

I am a title (RO SLAM Methods/Implementation Survey)

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Abstract—This is my abstract, there are many like it, but this one is mine. Will fill this in once paper is written ****

An survey of current the current implementations and methodologies used for solving the range only systematic and localization problem (RO-SLAM).

I. INTRODUCTION

II. RANGE ONLY SENSORS/TECH

One of the key features of the systematic localization and mapping problem are landmarks. In RO SLAM the only information that can be obtained from landmarks is range data. This range data must then be interpreted by the robot in some way that will be advantageous towards the localization and mapping process. Beacons are a popular implementation of landmarks. Beacons refer to any devices which involves a signal transmission that can be used for the localization and mapping process without line of sight. The most popular beacons can largely be broken down into two categories: acoustic based and radio frequency based.

A. Acoustic

Acoustic ranging systems are primary used with robotics and beacons that operate in underwater locations. The reason for this that radio waves experience strong attenuations, especially in salt water environments. As [1] states, the issue of attenuations makes radio waves extremely impractical, thus making acoustics the logical alternative. Acoustic still suffer from a range of problems such as multipathing and propagation delays, but are one of the only meaningful alternatives. Papers such as those by [2] and [3] explore a wide variety of issue and possible techniques that relate to acoustic sensors, such as the added complexity of assuming a 2D environment vs a 3D environment, or design challenge that accompany underwater deployment like spatial correlation and power.

An interesting beacon for underwater localization that is not specifically range only or acoustic based is the Dive'N'Rise (DNR) beacons presented by [4]. These DNR beacons rise to the surface, receive their location through GPS, then sink into the water and transmit their coordinates. The distance to an agent and the transmitting beacon can be determined via time of flight from the transmissions. A localization implementation using these beacons was accomplished by [5]. Again while this is not purely range only or acoustic based it was found to be interesting solution worth mentioning.

B. Radio Frequency

Radio frequency encompass a massive spectrum of devices capable of transmitting or receiving transmission on the radio

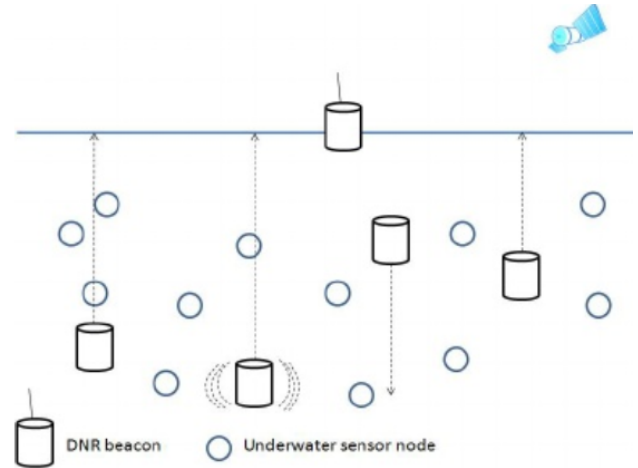


Fig. 1. DNR being used to implement Dive and Rise Localization [2]

frequency. There are two methods primarily utilized to determine distance from radio frequency. One is by examining the received signal strength indicator (RSSI) and the other is by measuring the time of flight of the signal. A system presented by [6] processes rf signal strength and utilizes nearest neighbors heuristics to achieve localization based on said signal strength. [7] describes a method for using very small RF tags as beacons throughout the environment. As a robot moves throughout an environment it emits a query to which any RF tags that are within the transmission range respond to. The robot then estimates the distance to the tag based on the delay. The response from the RF tags include a data tag which contains a unique ID number.

Wireless sensors networks (WSN) are also a very popular choice, especially since many of them come with the ability to transmit RSSI. [8], [9], [10], and [11] each presents surveys relating to WSNs. [8] and [10] both provide very well developed survey that discuss hardware, protocols, standards, security, energy efficiency and much more. [8] specifically focuses on state of the art 802.15.4 and ZigBee standards. [11] examines the limitations of original IEEE 802.15.4 MAC and reviews adaptive methods that have been used to overcome these limitations. [9] specifically survey methods meant to improve the performance of IEEE 802.15.4 MAC protocol.

