Ultra-Wide Band Real Time Location Systems: Practical Implementation and UAV Performance Evaluation

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***Abstract*— Several different methods can be used to determine the 3-dimensional position of an object. A common solution is use of Global Navigation Satellite System (GNSS). However, for some operation the specific characteristics of GNSS can be challenging, e.g. time-to-fix on GPS RTK or unavailability of GNSS signals. When considering operations within limited range (a few hundreds of meters) another solution based on Ultra-wideband Real Time Location Systems (UWB RTLS). In this paper authors have tested a set-up of a tag and five anchors in order to determine if such solution can be used in local operations of Unmanned Aerial Vehicles (e.g. landing). Experimental data are analyzed and comapred against GPS RTK measurements.**

I. INTRODUCTION

In recent years a fast development of wireless technologies has led to increased capability and performance of Real Time Location Systems (RTLSs). RTLS has an ability to determine the position of a tag – limited by range of anchors – in real time or close to real time [1] (Fig. 1). Some applications for RTLSs are positioning of industrial robots, containers in terminals [2] and warehouses [3], mobility assistance for handicapped people, patient monitoring, and safety applications in construction sites [4]. In many cases RTLSs are based on an Ultra-wideband (UWB) transceivers [5]. UWB technology is a short-range, robust and energy efficient radio for high-bandwidth wireless communication [6]. UWB technology can be also used as measurements corrections in inertial odometry localization system [7] tested on board of hexacopter UAV. As shown in [8] ultra-wideband distance measurements can be sucessfully fused with accelerometers and rate gyroscopes for UAV estimated state. Some UWB features are (1) High data rate, up to $2\,\mathrm{Mbps}$; (2) High density of devices; (3) Low susceptibility to multipath fading; (4) High immunity against wireless networks interference; (5) Secure communication; (6) Mitigation techniques supported: LDC (Low duty cycle), DAA (Detect and Avoid), TPC (Transmit Power Control) [9].

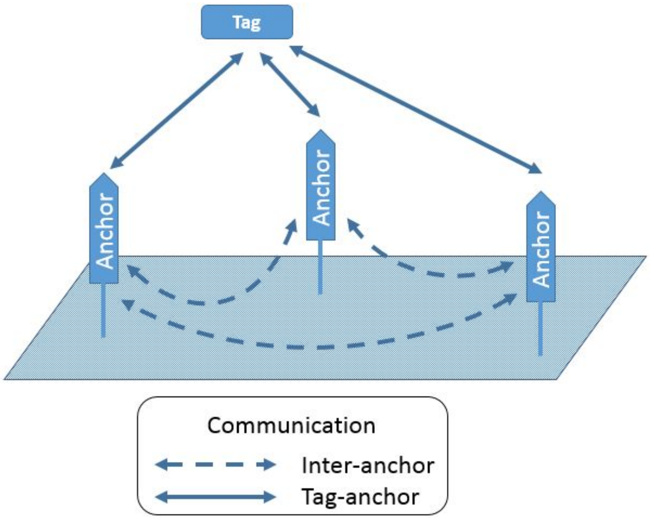

Fig. 1: RTLS principle of work

Our hypothesis is UWB based RTLS (UWB RTLS) can be successfully applied for Unmanned Aerial Vechicle (UAV) indoor and outdoor positioning. Positioning system is a vital resource for UAVs. Using Global Navigation Satellite System (GNSS) technology is a common practice for outdoor localization, which in some cases can be also used indoor [10]. In most cases however indoor localization is realized using a system based on camera or custom radio systems[11]. Some limitations of GNSS systems are accuracy and update rate which may not be sufficient for all dynamic and precise tasks. Although, a Real Time Kinematic (RTK) GNSS can be used to increase GNSS accuracy, its use puts several constrains on the UAVs behaviour. The RTK requires a good satellite coverage, and the time-to-fix can be significant. In order to transmit corrections between a base node and a receiver a communication between these two units has to be established using separate transceivers. The RTK accuracy may also be affected by the Selective Availability if applied [12]. UWB RTLSs technology, that is based only on local nodes, is not affected by these constrains. Despite its limited area coverage, UWB RTLS can be suitable for indoor, and some outdoor operations in local space, e.g. landing of an UAV on-board of moving platform, such as a vessel or a truck.

