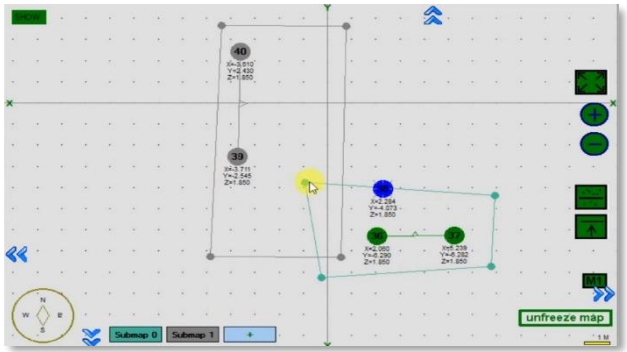
What to do in Non-LOS situations?

- Make line of sight possible
  - Proper network planning and beacon placement*
  - Use submaps and install more stationary beacons*
  - N+m redundancy of stationary beacons (anchors)*
  - 2N and TDMA approach for redundancy*
- Use sensor fusion
  - Odometer+Indoor “GPS”*
  - IMU+Indoor “GPS”*
  - Special algorithms: instead of pure 3D – temporary 2D**
- Tolerate lack of tracking for some areas
  - More beacons & more cost vs. fewer beacons & lack of coverage in some areas – decision based on economics of the business case





Line of sight is a must for precise industrial RTSL

* Methods used in Marvelmind Indoor “GPS”

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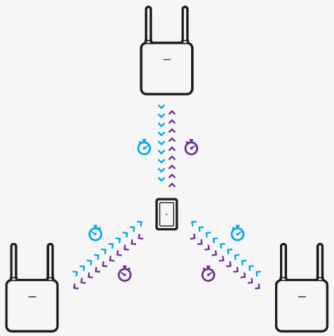
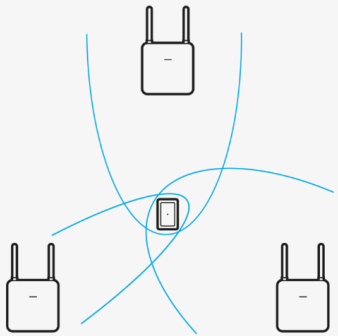
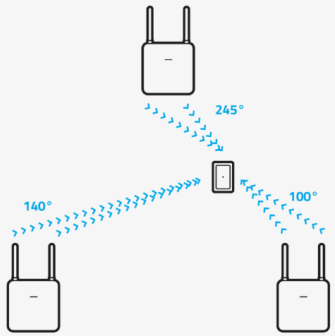
Different flavors of UWB



Two-Way Ranging (TWR)



Time-Difference of Arrival (TDoA)



Phase-Difference-of-Arrival (PDoA)

https://kinexon.com/technology/real-time-locating-system-rtls

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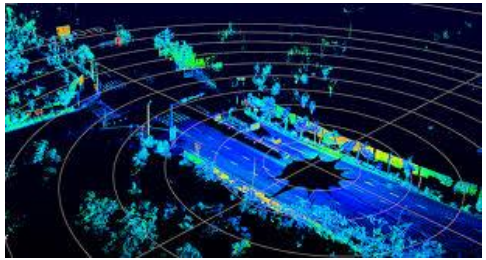
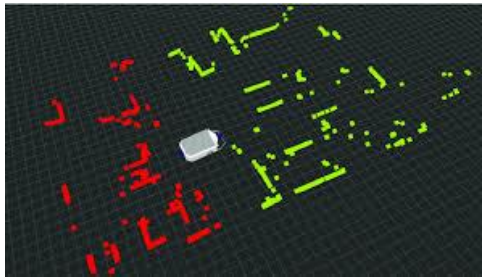
LIDARs: precise, but not really designed for positioning and navigation

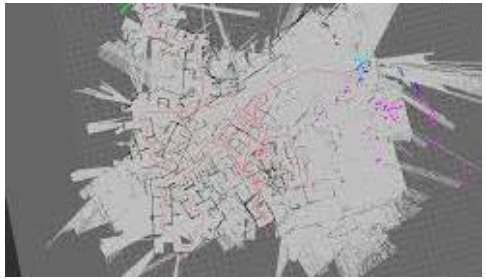
- **Price**: Long-range LIDARs are costly. For indoor less expensive LIDARs can be used
- **Applicability**: Good for obstacle avoidance and detection. Not really designed for positioning
- **Use cases**: robotics, AGVs. Rarer – drones. Hardly possible for people

- Rather complex SLAM algorithms with questionable performance in real-life environment of a factory floor or a busy warehouse

Quality of positioning very much depends on the complexity of the environment. In basic and simple rooms with few changes in the environment and few other mobile objects (AGVs/robots, people) – works rather well. In real complex ever-changing environment of production site or a warehouse – either unreliable or lost completely







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Use LIDARs for obstacle avoidance and detection. Don’t rely for positioning

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QR codes + IMU + odometry

- Kiva Robotics prominently used the method years ago. The very large number of robotics companies-copycats use now this very good and robust method
- Uses:
  - QR codes on the floor every 1-2m – absolute positioning
  - Odometry + IMU to move precisely, but with accumulated error – relative positioning between the QR code spots
- Suits for robots. Doesn't suit for forklifts, drones, people

