UNIVERSIDAD AUTONOMA DE MADRID

Escuela Politécnica Superior

Departamento de Tecnología Electrónica y de las Comunicaciones

ALO: SISTEMAS DE LOCALIZACIÓN Y ORIENTACIÓN POR ÁNGULOS BASADOS EN RECEPCIÓN DIFERENCIAL

TESIS DOCTORAL

Santiago Elvira Díaz

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Esta tesis sólo ha sido posible gracias al apoyo de mi familia y amigos, los cuales siempre han estado ahí y a los cuales debo ser la persona que soy hoy en día.

También deseo dar las gracias al grupo de investigación HCTLab de la Universidad Autónoma de Madrid, por hacerme sentir como en casa desde el primer día, y en especial a Ángel de Castro, sin el cual esta tesis no podría haberse realizado.

Resumen

La presente tesis doctoral presenta un algoritmo diseñado para proporcionar la localización y orientación a un nodo, necesitando para ello la existencia de una serie de balizas cuyas posiciones deben ser conocidas. El algoritmo propuesto se ha implementado utilizando señales de ultrasonidos como medio de comunicación entre balizas y nodos, obteniendo un sistema en el que los nodos son capaces de localizarse y orientarse en el interior de viviendas o naves de forma precisa (el sistema alcanza precisiones de unos pocos centímetros en la localización y de unos pocos grados en la orientación) acarreando un reducido coste adicional para cada nodo.

El algoritmo se basa en que cada uno de los nodos mide el retardo con el que se recibe la señal generada por cada baliza mediante el uso de varios receptores desplegados en el propio nodo. Posteriormente, el nodo utiliza esta información para determina el ángulo con el que se recibe la señal y, combinando los ángulos percibidos por el nodo respecto a varias balizas, determinar su posición y orientación en todo momento.

El algoritmo demanda un reducido coste computacional, lo que permite implementarlo en los microcontroladores o FPGAs de que ya disponen los nodos para realizar las tareas de navegación y sensado, por lo que no se incurre en un coste adicional en este sentido. Además, como el algoritmo se ejecuta en cada uno de los nodos de forma autónoma, el sistema resultante es altamente escalable, permitiendo desplegar cualquier número de nodos en un determinado espacio.

En esta tesis se presentan cuatro variantes del algoritmo, las cuales se analizan en detalle tanto analítica como experimentalmente. Cada una de estas variantes permite elegir entre diferentes prestaciones, permitiendo el desarrollo de sistemas en donde cada nodo sólo necesita de un receptor, pero demanda recibir la señal de al menos 4 balizas para poder conocer su posición, hasta dispositivos con cuatro receptores que sólo necesitan de 2 balizas para conocer su posición y orientación y, además, pueden funcionar incluso con la pérdida de uno de sus receptores (a costa de una menor precisión). La decisión entre una u otra variante del algoritmo depende de las necesidades del sistema, siendo posible combinarlas.

Adicionalmente, en la presente tesis se recogen los resultados obtenidos al cambiar la tecnología de ultrasonidos por una basada en sonido en el rango audible por el ser humano. Se demuestra que dicha tecnología no es adecuada al obtener mucha menor precisión debido, principalmente, al uso de una menor frecuencia en la señal de referencia y a la interferencia generada por los rebotes en las paredes, techo y objetos situados en el entorno de aplicación.

PALABRAS CLAVES: DOA, DTOA, TDOA, localización, orientación

Abstract

This doctoral thesis presents an algorithm designed to provide the localization and orientation information to a node, requesting the deployment of multiple beacons whose positions shall be known. The performance of the algorithm has been tested using ultrasounds as the reference signals between the beacons and the nodes, obtaining a system where the nodes can locate and orientate themselves precisely in an indoor environment (with an error of a few centimeters in their position and an error of a few degrees in their orientation), demanding a low cost increase to each node.

This algorithm is based on measuring the propagation delay of the signal generated at the beacons in multiple receivers deployed in each node. With this information, the node is able to know the reception angle of the signal and, combining the angles received with respect to different beacons, determines its position and orientation.

The computational cost of the algorithm is so low that it can be implemented in the microcontrollers or FPGAs already used in the node for the navigation and sensing tasks, so it does not incur in any additional cost for computational purposes. Additionally, as the algorithm is executed autonomously in each node, the system supports any number of nodes deployed in a defined region, resulting in a high scalable system.

Four versions of the algorithm are presented, analyzed and experimentally tested. These alternatives allow choosing a different algorithm in function on the performance demanded by the system: from systems where the node only needs one receiver, but demands staying in an area covered by four beacons to know the position of the node, up to systems where the node demands four receivers, but only needs two beacon signals to know its position and orientation. These alternatives can be combined, increasing the performance of the system.

Additionally, this document shows the results obtained when the algorithm is implemented with sound signals, concluding that this technology is not a good choice as it obtains lower performance than the same algorithm implemented with ultrasonic technology. This lower performance is caused due to the lower frequency of sound signals and due to the interferences of the rebounds on the ceiling, walls and objects deployed in the environment.

KEY WORDS: DOA, DTOA, TDOA, localization, orientation

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Notación

®	Marca registrada
ALO	*Angle Localization and Orientation* Sistema de localización y orientación basado en ángulos
ALO3	*Angle Localization and Orientation with 3 receivers* Sistema de localización y orientación basado en ángulos con 3 receptores
ALO4	*Angle Localization and Orientation with 4 receivers* Sistema de localización y orientación basado en ángulos con 4 receptores
AoA	*Angle of Arrival* Ángulo de llegada
CAL4	*Celing Angle Localization with 4 transmitters* Sistema de localización basado en ángulos con 4 transmisores
DOA	*Direction Of Arrival* Dirección de llegada
DTOA	*Differential Times of Arrival* Diferencia de tiempos de llegada
FPGA	*Field Programagle Gate Array* Dispositivo semiconductor que contiene bloques de lógica cuya interconexión y funcionalidad puede ser configurada mediante un fichero de programación
GPS	*Global Positioning System* Sistema de Posicionamiento Global
HALO4	*Horizontal Angle Localization and Orientation with 4 receivers* Sistema de localización y orientación basado en ángulos horizontales con 4 receptores
TDOA	*Time Difference of Arrival* Diferencia de tiempos de llegada
TOA	*Time of Arrival* Tiempo de llegada
TOF	*Time of Flight* Tiempo de vuelo

1. INTRODUCCIÓN GENERAL

1.1. Motivación

Desde la revolución industrial, los sistemas robóticos han ido evolucionando, haciendo que estos sean capaces de realizar cada año tareas más complejas (desde tejer ropa hasta fabricar coches).

Inicialmente, estos dispositivos se desarrollaron pensando en aplicaciones industriales debido, principalmente, al alto coste que suponía su implementación y al inmenso beneficio que se obtenía con su uso. Sin embargo, con el paso de los años, los costes de los propios componentes electrónicos, así como los procesos de fabricación, se han visto drásticamente reducidos, lo que ha posibilitado que, paulatinamente, cada día tengamos más dispositivos electrónicos en nuestras casas capaces de realizar tareas cada vez más complejas (desde lavar la ropa hasta cocinar).

Uno de los principales puntos débiles de los dispositivos robóticos existentes hoy en día es su escasa capacidad para navegar por un determinado entorno. A pesar de que esta área de investigación es una de las más antiguas (con más de 2000 años), casi siempre se ha centrado en el desarrollo de sistemas de navegación para exteriores (posibilitando explorar continentes y el comercio entre civilizaciones situadas a miles de kilómetros), siendo la navegación en interiores relativamente olvidada hasta hace unos pocos años.

Esto ha sido debido, principalmente, a que no existía una necesidad real antes de que la robótica alcanzase cierto nivel tecnológico. Con el avance de la robótica, se detectó que aunque era relativamente sencillo dotar a un robot de capacidades de movimiento, hacer que pudiese desplazarse de forma autónoma dentro de un edificio suponía un desafío tecnológico. Por ejemplo, cada casa tiene su propia distribución y, además, suelen aparecer obstáculos (sillas, bolsas,…) en el entorno de manera incontrolada, lo que demanda el desarrollo de sistemas de navegación con unos requisitos diferentes a los ya existentes.

Mientras que entre los sistemas pensados para exteriores el GPS ha demostrado ser el mejor sistema para casi cualquier aplicación, actualmente no existe ningún dispositivo de navegación para interiores que reúna todas las características necesarias para imponerse respecto al resto, siendo la solución óptima dependiente de:

- La precisión requerida.
- El entorno en el que se va a desplegar el sistema de navegación.
- El máximo coste asumible.
- La autonomía que se desee para cada nodo del sistema.

Por este motivo, los pocos sistemas comerciales desarrollados hasta la fecha, capaces de proporcionar capacidades de navegación a nodos dentro de edificios, necesitan combinar varios tipos de sensores. Este hecho incrementa el coste final del producto, restringiendo su uso, principalmente, a las grandes empresas de distribución como Amazon®.

La presente tesis propone un sistema que permite obtener la localización y la orientación (dos de los principales pilares de cualquier sistema de navegación) de un objeto en interiores mediante el uso de ultrasonidos, utilizando para ello un *array* de receptores desplegados en un nodo. Con la información obtenida del *array* de receptores, el nodo determina la orientación del objeto respecto a varias balizas transmisoras, utilizando dicha información para obtener la localización y orientación del nodo, siendo capaz de proporcionar una alta precisión (del orden de centímetros) y generar sistemas altamente escalables, confidenciales y donde los nodos son completamente autónomos. Este sistema demanda una reducida capacidad computacional, lo que permite implementarlo en dispositivos de bajo coste y de baja demanda energética.

Debido a que la actual tesis se presenta como un compendio de publicaciones, es decir, reúne todas las publicaciones relacionados con el actual proyecto de tesis doctoral, este documento se ha organizado en los siguientes capítulos:

- **Capítulo 1:** Se introduce el ámbito del proyecto de investigación, se hace una breve descripción del estado del arte de los sistemas de localización y orientación, se analiza la aportación de esta tesis y se resumen los trabajos compendiados en la misma.
- **Capítulo 2 "ALO":** Recoge uno de los trabajos compendiados. Este artículo presenta la base del sistema de localización y orientación desarrollado.
- **Capítulo 3 "ALO4":** Recoge uno de los trabajos compendiados. Este artículo desarrolla la primera evolución del sistema ALO, la cual a costa de añadir un receptor adicional consigue reducir drásticamente el error intrínseco al sistema original.
- **Capítulo 4:** Recoge uno de los trabajos compendiados. Este artículo muestra los resultados obtenidos al implementar el sistema ALO4 al sustituir la tecnología de ultrasonidos por altavoces y micrófonos convencionales en la banda audible.
- **Capítulo 5 "HALO4":** Recoge uno de los trabajos compendiados. Este artículo presenta una nueva aproximación del algoritmo de localización basado en el sistema ALO4, sustituyendo el uso del ángulo vertical respecto a los transmisores por el ángulo horizontal.
- **Capítulo 6 "CAL4":** Recoge uno de los trabajos compendiados. Este artículo analiza un cambio de concepto del sistema ALO4, donde el nodo pasa de utilizar cuatro receptores y localizarse respecto a dos transmisores, a sólo utilizar un receptor y recibir la señal generada por cuatro transmisores.
- **Capítulo 7:** Resumen los resultados obtenidos por cada uno de los sistemas presentados anteriormente y análisis de los mismos.
- **Capítulo 8:** Conclusiones de la tesis y Trabajo futuro.