This paper discusses implementation and performance evaluation of UWB RTLS with focus on a future use as an outdoor navigation aid for UAVs. The paper evaluates several UWB RTLS systems, and concentrate on estimation of anchors and UAV tag positions accuracy.

The main contributions of this paper are:

- Description of a system for UWB RTLS measurements evaluation using RTK GNSS
- Evaluation of UWB point-to-point measurements accuracy
- Evaluation of the positioning accuracy for a tag in 3D
- Evaluation of UWB RTLS with different tag position estimation algorithms

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TABLE I: Comparison of tested radio distance measurement devices

board	BeSpoon Standard EVK [13]	Pozyx [14]
chip	UM100 [9]	Decawave DW1000 [15]
freq range [GHz]	3.5-4.5	3.5-6.5
bandwidth [MHz]	450-1500	499.2-1331.2
range [m]	800	up to 100
refresh rate [Hz]	73	up to 140
precision [cm]	10	down to 10
size of module [mm]	13.4x13.4x2.6	6x6
board size [mm]	75x75x10	60x53
max speed of tag [m/s]	N/A (25 - field tested)	5
data rate [Mb/s]	2	2
tag density	N/A	11000 at 20 m radii

Section II describes UWB RTLS work principles, a selection of UWB modules, and discusses algorithms that can be used to determine anchors and tag positions. Section III gives details on the hardware used for system evaluation. Section IV describes data analysis of the UWB RTLS. Section V discusses the results of the performance analysis.

II. UWB RTLS WORK PRINCIPLE

UWB is defined as any radio with bandwidth spectrum at least 500 MHz or 25% of center frequency [16]. Narrow band technologies, on the other hand, typically have bandwidth of 10% of center frequency or less.

An UWB transmission uses Time-division multiple access (TDMA) to communicate between nodes. An UWB tag sends a periodic data request to all anchors within its range. The tag measures response time (TOA/TDOA) and is able to determine distance to each anchor. The RTLS uses this information to determine anchors and tag locations. To obtain anchors and tag position in global coordinate system, the position of the one anchor needs to be known.

A. *Comparison of UWB modules*

Several UWB Commercial-of-the-shelf (COTS) solutions are currently available on the market. To the authors best knowledge are based on one of two available Systems-on-a-chip (SOC). Table I provides comparison of 2 selected devices representing each SOC.

1) BeSpoon with UM100: UM100 chips are available as SoC modules. The device works in a significant range up to 800 m. The module offers advanced configuration options and is well documented. The module's firmware offers an additional user-space where additional functions can be implemented. Manufacturer provides extensive documentation and a Software Development Kit (SDK). In this paper, BeSpoon Evaluation Kit (EVK) with UM100 [9] modules were tested.

2) Pozyx with Decawave DW1000: Pozyx modules with DW1000 are available in a form of standalone devices and Arduino add-on modules. The DW1000 range is limited to 100 m. However, device provides the highest refresh rate among all tested solutions (up to 140 Hz). Manufacturer provides good documentation and a Software Development Kit (SDK).

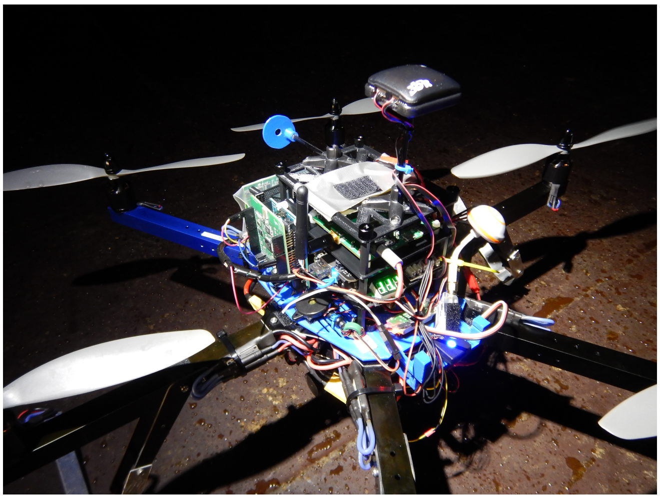


Fig. 2: Experimental hexacopter NTNU-HEXA-002 UAV with UWB system

Fig. 3: One of the UWB anchors

B. *RTLS anchor position determination*

The anchors' positions can be found using an auto-localization or auto-positioning method, similar to proposed in [17]. In this approach nodes are automatically measuring inter-anchor distances and sending data to main computer. Due to the method simplicity, five anchors are required, of which first three need to be placed at the same height (small

Fig. 4: UWB Anchor constellation view during field flight tests

differences in height can be neglected or compensated basing on differences measured by RTK or calibrated pressure sensors).