⇩

Sensor fusion systems optimally tuned for a task perform the best among all indoor navigation systems

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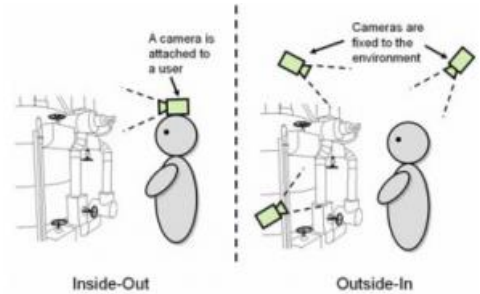
Visual positioning

Multiple flavors from limited and special to generic:

- Stargazing and landmark navigation
- Optical flow: drones, VR. Good for relative positioning
  - Works with special QR codes or with other encrypted in patterns information. Can be very practical in some cases
- Inside Out vs. Outside In positioning
  - VR/AR
- Motion capture => cinema/VR
- Quality of positioning depends on lighting and distance (a few meters at most, usually)



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Some visual positioning methods become good options despite immense internal complexity

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Requirements: Location update rate

GPS satellites send radio signals, but don't track all millions of users:

- Very often, we need to track multiple mobile users. Thus, there is a trade off between update rate per user and the number of mobile users supported

Marvelmind Robotics has two architectures:

1. Non-Inverse Architecture (NIA)
   - Great for drones and other noisy mobile objects
   - Simple to understand and to deploy. Very robust
2. Inverse Architecture (IA)
   - Great for tracking multiple 5-200 mobile objects without update rate reduction. More complex to deploy

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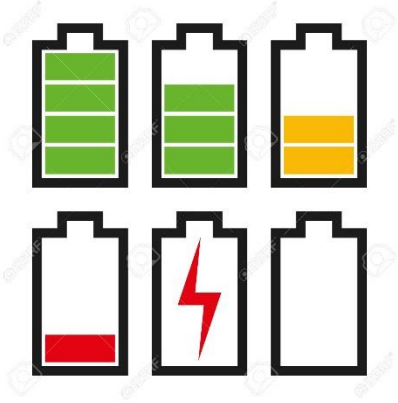
Requirements: Power supply & battery lifetime

Higher update rate => nearly proportionally shorter battery lifetime

- If only possible, use external power supply and have piece of mind
- Choose optimally between required update rate and battery lifetime
- Replaceable battery vs. re-chargeable batteries
- “5-year battery lifetime” is meaningless. What is the update rate? What is the range?

- Power supply of stationary beacons vs. mobile beacons
  - Powering of stationary beacons externally may be very challenging and costly
    - BLE stationary is great. UWB stationary – terrible
    - Mobile UWB great. BLE – terrible
    - Marvelmind Indoor “GPS” is in the middle between the BLE and UWB



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Requirements: Location vs. Location+Direction

Magnetometers or compasses are not reliable indoor

⇒ difficult to figure direction where robot / AGV / drone / person is facing

1. Solution 1: Moving 1m => IMU lock => constant IMU drift correction – complex and not always possible and reliable
2. Solution 2: Use Marvelmind feature called Paired Beacons – but very precise positioning required for small base between mobile beacons => works with Marvelmind's Indoor "GPS" and RTK GPS. Not really works with UWB and reasonable size base due to insufficient precision of UWB. Doesn't work with BLE v4.0 but may work to some extend with BLE v5.1 supporting AoA

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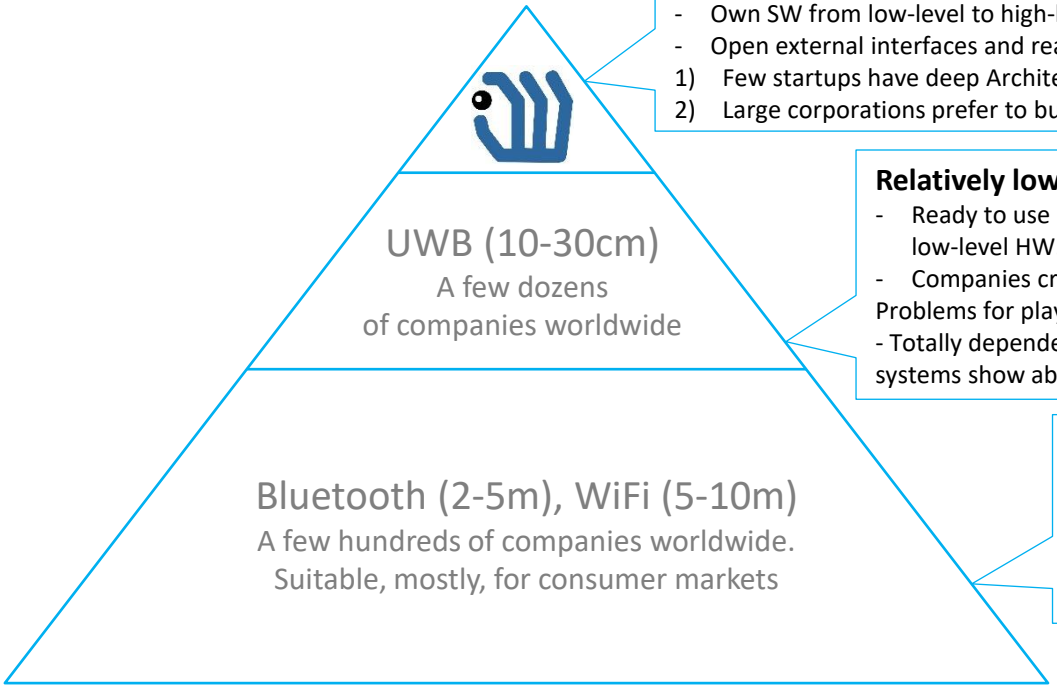
Market approach by Marvelmind Robotics



