

Marvelmind Indoor Navigation System

Operating Manual

V2016_05_21

www.marvelmind.com



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Version changes:

V2016_05_21:

- Detailed description of HW v4.5 added (5-sensor beacon)
- New Dashboard with multiple sub-maps introduced
- Some less relevant older HW versions descriptions are removed
- General updates and description improvements

1) Executive summary

Marvelmind Indoor Navigation System is off-the-shelf indoor navigation system designed for providing location data to autonomous robots, vehicles (AGV) and copters. It can also be used for tracking other objects, where the mobile beacon can be installed, for example, virtual reality (VR) systems.

The navigation system is based on stationary ultrasonic beacons united by radio interface in license-free band. Location of a mobile beacon installed on a robot (vehicle, copter, human, VR) is calculated based on the propagation delay of ultrasonic signal (Time-Of-Flight or TOF) to a set of stationary ultrasonic beacons using trilateration. Stationary beacons form the map automatically. No manual entering of coordinates or measuring distance is needed.

Key requirement for the system to function properly is:

- An unobstructed sight by a mobile beacon of three or more stationary beacons simultaneously - for the full set
http://www.marvelmind.com/pics/marvelmind_indoor_GPS.png - and 3D (x, y, z) coordinates
- An unobstructed sight by a mobile beacon of two stationary beacons simultaneously - for the Starter Set
Mini
http://www.marvelmind.com/pics/marvelmind_indoor_GPS_mini.png – and 2D (x, y and manually fixed z) coordinates



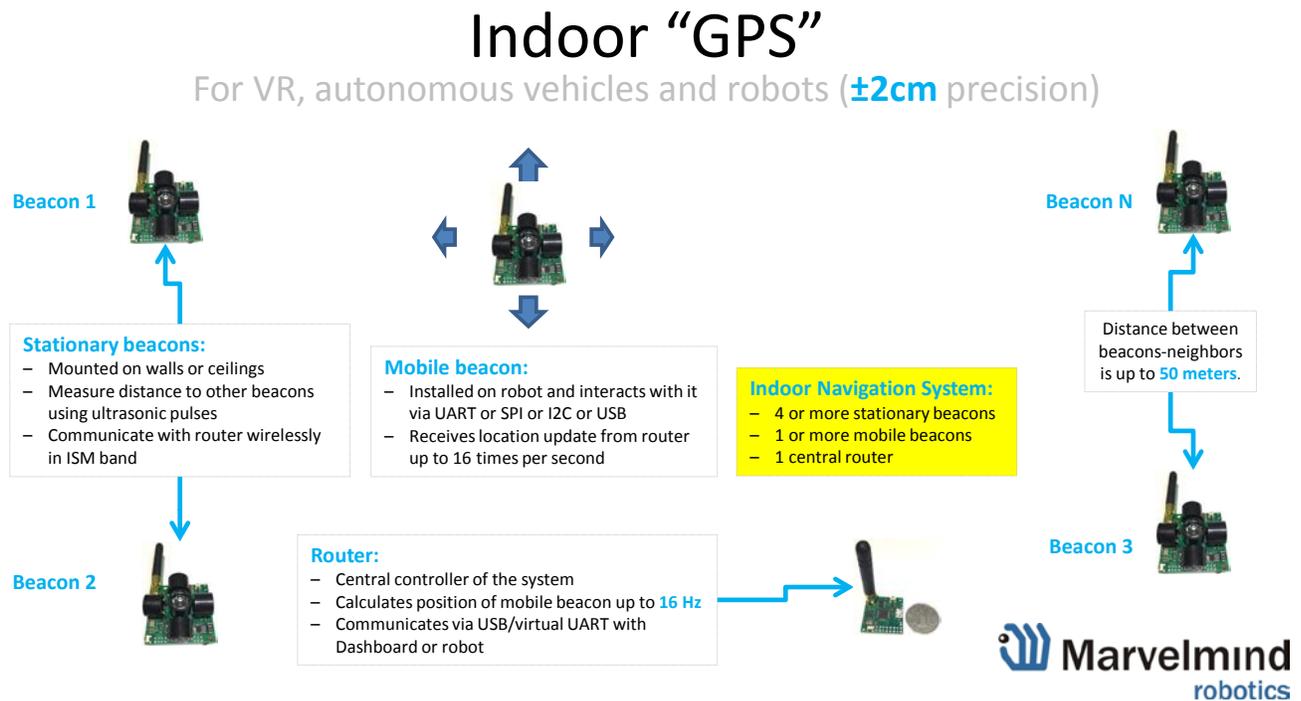
Main capabilities:

- Distance between neighboring beacons: up to 50 meters
- Coverage area:
 - o Up to 1000 m² for Starter Set
 - o Coverage for larger areas is done similar to cellular networks; can be much larger, than 1000 m² and depends on the radio interface that can be further extended
- Location precision:
 - o 1-3% of the distance to the beacons
 - o Differential precision: **±2 cm**
- Location update rate:
 - o 0.5-24Hz (can be manually selected and depend on the distance and number of beacons)
- Beacons form the navigation system automatically – no manual coordinates measurements or entering required

