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OPTIMAL TRAJECTORY DESIGN FOR A DTOA BASED MULTI-ROBOT ANGLE OF ARRIVAL ESTIMATION SYSTEM FOR RESCUE OPERATIONS

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ABSTRACT

In this article we present an angle of arrival (AoA) multi-robot system for rescue purposes which takes advantage of robots' mobility to improve the position estimate of an unknown target. The robots move according to a certain trajectory (a sequence of stopping points) designed to minimize the variance of the AoA estimation. We present two different techniques to generate these optimal trajectories, with each technique having its own advantage.

***Index Terms*—** AoA estimation, multi-robot, trajectory planning.

1. INTRODUCTION

Recently the application of a robot's mobility to combat fading in a wireless channel has been studied [5]-[10]. In addition, there has also been an increasing interest in rescue robots [1]-[4]. Here we combine both of the above aspects and show that a robot's mobility can also be beneficial in the AoA estimation problem when applied to rescue robots.

The scenario we are considering here is the following. An individual may be lost due to an accident or a natural disaster. The objective is to locate his/her position so that a rescue team can find him/her. We will assume that the lost individual possesses an UWB emergency transmitter (ET) that emits periodically an S.O.S. r.f. signal which is known by the rescue team. To locate the position of the ET, teams composed of M multi-rotor aerial [11] robots are deployed in the area of interest. Each robotic team (which we will assume knows its own location via some method) performs an estimation of the AoA of the received r.f. wave radiated by the ET using the difference time of arrival (DToA) between all the members of the team (e.g., in [15] the authors also used the DToA principle to estimate the AoA for a radar application using a fixed antenna array).

As the robots' mobility will be a factor in minimising the variance of the AoA estimation, so an appropriate optimal trajectory must be designed. Finally, the robotic teams will combine their individual AoA estimates to obtain the ET's location. In this article we will only focus on the design of the trajectory for the AoA estimation (i.e., as opposed to how triangularisation is implemented across many robotic teams) and so we need only consider the performance of just one single team of robots. To the authors' knowledge this is the first time that devising an optimal trajectory has been used to reduce the variance of an AoA estimate in any application.

So, in section 2 we describe the system model as well as the principle used to estimate the AoA. In section 3 we show how to derive the optimal trajectories. In section 4 we explain how the DToA is obtained. Then, section 5 gives simulation results and finally conclusions are presented in section 6.

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2. SYSTEM MODEL

The composition and the physical configuration of the robotic team is presented in the first subsection and in the second subsection we explain how the AoA is estimated using the DToA. For mathematical simplicity we will focus only on the azimuthal component of the AoA and restrict the movement of the robots to a horizontal plane (see justification later).

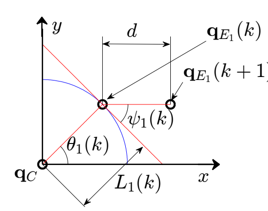


Fig. 1. Geometry of double robot formation.

2.1. Robotic Team Configuration

The robotic team is composed of two types of robots: (i) the central robot (CR) which remains stationary during the AoA estimation process, provides a temporal reference for the DToA estimation, calculates the DToA estimate (see section 4) and orders the explorer robots (ERs) to move; (ii) any ER searches the space around the CR in order to gather DToA measurents at different stopping points in order to estimate the AoA (see section 3). We assume that all the robots are multi-rotor aerial robots [11]. The difference between the CR and the ER is just their role in the team, i.e., both types of robots are physically identical (i.e., the same model of robot). Each robot posses a transceiver with a single antenna located at its geometrical center and we consider that all the robots have a localization system that allows each robot to know its own absolute location. In this paper we will consider only two sizes of robotic teams: (i) a robotic team with two robots (one CR and one ER) and (ii) a robotic team with three robots (one CR and two ERs). This is because obtaining the optimal trajectory for more than three robots is still an open problem.