III. BEACON INITIALIZATION

Beacons initialization refers to the process by which beacons (or landmarks) at an unknown position receive their initial position estimation. One of the complications with RO-SLAM involves the issue of determining the location of landmarks when their initial placement is unknown, the EKF, which is used by many implementations, is especially sensitive to poorly initialized landmarks as they are used as the basis for the convergence of an accurate estimate. [12] presents a solution for this complication. A Gaussian Mixture Model is integrated into the EKF to create a multiple hypothesis filter. This multiple hypothesis approach is used to solve the RO-SLAM problem and its use allows for the undelayed initialization of landmarks, however a large number of hypothesis can lead to increased computational burden. [13] also puts forward a method that utilizes a Gaussian mixtures for beacon initialization in EKF, but in this method only two hypotheses and a Cartesian plane. [14] proposes to reduce the computational burden of methods, such as the one proposed by [12], by introducing a novel state vector that eliminates the need for multiple hypothesis landmark representation. The paper proposes that under different circumstances the landmark could be represented using different parameters. Four circumstances are presented in the paper and the method is tested in simulation using both the EKF and a least squares optimization approach. The results showed that when the circumstances can be clearly distinguished between, an increase in performance is seen.

IV. METHODS AND THEIR IMPLEMENTATIONS

A. EKF

The Extended Kalman Filter (EKF) is one of the most popular and widespread methods used to solve the SLAM problem. It is used to overcome the assumption of linear state transitions and measurements, which are rarely seen in practical environments [15]. The derivation of the EKF is very well documented, as such, detailed explanations can be viewed from a variety of sources such as: [15], [16], and [17]. When used to solve SLAM the map applied to the EKF is a feature based map, meaning it is composed of observable features (landmarks) which can be distinguished between during re-observation [15]. This distinction becomes important when examining range only SLAM (RO-SLAM) where only the range to a landmark, or the range between landmarks, is known. This restriction means that landmarks often need to be manufactured, such as the beacons discussed in previous sections, and physically placed in an environment. However, that does not mean that the exact location of the landmarks, or even their initial existence, is recognized. Initialization is a critical element in many algorithms that make use of the EKF. If the initialization is inaccurate then the convergence to a correct estimation becomes much more difficult for the filter. The EKF has seen a wide variety of implementation ranging from ground based robotics[18], to unmanned air vehicles [19], and to autonomous underwater vehicles [20]. This section

will proceed to give a summary of the various ways EKF has been implemented in regards to RO SLAM, as well as examine improvements to the general RO SLAM problem that are applied via methods with EKF mind.

A system for robust range only localization was proposed by [20]. The system utilized an Autonomous Underwater Vehicle (AUV) and beacons without carefully surveyed locations. The paper notes that one of the major issues was noise present in the received data. A method for outliers rejection caused by the noise was accomplished via spectral graph partitioning. A voting scheme was implemented similar to a Hough transform to get approximate beacon locations [21]. The approximate locations were then incorporated into an EKF. It is noted by the paper that this method is particularly CPU intensive, however they state that since the rate at which data is acquired from a landmark is slow, every 5 or so seconds, that the AUV can afford the expensive computation since there will be an adequate amount of time between readings for the data to process. The methodology was simulated using a dataset and can be seen in the paper.

[22] presents a comparison of how three methods process a collected data set. The methods are a EKF, a sliding batch, and a particle filter. The comparison considers the cross-track error, and along track error. The results state that the particle filter works well when used to acquire an initial pose estimate, and EKF works well with real-time localization. It is suggested that in the future that the two could be switched between when appropriate to improve the overall system.

[23] presents a solution utilizing a Sum of Gaussian (SOG) filter for a single range only beacon. It uses multivariate Gaussian mixtures to represent the probability distribution functions of the robot and beacon positions as Gaussian particles which each contain an EKF for vehicle position, velocity, and estimated beacon position. The paper presented experimentation where the method was used to map a beacon while correcting the navigation of the vehicle.

Several techniques have also been implemented that involve cooperative sensors. Traditionally sensors were used to only determine the range between themselves and the robot. The sensors in these cases provide the ability to determine the range between themselves and other sensors and or the robot [24].