1.2. Estado del arte

Debido a que este trabajo trata sobre el desarrollo de un sistema para interiores que proporciona la localización y orientación a un nodo con el fin de posibilitar la implementación de sistemas de navegación, en este apartado nos centraremos en mostrar las diferentes alternativas desarrolladas hasta la fecha en estos dos aspectos, sin entrar en detalles respecto a los sistemas de mapeo y los algoritmos de rutado (los cuales tienen su propia área de investigación).

El estado del arte que se recoge en este capítulo muestra de forma genérica el estado actual de los sistemas de localización y orientación. Cada capítulo en donde se recoge cada uno de los trabajos publicados contiene su propio estado del arte asociado a dicha publicación.

1.2.1. Sistemas de localización

Actualmente, existen multitud de sistemas que permiten proporcionar la localización de un objeto, pudiendo dividirse en dos grandes grupos:

- Los que se basan en medidas relativas, es decir, conocen la posición inicial del objeto y calculan la dirección y cuánto se mueve el objeto para conocer su nueva posición.
- Los que se basan en medidas respecto a puntos de referencia.

1.2.1.1. Sistemas de localización relativos

La principal ventaja de estos dispositivos es que todo el proceso de localización está centralizado en el propio nodo, lo cual aumenta su autonomía y elimina la necesidad de desplegar un sistema de balizas como en los sistemas basados en puntos de referencia. Sin embargo, estos sistemas tienden a ir acumulando errores, por lo que su precisión va decayendo a medida que el nodo se mueve, siendo necesario resincronizarlos cada cierto tiempo.

1.2.1.1.1. Sigue-Líneas

La forma más sencilla de implementar un sistema de navegación es utilizando módulos [1-3] como el mostrado en la Fig. 1–1:

Fig. 1–1: TCTR5000 (ejemplo de sensor usado en los sigue-líneas)

Este tipo de dispositivos están compuestos por un emisor de luz (que suele ser en el espectro de infrarrojos) y un foto-receptor. Su principio de funcionamiento consiste en desplegar estos módulos cerca del suelo y tirar una línea negra que marque el camino que queremos que recorra el robot. Básicamente, cuando el sensor está sobre la línea oscura, la luz emitida por el emisor no se refleja en el suelo, y esta no se percibe en el foto-receptor, mientras que si el módulo no está sobre la línea, el receptor sí recibirá la señal emitida.

En base a esta información, y utilizando al menos dos módulos, el robot puede ir corrigiendo su dirección de avance para moverse desde el punto inicial al punto final (Fig. 1–2).

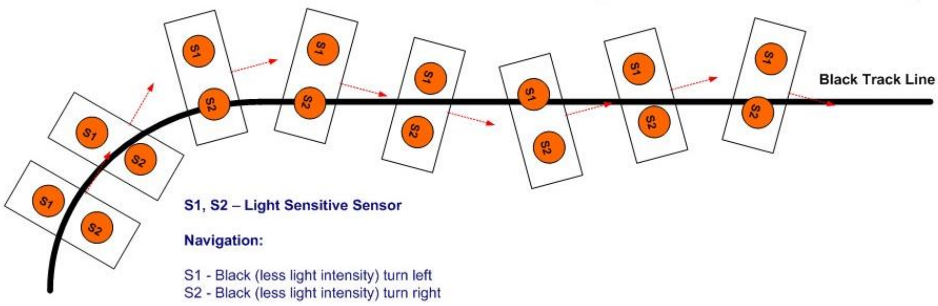

Fig. 1–2: Robot sigue-líneas, principio de funcionamiento (imagen extraída de www.ermicro.com)

El principal problema de este tipo de sistemas es que el nodo no sabe su posición mientras se mueve, sólo conociendo que ha terminado si se define una marca especial para tal fin. Su principal ventaja es que requiere muy pocos recursos, que el nodo se desvía muy poco de la ruta definida con la línea negra (la distancia entre los sensores) y su coste computacional es despreciable.

1.2.1.1.2. Encoders

Este tipo de sistemas utilizan la velocidad para saber cuánto se ha desplazado el objeto [4-5]. Para obtener la velocidad de movimiento en robots que utilizan ruedas para moverse se suelen utilizar encoders.

Este tipo de dispositivos suelen ser un círculo unido al eje de giro de la rueda al que se le agujerea un determinado patrón, junto con una serie de foto-emisores y foto-receptores (Fig. 1–3). Al estar unido el círculo con el patrón al propio eje de la rueda, su giro es idéntico al de esta. A medida que la rueda gira, la señal capturada en los foto-receptores va evolucionando en función del patrón y de la propia velocidad de giro, por lo que el sistema es capaz de deducir la velocidad y posición de la rueda en todo momento.

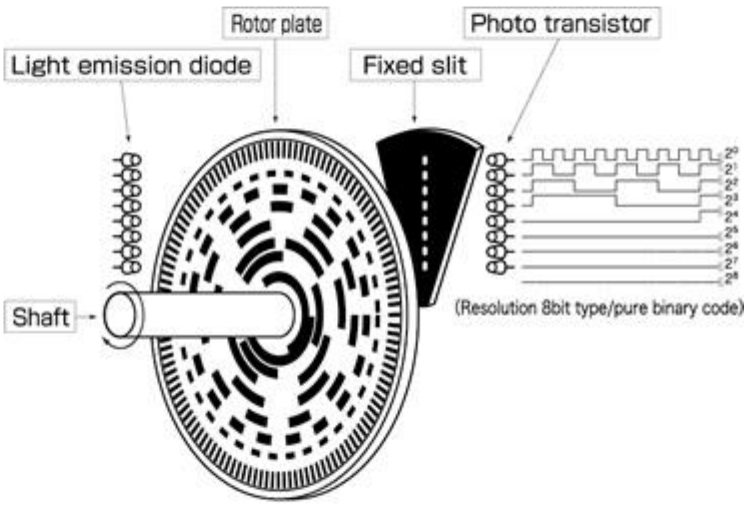

Fig. 1–3: Principio de funcionamiento del encoder óptico (imagen extraída de www.tamagawa-seiki.com)

Otra forma de implementar este tipo de sensores es mediante el uso de un sensor magnético de efecto Hall, un imán y una rueda dentada metálica. Utilizando una distribución semejante a la mostrada en la Fig. 1–4, se puede obtener un tren de pulsos semejante al obtenido con los encoders ópticos con una mayor fiabilidad (por lo que su uso es más extendido que los primeros).

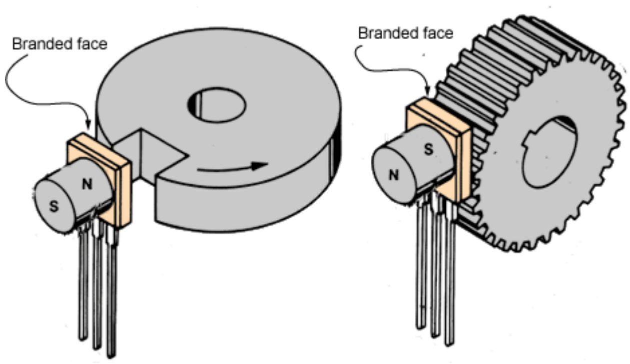

Fig. 1–4: Principio de funcionamiento del encoder de efecto Hall (imagen extraída de www.allegromicro.com)

Este tipo de sistemas permiten una localización muy precisa del objeto (llegando a cometer errores de menos de 1 mm) a un coste relativamente bajo. Sin embargo, su principal problema es que acumulan errores, es decir, que si el agarre de la rueda no es ideal, y la rueda gira más de lo que el robot se desplaza, el encoder reportará una determinada velocidad cuando la velocidad del robot es otra. Aunque esta diferencia sea pequeña, si el sistema basa su funcionamiento sólo en esta información, la precisión del sistema de localización va degradándose, por lo que es necesario recalibrar el sistema cada cierto tiempo. Pese a este inconveniente, este tipo de sistemas suele ser utilizado junto con otros que no acumulan errores ya que permite proporcionar la localización del objeto sin necesitar estar en una región de cobertura del sistema principal y para detectar errores en las medidas capturadas por los otros sistemas.

1.2.1.1.3. Acelerómetros

Otra de las formas de determinar la posición de un objeto es conocer la evolución de su velocidad a lo largo del tiempo [6-7].

Existen diferentes sensores que proporcionan la aceleración de un objeto, siendo su uso muy extendido a partir de la aparición de la consola Wii de Nintendo® (Fig. 1–5).

Fig. 1–5: Consola Wii de Nintendo®

Esto se debió a que el mando de esta consola llevaba uno de estos sensores, el cual se utilizaba para determinar los movimientos de las manos y brazos que hacia el jugador. Este mando permitió que Nintendo® posibilitara el desarrollo de videojuegos que hacían que el jugador interactuara de una manera totalmente nueva con el juego, convirtiendo a su consola en una de las más vendidas de la historia.

Analizando en más detalle este mando, lo que hizo Nintendo® fue implementar un acelerómetro en el mando con el cual, a partir de una situación de reposo, analizaba la evolución de la aceleración para deducir la nueva posición del brazo del jugador. Esta información se transmitía al juego el cual hacía que el personaje interactuara acorde a dicha información.

La gran ventaja de este tipo de sensores es que son capaces de proporcionar la aceleración de un objeto sin tener en cuenta el comportamiento de los actuadores que se encargan de mover el objeto, por lo que no se ven afectados por los errores de estos. Pese a que este tipo de sensores se pueden encontrar con relativa facilidad en los mandos de las consolas de nueva generación, mando para televisores y teléfonos móviles, su uso en sistemas de navegación es bastante escaso debido a que su precisión es bastante limitada, lo que unido a que acumula errores, hacen que sean sistemas cuyas prestaciones no sean suficientes para casi ninguna aplicación.

1.2.1.2. Sistemas de localización basados en puntos de referencia

Estos sistemas tienen la principal ventaja de que no acumulan errores, ya que la posición se calcula sin tener en cuenta la posición anterior del objeto. Sin embargo, este tipo de sistemas tienden a ser más costosos que los sistemas de localización relativos al ser necesario desplegar balizas en el entorno, y tienen el problema de que solo proporcionan la localización cuando el objeto está en la zona de cobertura de al menos dos balizas.

Existen varias formas de clasificar estos sistemas, existiendo dos categorías principales:

- **Principio de localización**: Define qué tipo de medida respecto a las balizas es necesaria para localizar al objeto, así como la formulación necesaria para convertir dichas medidas en una posición del entorno.
- **Tecnología**: Tipo de tecnología utilizada para conseguir la medida utilizada por el algoritmo de localización.

1.2.1.2.1. Principio de localización

Entre los diferentes sistemas de localización, destacan principalmente los basados en tres aproximaciones:

- **Dirección de llegada**: Consisten en determinar la dirección respecto a la baliza que genera la señal de referencia.
- **Tiempo de llegada**: Sistemas capaces de medir el tiempo requerido por la señal de referencia para viajar desde la baliza al receptor.
- **Diferencia de tiempo de llegada**: Basados en medir la diferencia de retardo de la señal generada en una baliza en varios puntos del entorno.