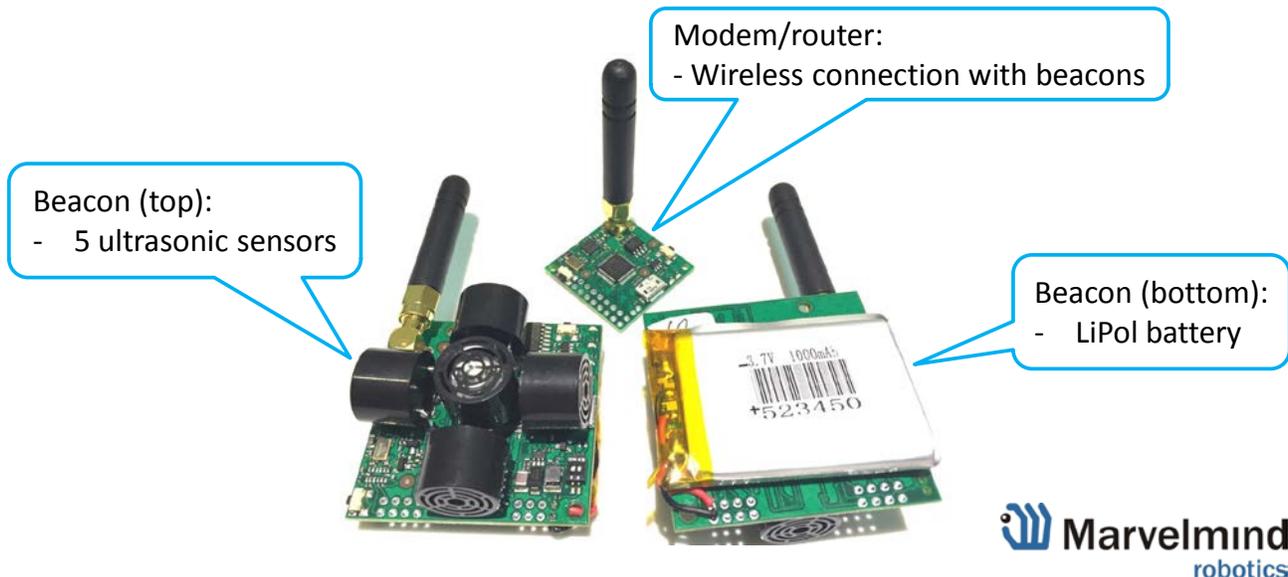
2) Basics of the system

Marvelmind Indoor Navigation System provides high-precision indoor coordinates for autonomous robots and systems (“indoor GPS”).

Short description of key elements of the system is given on scheme below:



Beacon and modem



Stationary beacons

- Shall be mounted on walls and ceilings – above the robot – to provide the easiest unobstructed coverage of ultrasonic signal. However, for automatic landing and indoor navigation of copters, for example, it is recommended to place beacons on the floor/ground and install the mobile beacon horizontally downwards looking on the belly of the copter
- Position for the beacons and angles of positioning shall be chosen in such a way that maximum coverage in ultrasonic is provided for the maximum territory. Proper ultrasonic coverage is the utmost important element for the system to function most effectively
- Stationary beacons emit and receive ultrasound, when the map is being formed. And they only receive the ultrasound, when the map is formed and frozen
- In the current HW implementation v4.5 the mobile and stationary beacons can be easily interchanged by selecting the [option](#) in the Dashboard
- Main version uses 433-MHz ISM band and proprietary protocol for communication and synchronization; other ISM bands are available upon request too



Mobile beacon (“hedgehog”)

- In the HW v4.5 implementation of the mobile and stationary beacons can be easily interchanged by selecting the [option](#) in the Dashboard
- The mobile beacons are designed to be placed on the robot vehicle or helmet to trace its location. Formally speaking, location of the mobile beacon is traced – not the robot itself. Since the sizes and the location of the central point of the mobile beacon and the robot are different, the difference has been taken into account in the robot’s SW
- The mobile beacon has to be placed horizontally to provide optimal ultrasonic coverage
- Its sensors must not be closed with anything that can reduce the strength of ultrasonic signal
- The beacon’s coordinates are updated according to the rate set in the Dashboard
- System may contain one or more mobile beacons. Current implementation relies on time division multiple access approach. Thus, if two mobile beacons are activated, they share the time. It means that, if 16 Hz update rate is selected and there are 2 mobile beacons in the system, each beacon’s location will be updated with the rate of $16\text{Hz}/2 \sim 8\text{Hz}$. If there are 3 mobile beacons $\Rightarrow 16\text{Hz}/3 \sim 5\text{Hz}$, etc. Future SW implementation will contain different solution that will improve update rate in the setup with multiple mobile beacons
- Location data is obtained either from the “hedgehog” via USB (virtual UART), UART, SPI or the modem/router via USB (virtual UART). More on interfaces:
 - <http://www.marvelmind.com/#Interfaces>
- Data from the beacon is sent in a streaming format resembling that of GPS
- Main version uses 433-MHz ISM band and proprietary protocol for communication and synchronization; other ISM bands are available too
- The “hedgehog” has been successfully integrated with Windows PC, Linux machines, Raspberry Pi, Arduino boards, Intel boards



Modem/router

- The central controller of the system. It must be powered all the time, when the Navigation System works. It is recommended to use active USB hub for that purpose
- It is used to setup the system, monitor it, interact with the Dashboard
- It can be placed anywhere within radio coverage to have permanent radio connection with all beacons – usually in the radius of 100 meters (with $\lambda/4$ antenna – 165mm) from the beacons in the office environment. With trading off the update rate, the radio coverage can be further extended to a few hundred meters by using lower speed of inter-system radio communication and larger antennas
- Main version uses 433-MHz ISM band and proprietary protocol for communication and synchronization; other ISM bands are available upon request too



What in the box

Starter Set:

- 4xStationary beacons
- 1xMobile beacon (“hedgehog”)
- 1xModem/Router

* Exact appearance may vary depending on the HW version. Characteristics are kept the same or better unless specially noted



3) Technical Specifications

Table: Technical Specifications

Parameter	Technical Specifications
Distance between beacons	Up to 50 meters (Transducer4 to Transducer4 looking straight to each other and other transducers are off)
Coverage area	Up to 1000 m ² for Starter Set configuration Coverage for larger territories done similar to cellular networks
Location precision	- Absolute: 1-3% of the distance to the beacons - Differential precision: ±2 cm
Power supply	Internal: LiPol battery 1000mAh External: microUSB
Weight	Mobile beacon from Starter set: - 47 grams (including battery 1000mAh) - 25 grams (without battery)
Beacon size	Size: 50x50x25 mm

Table: Power Consumption

- Recommended mode of operations:
 - Stationary beacons are powered from a clean source of +5V USB
 - Mobile beacon is power from the a clean source of +5V USB from a robot
- For fully autonomous and easy use and testing, each beacon has its own power LiPol battery
- Typical power consumption in deep sleep mode is 50uA that gives ~2y shelf time with a regular 1000mAh battery. Beacon can be woken up from deep sleep only by pressing HW reset button
- In regular sleep mode the beacons wake up automatically every 2 seconds for ~20ms to monitor external calls from modem/router. That brings some additional consumption, but still leaves several months in sleep mode
- Active mode work time directly depends on the location update rate. For example:
 - With the standard 1000mAh battery and 16Hz update rate, the expected work time will be 97h => **8 days** (assuming 12h working day)
 - With the extended 4300mAh battery and 1Hz location update rate the expected work time will be ~5800h or **484 days** (assuming 12h working day)

