

RANGE-BASED COOPERATIVE AND NON-COOPERATIVE LOCALIZATION USING NON-LINEAR PROGRAMMING

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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This dissertation is dedicated to

Makhan Lal Mukhopadhyay, my dear Grandfather – who, as one of the hapless refugees in his own motherland, braved the immense horror of partition and remained honest and firm all through his life.

CERTIFICATE

This is to certify that the thesis titled **Range-based Cooperative and Non-cooperative Localization using Non-linear Programming** , submitted by **Bodhibrata Mukhopadhyay**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Range-based cooperative and non-cooperative localization refers to the ability to determine the location of the target nodes (nodes whose position is unknown at the time of deployment) based on the locations of the anchor nodes (nodes whose locations are known apriori) and the pairwise distances (or parameters related to pairwise distances) between neighbouring nodes. In this thesis, we propose various received signal strength (RSS)-based localization techniques, derive theoretical performance bounds, and validate their performance via extensive simulations and experiments. We derive the Cramer-Rao lower bound (CRLB) for each of the estimators and use them as a performance benchmark. The maximum likelihood (ML) formulation of the RSS-based localization is non-convex, non-linear, discontinuous, and cannot be solved with a convergence guarantee using standard optimization techniques. Therefore, we use various relaxation techniques to convert the ML into a constrained or unconstrained optimization problem with guaranteed convergence. We convert the ML into a tractable form using semidefinite/convex/invex relaxation, and solve it using constrained and unconstrained optimization methods.

First, we present an RSS-based distributed iterative cooperative localization technique, where the target nodes communicate with the anchor nodes to localize themselves in the first iteration. After that the target nodes behave as pseudo anchor nodes. In the second iteration, the target nodes update their location using measurements from the neighbouring anchor and pseudo anchor nodes. We observe that the localization error propagates from one iteration to the next and we mitigate this by eliminating the network edge nodes from updating their location information after the first iteration. The network edge nodes are detected using the proposed quadrant (Quad) method and geometric dilution of precision (GDOP) based method.

Next, we propose two RSS-based localization techniques in which we utilize a novel linearization technique (to linearize the non-linear relationship between inter-node distance and received power). Using semidefinite relaxation we convert the ML problem into a constrained

convex optimization problem. We also consider scenarios where the transmit power of the target node is unknown and estimate it along with the location of the target nodes.

We also propose novel techniques to convert the RSS-based localization problem into an unconstrained optimization problem. We relax the ML function to either a convex or invex (invariant convex) function, and solve it using gradient descent method. This relaxation is achieved by obtaining a function that underestimates the ML cost function. We derive the Lipschitz constants for the gradient of the relaxed ML functions, prove their theoretical convergence, and derive the rate of convergence. Using the distributive property of coordinate descent we solve the invexified ML in a distributed manner without any synchronization requirements.

Next, we address scenarios where malicious anchor node(s) attempt to disrupt the localization process of a target node in an uncoordinated or coordinated manner. We propose techniques based on weighted least squares and ℓ_1 -norm optimization to safeguard the localization process from the malicious nodes. The weighted least square based techniques are shown to offer significant advantages in uncoordinated attacks over existing techniques by detecting the malicious nodes and eliminating their measurements from the localization process. In a coordinated attack, the localization problem can be posed as a plane fitting problem where the measurements from non-malicious and malicious anchor nodes lie on two different planes. The ℓ_1 -norm based technique estimates the two planes and prevents disruption of the localization process. This technique can also determine the location where the malicious anchor nodes intend to make the target node appear to be located.

Finally, we implemented an indoor localization system using passive infrared (PIR) sensors, where we localized a human subject in a $7\text{ m} \times 7.5\text{ m}$ area. We have proposed a mathematical model for the analog response of the PIR sensor, the Fresnel lens, and associated electronic circuitry. Our model relates the analog output waveform of the sensor to the width of the sensing element, speed of movement and distance of the subject from the PIR sensor. Using this model, we propose techniques to estimate the distance from the peak to peak value of the analog output of the PIR sensor. Once the distances of the subject from the PIR sensors are estimated, multilateration or support vector regression (SVR) based techniques are used to compute the subject's location.

