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# HEURISTIC AND EVOLUTIONARY OPTIMIZATION FOR UWB ANCHOR PLACEMENT

## *OPTIMIZACIÓN HEURÍSTICA Y EVOLUTIVA PARA LA COLOCACIÓN DE ANCLAJES UWB*

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ABSTRACT: Accurate and semantically-aware indoor navigation presents a significant challenge for existing assistive technologies (AT), particularly for visually impaired users. This research proposes a comprehensive framework that integrates Ultra-Wideband (UWB) for high-precision localization with LiDAR for detailed 3D environment mapping. We present a methodology for optimizing UWB anchor placement that minimizes Geometric Dilution of Precision (GDOP). We implement and compare two distinct optimization strategies for this task: a Hill-Climbing (HC) algorithm and a Genetic Algorithm (GA). Both methods seek to maximize a novel objective function derived from the 3D semantic model, which rewards broad coverage, penalizes anchor overlap, and enforces Line-of-Sight (LoS). The HC provides an iterative path to a local optimum, while the GA explores a wider solution space to identify a potentially superior, globally optimal configuration.

*Keywords*: UWB localization; assistive technology; indoor navigation; visually impaired people.

RESUMEN: La navegación interior precisa y sensible al contexto semántico supone un reto importante para las tecnologías de asistencia (TA) existentes, especialmente para los usuarios con discapacidad visual. Esta investigación propone un marco integral que integra la banda ultraancha (UWB) para una localización de alta precisión con LiDAR para un mapeo detallado del entorno en 3D. Presentamos una metodología para optimizar la colocación de anclajes UWB que minimiza la dilución geométrica de la precisión (GDOP). Implementamos y comparamos dos estrategias de optimización distintas para esta tarea: un algoritmo Hill-Climbing (HC) y un algoritmo genético (GA). Ambos métodos buscan maximizar una nueva función objetivo derivada del modelo semántico 3D, que recompensa la amplia cobertura, penaliza la superposición de anclajes y aplica la línea de visión (LoS). El HC proporciona una ruta iterativa hacia un óptimo local, mientras que el GA explora un espacio de soluciones más amplio para identificar una configuración potencialmente superior y globalmente óptima.

*Palabras clave*: localización UWB; tecnología de asistencia; navegación en interiores; personas con discapacidad visual.

## 1 INTRODUCTION

Ultra-Wideband (UWB) technology has emerged as the standard for high-precision indoor localization due to its resilience to multipath interference. However, the accuracy of UWB is fundamentally constrained by the geometry of the anchor deployment. We measure this using the Geometric Dilution of Precision (GDOP) [1]. A poor geometric arrangement —such as placing anchors collinearly or in positions obstructed by furniture— can degrade sub-decimeter accuracy to meter-level errors, rendering the system unsafe for blind users.

The challenge lies in the complexity of modern indoor spaces. Manually determining the optimal 3D placement of anchors in a furnished room to ensure Line-of-Sight (LoS) and minimize GDOP is a hard problem for human installers.

This paper addresses this problem by automating the infrastructure design. We propose a pipeline that utilizes consumer LiDAR (via smartphones) to generate a semantic 3D model of the environment. We then formulate the anchor placement problem as a multi-objective optimization task. The core contribution of this work is the implementation and comparative analysis of two optimization approaches: a fast heuristic method (Hill Climbing) and a robust evolutionary method (Genetic Algorithm). We demonstrate that, while heuristics are computationally efficient, the evolutionary approach provides the global optimization needed to ensure user safety in complex geometric configurations.

## 2. RELATED LITERATURE

Traditional approaches often rely on simplified 2D floor plans, ignoring the verticality of obstacles which is critical for 3D UWB [2] positioning.

Heuristic methods, such as Simulated Annealing or Force-Directed algorithms, have been applied to maximize coverage in WSNs. These methods are generally fast but prone to entrapment in local optima, particularly in non-convex environments (e.g., L-shaped rooms).

Evolutionary computation, specifically Genetic Algorithms (GA) [3], has been identified as a powerful tool for discrete and continuous optimization problems where the search space is vast and rugged. Holland's schema theory suggests that GAs can process building blocks of solutions to locate global optima. In the context of UWB, limited research has combined 3D semantic obstacles (furniture, walls) with evolutionary optimization to minimize GDOP explicitly. This work bridges that gap by applying a real-valued Genetic Algorithm directly to a semantic digital twin of the environment.

## 3. SYSTEM AND METHODOLOGY

### 3.1. Problem Formulation (The Objective Function)

We define the fitness of a specific anchor configuration  via a multi-objective function . The goal is to maximize :

Where:

- *Coverage (C)*: The number of sampled points in the room volume that fall within the effective range of the anchors.
- *Overlap Penalty (O)*: A penalty applied if the Euclidean distance between any two anchors is less than 1.0 m. This enforces geometric diversity.
- *Line-of-Sight Penalty (L)*: The most critical factor for UWB accuracy. We use ray-casting to check the segment between every pair of anchors. If a ray intersects a semantic obstacle (furniture/wall), a heavy penalty is applied.