Calculated beacon's work time in active mode vs. location update rate

Current cons., mA	Time, ms	Charge, mAh	h	Location update rate, Hz			
				1	4	8	16
23.0	15.0	0.000096	10434783	2899	725	362	181
0.05	12.0	0.000000	6E+09	1666667	416667	208333	104167
42.0	7.0	0.000082	12244898	3401	850	425	213
0.10		0.000000	10000	10000	10000	10000	10000

		Location update rate, Hz				
		1	4	8	16	
Standard battery	1000	Expected working time				
		Hours	1352	376	192	97
		Days	56.3	15.7	8.0	4.0
		1/2-days	112.7	31.3	16.0	8.1
Extended battery	4300	Hours	5814	1618	824	416
		Days	242.2	67.4	34.3	17.3
		1/2-days	484.5	134.8	68.7	34.7

4) Models comparison

Parameter	Starter Set mini	Starter Set	Boxed Set	Boxed+Holder Set
Optimized for	Lowest price	Price	Overall	Overall + performance
Other important characteristics	2D coordinates only	Unprotected board – use with care 3D coordinates	Protecting case against mechanical impact. Limited outdoor protection 3D coordinates	Protecting case against mechanical impact. Limited outdoor protection 3D coordinates
Size	Smallest configuration: 2xBeacons + 1xModem	Small size and weight	Size and weight is about the same as for Starter Set	Larger size due holder of stationary beacons. Mobile beacons and modem are the same as for Boxed Set
Battery	Standard 1000mAh	Standard 1000mAh	Standard 1000mAh	Standard 1000mAh

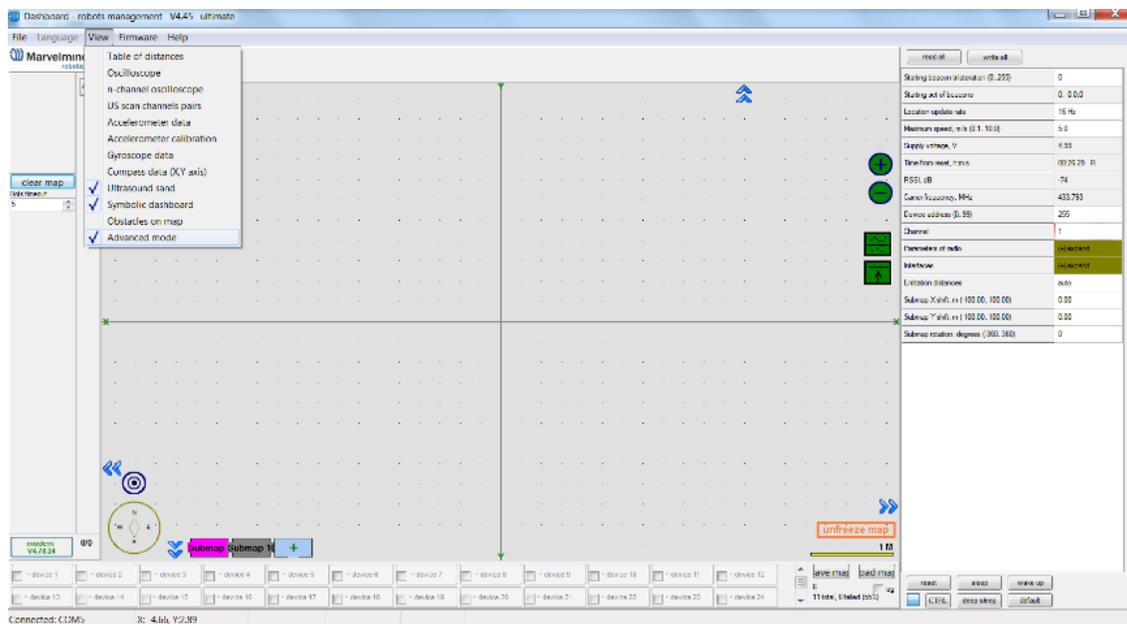
Indoor “GPS”: set comparison

	Starter Set	Starter Set Mini
Minimum number of stationary beacons	4	2
2D/3D location data	3D	2D
Precision	±2cm	±2cm
Possibility to expand from Starter Set Mini to Starter Set by adding more beacons	-	Yes
Robustness to ultrasonic shadows	High	Low
Price	349 USD	235 USD

