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Minimizing Localization error in Wireless sensor networks Taguchi method

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Abstract: - Localization is a key research area in wireless sensor networks. The study focuses on the system's behavioral analysis in terms of minimizing localization error by adjusting parameters such as nodes, network size, communication range, and network deployment. Implementing the Kalman filter in the localization algorithm helps strengthen the technique and improve the success rate in the presence of measurement malfunctions. A series of trials were carried out to an optimal level utilizing the Taguchi technique to determine the most influential parameter among them. Taguchi's experimental research demonstrated that the number of nodes is the most influential factor in reducing inaccuracy in Wireless Sensor Network (WSN) localization.

Keywords: Wireless sensor networks, localization, range-free, centroid, Taguchi.

I. Introduction

Wireless Sensor Networks (WSNs)[1][2] are made up of spatially distributed autonomous sensors that monitor and record environmental variables and wirelessly transmit the acquired data. These networks are utilized for a variety of purposes, including industrial monitoring, environmental sensing, healthcare, military surveillance, and smart infrastructure. WSNs are made up of low-power devices designed to enhance energy efficiency, and node location is crucial for wireless sensor networks, therefore localization is a significant challenge. Localization algorithms determine the location of unidentified sensor nodes in the network. Anchor nodes have known positions, either by GPS or specified coordinates. Unknown or non-anchor nodes are nodes that do not know where they are. The coordinates of non-anchor nodes must be determined using sensor network localization methods.

Localization [3][4][5][6][7][8] strategies in Wireless Sensor Networks (WSNs) are roughly divided into two types: range-based[9] and range-free algorithms[10][11]. Range-based procedures determine the location of sensor nodes by analyzing their spatial or angular information using techniques such as trilateration and triangulation. Range-based systems are classified into four types: Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Received Signal Strength Indicator (RSSI). Range-free localization methods, which are commonly utilized in large-scale WSNs due to their low cost and feasibility, are based on node connectivity data. Unidentified nodes calculate their placements by first gathering connection information and anchor node positions. Range-free approaches include the Approximate Point-in-Triangulation Test (APIT), DV-Hop, Multi-hop, Centroid, and Gradient. Range-based localization algorithms are more accurate, although they can be influenced by external conditions and are frequently more expensive and sophisticated. Range-free algorithms are less accurate in general, but they are more cost-effective and scalable for large-scale WSN deployment.

The Centroid Localization Algorithm[12][13] is a range-free localization algorithm for Wireless Sensor Networks (WSNs). It calculates the centroid of surrounding anchor node positions to approximate an unknown node's position. This approach is simple, inexpensive, and straightforward to deploy, making it appropriate for large-scale networks where precision is not a top requirement. To improve accuracy and precision, the Centroid Localization Algorithm can be combined with other optimization approaches or supplemented with additional data processing methods. These optimization strategies can improve range-free localization algorithms by enhancing location accuracy and reducing measurement errors.

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The Taguchi method[14][15][16] is a useful tool to optimize designs for high performance and quality with limited trials. Taguchi methods can be applied to optimize the localization process in WSNs, improving accuracy and reducing computational complexity and energy consumption. Applying Taguchi methods to localization in WSNs enables systematic and efficient optimization of the localization process. By identifying the key factors and their optimal levels, Taguchi methods help improve localization accuracy, reduce energy consumption, and enhance the overall performance of the wireless sensor network. Here address Some studies related to Taguchi method in WSN.

Jeng-Shyang Pan et al.[17] devised an evolutionary method for quasi-affine transformations that was improved using the Taguchi strategy. This algorithm selects a specific optimization route based on a probability, and the Taguchi approach aids the program in achieving more precise local exploitation. This approach is paired with a back-propagation neural network (BPNN) and used to detect faults in wireless sensor networks. The algorithm is also applicable to various WSN applications, including intrusion detection, node placement, 3D map planning, data fusion, and energy cycle.

Beyza[18] developed an experimental design study is presented for parameter optimization of quick artificial bee colony algorithm in dynamic deployment problem of wireless sensor networks using Taguchi method. Colony size, limit and neighborhood radius are considered as design factors. Then a comparative study is conducted between the predicted Signal to Noise ratio of the Taguchi model and the calculated one from the actual observations for the proposed values of the control parameters. Result indicates that these values are very close, and the model reliably predicts the Signal to Noise ratio.