The CR's location is denoted by $\mathbf{q}_C \in \mathbb{R}^2$ and the location of the mth ER at the kth iteration of the AoA estimation algorithm is given by $\mathbf{q}_{E_m}(k) \in \mathbb{R}^2$. We also define the following variables $L_m(k) = \|\mathbf{q}_{E_m}(k) - \mathbf{q}_C\|_2$ and $\theta_m(k) = \measuredangle\left(\mathbf{q}_{E_m}(k) - \mathbf{q}_C\right), \ m = 1, 2, \cdots, M-1$. Here, M is the number of robots in the team (CR plus ER). In Fig.1 we can see the geometry of the double robot formation (DRF).

2.2. Angle of Arrival Model

We assume that there is a line of sight (LoS) between the ET and the robotic team[1] so that even if there are multi-path components the AoA of the first wavefront that arrives comes from the direction where the ET is located. We also assume that the ET is sufficiently distant from the robotic team so that the incident wavefront is planar and the AoA (ϕ_0) to the antenna of every robot in the team is identical. Taking these assumptions into account the DToA between the mth ER and the CR (i.e., the difference between the instants at which the r.f. wave radiated by the ET first arrives at the antenna of the mth ER and the instant at which it first arrives at the antenna of the CR) is:

$$\begin{aligned}&\tau_m(\theta_m(k), L_m(k)) = \left(\tfrac{L_m(k)}{c}\right)\cos(\theta_m(k) - \phi_0)\cos(\omega)\\ &m = 1, 2, \cdots, M-1\end{aligned} \tag{1}$$

where ω is the elevation angle[2] and c is the speed of light. Therefore, by determining $\tau_m(\theta_m(k), L_m(k))$ at different formation angles ($\theta_m(k)$) the robots can estimate ($\hat{\phi}_0$) the AoA. In the following section, we will present two techniques to perform this estimation while taking advantage of the ER's mobility.

3. MULTI-ROBOT AOA ESTIMATION

In general the multi-robot AoA estimation uses M robots (one CR and (M-1) ERs) and each ER produces DToA measurements at K different positions or stopping points. Then the CR uses all the DToA measurements to estimate the AoA. In this section we explain how to obtain the optimal[3] trajectory (i.e., the sequence of stopping points) for teams of M=2 and M=3 robots.

The first technique, see subsection 3.1, requires only two robots but as the trajectory cannot be obtained analytically it needs significant computation. The second technique, see subsection 3.2, can only be implemented with a triple robotic team. But, in contrast to the first approach, it is possible to obtain analytically the optimum trajectory.

So, the normalized DToA estimate at iteration k, between the CR and the mth ER, is given by:

$$\hat{\tau}_m(\theta_m(k), L_m(k)) = \frac{c}{L_m(0)}\left(\tau_m(\theta_m(k), L_m(k)) + n_{\tau_m}(k)\right) \tag{2}$$

where $n_{\tau_m}(k) \sim \mathcal{N}(0, \sigma_n^2)$. Note that in [14] and [16] it was shown from experimental results that the error term for ToA and DToA estimation for UWB wireless channels similar to ours is Gaussian distributed. Thus this assumption for $n_{\tau_m}(k)$ is realistic here.

3.1. Double Robot AoA Estimation

In this subsection we explain how to obtain the optimum trajectory with K stopping points when we use only two robots. As already explained the trajectory is optimum in the sense that it minimizes the variance of the AoA maximum likelihood estimate (MLE) which is given by:

$$\hat{\phi}_0(\mathbf{\Theta}^{(2)}, \mathbf{L}^{(2)}) = \arg\min_{\phi} \sum_{k=1}^{K}\left(\hat{\tau}_1(\mathbf{\Theta}_k^{(2)}, \mathbf{L}_k^{(2)}) - \left(\frac{\mathbf{L}_k^{(2)}}{\mathbf{L}_1^{(2)}}\right)\cos(\mathbf{\Theta}_k^{(2)} - \phi)\right)^2 \tag{3}$$