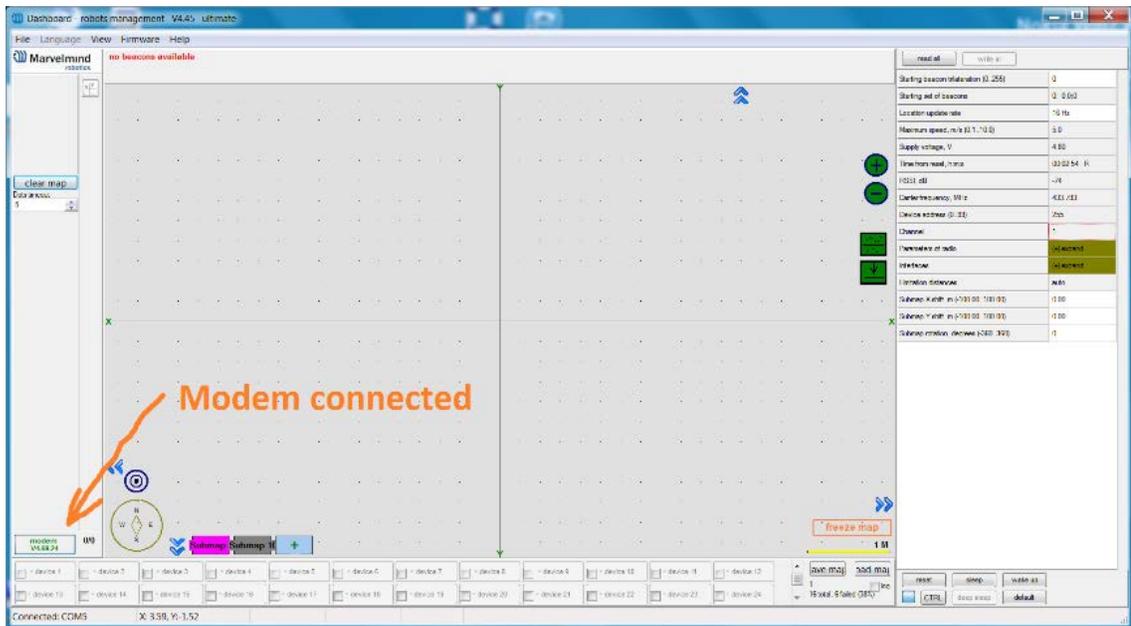
5) Setting up the system

Basic setup routine

1. Unpack the system. See the video: <https://youtu.be/7PsbmP3VP3Y>- note, that the video is shot for the beacon's HW v4.3 (4-sensors), so some details are different as compared with newer beacon's HW v4.5 (5-sensors)
2. Check that all switches on beacons are in the right position (different for HW v4.3 and for HW v4.5!):
 - Beacon HW v4.5 (5-sensors): **switch 1 must be OFF and switch 2 must be ON**. When the board is charged and switch is on, the LED on the board is blinking every a few seconds
 - Beacon HW v4.3 (4-sensors): http://www.marvelmind.com/pics/power_switch.jpg
3. Download and install Dashboard and STM32 driver on your laptop:
<http://www.marvelmind.com/#Download>.
 - If there are newer SW versions, run the Dashboard and update the SW using Run the **Dashboard => Advanced view => Firmware => Choose the file => Program**



- Make sure that you are programming modem's SW to modem and beacon's SW to beacon
4. Place stationary beacons on the walls vertically in such a way that optimal ultrasonic coverage is provided. To start with the system it is recommended to use a simple room of 4x6 meters or so and place the stationary beacons on the opposite walls on 1.85m height (default). After familiarizing with the system far more complex configurations can be done
 5. Connect the modem/router via USB to the Windows PC with the Dashboard installed
 6. Run the Dashboard
 7. Modem shall appear connected:



- Wake up all beacons by clicking on the buttons in the Dashboard. It may take beacons up to 8 seconds to wake up



- The map will form automatically
 - If map does not form well (the table of distances is not white and beacons are not green), use **View => Table of distances** to monitor the measured distances between beacons (See advanced system setting in the following chapters)
 - The new Dashboard (starting from v4.41) introduces submaps:



- Submaps allow building independent maps, for example, for separate rooms of the larger building, and then placing them on a combined maps. This allows creation of big maps consisting on partially overlapping or even not overlapping submaps
- Handling submaps is an advanced feature and will be described additionally in separate chapters

10. Freeze the map by clicking the button. Stationary beacons will stop measuring relative distances and will be ready to measure distance from the mobile beacon(s)



11. Turn on and wake up mobile beacon similar to the operations with the stationary beacon.

12. The system now is fully operational

Advanced system settings and optimization:

1. Use Dashboard => View => Table of distances to monitor the distances between beacons

The screenshot displays the Marvelmind robots management software interface. The main window is titled "Dashboard - robots management V3.58 ultimate". The "View" menu is open, showing the "Table of distances" option selected. The interface is divided into several sections:

- Left Panel:** Contains a "clear map" button and a "Data timeout" dropdown set to "5".
- Top Left:** A menu with options: "Table of distances", "Oscilloscope", "8-channel oscilloscope", "US scan channels pairs", "Rate of map update", "Ultrasound sand", "Show window of device deviations", "Radio debugging", "Symbolic dashboard", and "Advanced mode".
- Main Area:** A large grid representing the robot's field of view. A red dot indicates the robot's position. A "freeze map" button is visible. A small compass rose is in the bottom left of the grid.
- Bottom Panel:** A grid of checkboxes for 40 devices, labeled "device 1" through "device 40".
- Right Panel:** A settings panel with various parameters and their values, including:
 - Starting beacon trilateration (0.255): 0
 - Starting set of beacons: 0; 0;00
 - Max. deviation for case, cm (0..20000): 40
 - Max. conditional deviation, cm (0..20000): 100
 - Max. triangle deviation, cm (0..20000): 30
 - Interval of transmitting US by device, s (1..): 1
 - Frequency scan hedgehog/robot: 16 Hz
 - Maximum speed, m/s (0.1..10.0): 5.0
 - 3D navigation: enabled
 - Multiple threes: enabled
 - Power save functions: disabled
 - Hedgehog mode: disabled
 - Speed, % (0..100): 30
 - Motors stop, msec (0..200): 0
 - Time between motors stop, x16 msec (0..20): 64
 - Supply voltage, V: 3.90
 - Peak current, A: 0.000
 - Peak current of motors, A: 0.000
 - Height, m (-1.00..10.00): 0.00
 - Protection by motors current: (+) expand
 - Supply voltage motors, V: 0.00
 - Utilized energy, A*h: 0.0
 - Time to discharge, h: 0.0
 - Time from reset, h:ms: 00:00:00 R
 - Time of wakeup in sleep, s: 0.000
 - RSSI, dB: -74
 - Algorithm of positioning: (+) expand
 - Radio profile: 153 Kbps
 - Parameters of radio: (+) expand
 - Infrared sensors: (+) expand
 - Ultrasound: (+) expand
 - Sound: (+) expand

If you see in the table some empty cells or marked yellow or red, it is an indication that distances between some beacons are measured inconsistently or not measured at all. Try to check what the problems with those beacons are. Try to re-position them, because, usually, there is an obstruction of some sort in the between the beacons.

2. Use Dashboard => View => Oscilloscope to monitor ultrasonic signal from one beacon to another. It is a very powerful tool, because it gives also information on the background noise, level of the signal, echo. With this tool it is easy to set up the proper ultrasonic threshold in the Dashboard

The screenshot shows the Marvelmind Dashboard interface. The main window displays a map with a red dot and a 'freeze map' button. The 'Oscilloscope' window is open, showing a graph of 'Signal from beacon' with a y-axis ranging from -2000 to 2000 and an x-axis from 0 to 20. A sharp peak is labeled 'Ultrasonic signal front'. A noisy baseline is labeled 'Echo from the previous measurements; External noise looks similarly. Thus, choose the ultrasonic threshold below this value, for example, -500 to -2000'. A yellow callout box points to the top of the graph with the text 'Type the reference beacon number. And press Enter'. Another yellow callout box points to a device in the bottom list with the text 'Choose the beacon to test'. A fifth yellow callout box points to a parameter in the settings panel with the text 'Choose proper ultrasonic detection threshold'. The settings panel shows 'Detection threshold, DAC units (-2100..2100)' set to -500.