Dirección de llegada

Del inglés "Direction Of Arrival", son mundialmente conocidos como sistemas DOA (también se les conoce por "Angle Of Arrival" o AoA).

Este tipo de sistemas se basan en calcular el ángulo con el que se recibe la señal de referencia para determinar la dirección en la que se encuentra la baliza [8-10].

Inicialmente, fueron utilizados como el principal sistema de localización en los barcos (antes de la llegada del GPS). Utilizando una brújula para conocer la dirección del norte magnético y antenas muy direccionales que se van rotando hasta que la potencia recibida es máxima respecto a diferentes balizas localizadas en puntos conocidos, el sistema es capaz de determinar el ángulo existente entre el norte magnético y la baliza.

Dado que el norte magnético es muy estable (para una determinada región), basta con conocer el ángulo existente entre el norte magnético y una baliza para poder trazar una línea desde dicha baliza que cumpla con dicho ángulo. Repitiendo el proceso respecto a una segunda baliza, se obtiene un punto (en donde se intersecan ambas rectas) que es la posición del barco (Fig. 1–6).

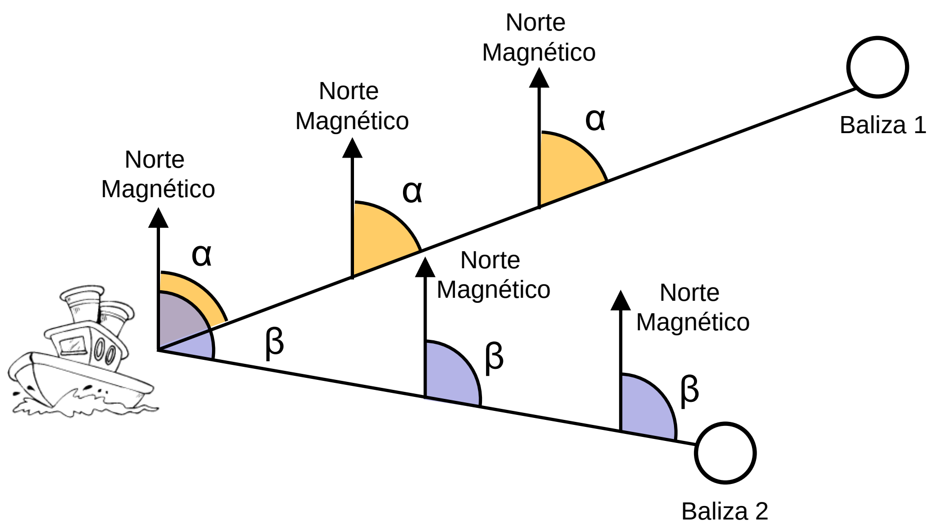

Fig. 1–6: Ejemplo de sistema de localización tipo DOA junto con brújula magnética

Este tipo de sistemas de localización ha quedado obsoleto principalmente por el alto coste que supone el uso de antenas direccionales y por la llegada del GPS (el cual además permite obtener la posición del objeto de manera más precisa).

Cabe resaltar que existe una aproximación que consiste en utilizar un *array* de antenas omnidireccionales (en vez de una antena direccional) con el fin de obtener la dirección de llegada de la señal generada en las balizas. Sin embargo, pese a que esta aproximación reduce considerablemente el coste de implementación, la necesidad de trabajar con ecuaciones trigonométricas complejas (si no se dota al sistema de una brújula electrónica) hace que la obtención de la posición de un objeto sea un proceso muy costoso computacionalmente (en el capítulo 5 se pone un ejemplo de la complejidad del este tipo de sistemas) por lo que actualmente este tipo de sistemas han quedado obsoletos.

Tiempo de llegada

Del inglés "Time Of Arrival", son mundialmente conocidos como sistemas TOA (también aparecen referenciados como "Time of Flight" o TOF).

Estos sistemas utilizan el tiempo que tarda en viajar la señal desde el emisor al receptor para conocer la distancia entre ambos puntos y obtener la posición del objeto [11-13]. Por cada tiempo obtenido, se traza una circunferencia o esfera centrada en el transmisor para posteriormente intersecar dichas formas para determinar la posición del objeto (Fig. 1–7).

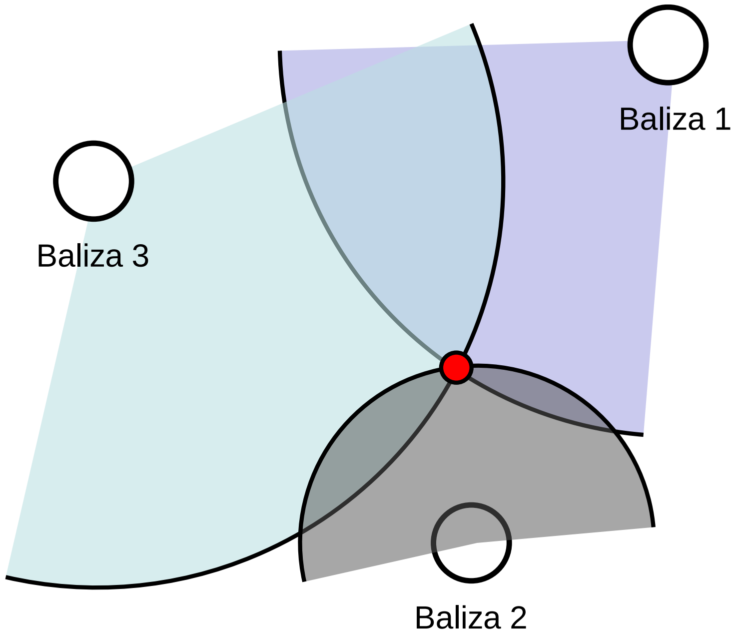

Fig. 1–7: Principio de funcionamiento de los sistemas de localización TOA

El dispositivo más famoso basado en este principio de funcionamiento es el GPS. En este sistema, todos los satélites están sincronizados entre ellos y cada satélite emite un patrón que le identifica. El receptor utiliza un reloj que se sincroniza con el satélite. Cuando el receptor captura los patrones provenientes de varios satélites, este es capaz de determinar la deriva de su reloj respecto al de los satélites y, al detectar los patrones enviados desfasados, el receptor puede estimar la diferencia del tiempo de propagación de la señal entre los diferentes satélites y el receptor, pudiendo obtener su posición en base a esta información.

La principal ventaja de estos sistemas es que el proceso para obtener la posición del objeto es bastante simple al tratarse de intersecar circunferencias o esferas. Sin embargo, se requiere que exista una sincronización entre emisores y receptores, lo cual incrementa considerablemente la complejidad del sistema.

Diferencia de tiempos de llegada

Del inglés "Differential Times Of Arrival", son mundialmente conocidos como sistemas DTOA (también aparecen referenciados como "Time Difference of Arrival" o TDOA).

Este tipo de sistemas basan su funcionamiento en calcular la diferencia del tiempo de propagación de una señal generada por una baliza y varios puntos de referencia [13-15]. Por cada diferencia de tiempos capturada en cada par de puntos de referencia, el sistema conoce que la posición del transmisor se encuentra en algún punto de una hipérbola (o hiperboloide para el caso de tres dimensiones) cuyos focos (F y F′ en la figura) son los puntos de referencia y cuyos vértices (A y A′) se encuentran a la mitad de la diferencia del tiempo medido multiplicado por la velocidad de propagación de la señal transmitida.

Nota: La hipérbola es la curva (superficie en el caso del hiperboloide) cuyo valor absoluto de la diferencia de sus distancias a dos puntos fijos, llamados focos, es constante e igual a la distancia entre vértices (Fig. 1–8)

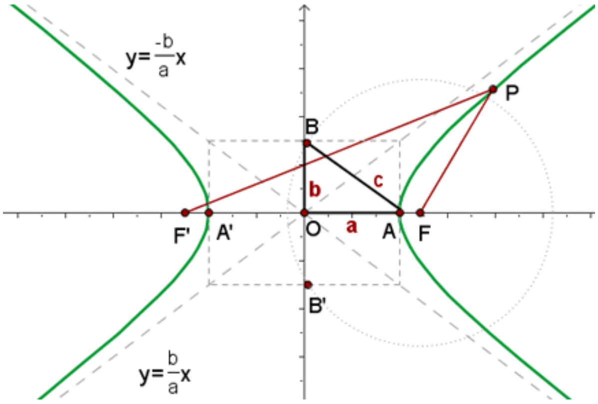

Fig. 1–8: Elementos de una hipérbola (imagen extraída de www.vitutor.com)

Si el sistema dispone de varios puntos de referencia, este puede intersecar las hipérbolas o hiperboloides generados por cada par de receptores y de este modo conocer la posición del emisor.

Uno de los sistemas que se basan en este principio es el que utiliza el ser humano para localizar sonidos (Fig. 1–9). Entre los múltiples factores que se tienen en cuenta para determinar la procedencia de un sonido, uno de los más importantes es el desfase que percibimos en la señal acústica con nuestros dos oídos, el cual nos permite determinar la dirección de la que procede.

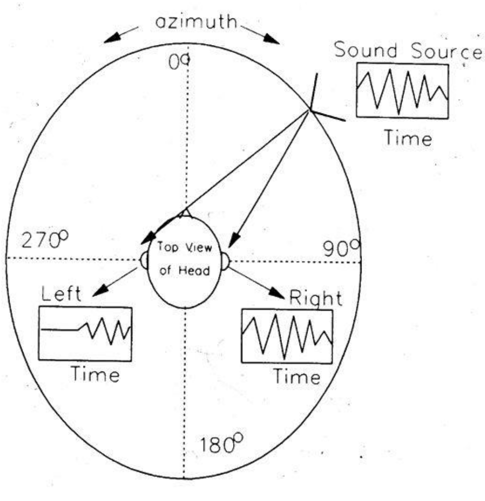

Fig. 1–9: Ejemplo de sistema de localización TDOA (imagen extraída de www.cns.nyu.edu)

El principal inconveniente de este tipo de sistemas es que son relativamente complejos, ya que se necesita que los nodos receptores o transmisores estén sincronizados entre ellos, pero son más sencillos que los sistemas TOA, los cuales necesitan que exista una fuerte sincronización entre el sistema emisor y el sistema receptor. Además, la necesidad de operar con hipérbolas o hiperboloides hace que el proceso para calcular la posición del objeto conlleve un alto coste computacional.

1.2.1.2.2. Tecnología

Dependiendo de la tecnología utilizada para obtener las medidas relativas a los transmisores, los sistemas pueden agruparse en:

- **Radiofrecuencia**: Basados en el uso de señales de radio que se propagan a la velocidad de la luz.
- **Imagen**: Utilizan cámaras con las que capturan el entorno en el que se encuentra el robot y en donde buscan puntos de referencia que utiliza el nodo para localizar respecto a ellos.
- **Ultrasonidos/Sonido**: Sistemas que utilizan señales acústicas como señales de referencia.

Radiofrecuencia

Este tipo de sistemas utilizan ondas de radio como señales de referencia para extraer la información relativa a las balizas. Dos aproximaciones son las más comúnmente utilizadas:

Medir la potencia de la señal recibida:

Este es el método más sencillo para extraer la información relativa a una baliza en base a una señal de radiofrecuencia. La mayoría de los sistemas de radiofrecuencia proporcionan junto con la señal recibida una medida de la potencia recibida (con el fin de poder determinar la calidad de la señal recibida).