where[4] $\mathbf{\Theta}^{(2)} = [\theta_1(0)\ \theta_1(1)\cdots\ \theta_1(K-1)]^T$, $\mathbf{L}^{(2)} = [L_1(0)\ L_1(1)\cdots\ L_1(K-1)]^T$, $\mathbf{\Theta}_k^{(2)}$ is the kth element of $\mathbf{\Theta}^{(2)}$ and $\mathbf{L}_k^{(2)}$ is the kth element of $\mathbf{L}^{(2)}$. Before explaining how to optimize the trajectory we add the following restriction to the ER movement[5]:

$$\begin{aligned}&\mathbf{q}_{E_1}(k+1) = \mathbf{q}_{E_1}(k) + d\mathbf{u}\left(-\psi_1(k) + \tfrac{\pi}{2} + \theta_1(k)\right)\\ &k = 0, 1, \cdots, K-2\end{aligned} \tag{4}$$

where $\mathbf{u}(\cdot) = [\cos(\cdot)\ \sin(\cdot)]^T$ and $\psi_1(k) \in [-\frac{\pi}{2}, +\frac{\pi}{2}]$ is the direction in which the robot performs this movement[6]. With-

[1] Since the robots are aerial robots and they are flying it is very likely that this assumptions holds if the terrain is relatively smooth.

[2] If the altitude of the robotic team is small compared to the distance between the robotic team and the ET then we will have $\omega \approx 0$ and consequently $\cos(\omega) \approx 1$. We will adopt this simplification throughout the article.

[3] The trajectory is optimal in the sense that it minimizes the variance of the AoA maximum likelihood estimate (MLE).

[4] The superscript "(2)" refers to $M = 2$ robots.

[5] This restriction forces the ER to move a fixed distance d in any direction that is always clockwise with respect to the CR. This is to reduce the overall size of the search space and eliminate duplicate optimal trajectories.

[6] The angle $\psi_1(k)$ is defined as the angle formed between the vector $[\mathbf{q}_{E_1}(k+1) - \mathbf{q}_{E_1}(k)]$ and the tangent at the point $\mathbf{q}_{E_1}(k)$ on the circle with center $\mathbf{q}_C$ and radius $L_1(k)$, (see Fig.1). In addition, we calculate $\psi_1(k)$ in the **OP-1** problem.

out loss of generality we consider $\theta_1(0) = 0$. Given this restriction on the ER movement, the optimum trajectory is obtained by solving the following optimization problem, **OP-1**.

$$\begin{aligned}
&\underline{\mathbf{OP-1}}\\
&\boldsymbol{\Psi}_{opt} = \arg\min_{\boldsymbol{\Psi}} \operatorname{var}\left[\hat{\phi}_0(\boldsymbol{\Theta}^{(2)}, \mathbf{L}^{(2)})\right]\\
&\text{s.t.}\\
&\mathbf{q}_{E_1}(k+1) = \mathbf{q}_{E_1}(k) + d\mathbf{u}\left(-\psi_1(k) + \tfrac{\pi}{2} + \boldsymbol{\Theta}^{(2)}_{k+1}\right)\\
&\mathbf{q}_{E_1}(0) = [\mathbf{L}_1^{(2)} \;\; 0]^T
\end{aligned} \tag{5}$$