ZhiSheng Wang et al.[19] developed an energy-adaptive clustering method based on the Taguchi-based grey wolf optimizer (EACM-TGWO) for networks with mobile sinks (MS). First, a method for calculating the appropriate number of cluster heads (CH) is developed by combining the characteristics of data transmission in MS-based WSNs. Second, the clustering fitness function is proposed, taking into account residual energy and average distance. The author proposed an enhanced version (TGWO) based on GWO and compared them.

Liang Li et al.[20] used the Taguchi approach to optimize a robotic fish's maximum swimming speed, taking into account four factors: caudal-fin aspect ratio, caudal fin stiffness, oscillation frequency, and spring stiffness. Frequency and spring stiffness were determined as critical parameters after 25 orthogonal design trials. The fish reached a speed of 870 mm/s (2.6 BL/s) with a frequency of 12Hz and an unlimited spring stiffness.

Gowri et al.[21] used the Taguchi technique to conduct a thorough performance analysis of a self-contained UV disinfection robot (UV bot). They designed a tiny, high-performance robotic system. This robot was validated with Taguchi analysis and tested for both static and dynamic obstacles.

T. Mathavaraj et al.[22] applied the Taguchi method to optimize relative localization (minimize odometry error) in a two-wheeled differential drive robot. The study considered parameters like total weight, speed, wheel diameter, and wheel width. Using the L9 orthogonal array, the experiments determined the optimum conditions for improved odometry.

Chen et al.[23] presented the Hybrid Taguchi-Genetic Algorithm (HTGA) for mobile location. HTGA combines the Taguchi methodology and the genetic algorithm (GA) to show that the Taguchi algorithm can improve genetic rule sets. Taguchi method can also be applied to various applications to figure out the essential components and increase the effectiveness of the system.

Dayong Wu et al.[24] used the Taguchi technique to calculate the ideal cutting parameters for surface roughness in turning operations. It uses orthogonal arrays, signal-to-noise ratio analysis, and variance analysis to study performance characteristics of TiN-coated tools used to machine AISI 1030 steel bars. The study optimizes three cutting parameters: insert radius, feed rate, and depth of cut, with a focus on surface roughness. Experimental results are presented to demonstrate the efficacy of this strategy.

Jing Xie et al.[25] presented pure waterjet surface treatment without abrasive particles, which has potential uses in the biomedical field due to its ability to create compressive residual stresses on metal surfaces without leaving hard particles. The Taguchi method is used to evaluate the effects of operating pressure, standoff distance, and the number of waterjet routes on surface topography and hardness.

The Taguchi approach is useful in WSN localization because of its capacity to efficiently optimize many parameters, resulting in better accuracy and reliability in finding the positions of sensor nodes, which is critical for the proper operation of WSN systems. This study uses Taguchi design of trials to determine the most influential elements among critical parameters. The goal is to investigate their impact. Determine the most influential parameter from the communication range, node deployment models, simulation area, and number of anchor nodes. ANOVA analysis to determine the contribution of each parameter.

II. MEHODOLOGY

The experiments are simulated using the MATLAB platform, and the simulations are run for various scenarios by changing simulation areas, communication ranges, the number of nodes, and the style of deployment (random or uniform). The parameters for the simulation scenario are presented in Table 1.

Table 1: Simulation scenario parameters

Simulation Scenario Parameters	
Network simulation area (m^2)	80 x 80, 100 x 100, 120 x 120 and 140 x 140
Number of anchor nodes	16, 20, 25 and 30
Communication range (m)	15, 18, 20 and 23
Radio propagation model	Ideal, no interference, no path loss
True location of the unknown node	(50,50)
Deployment model	Random and Uniform
Number of iterations	5000

Experiments were conducted to validate the parameters that influence the proposed range-free centroid localization methods with Kalman filter for a variety of scenarios. In each scenario, one parameter is changed while the others remain fixed, and the simulation is repeated up to 5000 times with different anchor geographic distributions. The localization error can be calculated for each anchor node distribution and averaged. The simulation results indicate a 95% possibility of reliability. The Taguchi approach is used to identify the most influential factor among the various parameters. Investigating the impact of important parameters using the Taguchi design of experiments and selecting the most relevant factor with MINITAB. Figure 1 depicts a schematic study of the operation using a flow diagram. The methodology's overview is to reduce the localization error using the suggested range-free centroid localization algorithm with Kalman, analyze the results using the Taguchi design of trials, and determine the most significant element among the parameters.