### 3.2. Optimization Algorithms

To solve the anchor placement problem defined by the objective function (P), we initially employed a Stochastic Hill Climbing [4] algorithm. This trajectory-based heuristic proved highly effective for simple, single-room environments where the search space is relatively small and the number of anchors is low. In these constrained scenarios, the algorithm rapidly converges to a satisfactory geometric configuration by iteratively perturbing the position of a single anchor and accepting the change if it improves the overall fitness score. However, as the scope of the problem expanded to multi-room environments requiring a network of more than 20 anchors, the limitations of this greedy approach became apparent. The search landscape in such complex topologies is rugged, characterized by numerous local optima created by walls, furniture, and exclusion zones. The Hill Climbing algorithm, lacking a mechanism to accept temporary performance degradation or explore distant regions of the search space, frequently stagnated in suboptimal configurations, failing to bridge the geometric gaps between separate rooms.

To overcome the tendency of heuristic methods to become trapped in local optima within high-dimensional search spaces, we implemented a Genetic Algorithm (GA). Unlike the single-solution approach of Hill Climbing, the GA evolves a population of simultaneous candidate solutions, allowing it to explore the global search space more effectively. We adapted standard evolutionary theory to our specific domain by utilizing a real-valued representation, where each chromosome consists of a list of 3D vectors corresponding to the physical coordinates of the anchors. This direct mapping ensures that the genetic operations remain semantically meaningful within the context of the physical room geometry. The evolutionary process is driven by tournament selection, which identifies high-performing parent configurations while maintaining sufficient population diversity to prevent premature convergence.

The algorithm employs two primary operators to drive optimization. First, a uniform crossover operator recombines the spatial features of two parent configurations, allowing the system to merge, for instance, a strong geometric arrangement in one room from the first parent with an optimal corridor placement from the second. Second, to prevent the stagnation observed in the heuristic approach, we utilized a random resetting mutation operator. This mechanism introduces stochastic diversity by randomly relocating an anchor to a new valid position within the candidate zones, effectively forcing the algorithm to jump out of local optima and explore new geometric possibilities. To ensure that the quality of the solution never regresses across generations, an elitism strategy preserves the highest-performing individuals. Our experimental analysis demonstrates that in complex scenarios involving large anchor networks, the Genetic Algorithm consistently identifies global optima that are superior to the results produced by Hill Climbing, justifying the additional computational cost with significantly improved localization accuracy and coverage. Results are presented in Figura 1.

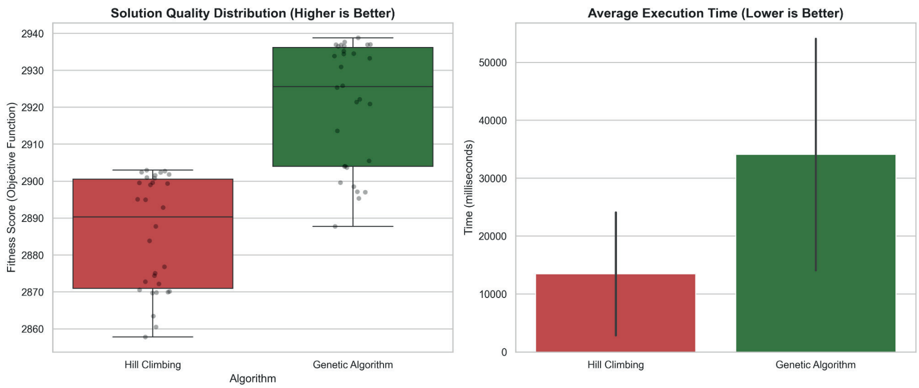


Figura 1. Performance comparison between Hill Climbing (red) and Genetic algorithm (green)

## 4. CONCLUSIONS AND FUTURE DEVELOPMENT

This paper presented a methodology for automating the deployment of UWB assistive navigation systems. By integrating semantic 3D mapping with evolutionary optimization, we addressed the critical dependency of UWB accuracy on anchor geometry.

Our comparative analysis demonstrates that while heuristic methods like Hill Climbing are computationally efficient, they are insufficient for complex indoor environments where safety is paramount. The Genetic Algorithm proved superior in navigating the rugged landscape of the objective function, reliably avoiding local optima to minimize GDOP.

For future development, we aim to extend this framework to multi-room environments, where the GA must optimize «hand-over» zones between different anchor clusters. Additionally, we plan to integrate «User-in-the-Loop» feedback, allowing the optimization process to account for specific user traversal patterns within the home.

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