Marvelmind's approach – superior precision and avoiding direct competition:
- Own architectures & own protocols → full independence and world's superior performance
- Own HW design from scratch on generic ARM processors → development speed and low cost
- Own SW from low-level to high-level → speed, low cost, easy scaling
- Open external interfaces and ready to use SW libraries and APIs → easy integration by end-users

1) Few startups have deep Architecture & HW & SW competences => simply can't develop as we did
2) Large corporations prefer to buy proven – either product from us or us as a company completely

Relatively low entry-barriers in UWB field:
- Ready to use UWB chipsets or even UWB modules (Decawave, etc.) – ready to use low-level HW. Ready to use low-level SW stack from chip vendors
- Companies create only high-level SW and make final product in HW

Problems for players:
- Totally dependent on chip vendors: in terms of performance (nearly all UWB systems show about the same performance) and in terms of roadmaps => delays

Very low entry-barriers in BLE positioning:
- Dozens of BLE beacon HW providers – no need to have HW competence. Nearly ready to use BLE SW stack

Thus, hundreds of players chasing large consumer market: navigating people with phones <=> not exactly tuned for industrial applications

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Marvelmind Indoor “GPS”

- **Off-the-shelf ready-to-use indoor navigation system** based on stationary **ultrasonic beacons** united by radio interface in license-free ISM band
- Location of a mobile beacon installed on a robot (vehicle, copter, human) is calculated based on the propagation delay of ultrasonic signal to a set of stationary ultrasonic beacons using **trilateration**

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Indoor “GPS” (±2cm)

- Starter Set configuration:
  - 1 mobile beacon – 99 USD
  - 4 stationary beacons – 4*99 USD
  - 1 router – 99 USD
  - All required SW included

Ready to use 3D (x, y, z) system for 499 USD

Covers up to 1000m²

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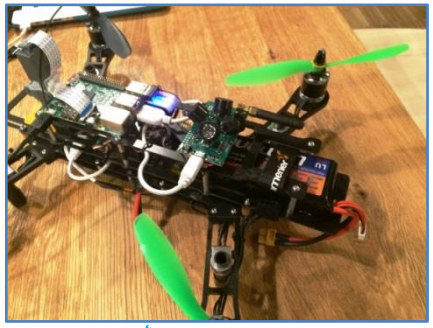
Selected customers

Customers in 50+ countries

Autonomous robots, drones, VR

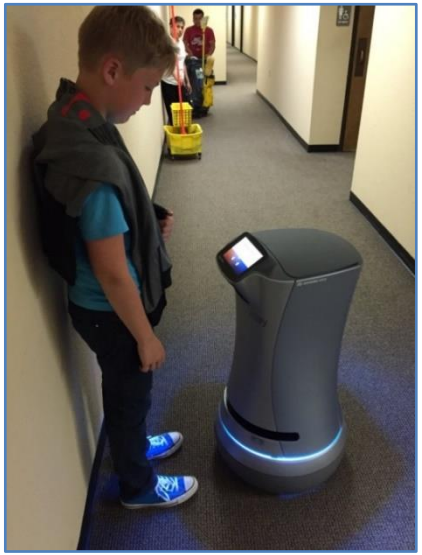
Virtual reality for BIM, quests, training and gaming

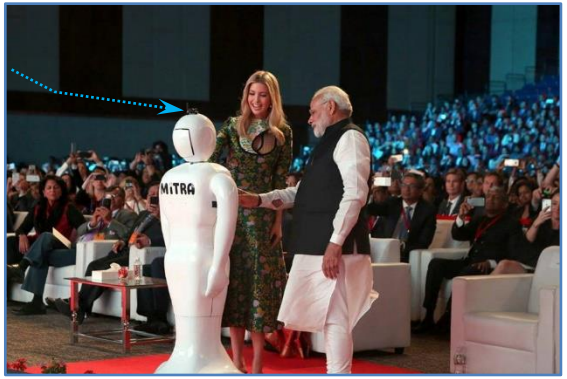


Autonomous drones indoor for inventory management, video/photo, security

Marvelmind beacon

Automatic delivery inside large buildings





PM of India Modi and Ivanka Trump

Advertising robots with high-tech charm - shows, shopping malls, conferences, museums

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Use cases: mobile assets tracking

Use case:

- Tracking vehicles, buggies, trolleys, forklifts and other mobile assets in tunnels, passenger and cargo areas of airports and warehouses

Problems solved:

- Speeding
- Accidents
- Broken equipment and goods
- Lost or underutilized mobile assets

Benefits:

- Precise knowledge of who is doing what and where => productivity increase
- Real-time data about speed, acceleration, position of the mobile assets => productivity increase
- Preventing accidents and decreasing insurance and other avoidable costs

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Use cases: safety & productivity