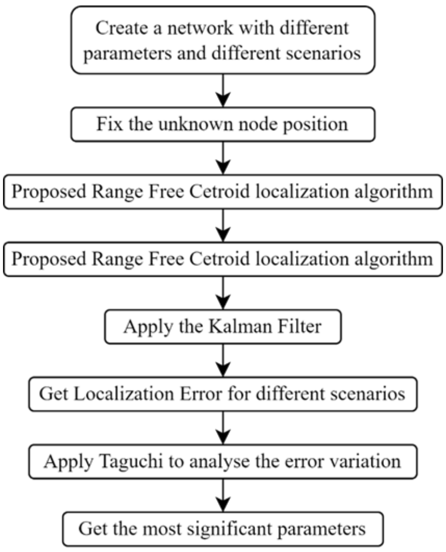

Fig 1 Schematic of research Methodology

A. Methodology of study

Research Methodology specifies the intent of carrying the research work in a systematic approach for achieving the research objectives. They mainly focus on the validity in the results from our research work carried out. Research comprises of two formulations like,

1. Qualitative Research

2. Quantitative Research

The basic methodologies include in the qualitative research are Experimental, Mathematical and Simulation approach. Experimental methodology is highly inclined to the practical orientation in the real world scenario's involving exposure to the sustainability in environmental conditions. Experimental setup involves the practical issues both environmentally and legally which makes research complicated. Mathematical orientation is tactical and highly confining to the approach chosen, but here node localization in identifying the anchor node involves the Centroid and Circumcenter method in determining the X&Y Co-ordinates. If the (X_a,Y_a), (X_b,Y_b) and (X_c,Y_c) are the co-ordinates of the triangle then Circumcenter method in Equation below here

$$X = \frac{(x_a^2-x_b^2)(y_c-y_a) + (x_a^2-x_c^2)(y_a-y_b) + (y_a-y_b)(y_b-y_c)(y_c-y_a)}{2((x_a-x_b)y_c + (x_c-x_a)y_b + (x_b-x_c)y_a)}$$

$$Y = \frac{(y_a^2-y_b^2)(x_c-x_a) + (y_a^2-y_c^2)(x_a-x_b) + (x_a-x_b)(x_b-x_c)(x_c-x_a)}{2((y_a-y_b)x_c + (y_c-y_a)x_b + (y_b-y_c)x_a)}$$

Simulation approach is used to conduct the research and the Matlab 2024a is used here in creating the scenarios. Taguchi method was applied to quantitatively calculate the effect of each parameter on localization error. Taguchi replaces a full factorial design to a partial factorial design, based on specially developed orthogonal arrays. Because, the partial experiment is only a selected set of the full factorial combinations, the analysis of the partial experiment benefits from inclusion of an analysis of variance (a measure of confidence) to qualify the results. ANOVA is used to provide a measure of confidence, measured from the variance. Analysis provides the variance of controllable and noise factors enabling the understanding of the source and magnitude of variance, which further would facilitate prediction of robust operating conditions.

III. Taguchi Method

Taguchi proposed a method based on statistical principles and engineering knowledge. Taguchi designed experiments to investigate the impact of process factors on the mean and variance of any process performance characteristic. Taguchi's design of the experiments contains orthogonal arrays, organizing the factors affecting the process and the levels at which they should be set. Taguchi method needs the minimum number of tests to evaluate the response instead of all possible combinations of the process parameters under study.

The control factor variations are identified by using the signal-to-noise ratio (S/N ratio), and ANOVA has determined which factors have statistically significant impact on the response. The flow Diagram for the Taguchi Approach is shown in Fig.2

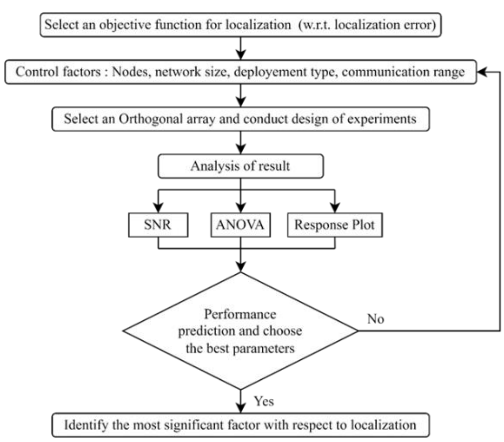

Fig. 2 Flow Diagram of Taguchi

Response plots show how each process factor affects the response characteristic including, S/N ratio, standard deviations, means, and slopes. When different levels of a factor affect the characteristic differently, the process factor is considered significant. Taguchi method allows for the minimum number of experimental runs to identify which factors are most significant. This method saves resources and time required to identify the most optimal factors and their corresponding levels.