The algorithm which is determining anchors positions uses the following procedure:

- First anchor position is assumed as $[0,0,0]$ (in $[x,y,z]$ coordinate system), here appear optional translation from real position on x,y and mainly z-coordinate.
- Second anchor is assumed to lay on x-axis, so the position is $[d_{12},0,0]$, (d_{12} is the distance between first and second anchor), here appear optional rotation on z-axis, if the height of anchors to in reference system is the same.
- Third anchor position is estimated using distances d_{13} and d_{23}, by triangle equation. There are always two solutions, but only one is taken to further calculations. Coordinates are $[x = d_{12}^2 + d_{13}^2 - d_{23}^2/(2d_{12}), \sqrt{d_{13}^2 - x^2}, 0]$.
- Fourth and fifth anchor positions are estimated using linear least square trilateration algorithm basing on first three anchor positions. The algorithm implementation is based on [18].
- If it is needed, translations and rotations can be optionally applied to anchor constellation to match a specific coordinate frame.

C. Tag position calculation

The UWB modules provide the user only with measured distances between anchors and the tag. In order to locate a specific position of the tag the RTLS need to use suitable mathematical methods. For a real-time operation on-board power-restricted computers, e.g. SBPCs, the tag position algorithm should require limited computational power. Among other, four suitable algorithms for multilateration are Linear Least Square [18], [19], Cayley-Menger Determination (CMD) [20] and Closed Form Position (CFP) estimation [21].

1) Linear Least Square method: the method relies on intersection of spheres with radius from distance measurement between tag and anchors. Using this knowledge it is possible to estimate position of the tag. The method is calculating position using all of the five anchors. The method show limited robustness but works well when measurements have good accuracy. The LS1 and LS2 methods only differs in the way how they are implemented in Matlab (first version is using Matlab function pinv and second is implemented directly from equation).

2) Cayley-Menger Determination (CMD): the method is closed-form solution, where result is obtained after finite mathematical operations. The method's advantage are low computation effort and robustness for errors in input data, disadvantage is relying only on data from three anchors. Method is based on geometrical calculations in Euclidean space.

3) Closed Form Position (CFP): the method also is closed-form type algorithm. It is based on calculating of the vector, and also based on measurements from three anchors. Behaviour is similar to CMD method. Author of the method [21] put attention to precise determining of height.