where $\boldsymbol{\Psi} = [\psi_1(0)\ \psi_1(1)\ \cdots\ \psi_1(K-2)]$. An analytical expression for $\operatorname{var}\left[\hat{\phi}_0(\boldsymbol{\Theta}^{(2)}, \mathbf{L}^{(2)})\right]$ is not available and so we must calculate it by simulation in order to solve **OP-1**. The numerical evaluation of $\operatorname{var}\left[\hat{\phi}_0(\boldsymbol{\Theta}^{(2)}, \mathbf{L}^{(2)})\right]$ causes a big problem from a practical point of view since it significantly increases the computation needed to solve **OP-1**. Therefore, in order to reduce this computation we impose the following restriction (see Fig.1): $\psi_1(0)$=$\psi_1(1)$=$\cdots$=$\psi_1(K-2)$=ψ. This will decrease the dimensionality of the search space from K-1 to 1. Of course, the drawback with this reduction in dimensionality is that the solution will now exhibit a sub-optimal performance. Finally, we will use a hill climbing search [17] approach to solve **OP-1**. And as a last remark, it is not difficult to show that the solution for **OP-1** does not depend on d and $L_1(0)$ but only on the quotient $\frac{d}{L_1(0)}$.

3.2. Triple Robot AoA Estimation with Quadrature Formation

The approach of the previous subsection was computationally complex, as there was no analytical solution. In this subsection we will now show how to reduce the computation required by means of an analytic solution using three robots (one CR and two ERs). During the simulations in section 5, we will also see that the estimation performance has improved. In addition, the restriction given in (4) will also apply to both ERs. First we need to calculate the optimal initial angular difference (ξ_{opt}) between the two ERs. To do this we will force both ERs to lie at the same radius[7] from the CR (i.e., $L_1(0) = L_2(0)$) and solve the following optimization for one initial (i.e., $K = 1$) stopping point[8].

$$\begin{aligned}
&\underline{\mathbf{OP-2}}\\
&\xi_{opt} = \arg\min_{\xi} \operatorname{var}\left[\hat{\phi}_0(\boldsymbol{\Theta}^{(3)}, \mathbf{L}^{(3)})\right]\\
&\text{s.t.}\\
&\mathbf{L}_1^{(3)} = \mathbf{L}_0^{(3)}\\
&\boldsymbol{\Theta}_1^{(3)} = \boldsymbol{\Theta}_0^{(3)} + \xi
\end{aligned} \tag{6}$$

where $\hat{\phi}_0(\boldsymbol{\Theta}^{(3)}, \mathbf{L}^{(3)})$ is given by (3) but where "(2)" is replaced by "(3)", $\boldsymbol{\Theta}^{(3)} = \{\theta_1(0), \theta_2(0)\}$ and $\mathbf{L}^{(3)} = \{L_1(0), L_2(0)\}$. Again, using a hill climbing search we obtain $\xi_{opt} = \pm\frac{\pi}{2}$. So the optimal initial robotic formation (i.e., the formation at $k = 0$) is the quadrature formation (i.e., the ERs and the CR form a right-angled triangle). And because it will simplify the AoA estimation (as will be shown later in this subsection) we constrain the angle between the CR and the two ERs to remain at 90^o and on the same circle for $k \geq 1$ (with center $\mathbf{q}_C$ and radius $L_1(k)$). Thus we will impose the following restrictions on the two ERs:

$$\begin{aligned}
\theta_2(k) &= \theta_1(k) - \pi/2,\\
L_2(k) &= L_1(k).
\end{aligned} \tag{7}$$

Now we will explain how to estimate the AoA and obtain the optimum trajectory. The DToAs between the two ERs and the CR are:

$$\begin{aligned}
\tau_1(\theta_1(k), L_1(k)) &= \left(\tfrac{L_1(k)}{c}\right)\cos(\theta_1(k) - \phi_0),\\
\tau_2(\theta_1(k), L_1(k)) &= \left(\tfrac{L_1(k)}{c}\right)\sin(\theta_1(k) - \phi_0)
\end{aligned} \tag{8}$$

since $\cos(\theta_2(k)) = \sin(\theta_1(k))$. We will also define the following complex variable $z(\theta_1(k), L_1(k)) = \tau_1(\theta_1(k), L_1(k)) + j\tau_2(\theta_1(k), L_1(k))$ as it will now allow us to estimate the AoA in a simplified manner. The estimate of $z(\theta_1(k), L_1(k))$ (i.e., $\hat{z}(\theta_1(k), L_1(k))$=$\hat{\tau}_1(\theta_1(k), L_1(k)) + j\hat{\tau}_2(\theta_1(k), L_1(k))$) can be written as:

$$\hat{z}(\theta_1(k), L_1(k)) = \left(\tfrac{L_1(k)}{c}\right)\exp\left(j\left(\theta_1(k) - \phi_0\right)\right) + n_z(k) \tag{9}$$

where $n_z(k) = n_1(k) + jn_2(k)$. The estimation of $A_0 = \exp(-j\phi_0)$ is a linear estimation problem and the best linear unbiased estimate (BLUE) of A_0 is given by[9]:

$$\hat{A}_0 = \frac{c\sum_{k=0}^{K-1} \hat{z}(\theta_1(k), L_1(k)) \cdot L_1(k) \cdot \exp(-j \cdot \theta_1(k))}{\sum_{k=0}^{K-1} L_1^2(k)} \tag{10}$$

where $\operatorname{var}\left[\hat{A}_0\right] = 2c^2\sigma_n^2\left(\sum_{k=0}^{K-1} L_1^2(k)\right)^{-1}$. In order to minimize this variance we need to maximize the denominator which is maximized when (see Fig.1):$\psi_1(k) = \frac{\pi}{2}\ \ \forall k$. In other words, for the quadrature formation the optimal trajectory for any ER is to move at each iteration a step d (design parameter) along the radial direction on the line joining the CR to the ER.

4. DTOA ESTIMATION

As stated in the previous section the robots need to estimate $\tau_m(\theta_m(k), L_m(k))$. Here we explain how this is achieved. First, as mentioned earlier, the ET will transmit periodically an UWB pulse $s(t)$ which is known by all the robots[10]. In

[7]This is done so that $\hat{\tau}_1(\theta_1(k), L_1(k))$ and $\hat{\tau}_2(\theta_2(k), L_2(k))$ will both have the same variance.

[8]Note that the superscript "(3)" refers to $M = 3$ robots.

[9]The estimate $\hat{\phi}_0$ is the angle of the phasor $\hat{A}_0$.

[10]This assumption is realistic in a rescue scenario since the signal $s(t)$ would be standard, i.e., known by everyone, and it would be sent periodically to allow the localization of the transmitter.

order to measure $\tau_m(\theta_m(k), L_m(k))$ the robots must be time synchronized and this can done (for example) by using the protocol in [18].

So we can now say that $\tau_m(\theta_m(k), L_m(k)) = T_{E_m}(k) - T_C(k)$, where $T_{E_m}(k)$ is the time of arrival (ToA) of the LoS component of the pulse $s(t)$ to the mth ER's antenna during the kth iteration and $T_C(k)$ is the ToA of the LoS component of the pulse $s(t)$ to the CR's antenna during the kth iteration. Each robot estimates its corresponding ToA. This can be done by detecting the first r.f. LoS component as was described in [14], [16], [19] and [20]. Once the robots have estimated the ToAs, the ERs send their estimates to the CR and then it calculates the normalized estimate of $\tau_m(\theta_m(k), L_m(k))$ as: $\hat{\tau}_m(\theta_m(k), L_m(k)) = c\left(\hat{T}_{E_m}(k) - \hat{T}_C(k)\right) L_1^{-1}(0)$.

5. SIMULATIONS

We first show the advantage of using the optimized trajectory. In order to consider realistic values we use the experimental results reported on [16]. So, if we assume a bandwidth of 500MHz then we get $c\sigma_n = 53.8$cm.