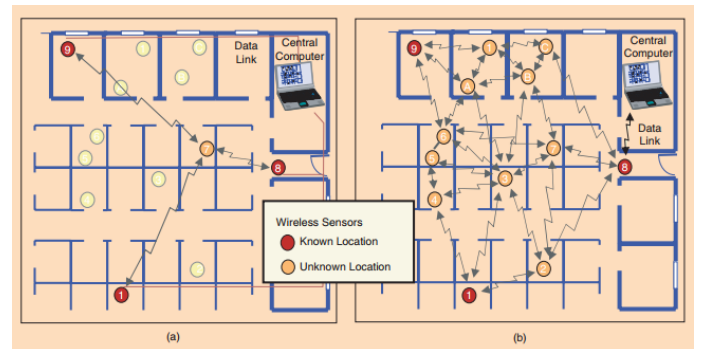


Fig. 2. Traditional(a) vs Cooperative(b) Sensors [24]

It is explained by [25] that methods utilizing inter beacon measurement should incorporate measurements with a configurable number of hops between beacons. This allows for the robot to gather range data from beyond the extent of the robots sensors. Experimentations was conducted utilizing this method via a particle filter EKF. The results showed that the more hops that were added the greater the performance of the system.

[26] presents a comparison of multiple RO SLAM methods utilized in two scenarios. One scenario involves the case where the robot only has access to range information between itself and beacons at unknown locations. In the second case the robot also has access to information about beacon to beacon distances. Several separate methods were compared in the given scenarios utilizing a data set and experimentation. The first method utilizes the Kalman filter in the case where only measurment between moving and stationary beacons are considered. Another method specifically uses the beacon to beacon measurements with an online Kalman filter. An off line batch method is used to get an estimate of the beacon location and robot path. Finally an method that considers the robot as a virtual node for creating submaps to be solved with a multidimensional scaling algorithm is also considered. The paper gives experimental results and analysis for each of the methods.

An extension to EKF called relative-over parametrized (ROP) EKF is presented by [18]. This extension uses specific parameterization to better represent the range only data utilized in RO-SLAM. ROP EKF operates in polar coordinates as opposed to the Cartesian space that typical EKF operates. The method provided improved results over EKF when sparse range measurement or data association errors were present. [27] presents a comparison of the ROP-EKF method presented by [18], to a smoothing and mapping method presented by [28]. Experimentation conducted by [27] on and indoor and outdoor environment show an improvement in the results of the SAM method over ROP EKF.

A method proposed by [29] is geared towards improving map building speed and accuracy for UAS dealing with the 3D RO-SLAM problem. The 3D RO-SLAM problem refers to the added complexity that devices such as submersibles [30] and aerial vehicles experience when having to operate in an environment where three dimensions must be considered as opposed to the planar environment many robots are assumed to operate in. The method utilizes inter-beacon measurements and a novel mode selection which is used to select a measurement gathering method based on current conditions [29]. The first mode is noted as mapping (MS) and the second localization (LS). When in mapping mode the measurment are integrated with a high probability to quickly create a map, when in localization mode the probability is lowered to create higher accuracy localizations. Based on experimentation performed by [29] the method performed well and a general increase in accuracy and map speed was noted, however it is stated that a wider variety of experimentation should be performed to validate the overall robustness and effectiveness of the method.

It is explored by [31] how interpolation can be used to

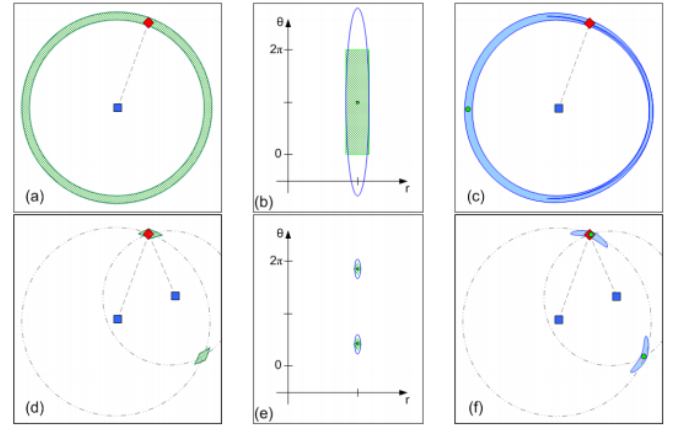


Fig. 3. Top Row: True and approximated distribution from one range observation. Bottom Row: True and approximated distributions with two observations from different locations. Left Column: Distribution in Cartesian Coordinates. Middle Column: True and Gaussian approximated distributions in Polar Coordinates. Right Column: Projection of the Gaussian approximated. [18]