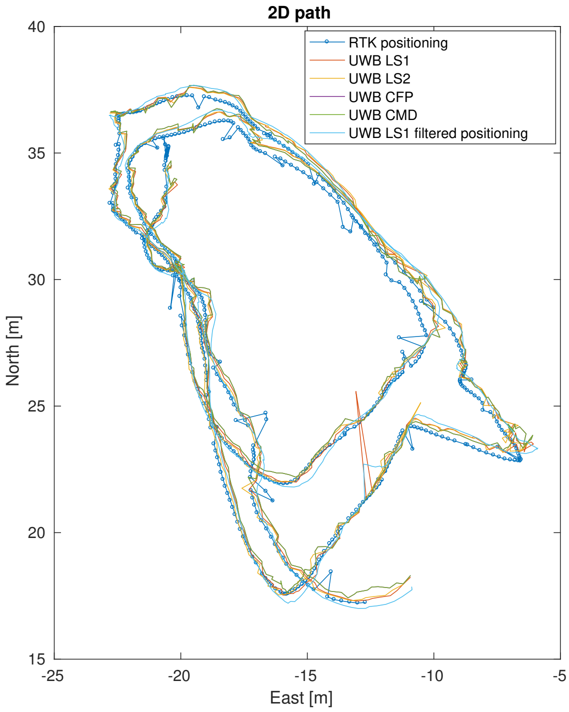
III. EXPERIMENT SETUP

In order to determine UWB RTLS system performance and accuracy, a several tests have been performed. A sensor set-up used during the experiment contains five anchors (Fig 3) and one tag, where the tag was mounted on board of an UAV (Fig 2). Each anchor and tag contain BeSpoon EVB with UM100 chip and Pozyx board with DecaWave chip. In addition, all nodes are equipped with a BeagleBone Black (BBB) Single Board PC (SBPC) that runs Linux operating system and the LSTS Toolchain software [22]. All anchors and UAV contain GNSS RTK receivers. In the anchor devices, BBB role is to send commands to UWB radio and receive stream of data from UWB radio during inter-anchor distance measurements. In the tag, BBB is used as the main control device in the system, during the initialization phase it is commanding anchors to do the inter-anchors measurements. Then tag's BBB is switching tag's UWB radio to normal operation state, which is performing tag-to-anchors distance measurements. Estimation of anchors and tag position can be calculated in real time at the tag's SBPC, however, to provide better analysis of various method accuracy in this paper we present results obtained during data post-processing in Matlab.

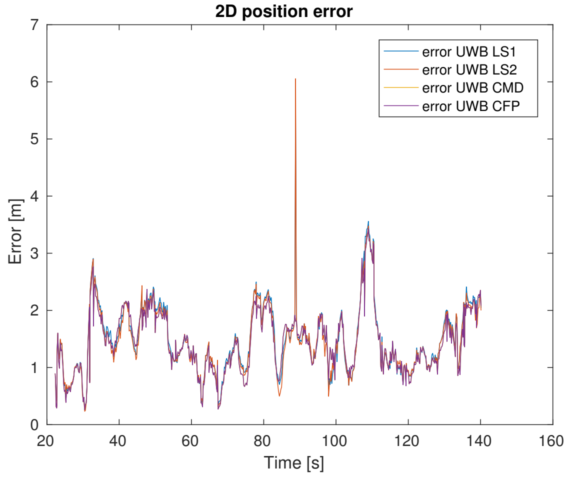
Initial tests between Pozyx and BeSpoon modules have risen concerns about the required practical range of the modules. When considering UAVs flying with speeds of approx $15 - 25\,\mathrm{m/s}$ and range of $100\,\mathrm{m}$ may not be sufficient to perform required UAV maneuvers.

Having in mind the focus on future use in the fixed-wings UAVs, the localization accuracy analysis has been performed only for the BeSpoon modules.

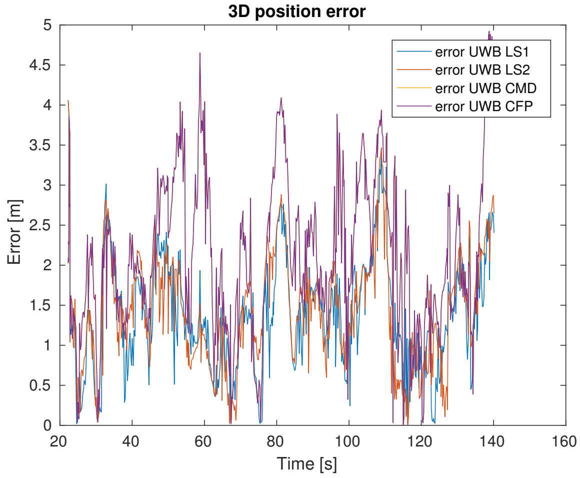
Distance measurements from UWB device with BeSpoon UM100 were verified with RTK GNSS. The tests were performed in outdoor environment at Breivika airfield, to



(a) A UWB tag path



(b) 2D position error



(c) 3D position error

Fig. 5: A UWB tag localization accuracy, BeSpoon system

provide RTK GNSS with good quality of the satellite signals and perform safe UAV flight. Location of the anchors is presented in Figure 4. Mean RTK heights differences between first anchor and the rest: $0.0309\,\mathrm{m}$, $-0.0655\,\mathrm{m}$, $-0.5024\,\mathrm{m}$, $0.4264\,\mathrm{m}$.

IV. DATA ANALYSIS

The collected data were analyzed in several stages. First the inter-anchor distance measurements accuracy were evaluated, as these can be a source of further errors in RTLS. The distances were evaluated against the GPS-RTK measurements. Next anchors and tag positions were computed using previously discussed algorithms. These results were also validated against GPS-RTK data and errors statistics are provided. Values in UWB distances are average from $120\,\mathrm{s}$ (1674 samples) between every anchor. In case of GNSS RTK distance measurements are euclidean distances calculated from mean value of position coordinates from 250 samples.