First we will consider arbitrarily[11] the DRF with $L_1(0) = 10.7$m and $d = 10.7$m. We compare two cases: (i) in the first case we will always select $\psi = 0$ (see subsection 3.1) for any number of stopping points K, (i.e., we do not optimize ψ). This will be used as a reference or benchmark; (ii) in the second case we will always select the optimal value $\psi = \psi_{opt}$ (see **OP-1**). Both cases consume the same amount of resources (bandwidth, distance travelled) and have the same initial configuration but the optimized version has a significantly lower variance[12] (see Fig.2). Note that in Fig.2, ψ_{opt} (for any K) is the value of ψ corresponding to the minimum of each curve. So, in general (see Fig.2) if we do not optimize ψ we may get a much lower performance (yet still consuming the same ressources). We now compare the performance

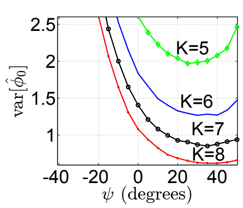
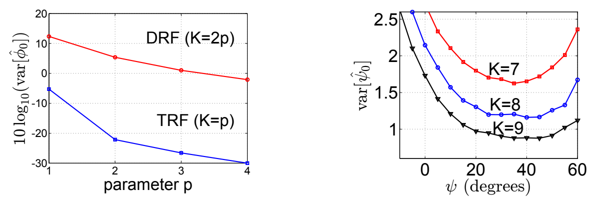


Fig. 2. DRF results with $c\sigma_n = 53.8$cm.

of the triple robot formation (TRF). To do a fair comparison we compare the TRF with p stopping points to the DRF with $2p$ stopping points. The reason for this is that the triple formation has two ERs and so for the same number of stopping points it has double the number of measurements. In addition, for both formations we use $L_1(0) = 10.7$m, $d = 10.7$m and $c\sigma_n = 53.8$cm. As we can see in Fig.3(a) the performance of the TRF is significantly better than the DRF. This means that the advantage of the TRF is not only its mathematical and computational simplicity for the design of the optimal trajectory but also its performance. So, if we want to maximize performance we should use the TRF, but if we want to minimize the number of robots in the team we should use the DRF.



(a) (b)

Fig. 3. (a) DRF and TRF comparison; (b) DRF results with $c\sigma_n = 107.6$cm and K stopping points.

Finally, we will now examine how our proposed algorithm copes with increased DToA estimation error (σ_n^2) in (2). In Fig.2 we set $c\sigma_n = 53.8$cm but in Fig.3(b) we will choose $c\sigma_n = 107.6$cm twice as large (e.g., it might be because the ET is further away and so the received signal is weaker). Also, as in Fig.2 we choose $L_1(0) = 10.7$m and $d = 10.7$m. Let us assume that we want an AoA estimate variance that is less than 1. From Fig.2, we can select $K = 7$ to satisfy this requirement, but from Fig.3(b) we need $K = 9$ stopping points.

Note that for AoA estimation methods which must use non-mobile fixed antenna arrays, then the performance depends on the number of elements of the array. And the number of antennas cannot be changed once the system is deployed. But with multi-robot systems the performance depends on the number of stopping points (K) which can be selected online according to each scenario (as illustrated in this example). Therefore the multi-robot system has the advantage of adaptability due to the robot's mobility. We can also obtain a large separation between the robots' antenna (which improves the performance) without any problem. Also, this kind of system is easy to deploy and transport. All these advantages are not present on fixed antenna array systems.

6. CONCLUSIONS

In this article we have proposed a multi-robot system (using either two or three robots) for rescue operations which can estimate the direction of the rescue target. The main contribution of this article is to show that the controlled mobility of the robots is beneficial to the AoA estimation process based on DToA measurements. We also have showed that there is an optimum trajectory and indicated how to derive it. This is the first time that controlled mobility has been used in such a scenario.

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[11] This is because d and $L_1(0)$ are design parameters.

[12] All the angles in this section are expressed in degrees.

7. REFERENCES

[1] Ventura R., Lima P.U.,"Search and Rescue Robots: the Civil Protection Teams of the Future", Proc. of Third International Conference on Emerging Security Technologies (EST), 2012.