सार

रैंज-आधारित सहकारी और गैर-सहकारी स्थानीयकरण एंकर नोड्स के स्थानों के आधार पर लक्ष्य नोड्स (नोड्स जिनकी स्थिति अज्ञात है) के स्थान को निर्धारित करने की क्षमता को संदर्भित करता है (नोड्स जिनके स्थानों को पहले से जाना जाता है) और पड़ोसी नोड्स के बीच जोड़ीदार दूरी (या जोड़ीदार दूरी से संबंधित पैरामीटर)। इस थीसिस में, हम विभिन्न प्राप्त सिग्नल शक्ति (आरएसएस) आधारित स्थानीयकरण तकनीकों का प्रस्ताव करते हैं, सैद्धांतिक प्रदर्शन सीमा प्राप्त करते हैं, और व्यापक सिमुलेशन और प्रयोगों के माध्यम से उनके प्रदर्शन को मान्य करते हैं। हम प्रत्येक अनुमानक के लिए क्रैमर-राव लोअर बाउंड (सीआरएलबी) प्राप्त करते हैं और उन्हें प्रदर्शन बेंचमार्क के रूप में उपयोग करते हैं। RSS-आधारित स्थानीयकरण की अधिकतम संभावना (ML) सूत्रीकरण गैर-उत्तल, गैर-रैखिक, असंतत है, और मानक अनुकूलन तकनीकों का उपयोग करके एक अभिसरण गारंटी के साथ हल नहीं किया जा सकता है। इसलिए, हम गारंटीकृत अभिसरण के साथ एमएल को एक विवश या अप्रतिबंधित अनुकूलन समस्या में बदलने के लिए विभिन्न छूट तकनीकों का उपयोग करते हैं।

हम अर्धनिर्धारित/उत्तल/इनवेक्स छूट का उपयोग करके एमएल को एक ट्रैक्टेबल रूप में परिवर्तित करते हैं, और इसे विवश और अप्रतिबंधित अनुकूलन विधियों का उपयोग करके हल करते हैं।

सबसे पहले, हम एक आरएसएस-आधारित वितरित पुनरावृत्त सहकारी स्थानीयकरण तकनीक प्रस्तुत करते हैं, जहां लक्ष्य नोड पहले पुनरावृत्ति में खुद को स्थानीयकृत करने के लिए एंकर नोड्स के साथ संचार करते हैं। उसके बाद लक्ष्य नोड्स छद्म एंकर नोड्स के रूप में व्यवहार करते हैं। दूसरे पुनरावृत्ति में, लक्ष्य नोड्स पड़ोसी एंकर और छद्म एंकर नोड्स से माप का उपयोग करके अपने स्थान को अपडेट करते हैं। हम देखते हैं कि स्थानीयकरण त्रुटि एक पुनरावृत्ति से दूसरे तक फैलती है और हम पहले पुनरावृत्ति के बाद नेटवर्क किनारे नोड्स को उनके स्थान की जानकारी को अपडेट करने से हटाकर इसे कम करते हैं। प्रस्तावित क्वाड्रंट (क्वाड) विधि और सटीक (जीडीओपी) आधारित विधि के ज्यामितीय कमजोर पड़ने का उपयोग करके नेटवर्क एज नोड्स का पता लगाया जाता है।

इसके बाद, हम दो आरएसएस-आधारित स्थानीयकरण तकनीकों का प्रस्ताव करते हैं जिसमें हम एक उपन्यास रैखिककरण तकनीक का उपयोग करते हैं (अंतर-नोड दूरी और प्राप्त शक्ति के बीच गैर-रैखिक संबंध को रैखिक करने के लिए)। अर्ध-निश्चित छूट का उपयोग करके हम एमएल समस्या को एक विवश उत्तल अनुकूलन समस्या में बदल देते हैं। हम उन परिदृश्यों पर भी विचार करते हैं जहां लक्ष्य नोड की संचार शक्ति अज्ञात है और लक्ष्य नोड्स के स्थान के साथ इसका अनुमान लगाते हैं।

हम आरएसएस-आधारित स्थानीयकरण समस्या को एक अप्रतिबंधित अनुकूलन समस्या में बदलने के लिए नई तकनीकों का भी प्रस्ताव करते हैं। हम एमएल फ़ंक्शन को उत्तल या इनवेक्स (अपरिवर्तनीय उत्तल) फ़ंक्शन में आराम देते हैं, और इसे ग्रेडिएंट डिसेंट विधि का उपयोग करके हल करते हैं। यह छूट एक फ़ंक्शन प्राप्त करके प्राप्त की जाती है जो एमएल लागत फ़ंक्शन को कम करके आंका जाता है।

हम आराम से एमएल कार्यों के ढाल के लिए लिप्सचिट्ज़ स्थिरांक प्राप्त करते हैं, उनके सैद्धांतिक अभिसरण को साबित करते हैं, और अभिसरण की दर प्राप्त करते हैं। समन्वय वंश की वितरण संपत्ति का उपयोग करके हम बिना किसी सिंक्रनाइज़ेशन आवश्यकताओं के वितरित तरीके से इनवेक्सिफाइड एमएल को हल करते हैं