The results of measurements are shown in the table II. The error between UWB and RTK results ranges from $2\,\mathrm{cm}$ to $24\,\mathrm{cm}$. The UWB results standard deviation does not exceed $9\,\mathrm{cm}$.

The distance data were used as an input to the RTLS methods. The tag position estimation results are given in Table III. The accuracy of each RTLS method can be divided into 2D and 3D positioning problem. The tag on board of UAV was traveling between the anchors on a relatively constant height. Therefore, algorithms show different performance in these two cases. For 2D localization the least error was achieved using the LS2 method. On the other hand for 3D localization the LS methods show the biggest differences. The CFP and CMd methods show the same performance in both 2D and 3D problems. In 3D the results is more than 50% more accurate than LS methods. The results are also visualized in Figures 5a, 5b, and 5c.

V. DISCUSSION

The presented experiment and additional work on the UWB modules revealed several characteristics of the modules. Maximum range achieved for BeSpoon during a pre-

TABLE II: Measurements of distance with RTK and UWB.

	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
RTK distance [m]	14.98	24.99	7.39	8.11	10.53	11.16	8.63	19.51	17.45	2.64
mean UWB distance [m]	15.20	25.22	7.46	8.26	10.75	11.26	8.67	19.70	17.43	2.88
error UWB to RTK [m]	0.22	0.23	0.07	0.15	0.23	0.10	0.05	0.19	-0.02	0.24
std dev UWB [m]	0.0238	0.0168	0.1290	0.0655	0.0393	0.0876	0.0791	0.0371	0.0333	0.0293

TABLE III: Comparison of mean errors and standard deviations for different tag positioning algorithms and reference position from RTK, in 2D distance (xy plane) and 3D distance (xyz space).

	LS1	LS2	CFP	CMD
mean error xy [m]	1.4891	1.4600	1.4367	1.4367
std. dev. xy [m]	0.6086	0.5998	0.5582	0.5582
mean error xyz [m]	1.4044	1.4570	2.1392	2.1392
std. dev. xyz [m]	1.3966	1.4742	1.0199	1.0199

liminary test exceeded value provided in the specification, resulting in achieved range of $740\,\mathrm{m}$). The module also proved to be reliable when tag was attached to a vehicle moving with speed typical for small UAVs (around $20\,\mathrm{m/s}$). Pozyx have very high refresh rate. However, maximum range achieved was $74\,\mathrm{m}$.

A. *Encountered challenges*

As the UWB RTLS project have status of work in progress it faced some challenges.

First issue is misalignment of the UWB RTLS coordinates frame and the RTK NED frame. The angle of rotation was computed for average measurements from RTL and UWB RTLS which could influence the error. Translation of coordinate frames is also needed, and it can be also source of error.

Another source of errors may be uncompensated offset between UWB radio and RTK antennas. The technologies use separate antennas therefore the measurement cannot be taken at exactly the same spot.

The test datasets were selected in order to keep minimum multipath and NLOS errors. Multipath and NLOS errors occurs in dataset as severe outliers, especially when obstacles appear between or close to the anchors.

The geometry of anchors can be improved as well. Three anchors have to be on the same height, fourth and fifth should be lower and higher then the first three, however optimal setting for anchors is limited by practical considerations.Last but not least, the executed tag on board of UAV is its small changes in altitude, due to another tests which were performed parallel. That created a poor geometry where z axis position errors were significant.

Another source of errors could be imperfect time synchronization of UWB and GNSS RTK data due to communication delays and used synchronization mechanisms.

VI. FUTURE WORK

The future work will be real-time implementation of UWB RTLS on-board the UAV, which work in flight. This task is also connected with researching for other or better positioning algorithms suitable to future applications.

Existing test setup will be upgraded with a fusion of data from pressure sensor and IMU into RTLS to improve positioning quality. Consequence of this fusion will be robust local positioning system which could be used as a navigation aid by UAV autopilot system. Another improvement will be data time synchronization made on specialized synchronization board.

The future RTLS will be able to adopt for anchors which will be changing their position, both as a constellation and between each other. This methods will allow to deploy the system in demanding locations.