[2] Dey G.K., Hossen R., Noor M.S., "Distance Controlled Rescue and Security Mobile Robot", Proc. of International Conference on Informatics, Electronics & Vision (ICIEV), 2013.

[3] Erdos D., Erdos A., Watkins S.E., "An experimental UAV system for search and rescue challenge", IEEE Aerospace and Electronic Systems Magazine, vol. 28, no. 5, May 2013.

[4] Murphy R.R., "A decade of recue robots", Proc. of International Conference on Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ.

[5] J. M. Smith, M. P. Olivieri, A. Lackpour and N. Hinnerschitz, "RF-mobility gain: concept, measurement campaign, and explotation", IEEE Wireless Communications,vol. 16, no. 1, February 2009.

[6] A. Ghaffarkhah and Y. Mostofi, "Path planning for networked robotic surveillance", IEEE Transactions on Signal Procesing, vol. 60, no. 7, July 2012.

[7] Y. Yan and Y. Mostofi, "Co-optimisation of communication and motion planning of a robotic operation in fading environments", IEEE Transactions on Wireless Communications, vol. 12 No. 4, April 2013.

[8] M. Lindhe and K. H. Johansson, "Using robot mobility to exploit multipath fading", IEEE Wireless Communications, vol. 16, no. 1, February 2009.

[9] D. Bonilla Licea, D. McLernon, M. Ghogho, "A robotic mobility diversity algorithm with markovian trajectory planners", Proc. of the 2013 23rd IEEE Signal Processing Society Workshop on Machine Learning for Signal Processing (MLSP), 2013.

[10] D. Bonilla Licea, D. McLernon, M. Ghogho, Syed Ali Raza Zaidi, "An Energy Saving Robot Mobility Diversity Algorithm for Wireless Communications", Proc. of the 21st European Signal Processing Conference (EUSIPCO), 2013.

[11] Mahony R., Kumar V., Corke P., "Multirotor Aerial Vehicles: Modeling, Estimation, and Control of Quadrotor", IEEE Robotics & Automation Magazine, September 2012.

[12] R. Ardoino, F. Capriati, "DTOA estimation of pulse trains by means of cross-correlation technique", Proc. of the IEEE Radar Conference 2008.

[13] Z. Xi, H. Yu, G. Huang, J. Lu,"DOA Estimation of Multiple Sources Based on Multiset Canonical Correlation Analysis", Proc. of the IEEE CIE International Conference on Radar (Radar), 2011.

[14] W. Wang, T. Jost, C. Mensing and A. Dammann, "ToA and TDoA Error Models for NLoS Propagation Based on Outdoor to Indoor Channel Measurement", Proc. of IEEE Wireless Communications and Networking Conference, 2009.

[15] R. Ardoino, F. Capriati, "DTOA Estimation of Pulses Trains by means of Cross-Correlation Technique", Proc. of IEEE Radar Conference, 2008.

[16] B. Alavi, K. Pahlavan, "Modeling of the TOA-based Distance Measurement Error Using UWB Indoor Radio Measurements", IEEE Communications letter, vol. 10, no. 4, April 2006.

[17] S. Russell and P. Norving, *Artificial Intelligence- A Modern Approach*, Prentice Hall, 2e, 2003.

[18] S.S. Woo "Analysis of Proximity-1 Space Link Interleaved Time Synchronization (PITS) Protocol", Proc. of IEEE Global Telecommunications Conference (GLOBECOM 2011), 2011.

[19] C. Xu, C.L. Law, "Delay-Dependent Threshold Selection for UWB TOA Estimation", IEEE Communications Letters, vol. 12, no. 5, May 2008.

[20] A. Giorgetti, M. Chiani, "Time-of-Arrival Estimation Based on Information Theoretic Criteria", IEEE Transactions on Signal Processing, vol. 61, no. 8, April 15, 2013.