Tracking workers' location underground, in metro or tunnels, on construction sites or railways stations or under bridges

Use case:

- Underground / mining / metro
- Construction sites
- Large manufacturing factories
- Dangerous manufacturing
- Oil refineries and gas companies

- Increasing productivity
- Improving safety

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Non-Inverse Architecture (NIA)

Mini-RX Beacon 1

Stationary beacons:
- Mounted on walls or ceilings
- Users have to measure distances between stationary Mini-RX beacons manually
- Communicate with router wirelessly in ISM/SRD bands

Mini-RX Beacon 2

Key requirement for the system to work: **unobstructed sight** by a mobile beacon of 2 or more stationary beacons simultaneously (like in GPS)

Mobile beacon:
- Installed on robot and interacts with it via UART or SPI or I2C or USB
- Receives location update from router up to 25 times per second
- May contain IMU (accelerometer + gyroscope + compass module)

Submaps:
- Advanced feature that allows building independent maps/clusters of beacons in separate rooms and thus covering large buildings (with area of thousands of m2) similar to cellular network coverage

Indoor Navigation System consists of:
- 2 or more stationary beacons
- 1 or more mobile beacons
- 1 central router

Mini-RX Beacon N

Distance between beacons-neighbors is up to **25 meters**.

Mini-RX Beacon 3

Router/modem:
- Central controller of the system
- Calculates position of mobile beacon up to **25 Hz**
- Communicates via USB/virtual UART with Dashboard or robot

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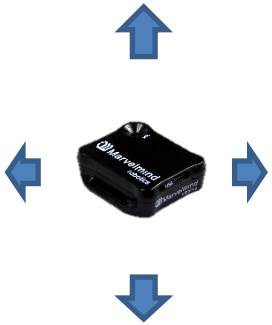
Inverse Architecture (IA)

Beacon 1 (19kHz)

Stationary beacons:
- Mounted on walls or ceilings
- In inverse system beacons belonging to the same submap should have different ultrasound frequencies (19 & 25kHz or 25 & 31 kHz, for example)
- Communicate with router wirelessly in ISM/SRD band (433/868/915MHz)

Beacon 2 (25kHz)

Key requirement for the system to work: **unobstructed line of hearing/sight** by a mobile beacon to 2 or more stationary beacons simultaneously (like in GPS)



Mobile Mini-RX beacon(s):
- Installed on robot (human) and interacts with it via virtual UART over USB
- Contains 3D IMU (accelerometer+gyroscope)
- Beacon's update rate doesn't directly depend on the number of mobile beacons unlike in NIA
- Calculates its location by itself – not by modem
- Recommended distance from mobile beacon to stationary ones up to 25m

Submaps:
- Advanced feature that allows building independent maps/clusters of beacons in separate rooms and thus covering large buildings (with area of thousands of m2) similar to cellular network coverage
- In Inverse Architecture every submap must have beacons with non-repeating ultrasound frequency
- Available frequencies: 19, 25, 31, 37, 45 kHz

Indoor Navigation System consists of:
- 2 or more stationary beacons
- 1 or more mobile Mini-RX beacons
- 1 central router

Beacon N (19, 25, 31, 37, 45 kHz)

Distance between beacons-neighbors is up to **25 meters**.

Beacon 3 (31kHz)

Router/modem:
- Central controller of the system
- Communicates via USB/virtual UART with Dashboard or robot
- Get location data from Mobile Mini-RX beacons
- Supports up to 250 beacons

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Huge AGV, transport and people