VII. SUMMARY

Fast progress in wireless technologies has led to development of RTLS based on UWB modules. This paper presents analysis of performance and accuracy of a selected UWB module available on a market, with future UAV applications in mind. Data were collected using custom set-up with a tag on board of an UAV and five anchor nodes on the ground. The paper presents a comparison of various RTLS methods: Linear Least Square, Cayley-Menger Determination, and Closed Form Position. Results are validated against GPS RTK measurements.

VIII. ACKNOWLEDGMENTS

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REFERENCES

[1] I. O. for Standardization, “Information technologyreal-time locating systems (rtls),” *ISO/IEC 24730-1:2014*, 2014.

[2] H. Cho, T. Kim, Y. Park, and Y. Baek, “Enhanced trajectory estimation method for rtls in port logistics environment,” in *2012 IEEE 14th International Conference on High Performance Computing and Communication 2012 IEEE 9th International Conference on Embedded Software and Systems*, June 2012, pp. 1555–1562.

[3] X. Ma and T. Liu, “The application of wi-fi rtls in automatic warehouse management system,” in *2011 IEEE International Conference on Automation and Logistics (ICAL)*, Aug 2011, pp. 64–69.

[4] R. Maalek and F. Sadeghpour, “Accuracy assessment of ultra-wide band technology in tracking static resources in indoor construction scenarios,” *Automation in Construction*, vol. 30, pp. 170 – 183, 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0926580512001720

[5] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. A. Al-Ammar, and H. S. Al-Khalifa, “Ultra wideband indoor positioning technologies: Analysis and recent advances,” *Sensors*, vol. 16, no. 5, p. 707, 2016.

[6] B. Jachimczyk, D. Dziak, and W. J. Kulesza, “Customization of uwb 3d-rtls based on the new uncertainty model of the aoa ranging technique,” *Sensors*, vol. 17, no. 2, 2017.

[7] G. N. Emil Fresk, Kristoffer Odmark, "Ultra wideband enabled inertial odometry for generic localization," jul 2017.

[8] M. W. Mueller, M. Hamer, and R. D'Andrea, "Fusing ultra-wideband range measurements with accelerometers and rate gyroscopes for quadrocopter state estimation," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*. IEEE, 2015, pp. 1730–1736.

[9] BeSpoon, "Full specification of ir-uwb module um100," *Full specification 2.13 AUGUST 2016*, 2016.

[10] H. S. Cobb, *GPS pseudolites: Theory, design, and applications*. Stanford University Stanford, CA,, USA, 1997.

[11] L. Mainetti, L. Patrono, and I. Sergi, "A survey on indoor positioning systems," in *Software, Telecommunications and Computer Networks (SoftCOM), 2014 22nd International Conference on*. IEEE, 2014, pp. 111–120.

[12] W. Ochieng and K. Sauer, "Urban road transport navigation: performance of the global positioning system after selective availability," *Transportation Research Part C: Emerging Technologies*, vol. 10, no. 3, pp. 171–187, 2002.

[13] Uposition evk standard. [Online]. Available: http://spoonphone.com/en/home/13-standart-evaluation-kit-with-bespoon-protocol.html

[14] Pozyx - centimeter positioning for arduino. [Online]. Available: https://www.pozyx.io

[15] decaWave, "Dw1000 datasheet," *Decawave Ltd 2016, Version 2.12*, 2016.

[16] J. M. Wilson, "Ultra-wideband/a disruptive rf technology?" *Version 1.3, Intel Research and Development*, 2002.

[17] M. Pelka, G. Goronzy, and H. Hellbrück, "Iterative approach for anchor configuration of positioning systems," *ICT Express*, vol. 2, no. 1, pp. 1–4, 2016.

[18] A. Norrdine, "An algebraic solution to the multilateration problem," in *Proceedings of the 15th International Conference on Indoor Positioning and Indoor Navigation, Sydney, Australia*, vol. 1315, 2012.

[19] K. Befus, "Localization and system identification of a quadcopter uav," 2014.

[20] F. Thomas and L. Ros, "Revisiting trilateration for robot localization," *IEEE Transactions on robotics*, vol. 21, no. 1, pp. 93–101, 2005.

[21] D. E. Manolakis, "Efficient solution and performance analysis of 3-d position estimation by trilateration," *IEEE Transactions on Aerospace and Electronic systems*, vol. 32, no. 4, pp. 1239–1248, 1996.

[22] Lsts toolchain. [Online]. Available: http://lsts.fe.up.pt/toolchain