generate range data that is equally spaced over time as opposed to the irregular time intervals that range data is typically received at and then applied to solve the RO SLAM problem. The method is tested on the EKF and an batch optimization algorithm with a simulated and physical robot. The results provided by the paper show that the interpolation based algorithms gave better landmark estimation than those without, with the exception of the EKF in two datasets where EKF was already performing poorly.

[32] presents a solution for the 3D RO-SLAM problem. The solution reduces computational load through reduced spherical parametrization of map feature positions. The paper also proposes a new EKF update method which incorporates a reduced spherical representation of the state vector. In addition the paper describes how to efficiently integrate multi-modal belief of elevations angles and azimuth from a range sensor into the EKF utilizing two independent Gaussian Mixtures [32]. In addition [33] expands upon this by presenting a pre-filtering algorithm to be applied to range measurement before being used in the EKF in order to reduce the effect of noise generated by environmental issue such as multipathing. It is then proposed by [34] that the above method can be utilized for decentralized multi-SLAM with range only sensors. This new method would allow for landmarks estimated by a robot to be incorporated into the estimation of another nearby robot, thus improving localization estimation. Based on experimental results obtained by [34] the integration of estimates from multiple robots of the same landmarks provides a benefit to landmark localization over a single robot. In [19] the author also validates and expands upon this method through indoor and outdoor experimentation with an Unmanned Aircraft System (UAS).

B. Graph SLAM

C. Particle

Particle filters are made up of various monte carlo algorithms that are used to estimate states in partially observable Markov chains (see [9]). In the initial application of particle filters in the field of robotics was in localization where it was used to estimate a robot's pose from sensor data. It is considered better and more robust to conventional estimation methods because it was able to solve the global localization [2] and the kidnapped robot problem [14]. It has also been applied to higher dimensional problems. Initially, the robot assumes global uncertainty through a set of particles that are distributed all over the map. Hence both the robot and the landmarks are uncertain. As the robot moves around and measures sensor data, it resamples the particle set weighted according to the probability of the particle being the right one. There are several resampling methods depending on computational complexities. After some iterations, only the particles which have a high degree of probability remain and eventually converge to the state of the robot and the landmarks. Assuming at time $t=0$, we have N particles equally

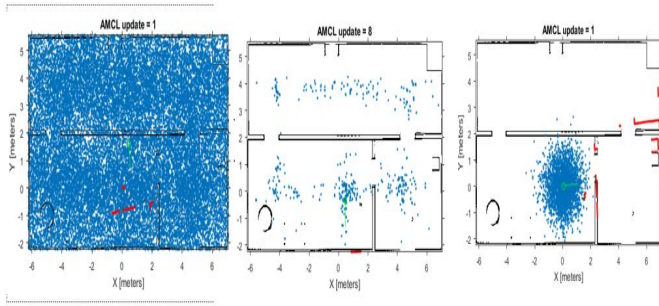


Fig. 4. The leftmost image describes the state of the robot when it just initializes the particle filter. The particles are uniformly distributed. The image in the center describes the particle filter after a couple of iterations. Only the particles which have a higher probability are resampled. The image on the right shows the particle filter eventually converging to estimate the robot location.

space in the environment that are drawn based on a uniform distribution $p(x_0)$. resampling methods depending on computational complexities. After some iterations, only the particles that have a higher probability are resampled. Once the robot starts moving, it collects measurements and at time $t > 0$, we sample a new particle set $x_t^{[i]}$ for each particle in $x_{t-1}^{[i]}$. It is sampled based on the probability of measurement $p(z_t | x_{t-1}^{[i]})$. Eventually, the particle filter converges to give us the true positioning of the robot.