Mobile Geofencing zone on AGV

Ind Super-Beacon

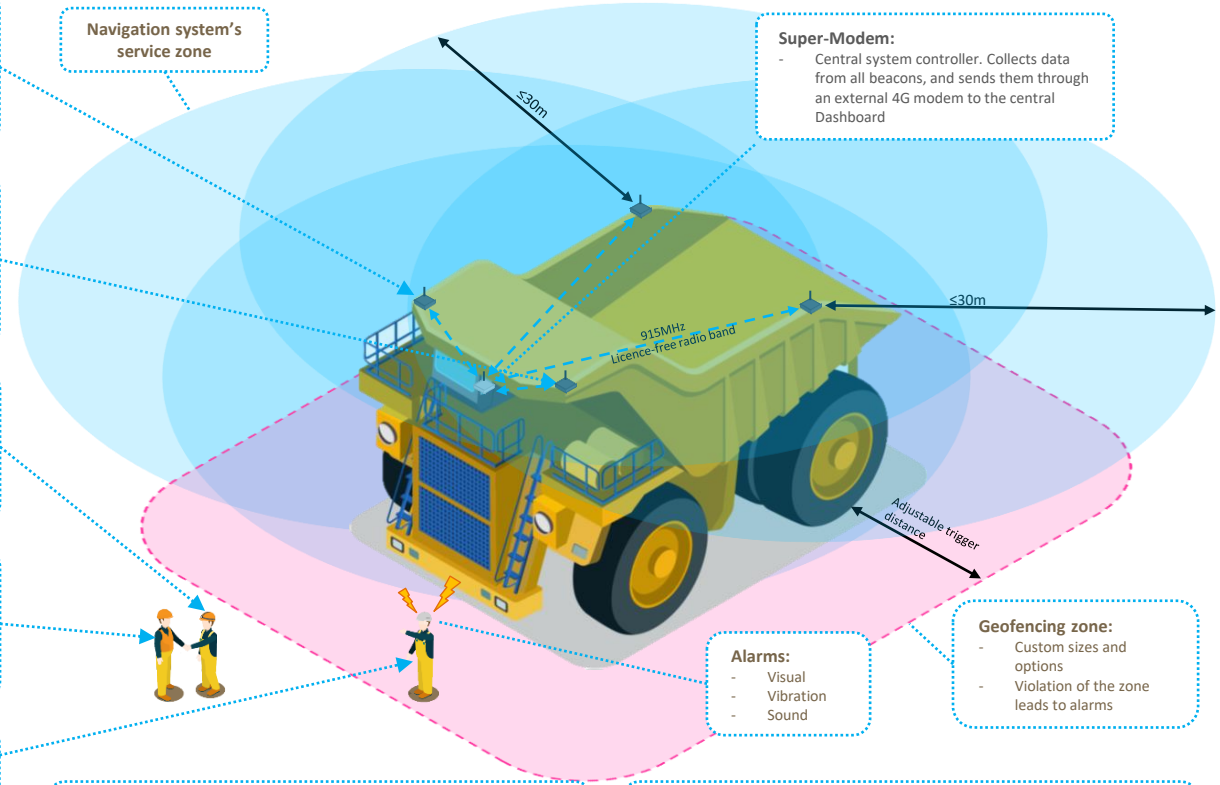
Super-Modem

Marvelmind Headlight

Marvelmind Jacket

Marvelmind Helmet

Navigation system's service zone



Super-Modem:
- Central system controller. Collects data from all beacons, and sends them through an external 4G modem to the central Dashboard

Alarms:
- Visual
- Vibration
- Sound

Geofencing zone:
- Custom sizes and options
- Violation of the zone leads to alarms

Task:
- Prevent dangerous proximity of AGV and humans
- Prevent AGV-Human Collision

Solution:
- Marvelmind Indoor GPS system installed directly on the AGV, with a mobile geofencing zone

Configuration:
- 4 x Industrial Super-Beacon-Plastic (Placed on AGV)
- N x Marvelmind Headlight (1 per worker, placed on the helmet)
- 1 x Super-Modem (Placed on AGV)

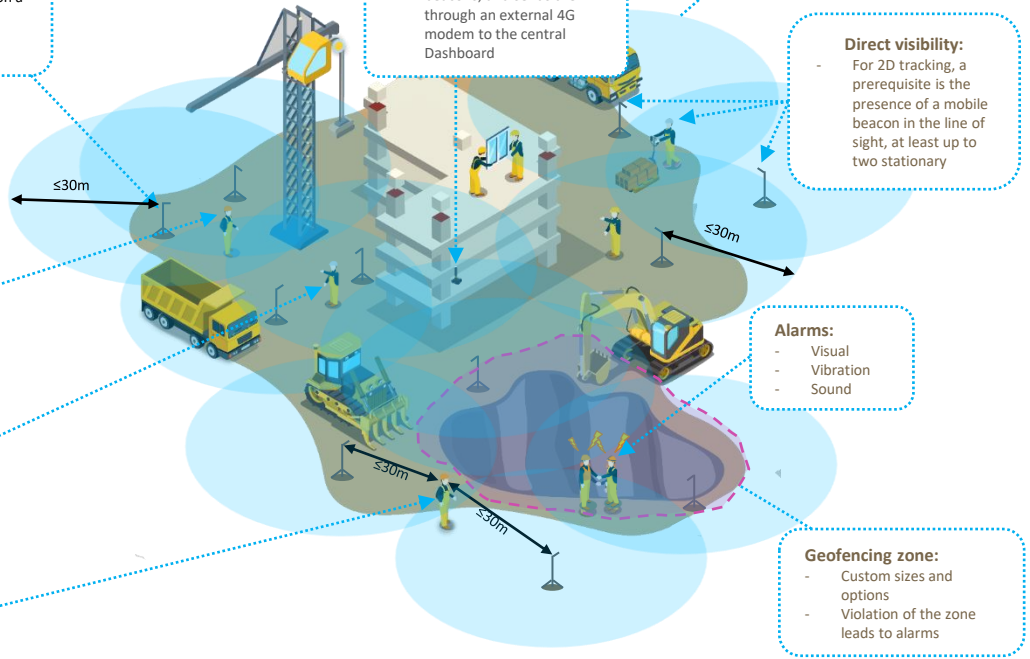
Principle of operation:
- The Marvelmind Indoor GPS system, where the AGV is a mobile map, the entrance to the Geofencing zone of which will warn the person and operator about a dangerous proximity, and also, at a critically dangerous proximity, stop the AGV

Result:
- High precision tracking Marvelmind Indoor GPS
- Alarm for workers and equipment drivers
- Recording violations in a CSV file for further analysis
- AGV auto stop (optional)

Marvelmind robotics

Safety at the construction site, people

Static Geofencing zones at a construction site



Super-Beacon-Outdoor, mounted on a tripod

or

Industrial Super-Beacon, mounted on a tripod

Battery-12V-5Ah-Outdoor

Super-Modem

Marvelmind Headlight

Marvelmind Jacket

Marvelmind Helmet

Super-Modem:
- Central system controller. Collects data from all beacons, and sends them through an external 4G modem to the central Dashboard