La potencia recibida depende, entre otros factores, de la distancia entre el transmisor y el receptor, por lo que se puede hacer una estimación de esta distancia asumiendo como constante el resto de factores. Esto permite implementar algoritmos TOA para localizar al objeto [11, 16-17].

Entre los sistemas más famosos que utilizan este tipo de sensores, está la localización basada en WiFi. Los móviles actuales tienen la capacidad de conocer en qué zona se encuentran de manera casi inmediata midiendo la intensidad con la que reciben la señal WiFi de los diferentes routers próximos. La precisión de esta tecnología es del orden de unos pocos metros, pero tiene la principal ventaja de que no utilizan ninguna tecnología que no esté disponible en el propio teléfono móvil. Esto permite implementar servicios de localización en interiores altamente escalables sin ningún coste adicional (sólo hay que determinar la posición de los routers y trazar el mapa de la zona). Actualmente ya existen empresas que desarrollan este tipo de servicios para comercios, como SITUM® (Fig. 1–10).

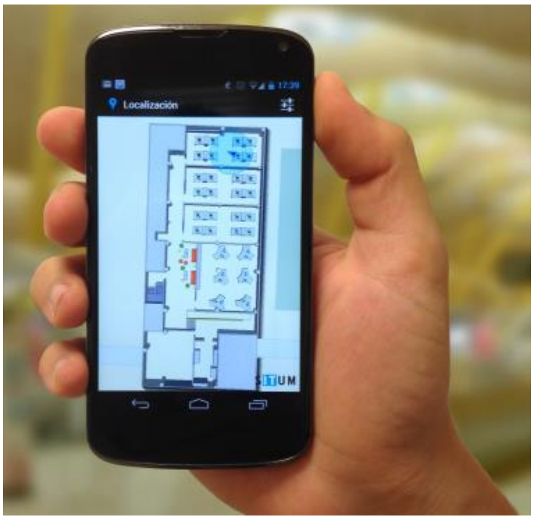

Fig. 1–10: Aplicación desarrollada por la empresa SITUM basada en medir la potencia de la señal WiFi recibida.

El principal problema de esta tecnología es que la potencia recibida depende de otros factores como la dirección con la que llega la señal al receptor, la orientación del transmisor o la existencia de obstáculos entre el transmisor o el receptor, lo que hace que esta tecnología no permita proporcionar precisiones mejores que un metro (a día de hoy).

Medir el retardo de la señal recibida:

Si disponemos de varios transmisores y/o receptores sincronizados entre sí, es posible extraer el tiempo que tarda en propagarse la señal de referencia entre transmisor y receptor [18-20] (o la diferencia de tiempo entre varios receptores o respecto a varios transmisores).

La señal de radiofrecuencia viaja a la velocidad de la luz ($3 \cdot 10^8$ m/s), lo que hace que para medir de forma precisa el retardo de propagación sea necesario procesar la fase de la señal recibida. Para hacernos una idea del motivo que nos llega a medir este tiempo de esta manera, si un sistema fuese capaz de medir con una precisión de 1 ns el tiempo de propagación de una señal, estaría cometiendo un error de ±30 cm en la estimación de dicha medida. Sin embargo, si el sistema estimase la diferencia de fase y cometiese un error del 10% (sobre una señal de 2GHz), dicho error sería de 0,05 ns (20 veces menos que en el caso anterior)

Hay que resaltar que en este tipo de sistemas puede ser necesario contemplar el caso de que el tiempo a medir sea mayor que el propio periodo de la señal de radiofrecuencia, y que la señal recibida en el receptor sea la suma de la señal que viaja de forma directa desde el transmisor al receptor (la que aporta información útil) junto con los rebotes de la misma señal en el entorno (que perturban la fase de la señal recibida). Esto hace que sea necesario un patrón que permita diferenciar estos casos lo cual incrementa la complejidad del sistema.

El sistema por excelencia que se basa en esta tecnología es el GPS (Fig. 1–11), el cual extrae el tiempo de propagación de la señal de radiofrecuencia midiendo el desfase con el que recibe los patrones generados en varios satélites.

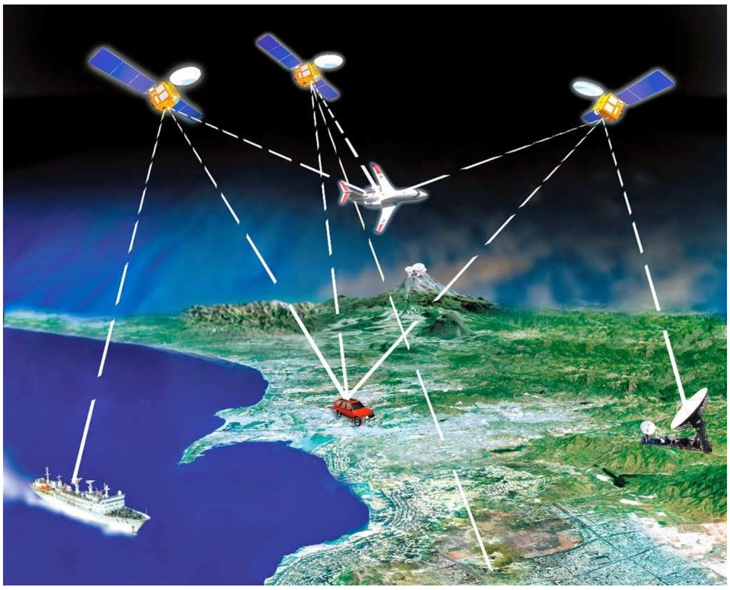

Fig. 1–11: GPS, sistema de localización que mide el tiempo de vuelo (imagen extraída de www.ubuntuleon.com)

El principal inconveniente de este tipo de sistemas es que son bastantes más complejos que el resto de sistemas (a excepción del basado en procesamiento de imagen) y que demandan una gran capacidad computacional, lo que hace que su uso esté poco extendido en aplicaciones en interiores.

Imagen

Esta tecnología se basa en capturar las medidas utilizadas durante el proceso de localización de marcas o puntos de referencia a través de una cámara [21-23].

La idea principal de este tipo de sistemas consiste en desplegar una serie de marcas (en el techo, paredes o suelo del entorno) y que se busquen dichos patrones para determinar su orientación y posición respecto a dichas referencias (Fig. 1–12), implementando, generalmente, sistemas DOA.

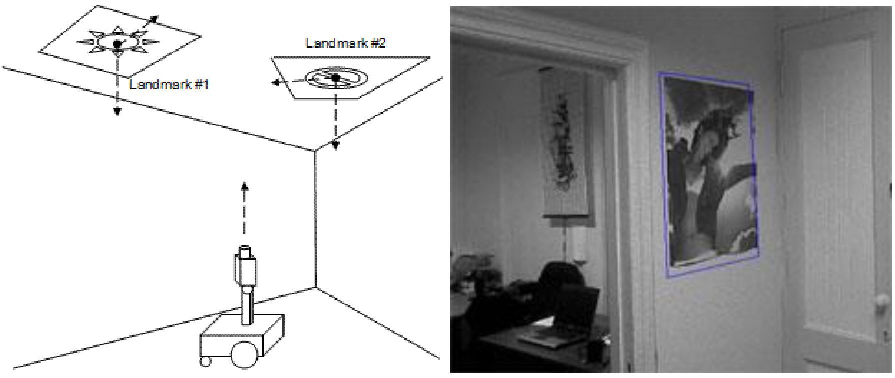

Fig. 1–12: Localización por imagen (imágenes extraídas de www.skilligent.com)

Los puntos más negativos de este tipo de sistema es que son los sistemas de localización que requieren mayor capacidad de computación (ya que necesitan procesar imágenes en tiempo real), son bastante costosos y demandan una gran cantidad de energía para poder funcionar.

Existe otra aproximación basada en el mismo principio que intenta mitigar estas limitaciones distribuyendo una red de cámaras fijas conectadas a un servidor centralizado (Fig. 1–13). Al estar las cámaras fijas, estas pueden alimentarse desde la red eléctrica, y al disponer de un nodo que hace de centralita, se puede implementar en dicho nodo un dispositivo especializado en procesamiento de imagen, el cual se encarga de determinar la posición de los objetos de interés en el entorno y reportárselo a aquellos que lo necesiten (reduciendo la carga computacional y el coste energético de los nodos en el sistema):

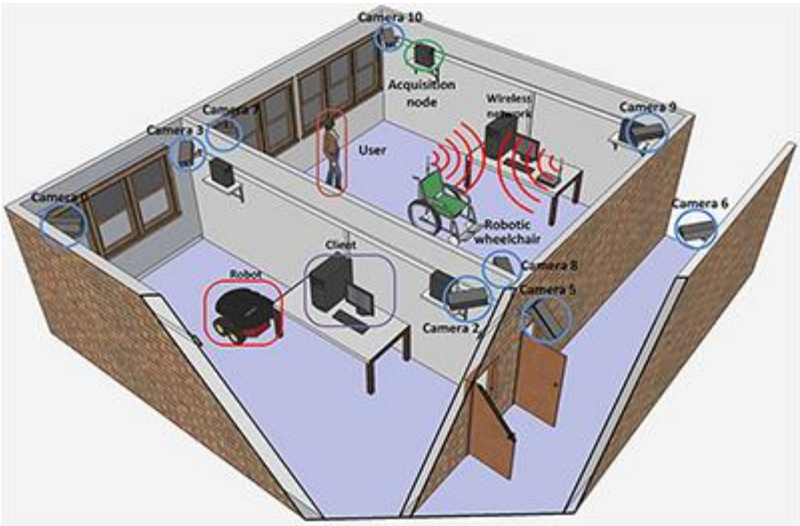

Fig. 1–13: Sistema centralizado basado en procesamiento de imágenes (imagen extraída de www.mdpi.com)

El problema de esta aproximación es que al estar toda la capacidad de computación concentrada en un solo nodo y necesitar reportar a cada nodo su posición, se reduce la escalabilidad del sistema, se reduce la autonomía de cada nodo y se reduce la confidencialidad del sistema (al comunicarse por radio la posición de cada nodo).

Ultrasonidos / Sonido

Una de las tecnologías que permite obtener tiempos precisos relacionados con lo que tarda en propagarse una señal de referencia entre varios puntos son las basadas en utilizar transductores de ultrasonidos [24-26] (Fig. 1–14) o sonido [27].

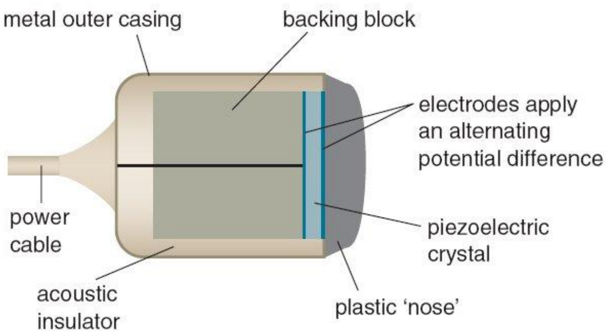

Fig. 1–14: Transductor de ultrasonido o sonido (imagen extraída de www.genesis.net.au)

La principal ventaja de este tipo de sistemas es que al enviarse una señal acústica, dicha señal viaja a unos 340 m/s (~10^5 veces más lenta que una señal de radiofrecuencia). Esto simplifica enormemente el sistema, permitiendo capturar el tiempo de propagación con simples contadores. Por ejemplo, si la precisión del sistema cuando captura la señal de referencia es de 1 us, el error cometido en la medida capturada es de ±0,34 mm.