As mentioned in [14], particle filters outperform EKF in applications involving global localization (the kidnapped robot problem form [14]) where the robot is randomly picked up and placed in an unknown environment. EKF cannot process negative information, but since particle filters use raw sensor data without any processing, they can process negative information [14]. As the number of particles increases, the computational complexity of the filter too increases. In order to address this, there were several new methods intro-

duced that exploit the independence among state variables. For example, the Rao-Blackwellized particle filters that exploit the independence of the landmarks with the robot path, thereby reducing the computation complexity, from [Fast slam paper]. It also solves the data association problem previously unsolved by EKF [8].

D. Graph

E. Fast SLAM

V. CONCLUSION

REFERENCES

- [1] J. Partan, J. Kurose, and B. N. Levine, "A survey of practical issues in underwater networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 11, no. 4, p. 23, 2007.
- [2] M. Erol-Kantarci, H. T. Mouftah, and S. Oktug, "A Survey of Architectures and Localization Techniques for Underwater Acoustic Sensor Networks," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 487–502, 2011. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5714973>
- [3] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, 2005.
- [4] M. Erol, L. F. M. Vieira, and M. Gerla, "Localization with DiveN'Rise (DNR) beacons for underwater acoustic sensor networks," in *Proceedings of the second workshop on Underwater networks - WuWNet '07*, 2007, p. 97. [Online]. Available: <http://dl.acm.org/citation.cfm?id=1287812.1287833%5Cnhttp://portal.acm.org/citation.cfm?id=1287812.1287833>
- [5] M. Erol, L. F. M. Vieira, A. Caruso, F. Paparella, M. Gerla, and S. Oktug, "Multi stage underwater sensor localization using mobile beacons," *Proceedings - 2nd Int. Conf. Sensor Technol. Appl., SENSORCOMM 2008, Includes: MESH 2008 Conf. Mesh Networks; ENOPT 2008 Energy Optim. Wireless Sensors Networks, UNWAT 2008 Under Water Sensors Systems*, pp. 710–714, 2008.
- [6] P. B. Padmanabhan and V. N., "RADAR: An in-building RF based user location and tracking system," *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No.00CH37064)*, vol. 2, no. c, pp. 775–784, 2000. [Online]. Available: <http://research.microsoft.com/en-us/groups/sn-res/infocom2000.pdf>
- [7] D. Kurth, G. Kantor, and S. Singh, "Experimental Results in Range-Only Localization with Radio," *Intelligent Robots and Systems, International Conference on*, no. October, pp. 974–979, 2003. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1250754
- [8] P. Baronti, P. Pillai, V. W. C. Chook, S. Chessa, A. Gotta, and Y. F. Hu, "Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards," *Computer Communications*, vol. 30, no. 7, pp. 1655–1695, 2007.
- [9] M. Khanafer, M. Guennoun, and H. T. Mouftah, "A Survey of Beacon-Enabled IEEE 802.15.4 MAC Protocols in Wireless Sensor Networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 856–876, 2014. [Online]. Available: <http://ieeexplore.ieee.org/ielx7/9739/6811383/06687312.pdf?tp=&arnumber=6687312&>
- [10] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1389128601003024>
- [11] F. Xia, R. Hao, Y. Cao, and L. Xue, "A survey of adaptive and real-time protocols based on IEEE 802.15.4," 2011.
- [12] F. Caballero, L. Merino, and A. Ollero, "A general Gaussian-mixture approach for range-only mapping using multiple hypotheses," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 4404–4409, 2010.
- [13] L. Geneve, O. Kermorgant, and E. Laroche, "A composite beacon initialization for EKF range-only SLAM," *IEEE International Conference on Intelligent Robots and Systems*, vol. 2015-Decem, pp. 1342–1348, 2015.
- [14] A. Ahmad, S. Huang, J. J. Wang, and G. Dissanayake, "A new state vector for range-only SLAM," *Proceedings of the 2011 Chinese Control and Decision Conference, CCDC 2011*, pp. 3404–3409, 2011.