इसके बाद, हम उन परिदृश्यों को संबोधित करते हैं जहां दुर्भावनापूर्ण एंकर नोड एक असंगठित या समन्वित तरीके से लक्ष्य नोड की स्थानीयकरण प्रक्रिया को बाधित करने का प्रयास करते हैं। हम दुर्भावनापूर्ण नोड्स से स्थानीयकरण प्रक्रिया को सुरक्षित रखने के लिए भारित न्यूनतम वर्गों और L1-मानक अनुकूलन पर आधारित तकनीकों का प्रस्ताव करते हैं। भारित न्यूनतम वर्ग आधारित तकनीकों को दुर्भावनापूर्ण नोड्स का पता लगाकर और स्थानीयकरण प्रक्रिया से उनके माप को समाप्त करके मौजूदा तकनीकों पर असंगठित हमलों में महत्वपूर्ण लाभ प्रदान करने के लिए दिखाया गया है। एक समन्वित हमले में, स्थानीयकरण समस्या को एक विमान फिटिंग समस्या के रूप में प्रस्तुत किया जा सकता है जहां गैर-दुर्भावनापूर्ण और दुर्भावनापूर्ण एंकर नोड्स से माप दो अलग-अलग विमानों पर होते हैं। L1 मानदंड आधारित

तकनीक दो विमानों का अनुमान लगाती है और स्थानीयकरण प्रक्रिया में व्यवधान को रोकती है। यह तकनीक उस स्थान को भी निर्धारित कर सकती है जहां दुर्भावनापूर्ण एंकर नोड्स लक्ष्य नोड को स्थित करने का इरादा रखते हैं।

अंत में, हमने निष्क्रिय इन्फ्रारेड (पीआईआर) सेंसर का उपयोग करके एक इनडोर स्थानीयकरण प्रणाली लागू की, जहां हमने एक मानव विषय को $7\text{m} \times 7.5\text{m}$ क्षेत्र में स्थानीयकृत किया। हमने पीर सेंसर, फ्रेस्नेल लेंस और संबंधित इलेक्ट्रॉनिक सर्किटरी की एनालॉग प्रतिक्रिया के लिए गणितीय मॉडल का प्रस्ताव दिया है। हमारा मॉडल सेंसर के एनालॉग आउटपुट वेवफॉर्म को सेंसिंग एलिमेंट की चौड़ाई, गति की गति और पीआईआर सेंसर से विषय की दूरी से संबंधित करता है। इस मॉडल का उपयोग करते हुए, हम पीर सेंसर के एनालॉग आउटपुट के शिखर से शिखर तक की दूरी का अनुमान लगाने के लिए तकनीकों का प्रस्ताव करते हैं। एक बार जब पीर सेंसर से विषय की दूरी का अनुमान लगाया जाता है, तो विषय के स्थान की गणना करने के लिए मल्टीलेटरेशन या सपोर्ट वेक्टर रिग्रेशन (एसवीआर) आधारित तकनीकों का उपयोग किया जाता है।

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ACRONYMS

ADC	Analog to Digital Converter
ADMM	Alternating Direction Method of Multipliers
ALE	Average Localization Error
AMAX	Average Maximum Error
AMIN	Average Minimum Error
ANN	Artificial Neural Network
AoA	Angle of Arrival
ARM MSE	Attack-Resistance Minimum Mean Square Estimation
CDF	Cumulative Distribution Function
CRLB	Cramer–Rao Lower Bound
DoC	Degree of Consistency
DV-Hop	Distance Vector-Hop
FIM	Fisher information matrix
FoV	Field of View
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GUI	Graphical User Interface
IoT	Internet of Things
IPM	Interior Point Method
IR	Infrared
k-NN	k-Nearest Neighbour
LMdS	Least Median of Square
LS	Least Square
MDS	Multidimensional Scaling
ML	Maximum Likelihood
MMSE	Minimum Mean Square Estimation
MSO	Mixed Signal Oscilloscope

PDF	Probability Density Function
PIR	Passive Infrared
PL	Polyak-Łojasiewicz
RAPS	Reliable Anchor Pair Selection
RF	Radio Frequency
RFID	Radio-Frequency Identification
RMSE	Root Mean Square Error
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SDP	Semidefinite Programming
SOCP	Second-order cone programming
SV	Support Vectors
SVR	Support Vector Regression
TDoA	Time delay of Arrival
ToA	Time of Arrival
WLS	Weighted Least Square
WMAX	Worst case Maximum Error
WMIN	Worst case Minimum Error
WPIR	Wireless and Pyroelectric System
WSN	Wireless Sensor Network