A. Design of Taguchi Approach - signal-to-noise ratio

The Taguchi technique is the best method for designing solutions that have every feature needed and are appropriate for the environment. With variations, the method developed by Taguchi finds uncontrollable aspects. Reducing the noises by uncontrollable variables, to reduce noise, the Taguchi technique analyzes the uncontrolled aspects. An Attempts to minimize noise results in particular produces that are credible and reliable in their results. The Taguchi design for the 4-factor level design parameters is shown in Table 2 and the Orthogonal Array of Taguchi Design is shown in Table 3

Table 2: 4-Level Factor Design

Factor	Type	Levels	Ranges
Nodes	Fixed	4	16, 20, 25, 30
Communication Range	Fixed	4	15, 18, 20, 23
Network Size	Fixed	4	80, 100, 120, 140
Deployment Type	Fixed	2	Random, Uniform

To find the best control aspect values that make the technique resistant to variation from the noise factors, a Taguchi-designed experiment consists of converting the noise factors. Adjust element settings to decrease the effects of noise elements when the signal-to-noise ratio (S/N) is higher. Typically, the Taguchi approach consists of two steps: first, utilize the signal-to-noise ratio to identify variables that reduce variability; then, identify the control factors that minimize the effect of the variable on the goal fee at the sign-to-noise (S/N) ratio. The suitable price, or average fee of the statistics, of the trial statistics is represented by the term "signal" in the sign-to-noise (S/N) ratio, and the undesired fee, or standard deviation, or S.D., of the records, is represented by the time period "noise". Based on the goal of the experiment, the signal-to-noise ratio values vary. The Minitab tool includes, smaller is better, larger is better, and the nominal is better options for the signal-to-noise ratio. As we wanted to minimize the localization error of WSN, the smaller is better analysis method was chosen in this experiment. For smaller is better the signal-to-noise ratio is [14]

$S/N = -10\ \mathrm{Log}_{10}$ [mean of the sum of squares of measured data]

$S/N = -10*\log(\Sigma(Y^2)/n)$

Where Y = responses for the given factor level combination

n = number of responses in the factor level combination.

Table 3: L_{16} Orthogonal Array

Expt.No.	Nodes	Communication Range (m)	Network Size (m²)	Deployment	LocalizationError (m)	S/N Ratio
1	16	15	80	Random	1.7839074	-5.0274461
`2	16	18	100	Random	2.7143674	-8.6733726
3	16	20	120	Uniform	3.2277606	-10.178026
4	16	23	140	Uniform	2.8	-8.9431606

5	20	15	100	Uniform	2.6374204	-8.4235872
6	20	18	80	Uniform	1.5349964	-3.7221471
7	20	20	140	Random	1.8	-5.1054501
8	20	23	120	Random	2.3657645	-7.4794302
9	25	15	120	Random	2.7909274	-8.9149708
10	25	18	140	Random	2	-6.0205999
11	25	20	80	Uniform	2.1937873	-6.8238902
12	25	23	100	Uniform	2.4055976	-7.6244597
13	30	15	140	Uniform	1.7	-4.6089784
14	30	18	120	Uniform	2.0643094	-6.2954958
15	30	20	100	Random	1.4942388	-3.4883999
16	30	23	80	Random	1.1614531	-1.3000333

The total possible number of experiments for all levels of combinations is 4x4x4x2 =128. But Orthogonal design needs the minimum number of experiments for optimum results and also balanced to ensure that all levels of all factors are considered equally. An orthogonal array L_{16} (mixed level 4^3, 2^1) was selected for the conduct of experiments.