La gran diferencia existente entre la velocidad de propagación de la señal de ultrasonidos y la señal de radiofrecuencia permite, además, implementar sistemas TOA de forma sencilla. Para ello, el sistema emite junto con la señal de ultrasonido/sonido la señal de radiofrecuencia, la cual llega al receptor tras unos pocos nanosegundos. Como la señal de ultrasonidos se recibe tras unos cuantos microsegundos, se puede asumir que cuando se empezó a recibir la señal de radio es el instante en que se empezó a transmitir la señal de referencia, ya que el error del orden de nanosegundos representa una ínfima parte de la medida capturada.

Este tipo de sistemas se suelen implementar con ultrasonidos, con el principal objetivo de no generar una fuente ruidosa molesta para el ser humano en el entorno de la aplicación. Sin embargo, para algunas aplicaciones (como los sistemas para localizar fuentes de ruido) se sustituyen los transmisores y receptores de ultrasonidos por micrófonos y altavoces.

Actualmente este tipo de sistemas se restringen casi exclusivamente al ámbito de investigación. Pese al bajo coste de los transductores y la alta precisión permitida por el sistema, el escaso alcance de las balizas hace que desplegar este tipo de sistemas no sea sencillo ni eficiente. Además, aunque la precisión proporcionada es superior al resto de sistemas, actualmente apenas existen aplicaciones que demanden dicha precisión, siendo más eficiente recurrir a combinar otros sistemas de localización cuando dicha precisión es necesaria.

1.2.2. Sistemas de orientación

Hoy en día se pueden encontrar multitud de sistemas que permiten proporcionar la orientación de un objeto, destacando:

- Los que se basan en puntos de referencia, es decir, deducen la orientación del objeto analizando su orientación respecto a puntos de referencia.
- Los que se deducen su orientación calculando su deriva respecto al norte magnético.
- Los que analizan la evolución de la posición del objeto para conocer su orientación.
- Aquellos que observan medidas indirectas (la velocidad o aceleración de un objeto) y a partir de una orientación conocida van actualizando dicha orientación en base a las medidas capturadas.

1.2.2.1. Respecto a puntos de referencia

Una de las formas más antiguas para conocer la orientación de un objeto es realizar mediciones respecto a ciertos puntos de referencia. Tradicionalmente, estos puntos de referencia eran los cuerpos astrales, datando de antes del siglo IV de nuestra era el primer instrumento (Fig. 1–15) utilizado para obtener medidas respecto a las estrellas, el astrolabio (tanto el inventor como la fecha en la que se creó no está claramente definido, siendo la referencia más antigua del siglo II después de Cristo).

Fig. 1–15: Astrolabio de al-Sahlî, del siglo XI (imagen extraída de es.wikipedia.org)

Para poder utilizar este tipo de sistemas, es necesario medir el ángulo respecto a los puntos de referencia y adaptar la orientación respecto a dichos puntos para conocer la orientación respecto al norte del sistema [28]. Debido a esto, aquellos sistemas que basan su localización en un algoritmo DOA, disponen de toda la información necesaria para implementar estos sistemas de orientación, por lo que dicha información se suele extraer de este forma en vez de utilizando sensores adicionales.

Cabe destacar que suele ser necesario conocer la orientación respecto a varios puntos de referencia y/o la posición del objeto antes de poder obtener su orientación respecto al norte del sistema. Así, si utilizamos el mismo ejemplo descrito en el apartado "0 Dirección de llegada" pero eliminamos el conocimiento por parte del barco del norte magnético, tomando medidas respecto a dos balizas el sistema es incapaz de conocer la orientación y posición del objeto (Fig. 1–16).

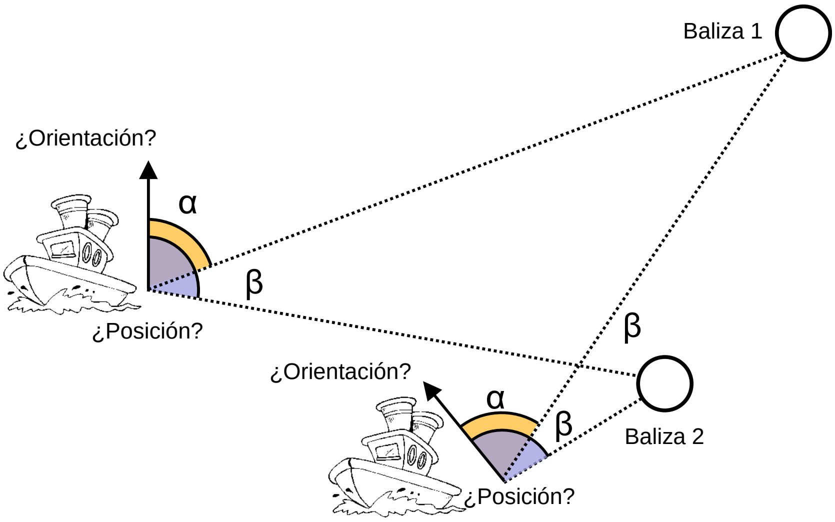

Fig. 1–16: Orientación respecto a puntos de referencia.

Para conocer la posición y orientación del barco en el ejemplo anterior, es necesario disponer de una tercera baliza en el sistema y resolver un complejo algoritmo basado en funciones trigonométricas (un ejemplo de esta complejidad puede encontrarse en el capítulo 5), lo que hace que pese a que los sistemas DOA pueden proporcionar la posición y orientación del objeto, estos estén hoy prácticamente obsoletos.

1.2.2.2. Brújula magnética

Una de las formas más tradicionales para conocer la orientación de un objeto es conocer el ángulo respecto al norte magnético. Su uso como sistema de orientación es anterior al siglo IX después de Cristo, y desde entonces hasta la llegada del GPS, ha sido uno de los principales pilares de los sistemas de navegación (al no depender del clima como pueden ser la navegación basada en estrellas).

Hay que tener en cuenta que debido a que el norte magnético no coincide con el norte geográfico, existe una desviación entre ambos que depende de la posición del objeto en el globo terráqueo. Esta desviación se conoce como declinación magnética (Fig. 1–17).

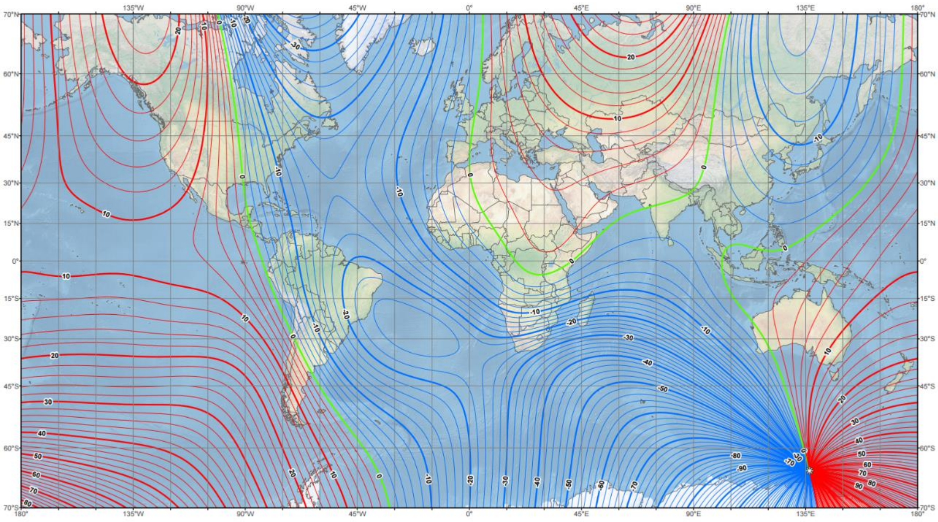

Fig. 1–17: Declinación magnética 2015 (imagen extraída de www.ngdc.noaa.gov)

La gran ventaja de este tipo de sistemas es que el norte magnético apenas depende de la posición del objeto (siempre que no hablemos de navegación a nivel global) por lo que si se conoce la zona sobre la que está el objeto y la deriva respecto al norte magnético en dicha zona, el sistema es capaz de deducir de forma sencilla la orientación del objeto.

Aunque existen sensores capaces de determinar la dirección del norte magnético [29-31], su uso en aplicaciones de navegación en interiores es bastante escaso debido, principalmente, a que los equipos electrónicos y los componentes metálicos desplegados en estos entornos introducen perturbaciones que hacen que estos sensores dejen de proporcionar información útil cuando se acercan a este tipo de objetos.

1.2.2.3. Posiciones relativas

La mayoría de los sistemas de navegación actuales proporcionan la orientación del objeto en base a las posiciones del elemento a medida que pasa el tiempo [32].

Si disponemos de un sistema (como el GPS) que permite proporcionar la posición de un objeto de forma precisa, y existe un objeto que se desplaza en una dirección indeterminada, si observamos la evolución de la posición de dicho objeto podemos obtener la orientación del mismo, asumiendo que dicha orientación no cambia abruptamente respecto a la tasa de actualización de la posición del objeto (Fig. 1–18)

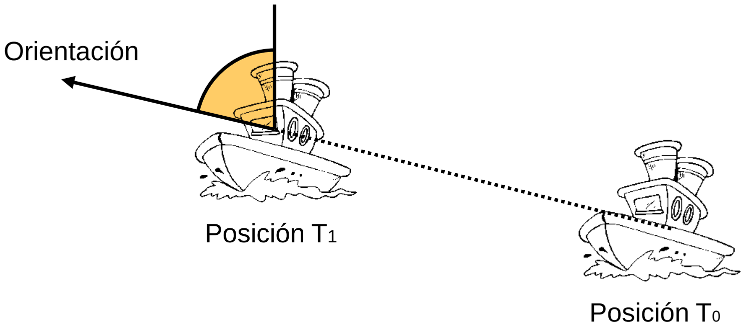

Fig. 1–18: Orientación basada en posiciones relativas

El problema de estos sistemas es que requieren que el objeto se mueva para poder conocer su orientación y que dependen en gran medida de la precisión que proporcione el sistema de localización.

1.2.2.4. Medidas indirectas

Existen sistemas capaces de determinar la orientación de un objeto en base a medidas indirectas. Del mismo modo que existen sistemas capaces de determinar la posición de un robot considerando cuánto se ha desplazado el robot en función de cuánto han girado sus ruedas, se puede conocer la orientación del robot analizando cómo giran las ruedas del mismo (cuando el robot gira hacia un lado, la rueda cercana al punto de giro, se mueve menos que la rueda más alejada) [4-5].

Al igual que pasaba con los sistemas que determinaban la posición del robot en base a este tipo de medidas, pese a que pueden proporcionar gran precisión con un coste reducido, los errores generados durante el proceso de adquisición se van acumulando, por lo que pasado cierto tiempo es necesario recalibrar el sistema (siendo necesario implementar un sistema auxiliar para ello).