Navigation system's service zone

Direct visibility:
- For 2D tracking, a prerequisite is the presence of a mobile beacon in the line of sight, at least up to two stationary

Alarms:
- Visual
- Vibration
- Sound

Geofencing zone:
- Custom sizes and options
- Violation of the zone leads to alarms

Task:
- To warn the employee's dangerous approach to the danger zone, to obtain data on the movement of people

Solution:
- Marvelmind Indoor GPS system installed on site with customizable geofencing zones

Configuration:
- N x Industrial Super-Beacon-Plastic (mounted on a tripods)
- N x Marvelmind Headlight (1 per worker, placed on the helmet)
- 1 x Super-Modem (placed in the center)

Principle of operation:
- The Marvelmind Indoor GPS system in this configuration provides tracking of people with customizable geofencing zones and warns a person of approaching danger

Result:
- High precision tracking Marvelmind Indoor GPS
- Alarm for workers and shift supervisor
- CSV file with recording of all movements during the shift
- Automatic recording of all violations in a file for further analysis (optional)

Marvelmind robotics

Safety when working cranes and people

Mobile geofencing zone on crane boom

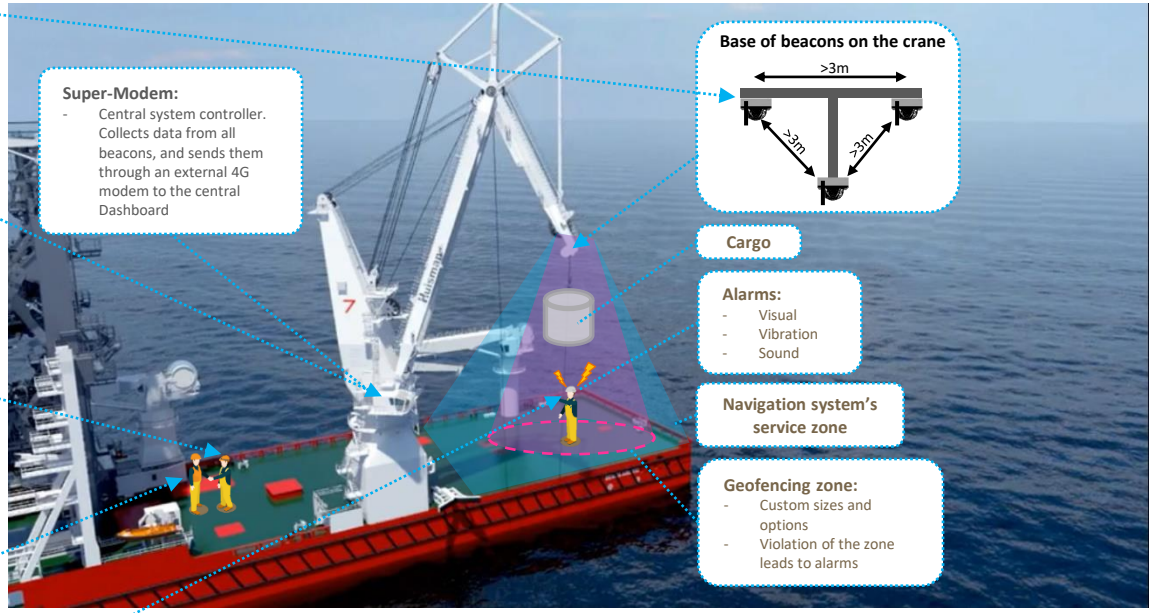
Ind Super-Beacon

Super-Modem

Marvelmind Headlight

Marvelmind Jacket

Marvelmind Helmet



Configuration:

- 3 x Industrial Super-Beacon-Plastic (placed on the crane)
- N x Marvelmind Headlight (1 per worker, placed on the helmet)
- 1 x Super-Modem (placed on the crane)

Principle of operation:

- In this configuration, the end of the crane boom is a card, the entrance to the Geofencing zone of which will warn the person and operator about a dangerous proximity

Result:

- High precision tracking Marvelmind Indoor GPS
- Alarm for workers and shift supervisor
- CSV file with recording of all movements during the shift
- Automatic recording of all violations in a file for further analysis (optional)

Task:

- Prevent dangerous approach and collision of cargo with a person

Solution:

- Marvelmind Indoor GPS system installed directly on the crane with a mobile geofencing zone, which moves after the crane's boom