3. Choosing proper ultrasonic detection threshold

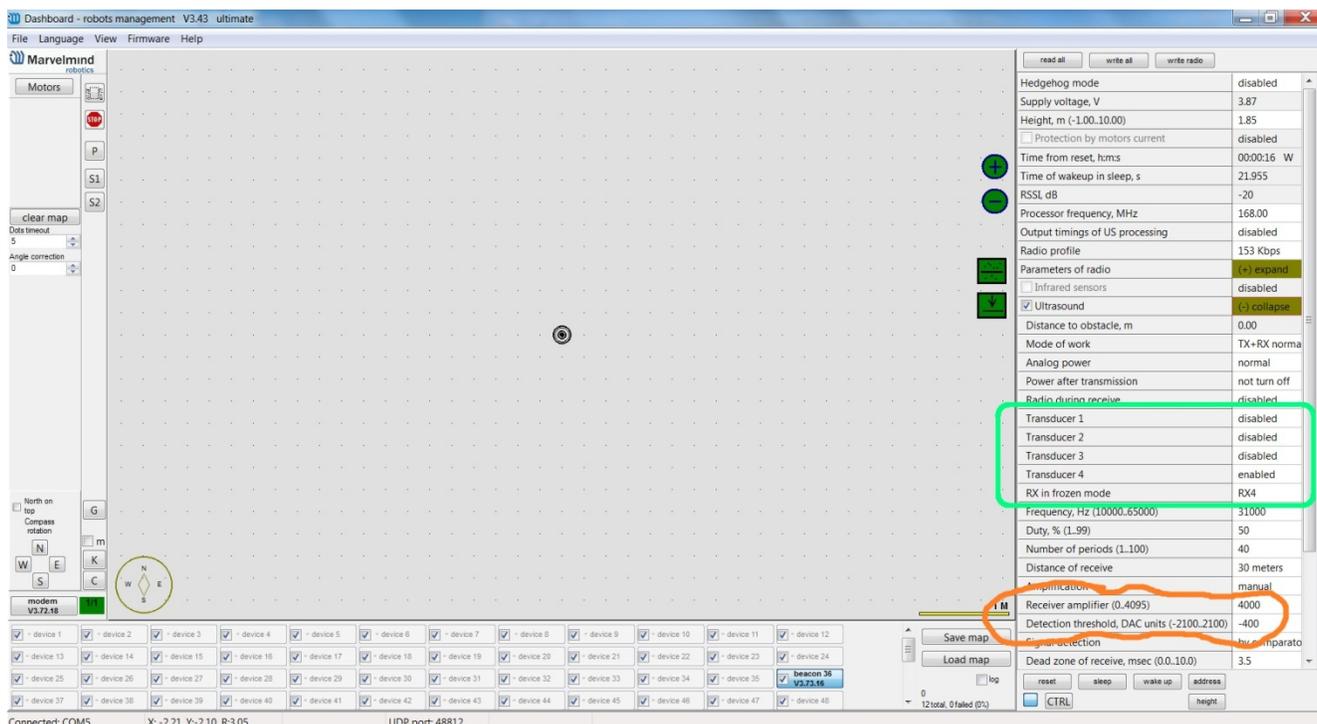
This is important!

Choose the ultrasonic threshold below the external noise, but higher than the minimal expected ultrasonic signal from other beacons or the hedgehog. For the example above: -500 to -2000 would be safe choice. However, as mentioned, the shown noise is not a real external noise, but echo from the previous measurements that will settle to the time of the measurement in the real system, as opposite to the oscilloscope setup. In this configuration the external noise is not visible at all – too low.

When external noise is high:

- Identify the source. Usual suspects:
 - o Ultrasonic based volume or movement detecting alarm systems
 - o Other robots using ultrasonic
 - o Parktronic
 - o Sources of very strong white or impulse noise (air guns, air press, cutters, vacuum cleaner, etc.)
- Marvelmind Indoor Navigation System uses proprietary 31kHz frequency for ultrasonic signal and employs additional filtering to combat external noise. And it makes the system rather immune against “usual suspects”. However, if the external noise is too strong, its source is too close, or it is emitting strong signal on frequencies close to 31kHz or white noise, the system functionality can be affected

- When map is formed, only mobile beacon is emitting, whereas stationary beacons are not. Thus, it does not matter how close the mobile beacon is to the source of noise. But it matters how the stationary beacons are close to those sources. So, select the position accordingly
- If noise is still there, one can choose to reduce the gain of the ultrasonic receiver while keeping the level of own ultrasonic signal strong above the noise above the threshold. Also right selection of the threshold is the key in such a noisy environment. The gain is very non-linear.