- [15] S. Thrun, "Probabilistic robotics," *Communications of the ACM*, vol. 45, no. 3, 2002. [Online]. Available: <http://portal.acm.org/citation.cfm?doid=504729.504754>
- [16] M. I. Ribeiro, "Kalman and Extended Kalman Filters : Concept , Derivation and Properties," *Institute for Systems and Robotics Lisboa Portugal*, no. February, p. 42, 2004. [Online]. Available: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.2.5088&rep=rep1&type=pdf>
- [17] S. Haykin, *Kalman Filters*, 2001, vol. 5.
- [18] J. Djugash and S. Singh, "A robust method of localization and mapping using only range," *Proceedings of International Symposium on Experimental Robotics*, pp. 341–351, 2008.
- [19] F. R. Fabresse, F. Caballero, I. Maza, and A. Ollero, "Robust Range-Only SLAM for Unmanned Aerial Systems," *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 84, no. 1-4, pp. 297–310, 2016.
- [20] E. Olson, J. J. Leonard, and S. Teller, "Robust range-only beacon localization," *IEEE Journal of Oceanic Engineering*, vol. 31, no. 4, pp. 949–958, 2006.
- [21] P. V. C. Hough, "Machine analysis of bubble chamber pictures," *2nd International Conference on High-Energy Accelerators and Instrumentation*, vol. 73, pp. 554–558, 1959. [Online]. Available: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Machine+analysis+of+bubble+chamber+pictures#0>
- [22] D. Kurth, "Range-only robot localization and SLAM with radio," *Robotics Institute*, no. May, 2003. [Online]. Available: http://www.ri.cmu.edu/pub_files/pub4/kurth_derek_2004_1/kurth_derek_2004_1.pdf%5Cnpapers://c1ff9a07-d93a-4c8c-9965-c2843865360b/Paper/p472
- [23] G. Vallicrosa, P. Ridao, and D. Ribas, "AUV single beacon range-only SLAM with a SOG filter," *IFAC-PapersOnLine*, vol. 28, no. 2, pp. 26–31, 2015. [Online]. Available: <http://dx.doi.org/10.1016/j.ifacol.2015.06.005>
- [24] N. Patwari, J. Ash, S. Kyperountas, A. Hero, R. Moses, and N. Correal, "Locating the nodes: cooperative localization in wireless sensor networks," *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 54–69, 2005. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1458287>
- [25] A. Torres-González, J. R. Martínez-De Dios, and A. Ollero, "Exploiting multi-hop inter-beacon measurements in ro-slam," *Studies in Computational Intelligence*, vol. 604, pp. 101–119, 2015.
- [26] J. A. Djugash, S. Singh, G. Kantor, W. Zhang, and J. Djugash, "Range-Only SLAM for Robots Operating Cooperatively with Sensor Networks," no. May, pp. 2078–2084, 2006. [Online]. Available: <http://repository.cmu.edu/robotics>
- [27] F. Herranz, A. Llamazares, E. Molinos, and M. Ocana, "A comparison of SLAM algorithms with range only sensors," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 4606–4611, 2014.
- [28] F. Dellaert and M. Kaess, "Square root SAM: Simultaneous localization and mapping via square root information smoothing," in *International Journal of Robotics Research*, vol. 25, no. 12, 2006, pp. 1181–1203.
- [29] J. R. M.-d. Dios and A. Ollero, "Accurate fast mapping Range Only SLAM for UAS applications," 2015.
- [30] P. Newman and J. Leonard, "Pure range-only sub-sea SLAM," in *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*.
- [31] A. Kehagias, J. Djugash, and S. Singh, "Range-only SLAM with Interpolated Range Data," no. May, pp. 1–23, 2006.
- [32] F. R. Fabresse, F. Caballero, I. Maza, and A. Ollero, "Undelayed 3D RO-SLAM based on Gaussian-mixture and reduced spherical parametrization," *IEEE International Conference on Intelligent Robots and Systems*, pp. 1555–1561, 2013.
- [33] —, "Robust range-only SLAM for aerial vehicles," *2014 International Conference on Unmanned Aircraft Systems, ICUAS 2014 - Conference Proceedings*, pp. 750–755, 2014.
- [34] F. Fabresse, F. Caballero, and A. Ollero, "Decentralized simultaneous localization and mapping for multiple aerial vehicles using range-only sensors," *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 6408–6414, 2015. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7140099>