Marvelmind robotics

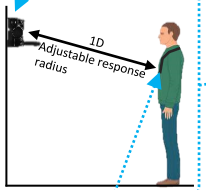
Tracking service staff

On the example of one floor of a shopping center

Super-Beacon

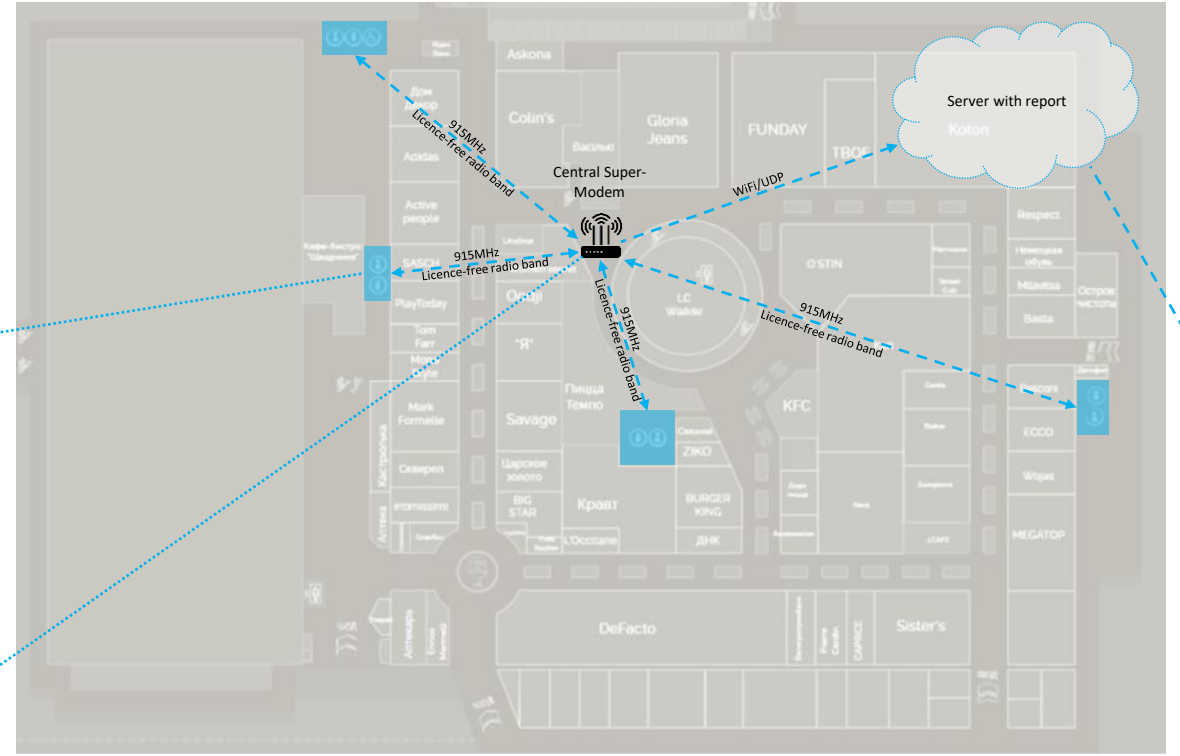
Restroom

Side view



Badge

Super-Modem



Configuration:

- N x Super-Beacon (1 per restroom)
- N x Badge (1 per worker)
- N+1 x Super-Modem (1 per floor + 1 central)

Result:

- Automatic report on movements in the areas of responsibility of service employees (CSV file)
- Auto-fill table (optional)

Reporting Table (Marvelmind)

- The report is generated by the Central Super-Modem, and sent via Wi-Fi to your IP address on request or in a pre-set time (for example, nightly)

Time	Worker 1 (>80%)	Worker 2 (>50%)	Worker 3 (<50%)
8:00-8:15			
9:00-9:15			
11:00-11:15			
20:00-20:15			
21:00-21:15			
22:00-22:15			
23:00-23:15			

Task:

- Tracking service staff
- Performance monitoring

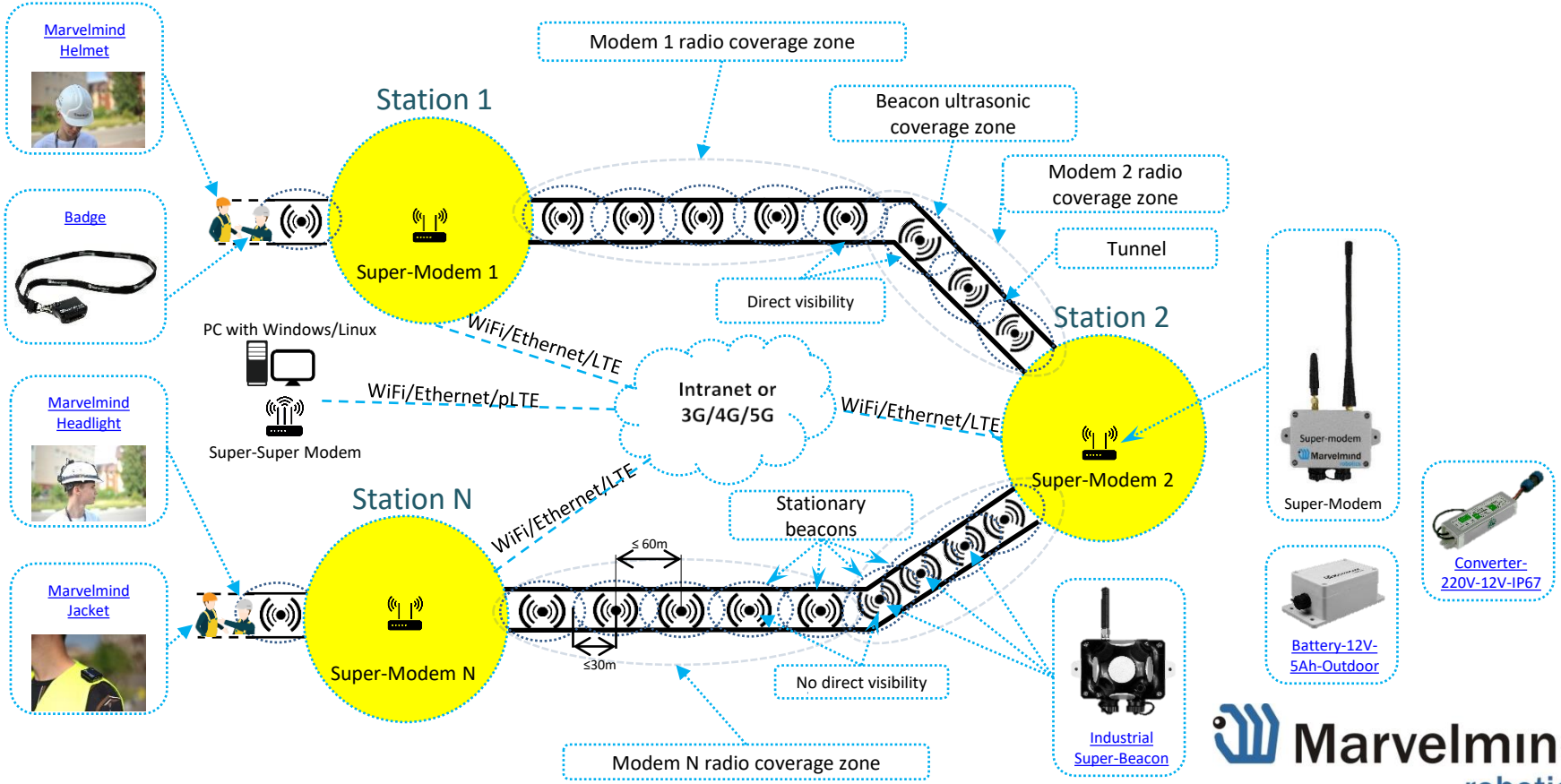
Solution:

- Marvelmind Indoor GPS system for monitoring and analyzing the work of service personnel in 1D configuration

Marvelmind robotics

Tunnel safety and performance

Multi-modem system for underground tracking



Marvelmind robotics

Beacons comparison






	Beacon Mini-RX/Beacon Mini-RX-Outdoor	Beacon Mini-TX	Beacon Mini-TX batteryless	Super-Beacon/Super-Beacon-Outdoor	Industrial-Super/Industrial-Super-EX	Industrial-RX/Industrial-RX-EX
Specialty and main use	Universal, multi-frequency and high-sensitivity RX-only beacon	Small TX only beacon	The lightest TX only beacon	Universal dual-use beacon. Support of 433- or 915/868MHz bands	Heavy-duty outdoor/Explosion dangerous environment; RS485 or CAN	Heavy-duty outdoor/Explosion dangerous environment; RS485 or CAN
Mode of operation	RX only	TX only		Dual-use (RX and TX)	Dual-use (RX and TX)	RX only
Range	- Up to 30m with Super-Beacons	- Up to 30m with Super-Beacon		- Up to 30m with Super-Beacons - Up to 30m with Beacon v4.9[3]	- Up to 30m with Industrial-RX	- Up to 30m with Ind. Super-Beacon
Ultrasonic frequencies	- 19/25/31/37/45kHz - Several at the same time	- 31/45kHz - Only one HW defined frequency at the time		- 19/25/31/45kHz - Only one frequency at the time	- 19/25/31/45kHz	- 19/25/31/45kHz - Several at the same time
Radio band	915/868MHz	915/868MHz		915/868MHz or 433MHz	915/868MHz or 433MHz	915/868MHz or 433MHz
Power/LiPol battery	USB/750mAh	USB/250mAh	USB/No embedded battery	USB/1000mAh	+6..16V or IP67 converter/Ext.battery	+6..16V or IP67 converter/Ext.battery
Environmental conditions	- Indoor/Outdoor up to IP67 - t=0..40C[6]	- Indoor/Outdoor[2] - t=0..40C[6]	- Indoor - t=0..40C[6]	- Indoor/Outdoor[2] - t=0..40C[6]	- Outdoor[2]/Intrinsically Safe[5] - t=-20..40C[6]	- Outdoor[2]/Intrinsically Safe[5] - t=-20..40C[6]
Size and weight	47x42x15mm & 25g	35x35x26mm & 19g	35x35x20mm & 12g[9]	55x55x33(64[7])mm & 62/75g	83x58x65mm[8] & 250g	83x58x33mm[8] & 200g
IMU (3D gyro+acc+mag)	Yes (6D)	Yes (6D)	Yes (6D)	Yes (6D)	Yes (6D)	Yes (6D)
Price	99/129 USD	89 USD	89 USD	99/129 USD	149/189 USD	149/189 USD

1) Withstand submersion to water on 1m up to 30m (IPx7 requirements)
2) IP56. Performance during this time is no guaranteed
3) 1D mode: RX4 to RX4 sensors; other sensors are disabled
4) Other power options available upon request
5) Exact type of certification shall be discussed separately
6) Temperature range down to -40C is available with external power supply only and upon request
7) With antenna
8) Sizes without mounting holes
9) 6.3g without housing

Marvelmind robotics

Summary

1. No method suits all needs → choose yours
2. Systems specifically designed for positioning (Marvelmind's Indoor "GPS", UWB), expectedly, perform significantly better than regular data transmission systems (BLE, WiFi, LoRa)
3. Sensor fusion systems shows the best results

Marvelmind robotics

Thank you!

Marvelmind Robotics

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