NOTATION

$\mathbb{R}^k$	k dimensional Euclidean space
a or A	Scalar Quantity
$\mathbf{a}$	Vector Quantity
$[\mathbf{a}]_i$	i^{th} element of $\mathbf{a}$
$\ \mathbf{a}\ $ or $\ \mathbf{a}\ _2$	ℓ_2 norm of $\mathbf{a}$
$\ \mathbf{a}\ _1$	ℓ_1 norm of $\mathbf{a}$
$\mathbf{1}_N$	Column vector of size N with all its elements being 1
$\mathbf{0}_N$	Column vector of size N with all its elements being 0
$\mathbf{A}$	Matrix
$[\mathbf{A}; \mathbf{B}]$	Vertical concatenation of matrices $\mathbf{A}$ and $\mathbf{B}$
$[\mathbf{A} \ \mathbf{B}]$	Horizontal concatenation of matrices $\mathbf{A}$ and $\mathbf{B}$
$[\mathbf{A}]_{ij}$	Element located at the intersection of i^{th} row and j^{th} column of $\mathbf{A}$
$\mathbf{I}$	Identity matrix
$\text{diag}\{\cdot\}$	Diagonal matrix
$\mathbf{A}^T$	Transpose of $\mathbf{A}$
$\text{tr}(\mathbf{A})$	Trace of $\mathbf{A}$
$\det(\mathbf{A})$	Determinant of $\mathbf{A}$
$\mathbf{A}^\dagger$	Moore Penrose pseudo inverse of $\mathbf{A}$
$\mathcal{A}$	Represents a set
$ \mathcal{A} $	Cardinality of $\mathcal{A}$
$\{\mathbf{t}^k\}$	Sequence
$\mathbf{t}^*$	Limiting point of sequence $\{\mathbf{t}^k\}$
$\mathbf{t}^k \rightarrow \mathbf{t}^* / \lim_{k \rightarrow \infty} \mathbf{t}^k = \mathbf{t}^*$	$\{\mathbf{t}^k\}$ converges to $\mathbf{t}^*$ or $\mathbf{t}^*$ is the limiting point of sequence $\{\mathbf{t}^k\}$
$\sup(\cdot)$	Least upper bound
$\inf(\cdot)$	Greatest lower bound
∇f	Gradient of f
$\mathbf{A} \succcurlyeq \mathbf{B}$	$(\mathbf{A} - \mathbf{B})$ is a positive semidefinite matrix
$\mathbf{A} \succ \mathbf{B}$	$(\mathbf{A} - \mathbf{B})$ is a positive definite matrix
$\mathcal{T}$	Set of target nodes
$\mathcal{A}$	Set of anchor nodes
N	Total number of anchor nodes present in the network
M	Total number of target nodes present in the network
$\mathbf{a}_i$	Coordinate of i^{th} anchor node
$\mathbf{t}_i$	Coordinate of i^{th} target node
$\mathcal{T}_i$	Set of neighbouring target nodes of $\mathbf{t}_i$
$\mathcal{A}_i$	Set of neighbouring anchor nodes of $\mathbf{t}_i$
$\mathcal{N}_i$	Set of all neighbouring nodes (anchor nodes and target nodes) of $\mathbf{t}_i$
R^c	Communication range of the nodes
P_{ij}^{rx}	Received power (in dBm) at $\mathbf{a}_j$ or $\mathbf{t}_j$ when $\mathbf{t}_i$ transmits or

P_i^{tx}	Received power (in dBm) at $\mathbf{t}_i$ when $\mathbf{a}_j$ or $\mathbf{t}_j$ transmits
$\mathbf{p}_i^{\text{rx}}$	Transmit power (in dB) of $\mathbf{t}_i$
$\mathbf{P}^{\text{rx}}$	RSS measurements of all neighboring anchor-target and target-target links of the i^{th} target node
$p(\mathbf{p}_i^{\text{rx}} \cdot)/p(\mathbf{P}^{\text{rx}} \cdot)$	RSS measurements of all anchor-target and target-target links
d_{ij}	The conditional joint probability density function of RSS measurements
n	Euclidean distance between $\mathbf{t}_i$ and $\mathbf{a}_j$ (or $\mathbf{t}_j$) or
η_{ij}	Euclidean distance between $\mathbf{t}_j$ and $\mathbf{a}_i$ (or $\mathbf{t}_i$)
$o(\cdot)$	Path loss exponent
$\mathcal{O}(\cdot)$	Zero mean Gaussian random variable with variance σ^2 ($\eta_{ij} \sim \mathcal{N}(0, \sigma^2)$)
	Little o notation
	Big $\mathcal{O}$ notation