1.3. Aportación de la Tesis

En la presente tesis doctoral se propone un nuevo sistema de localización para interiores con las siguientes características:

- El sistema alcanza una precisión del orden de centímetros utilizando ultrasonidos, resolución suficiente para poder implementar cualquier sistema de navegación en estos entornos.
- El sistema implementa una arquitectura DTOA donde un nodo despliega varios receptores con los que obtiene la diferencia de tiempo de llegada de señales generadas en transmisores situados en el techo.
- Con la diferencia de tiempos medida respecto a varios transmisores, el sistema es capaz de determinar la dirección desde la que se generó la señal de referencia a cada transmisor, implementando un sistema de localización DOA que requiere poca capacidad computacional (del mismo orden que el demandado por los sistemas TOA).
- Al utilizar un sistema DOA para obtener la localización del nodo, el nodo conoce en todo momento su orientación sin necesidad de utilizar sistemas auxiliares.
- Transmisores y receptores no están sincronizados entre sí, lo cual reduce considerablemente la complejidad del sistema.
- Todo lo requerido para obtener la localización y la orientación del nodo se gestiona de manera autónoma por el propio nodo.

Estas características permiten proporcionar a un nodo capacidades de localización y orientación dentro de edificios, permitiendo desarrollar sistemas de navegación escalables donde cada nodo dispone de una gran autonomía y donde la complejidad del sistema es mínima.

1.3.1. Trabajos compendiados

A lo largo del desarrollo de esta tesis, se han intentado diferentes aproximaciones al sistema con las que se intenta mejorar las prestaciones del mismo. Dichas aproximaciones, así como los resultados obtenidos con cada una de ellas, se han publicado en los siguientes artículos:

- Santiago Elvira, Ángel de Castro, Javier Garrido. "ALO: An ultrasound system for localization and orientation based on angles", Microelectronics Journal, Volume 44, Issue 10, October 2013, Pages 959-967, ISSN 0026-2692, (Revista JCR con índice de impacto en 2013 de 0,924).
- Santiago Elvira, Ángel de Castro and Javier Garrido. "ALO4: Angle Localization and Orientation System with Four Receivers". International Journal of Advanced Robotic Systems, Volume 11, issue 152, September 2014, pages 1-10, ISSN 1729-8806. (Revista JCR con índice de impacto en 2014 de 0,526).
- Santiago Elvira, Ángel de Castro, Guillermo Glez-de-Rivera and Javier Garrido. "Angle Localization and Orientation System with 4 receivers and based on Audible Sound Signals". IEEEXplore DCIS 2014, pages 1-6, ISBN 978-1-4799-5743-9. (Congreso).
- Santiago Elvira, Ángel de Castro and Javier Garrido. "HALO4: Horizontal Angle Localization and Orientation System with 4 receivers and based on Ultrasounds". Journal of Intelligent & Robotic Systems, online october 2015, pages 1-13, ISSN 0921-0296. (Revista JCR con índice de impacto en 2014 de 1,178).
- Santiago Elvira, Ángel de Castro and Javier Garrido. "CAL4: Ceiling Angle Localization System with 4 transmitters based on Ultrasounds". XXIII Seminario Anual de Automática, Electrónica Industrial e Instrumentación SAAEI 2016. (Congreso, aceptado y pendiente de publicación en las actas del congreso).

1.3.1.1. ALO: An ultrasound system for localization and orientation based on angles

En este artículo se propone un sistema de navegación para interiores basado en la tecnología de ultrasonidos y en utilizar un *array* de 3 receptores desplegados en un robot que toman medidas respecto a 2 transmisores situados en el techo de una habitación.

El sistema se basa en utilizar los tres receptores para, a través de una aproximación TDOA, obtener la dirección con la que se recibe la señal de ultrasonidos en el receptor. Esto permite aplicar ecuaciones propias de los sistemas DOA para obtener la posición y orientación del robot en el entorno.

La principal aportación de esta publicación consiste en el propio algoritmo utilizado para obtener el ángulo de recepción de la señal de ultrasonidos en el nodo receptor, junto con el algoritmo utilizado para convertir estas medidas en la posición y orientación del nodo. Su reducida complejidad hace que el sistema demande una capacidad computacional equivalente a la requerida por los sistemas TOA, pero sin demandar que exista una fuerte sincronización entre transmisores y receptores.

Los resultados obtenidos al implementar este sistema obtienen un importante error al calcular la posición y orientación del objeto. En el artículo se recogen, junto con los resultados obtenidos, un análisis de las principales fuentes de error así como sus efectos en el sistema.

1.3.1.2. ALO4: Angle Localization and Orientation System with Four Receivers

Esta publicación presenta una evolución del sistema de localización ALO, la cual consiste en añadir un receptor adicional al sistema. Al añadir un cuarto receptor, se reduce, hasta poder considerar despreciable, el error de aproximar la señal recibida como una onda plana.

Esta evolución permite aumentar las prestaciones del sistema sin modificar el algoritmo utilizado para obtener la dirección de llegada o la posición / orientación del robot, por lo que su coste computacional sigue siendo equivalente al demandado por los sistema TOA.

Además de analizar las principales fuentes de error de esta aproximación, en el artículo se recoge un análisis del coste computacional necesario (en ciclos de reloj del microprocesador MicroBlaze) para obtener la posición y orientación del robot. Además, se detalla cómo es recomendable desplegar los transmisores con el fin de minimizar el tiempo requerido para obtener todas las medidas demandadas por el sistema y se hace un análisis de las prestaciones del sistema cuando el robot con los receptores está en movimiento.

Los resultados obtenidos al implementar este sistema y compararlo respecto al sistema ALO muestran que el sistema mejora la precisión en la localización y orientación del robot, pero que dicha precisión dista de la obtenida por los sistema TOA basados en ultrasonidos.

1.3.1.3. Angle Localization and Orientation System with 4 receivers and based on Audible Sound Signals

Este artículo recoge los resultados obtenidos al sustituir, en el sistema ALO4, la tecnología de ultrasonidos por sistemas basados en procesar señales en el rango audible por el ser humano.

Esta aproximación facilita el uso de modulaciones en la señal de referencia sin incurrir en un mayor coste del sistema al utilizar micrófonos y altavoces convencionales, lo que permite eliminar el error de offset existente en el sistema de recepción basado en la tecnología ultrasónica.

Al implementar el dispositivo se observó que era imposible reducir la frecuencia de la señal de referencia tanto como se deseaba debido, principalmente, a los rebotes existentes en el entorno. Estos rebotes afectaban a la señal de referencia antes de que esta fuese validada por el robot, lo que hacía que las medidas capturadas por el sistema no fuesen válidas. Debido a este problema, en el artículo se propone una solución que pese a no eliminar el problema del offset en todas las situaciones, lo reduce significativamente, llegando a no existir en las pruebas realizadas.

Pese a que el sistema basado en sonido mitiga significativamente el error de offset, el hecho de trabajar con señales de menor frecuencia decrementa las prestaciones del sistema, llegando a alcanzar, aproximadamente, un 30% peor precisión que un sistema equivalente basado en ultrasonidos.

1.3.1.4. HALO4: Horizontal Angle Localization and Orientation System with 4 receivers and based on Ultrasounds

En esta publicación se recoge una evolución del sistema ALO4 basada en sustituir el uso del ángulo vertical para obtener la posición del objeto, por el uso del ángulo horizontal.

Esta aproximación hace que el sistema no necesite conocer en todo momento la velocidad de propagación de la señal de ultrasonidos (la cual depende de factores como son la presión, la humedad o la temperatura del ambiente) lo que se traducía en un error significativo en el sistema ALO4.

Esta evolución solo requiere modificar el algoritmo implementado para obtener la posición del objeto, el cual es relativamente complejo, siendo difícil encontrar una solución analítica al problema.

En el artículo se propone un proceso de minimización con el que el sistema es capaz de resolver la ecuación para deducir la posición del objeto. Pese a que este proceso demanda una mayor capacidad de computación que el necesario para los sistemas TOA, este es significativamente menor que el demandado por otros algoritmos de minimización utilizado en otras aproximaciones DTOA.

Los resultados obtenidos con esta aproximación mejoran los reportados por el sistema ALO4, hasta hacerlos comparables a los obtenidos por sistemas TOA.

1.3.1.5. CAL4: Ceiling Angle Localization System with 4 transmitters based on Ultrasounds

En este artículo se muestra una evolución del sistema ALO4, pasando de utilizar 4 receptores y dos transmisores para obtener la posición del objeto, a utilizar un sólo receptor en el robot y demandar cobertura por cuatro transmisores en el techo, ofreciendo una precisión equivalente y demandando una capacidad computacional similar a los sistemas TOA.

Midiendo la diferencia de llegada de las señales emitidas por los transmisores (las cuales deben estar fuertemente sincronizadas), el sistema es capaz de estimar el ángulo con el que se recibiría una señal ficticia, generada en el receptor del robot, en el punto que representa el centro del cuadrado en cuyos vértices se despliegan los transmisores aplicando las mismas ecuaciones que las del sistema ALO4.

Esta aproximación permite desplegar los transmisores a la distancia que se desee sin estar limitados por el propio tamaño del robot, lo cual aumenta considerablemente la precisión del sistema.

Tras implementar este sistema, se observa que el efecto de la mayoría de los errores que afectaban al sistema ALO4 son despreciables, pasando a ser el error de offset el principal error del sistema (el cual, además, ya no puede ser eliminado vía software como en el resto de sistemas ALO). Este error ocasiona que las medidas en una determinada zona sean muy precisas pero que exista un error significativo cuando el robot se acerca a uno de los transmisores.

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2. ALO: AN ULTRASOUND SYSTEM FOR LOCALIZATION AND ORIENTATION BASED ON ANGLES

Abstract:

This paper presents a low cost system based on ultrasound transducers to obtain the localization and orientation information of a mobile node, such as a robot, in a 2D indoor space. The system applies a new differential time of arrival (DTOA) technique with reduced computational cost, which is called ALO (Angle Localization and Orientation). Instead of directly calculating its position, the system calculates the direction of arrival of the received ultrasonic signal and, through it, its position and orientation. A prototype of a robot has been built in order to show the validity of the method through experimental results.

Keywords:

DTOA, DOA, location, orientation, ultrasonic, triangulation, robot, Field Programmable Gate Array

2.1. Introduction

In the last years, localization systems for indoor spaces have been deeply studied. The advantages obtained by outdoor localization systems, like GPS, and the problems to adapt these systems to indoor environments have been the base for the research of alternative localization methods suitable for indoor environments.

For indoor localization, there are many systems already developed and tested. From RFID [1] localization systems, based on measuring the strength of the received signal and the knowledge of the position of the transmitters, to systems based on image recognition [2, 3], where the system must identify patrons on the floor, ceiling or walls, there are a lot of techniques that can be used. The selection is done in function of the computational capacity of the system and the accuracy requested by the application. Some of the most extended localization systems for indoor applications are the ones based on ultrasonic technology. This is because this technology allows high accuracy with low cost and low computational effort.

The main advantage of ultrasonic signals is their low propagation velocity, at least when compared to electronic circuits processing speed. This characteristic allows capturing the propagation delay between known points with high precision and using relatively low frequency counters.