Table 4: Response-Table for SNR

Response Table for Signal-to-Noise Ratios				
Smaller is better				
Level	Nodes	Comm. Range	Network Size	Deployment Type
1	-8.206	-6.744	-4.218	-5.751
2	-6.183	-6.178	-7.052	-7.077
3	-7.346	-6.399	-8.217	
4	-3.923	-6.337	-6.17	
Delta	4.282	0.566	3.999	1.326
Rank	1	4	2	3

The Main effect plots of Signal-to-Noise Ratio is shown in the Fig 3

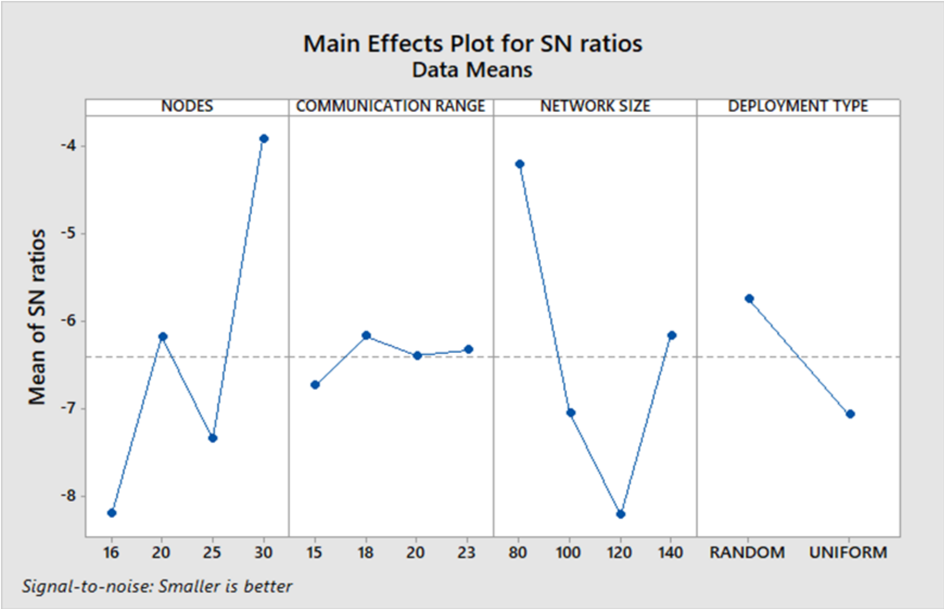

Fig. 3 main effect of S-N-R Ratio

The optimal level for each parameter as well as the optimal S/N ratio value are recorded, based on the response desk and basic consequences map. It was stated that the ideal conditions are nodes = 30, discussion variety = 18 m, community length = 80 m^2, and random deployment kind. The reaction graph shown in Figure 3 illustrates how each control parameter varies at the average localization error willpower. Based on the response graph and response table, it can be inferred that nodes together with network length, deployment, and conversation diversity, respectively, have a typical influence on common localization errors. Thus, in order to further analyze the experimental data, ANOVA and the F-test have been employed.

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B. ANOVA

To determine which parameter is essential for the localization, we also performed a statistical evaluation of variance (ANOVA). Sign-to-noise ratios were subjected to analysis of variance in order to determine the highest significant parameters and their role in the average localization errors computation. The S/N Ratio ANOVA is displayed in Table 5.

Table 5: ANOVA for Signal-to-Noise Ratio

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Nodes	3	2.28408	0.76136	11.87	0.010
Comm. range	3	0.04792	0.01597	0.25	0.859
Network size	3	1.90565	0.63522	9.91	0.015
Deployment type	1	0.37614	0.37614	5.87	0.060
Error	5	0.32059	0.06412		
Total	15	4.93438			

S	R-sq	R-sq(adj)	R-sq(pred)
0.253214	93.50%	80.51%	33.47%

ANOVA analysis shows that among all four parameters, anchor nodes contribute 46.29% which is the most significant factor, network size contributes 38.06% in the total output response. The predicted values obtained from the Taguchi method are in good agreement with the experimental values.

IV. CONCLUSION

Integrating Kalman filtering with the suggested localization guidelines to improve the performance of unknown nodes and boost localization precision. The simulation results demonstrate that the rule set includes a simple Kalman filter that can improve location accuracy with few iterations and prevent machine problems. The Taguchi technique identified that the optimal conditions for achieving the highest quality are: 30 nodes, a communication range of 18m, network size of 80m^2, and a random deployment type. The reaction graph ranks nodes as one, network size as two, deployment as three, and verbal interchange range as four.

An ANOVA analysis shows that anchor nodes account for 46.29%, network length for 38.06%, and deployment for 7.62% of the total output response. The results obtained using the Taguchi Method and ANOVA are highly consistent and indicate that the most influential factor in localization is the number of nodes in the network.

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