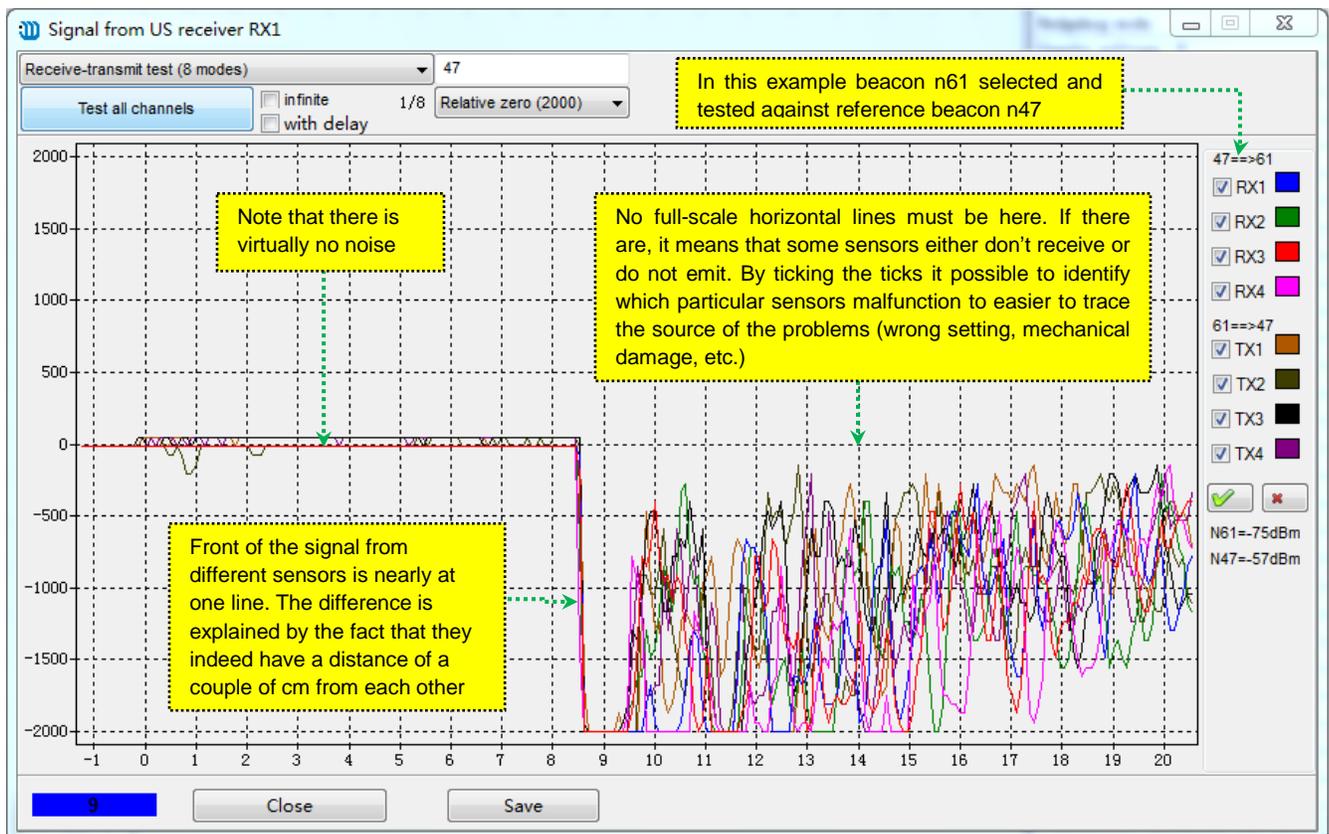
4000 to 3000 – almost no change. But around 2500 the gain starts reducing quickly (1200 – for some HW versions). Thus, it is possible to find the optimal gain to obtain the highest Signal/Noise ratio. Set the threshold value accordingly

4. Use Dashboard => View => 8-channel oscilloscope for very deep analysis of transducers performance

Hints:

- Choose the reference beacon and press Enter, like with regular Oscilloscope described above

Example of the test result:



6) Mobile beacon interfacing robots

a) Mobile beacon ("hedge") interfacing protocol to robots

1a) Virtual UART via USB

This is the easiest way to connect since no soldering is required and protocol is the same for different operating systems:

- Hedge HW v4.4 and earlier ([4 sensors](#)): [USB protocol for mobile beacon](#) - description of the USB protocol between mobile beacon and a host device for Windows and Linux
- Hedge HW v4.5+ ([5 sensors](#)): [USB protocol for mobile beacon](#) - description of the USB protocol between mobile beacon and a host device for Windows and Linux

1b) SPI

SPI & UART interface [pins](#) on beacon board.

- Hedge HW v4.5+ ([5 sensors](#)): [USB protocol for mobile beacon](#) - description of the USB protocol between mobile beacon and a host device for Windows and Linux

b) Integration with Raspberry Pi via virtual UART via USB in Python

- Here is the Python [code](#) for Raspberry Pi (potentially, with any Linux) integration via virtual UART via USB
- Code is fairly universal; at least, it worked on Mac (OS X 10.10) too
- Python v2.7
- CRC calculation is done in "pythonic way", i.e. library `crcmod` is used. Comments on usage of the library are inside the code
- There are handlers of different exceptions, for example, Ctrl+C, non-standard states of COM/USB

Credits: *the Python script provides interface for a mobile beacon attached to the robot built by openBerlin innovation center team. Written by Boris Zinin (b.zinin@gmail.com). This code is free to use in your applications (please include a reference link to this web page or original author's e-mail).*

Note! The code has not been verified by Marvelmind Robotics team. Use on your own risk.

c) Modem and dashboard interfaces

It is possible to get location data not only from the mobile beacon, but directly from the modem or the Dashboard:

- [Protocol of data exchange with modem via USB interface](#)
- [Protocol of data exchange with Dashboard via UDP](#)

d) Connection of Marvelmind hedgehog to Arduino

Marvelmind hedgehog can be connected to Arduino boards via UART or SPI interfaces.