Two main approaches are used when using ultrasonic technology: "time of arrival" (TOA) localization techniques, in which the system estimates the propagation delay between transmitter and receiver; and "differential time of arrival" (DTOA) techniques, in which the system estimates the propagation delay between multiple receivers but not between transmitter and receiver. TOA systems based on ultrasonic transceivers need an auxiliary radiofrequency signal in order to know both the time of transmission and reception, while DTOA systems can use only ultrasounds because they only need reception times.

TOA localization systems usually calculate the position of the mobile node with the intersection of spheres, whose radii are the measured distances and whose centers are the positions of some known points, called anchor points. These anchor points can be either the transmitters (passive architecture) or the receivers (active architecture). Examples of systems that use this technology are the BAT Ultrasonic Location System [4], The MIT Cricket Indoor System [5, 6], the system developed at the UAM [7, 8] or the Single Compact Base Station system [9]. In all these proposals, the anchor points are deployed in the ceiling, except in [9], where the three transmitters are included in a compact platform. This simplifies deployment, but at the cost of obtaining less precision.

DTOA localization systems are divided in two main groups. The systems of the first group, called multilateration systems, calculate the position of the mobile nodes with the intersection of hyperboloids where the focuses are the anchor points, while the systems of the second group estimate the direction of arrival (DOA) of the reference signal.

The multilateration systems have been implemented in multiple proposals, like the one developed in the Univ. of Bristol [10, 11], Decca Navigator System [12] or LORAN-C [13]. Their main disadvantage is their high computational cost, so when they are implemented in low cost robots they are usually implemented using linearized equations [14] or with minimization functions [15].

The DOA algorithms allow obtaining both the position and orientation of the mobile node. The main problem of these systems is their high complexity because they use complex trigonometric equations. An example of DOA based in DTOA techniques is the MUSIC algorithm [16] that allows estimating, simultaneously, the reception angle of different signals from multiple transmitters, checking the correlation of the received signal in the array of receivers. Other example, but using audible signals instead of ultrasounds, is presented in [17]. Although the algorithm is simplified, it still uses FFT (Fast Fourier Transform) apart from other calculations.

In this paper, a new localization and orientation DTOA system, ALO (Angle Localization and Orientation), is presented, which is based on the angle of reception of an ultrasonic signal in a mobile node moving in a 2D space (i.e. the floor). This allows obtaining the position of the node and its orientation. The main novelty of the proposed system is that it uses low complexity calculations, so it can be implemented in low cost devices. The rest of the paper is organized in five main sections: "Angle Estimation", where the base of the system and the mathematical equations are described; "Localization and Orientation", where the localization and orientation technique based on angles is presented; "Implementation", where the implementation of the system can be found; "Error Analysis", section that describes the main error sources and their effect on the precision of the localization system; and "Results", where the experimental results are presented.

2.2. Angle Estimation

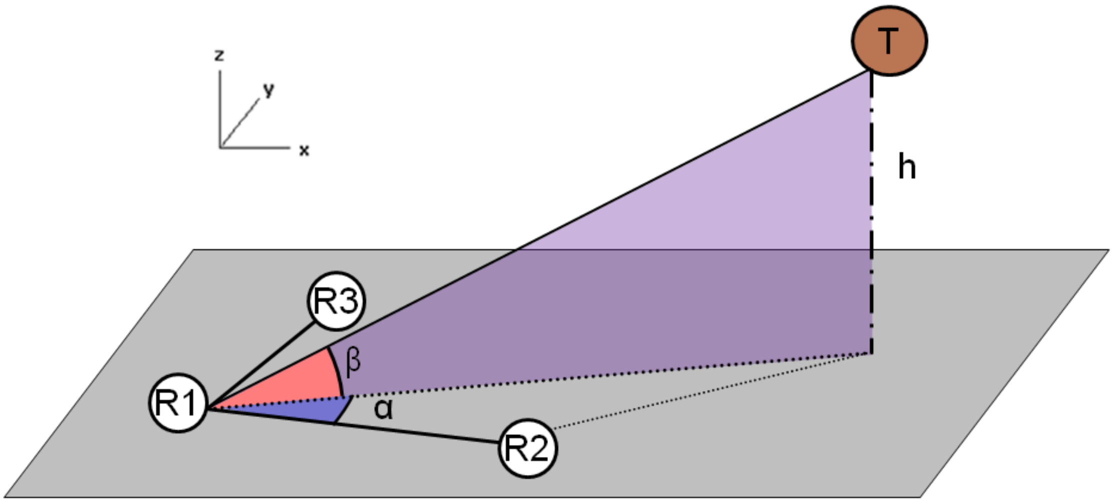

Fig. 2–1: Angles in the receiver

To estimate the reception angle to any transmitter, it is only necessary to measure the time elapsed between the receptions of the same ultrasonic signal in different points. The only assumption of our proposal is that all the receivers see the transmitter under approximately the same angle. This is true if the distance between the transmitter and the receivers is much greater than the distance between receivers. With this condition, the approximation error on the angle of the proposed method is negligible.

First, an object must be defined as a group of receivers located in a plane. This object will have a reference receiver (R1 in Fig. 2–1) and one or two auxiliary receivers (R2 and R3 in Fig. 2–1). All the angle estimation process will make reference to this reference receiver, using the auxiliary receivers to measure the propagation delay and direction of the reference wave.

This object, which moves in a plain (which will be the floor in the real world), has two main orientations with respect to any point in the space: the first orientation, that will be called horizontal orientation (α in Fig. 2–1), makes reference to the angle that forms the north of the object (R1 to R2 direction) with the projection of the vector that joins the reference receiver and the transmitter on the receiver's plane. The other orientation, called vertical orientation (β in Fig. 2–1), makes reference to the angle between the plane that contains the receivers and the vector that joins the transmitter and the reference receiver.

To calculate the localization of the object, the vertical angle must be always obtained, while the horizontal angle has only two possible values (0º or 180º) when the object moves in a 1D space (a line), but can have any value when the object has 2 or 3 degrees of freedom.

2.2.1. Estimating the reception angle in a 1D space

If the object can only move in a line, a plane that contains that line and the transmitter can be defined. In this plane, the axis X will be the same as the movement line, and the axis Y will be a line perpendicular to the movement line and that contains the transmitter (see Fig. 2–2). In this case, if the system north reference is +X, the horizontal angle can only be 0º (if R2 is nearer to X=0 than R1) or 180º (if R1 is nearer to X=0 than R2), and given that the object can't rotate, once the object is deployed it can be deduced in function of the receiving order of the reference wave. This allows calculating the sign of the X position of the receiver R1 (positive for 0º, negative for 180º). To estimate the vertical angle, the system must measure the difference in the time of arrival between the two receivers.

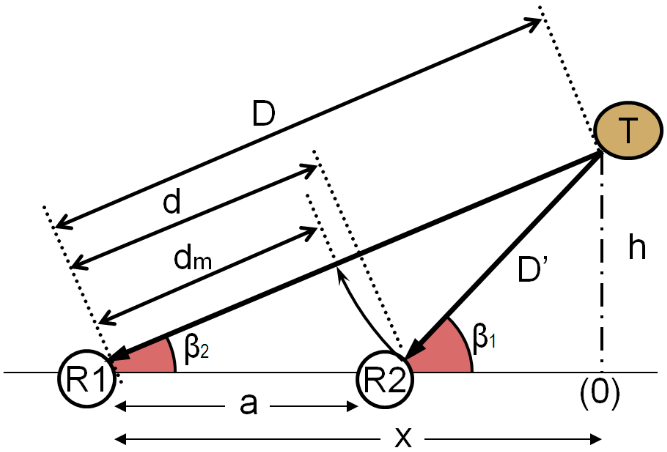

Fig. 2–2: Angle estimation for 1D space system

For this example, the transmitter will be in the position (0, h), the reference receiver (R1 in Fig. 2–2) in (x, 0) and the auxiliary receiver (R2 in Fig. 2–2) in (x-a, 0). If the transmitter is omnidirectional and there are not obstacles in the space, the propagation delay from the transmitter to the receivers will be proportional to the distance between the transmitter and each receiver (D and D′ in Fig. 2–2). As both receivers are in different positions, the difference in the time of arrival (d_m in Fig. 2–2) can be measured counting the number of clock cycles between the arrivals of the ultrasonic signal in each receiver (N_{clk}).

If the distance between the transmitter and the receivers is much greater than the distance between the receivers ('*a*′ in Fig. 2–2):

$$D >>> \text{a} \quad D' >>> \text{a} \Rightarrow \beta_1 \approx \beta_2 \quad d_m \approx d \qquad (1)$$

This difference can be considered as a cathetus of a right triangle (*d* in Fig. 2–2). In this right triangle, the hypotenuse is the distance between the receivers (*a*), that is known, so the reception angle can be easily estimated as:

$$\cos(\beta_1) = \frac{d}{\text{a}} \approx \frac{d_m}{\text{a}} \qquad (2)$$

$$d_m = \frac{V \cdot N_{clk}}{f_{clk}} \qquad (3)$$

Where V is the propagation speed of the reference wave (speed of sound), f_{clk} is the frequency of the counter that measures the difference in the times of arrival and N_{clk} is the number of clock cycles measured.

2.2.2. Estimating the reception angle in a 2D or 3D space

If the object can move in a 2D or 3D space, the system needs to estimate two angles in order to calculate its position and orientation. In these cases, a third receiver is needed, and to simplify the future localization process, the three receivers should be placed in a right isometric triangle distribution.

If we define a plane as the surface that contains the three receivers, the axis X will be the line that contains R1 and R2 (Fig. 2–1) while axis Y will contain receivers R1 and R3 (Fig. 2–1). The axis Z is orthogonal to the XY plane. In this distribution, R1 will be defined as the reference receiver, with position (0, 0, 0), while R2 and R3 will be the auxiliary receivers with positions (a, 0, 0) and (0, a, 0) respectively. The transmitter will be placed at (Tx, Ty, Tz).

To estimate the horizontal and vertical angles, the next procedure is followed. Given that the distance between receivers, *a*, is negligible with respect to the distance between transmitter and receivers, the ultrasonic signal will be received as a plane wave, with a normal vector as the difference of position between the transmitter and the reference receiver. In this case, the normal vector of the reception plane is (-Tx, -Ty, -Tz).

With 3 receivers it is possible to take two differential time measures, t1 and t2, counting the number of clock cycles between the arrival at the auxiliary and reference receivers. These two time measures can be transformed into distances, d1 and d2, because the propagation speed of the reference signal is known. The propagation speed of an ultrasonic signal is the speed of sound, which is ~343 m/s.

These distances can be considered as the radii of two spheres (S2 and S3 in Fig. 2–3, which is an orthographic projection showing the top and front views) centered in the reference receiver (R1) and that are tangential to the ultrasonic wave when it reached the auxiliary receivers (R2 and R3). With one measure, the intersection of the possible planes that contain the secondary receiver R2 and are tangential to the sphere S2 are limited to a circumference, C2, over the surface of the sphere S2. The direction of arrival can be any of the lines joining the reference receiver, R1, and the circumference, C2, which forms a cone. Using the second distance, the circumference C3 over the sphere S3 is obtained with the planes that contain R3 and are tangential to S3. This second circumference gives other cone of possible directions of arrival. The intersection of both cones gives only two possible directions of arrival. However, as the receivers are in the floor, the direction that goes below the floor can be discarded, so the direction of arrival is completely defined.