Connection of Marvelmind hedgehog to Arduino via UART and SPI

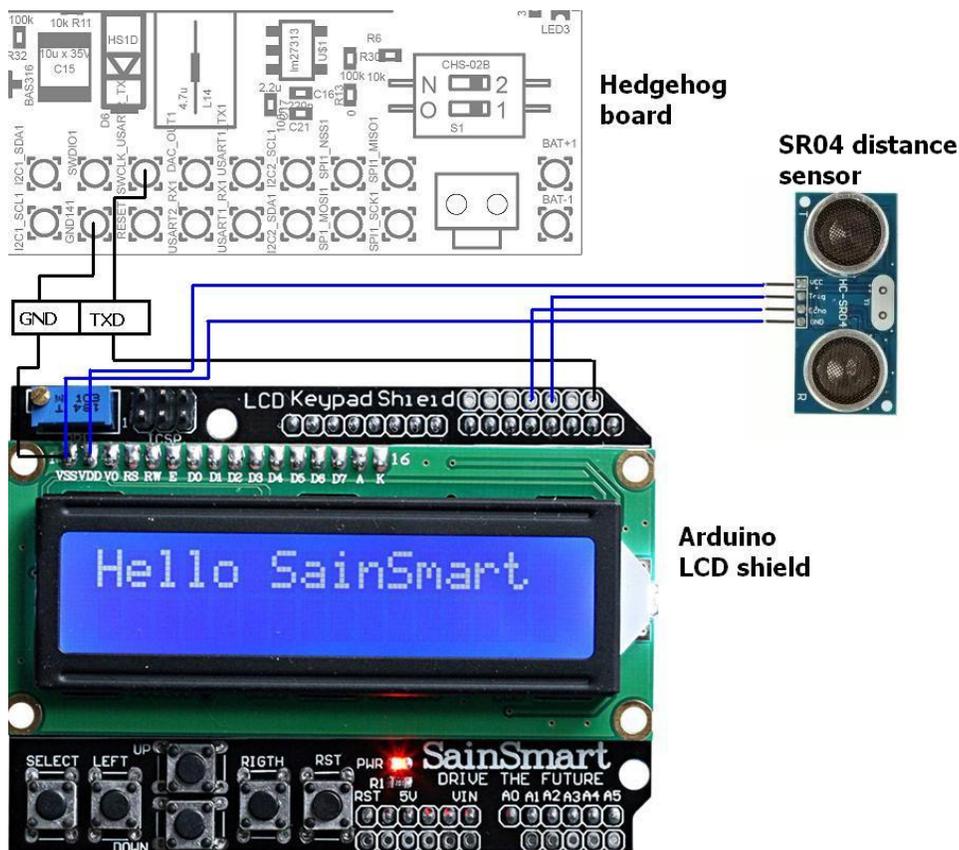
- The detailed description of connection to Arduino shield via UART and SPI is described in:
 - Hedge HW v4.4 and earlier ([4 sensors](#)): the [link](#) and the [Operating Manual](#)
 - [Arduino sample code - UART](#)
 - [Arduino sample code - SPI](#)
 - Hedge HW v4.5+ ([5 sensors](#)): the [link](#) and the [Operating Manual](#)

Examples of Arduino sketches for getting data from hedgehog are available for Sainsmart Arduino kit: <http://www.sainsmart.com/arduino/arduino-kits/uno-r3-smartkits/sainsmart-uno-lcd-keypad-prototype-shield-hc-sr04-distance-sensor-kit-4-arduino.html>

This kit includes Arduino Uno board, LCD board and ultrasonic distance sensor. Distance sensor works on frequency 40 kHz, which does not interfere with frequency of 31 kHz of hedgehog and Marvelmind Navigation System. So, both systems perfectly work even in proximity.

UART connection

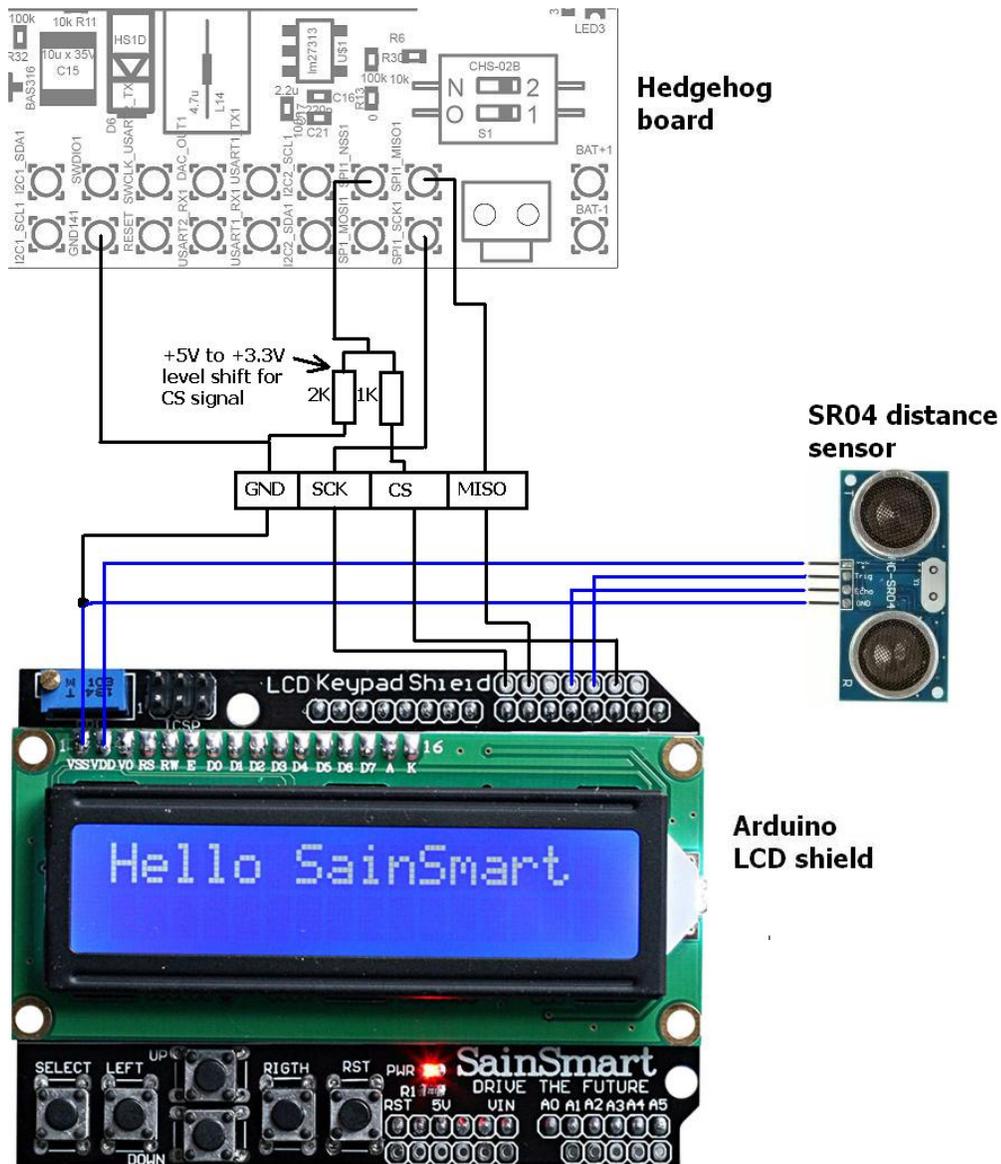
Connection of hedgehog UART to Arduino LCD shield is shown on following picture:



Hedgehog transmits data through UART with parameters: 500 Kbit/sec, 8 bits of data, no parity.

SPI connection

Connection of hedgehog to Arduino LCD shield is shown on following picture:



Arduino reads data from hedgehog from SPI interface, hedgehog acts as SPI slave device. Parameters of SPI: SPI mode 0, MSB inside each byte transmits first. Connection was tested on SCK speed up to 8 MHz. Be careful to provide quality wiring connections on high speeds (more than 500 KHz). Chip select input on hedgehog is not compatible with +5V level signals of Arduino, so you need to provide +3.3V level shift like resistor divider on a picture or some another one.

7) Important aspects and hints

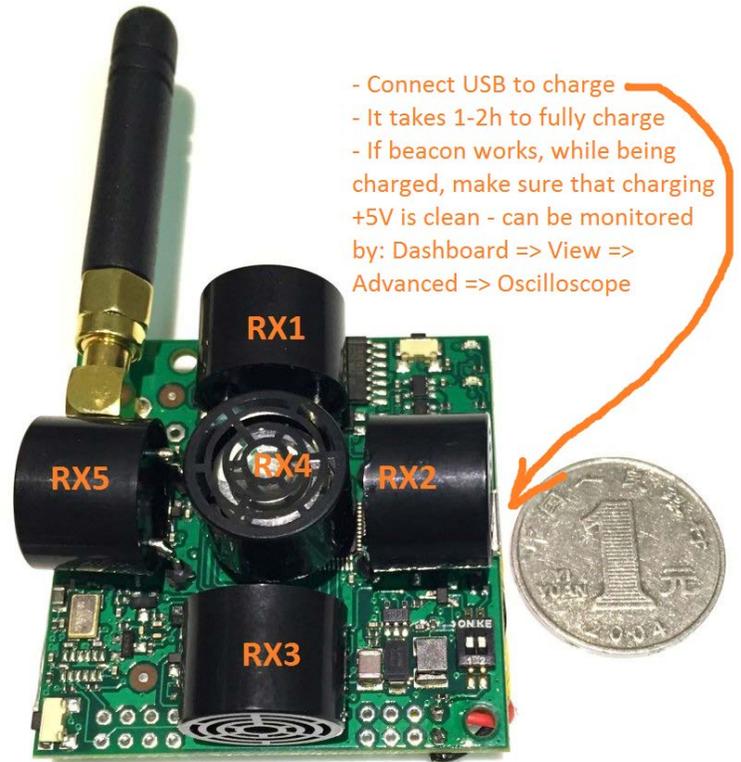
- The single most important aspect for the system to work well is to have proper ultrasonic coverage
 - o Each sensor has an ultrasonic beam of ~ 90 degrees. Outside of that range the emitting power and sensitivity drops quite rapidly. From the left, right, or back sides of the ultrasonic sensor the signal is received highly attenuated. Thus, it is crucially important to provide proper ultrasonic coverage for the area where the robot will be moving
 - o Also it is very important to provide proper ultrasonic coverage to other stationary beacons when the map is being formed
- Mobile beacon (“hedgehog” or “hedge”) is designed to be placed horizontally
 - o Mobile beacon has four horizontal and one vertical sensors each covering its own sector. Together they cover 360 degrees horizontally and upper hemisphere. Lower hemisphere is highly attenuated, so don't expect ultrasonic coverage in that area
 - o It is advised to place the mobile beacon as high as possible on the robot, if stationary beacons are above the mobile beacon, to minimize shadows from other objects, people, etc.
 - o Example of proper positioning of the mobile beacon: <https://youtu.be/PFqNPkLGCDk> - the beacon is placed horizontally and above other objects that can produce shadow to the stationary beacons
- Keep the radio signal's strength under control
 - o RSSI (Dashboard => right menu) of any beacon/modem must not be higher than -25dBm. Otherwise, the system may malfunction (packets lost unnoticeable, etc.)
 - o It is also preferred that the distance between beacons is more than 0.5-1m

The screenshot shows the Marvelmind robotics dashboard interface. On the left, there is a grid of sensor data. The main area is a 2D map with several green circular beacons labeled 'beacon 1' through 'beacon 13'. A blue robot icon is positioned on the map. On the right side, there is a configuration panel for a beacon. The 'RSSI: dBm' field is circled in orange. Handwritten text in the center of the map reads: 'RSSI: - Keep RSSI for beacons below -20 dBm - Optimal range: -20..-70dBm'. The dashboard also shows a 'clear map' button and a 'unfreeze map' button.

- **Start using advanced settings only when you know what you are doing**
 - o If you ran into troubles, connect beacon/modem to PC via USB and use “Default” button. It uploads “factory settings” to the board while keeping the device address untacked

- Charging

- Charging is done automatically every time, when the USB charger is attached to the board
- It takes 1-2h to fully charge the board's battery.
- After charging is finished the right LED goes dark
- Make sure that the power switch is ON. Otherwise, the battery is fully disconnected and won't be charged



Deep hints:

- **Avoid placing beacons on long sound conducting objects**
 - o This is a very rare case, but may happen in some special circumstances
 - o The best practice is to place beacons (stationary and mobile) in such places that would not result in transferring ultrasound energy from the beacon's board/case directly to place it is attached via other medium than air. For example, solid attachment of a beacon to a long horizontal metal tube may result in the following:
 - Sound emitted from the beacon propagates directly to the metal tube
 - Propagation losses inside metal are much smaller than in the air. Moreover, the tube may act as a low-loss waveguide
 - If the tube is solid enough and long enough, there may be a weird effect when the receiving beacon receives the signal sooner than expected, i.e sooner than the distance divided by the speed of sound in air. That happens because of speed of sound in metal is much higher than speed of sound in the air and some part of the path the sound travelled in the metal. The ultrasound signal may even look stronger than the real signal propagated through the air due to lower losses of ultrasonic in metal than that in the air
 - o It is good practice to place beacons on something relatively soft or not so sound conductive

8) Frequently Asked Questions

<http://www.marvelmind.com/forum/>

9) Contacts

For more support, please, send us your questions to info@marvelmind.com. We will guide and advise you

And visit our web site www.marvelmind.com