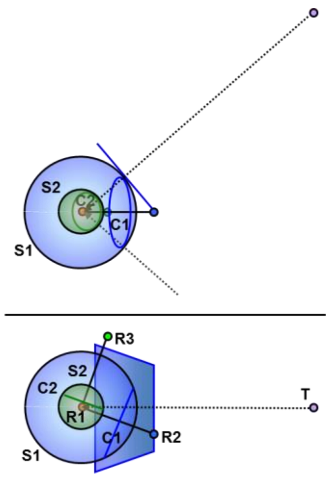

Fig. 2–3: Angle estimation for 2D space, top view (top) and front view (bottom)

To conclude, the last operation consists in extracting the horizontal and vertical angles of the direction of arrival. It can be deduced that:

$$\cos(\alpha) = \sqrt{\frac{d_1^{\,2}}{d_2^{\,2} + d_1^{\,2}}} \qquad \sin(\beta) = \sqrt{1 - \frac{d_2^{\,2} + d_1^{\,2}}{a^2}} \tag{4}$$

The sign of α can be deduced taking into account the reception order of the ultrasonic signal in the different receivers, while the sign of β can be only positive because our receivers can only capture the ultrasonic wave from above the floor.

2.3. Localization and Orientation

2.3.1. Localization for 1D space

If the object can only move with one degree of freedom, it limits its possible positions to a line. This enables to limit the complete space to a plane, where the object can be in any position of the X axis (x, 0) and the transmitter is fixed at the point (0, h). The object must have at least two receivers at positions (x, 0) and (x-a, 0) to calculate its position (see Fig. 2–2).

After estimating the reception angle as seen in the previous section, the process to calculate the position of the object is:

$$h = D \cdot \sin(\beta) \Rightarrow D = \frac{h}{\sin(\beta)} \quad (5)$$

$$h^2 + x^2 = D^2 \Rightarrow x = h\sqrt{\frac{1}{\sin^2(\beta)} - 1} \quad (5)$$

$$x = h\sqrt{\frac{1}{1-\cos^2(\beta)} - 1} = h\sqrt{\frac{a^2}{a^2 - d^2} - 1} \quad (5)$$

The sign of x can be deduced according to the reception order in the two receivers of the ultrasonic signal. For example, in Fig. 2, R2 receives the reference signal earlier than R1, so the robot knows that R2 is nearer to X=0 than R1, so the horizontal angle is 0º (see section 2.1) and X is positive. In the opposite case, the horizontal angle would be 180º and X would be negative.

The last expression of equation (5) is the one implemented in the robot, avoiding the use of trigonometric functions.

2.3.2. Localization for 2D space

If the object can move in a 2D space (i.e. the floor), the object must be provided with at least three receivers in order to estimate its horizontal and vertical orientation with respect to the transmitters. In this case, the horizontal plane of the system that contains the axis X and Y will be defined as the plane that contains the three receivers, which is also the movement plane.

It is also necessary to use two different transmitters in order to calculate the position. The reason for this requirement is that an orientation with respect to a single transmitter is satisfied by an infinite group of points in a circumference centered in the projection of the transmitter to the horizontal plane. Each point of this circumference will return its relative orientation identically, but with different absolute orientation (see Fig. 2–4).

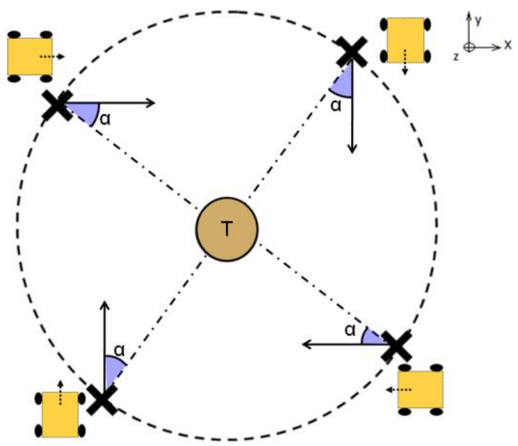

Fig. 2–4: Single transmitter: undefined position

To deduce its absolute orientation and, therefore, its absolute position, a second transmitter is needed. With two orientations with respect to two different transmitters, the possible positions of the object are reduced to only two points, but only one of these two points matches both absolute orientations, so the problem is solved (see Fig. 2–5).

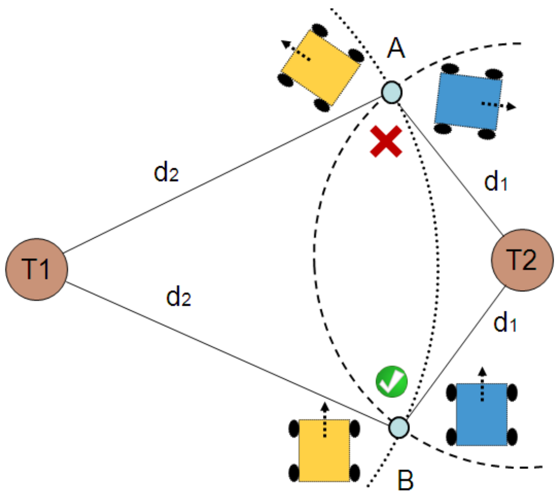

Fig. 2–5: Two transmitters: position defined by distance and orientation

Mathematically, the solution is based on the intersection of circumferences, where the center of these circumferences is the projection over the horizontal plane of the transmitters. To simplify the calculus, the plane where all of the transmitters are placed is parallel to the horizontal plane, at a distance of 'h' (i.e. the height to the ceiling). The point (0, 0, 0) is the projection over the horizontal plane of the first transmitter (0, 0, h). The axis X is defined as the line parallel to the line that joins both transmitters, so the second transmitter is placed at the position (b, 0, h) (Fig. 2–6):

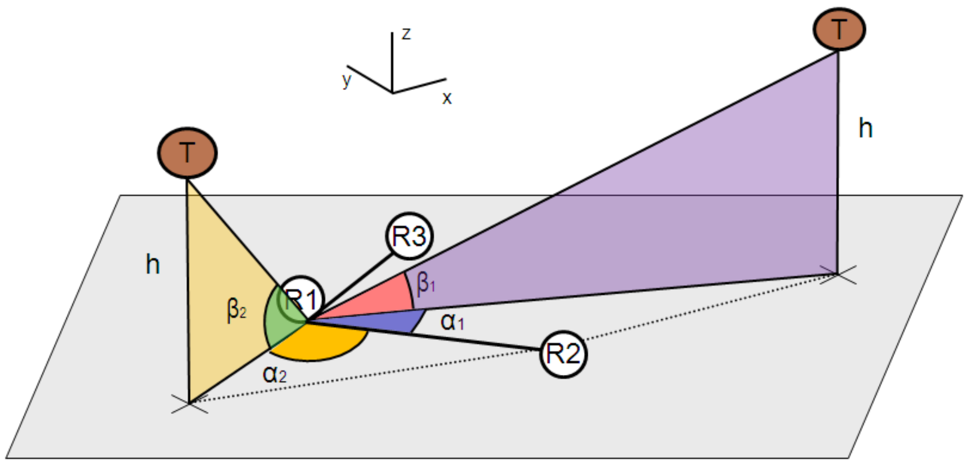

Fig. 2–6: Localization in a 2D space

$$h = D_1 \cdot \sin(\beta_1) \Rightarrow D_1 = \frac{h}{\sin(\beta_1)} \quad (6)$$

$$d_1 = D_1 \cos(\beta_1) = \frac{h}{\tan(\beta_1)} \qquad d_2 = \frac{h}{\tan(\beta_2)} \quad (6)$$

With these distances, the problem is reduced to intersecting circumferences:

$$x = \frac{d_1^{\,2} - d_2^{\,2} + b^2}{2 \cdot b} \qquad y = \pm\sqrt{d_1^{\,2} - x^2} \quad (7)$$

To solve the sign of y, the system obtains the absolute orientation in both points with respect the two transmitters, and discards the point whose absolute orientations don't match.

2.3.3. Orientation

When the object can move in a 2D or 3D space, the horizontal orientation takes special interest. All navigation systems need to know its orientation. The angle estimation explained before only informs about the relative orientation with respect to one transmitter, but is not the robot absolute orientation.

Given that our system can obtain its absolute position and the positions of the transmitters are also known, the relative orientation can be transformed into the absolute orientation. In order to do so, the system must only calculate an orientation correction factor (θ in Fig. 2–7), which is the angle between the vector that represents the system north (Nx, Ny) and the vector that joins the object position and the transmitter projection (Px, Py). If this correction factor is added to the relative horizontal angle, the absolute orientation of the object is obtained.

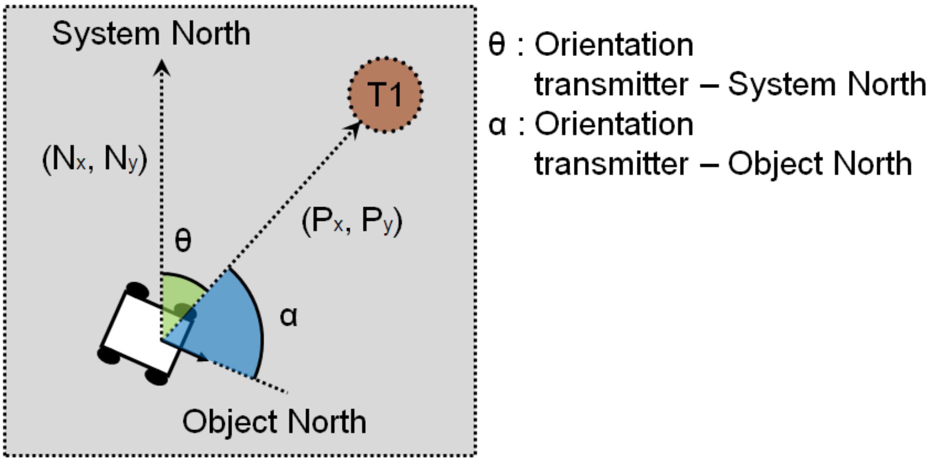

Fig. 2–7: Absolute and relative orientation angles

$$\cos(\theta) = \frac{P_x \cdot N_x + V_y \cdot P_y}{\sqrt{P_x{}^2 + P_y{}^2} \cdot \sqrt{N_x{}^2 + N_y{}^2}} \qquad (8)$$

If the system north is defined as the vector (1, 0), the algorithm to obtain the position orientation correction factor is simplified to:

$$\cos(\theta) = \frac{P_x \cdot N_x}{\sqrt{P_x{}^2 + P_y{}^2}} = \frac{P_x}{d} \qquad (9)$$

2.4. Implementation

To test the precision of the system, two transmitters, separated by 240 cm, were placed on the ceiling of a room. The ceiling height is 280 cm. Both transmitters are connected to a unique FPGA (Xilinx Spartan3 model) that transmits sequentially each 100 ms a train of pulses at 40 kHz, one time using transmitter 1 and the next using transmitter 2. These signals are sent to drivers that increase their voltages from 3.3V to 20V, and these amplified signals are the inputs of the ultrasonic transmitters (400ST120 model). The robot, which is equipped with three receivers, is deployed in the floor of the room. This distribution allows the implementation of the localization system for 2D space (Fig. 2–8).

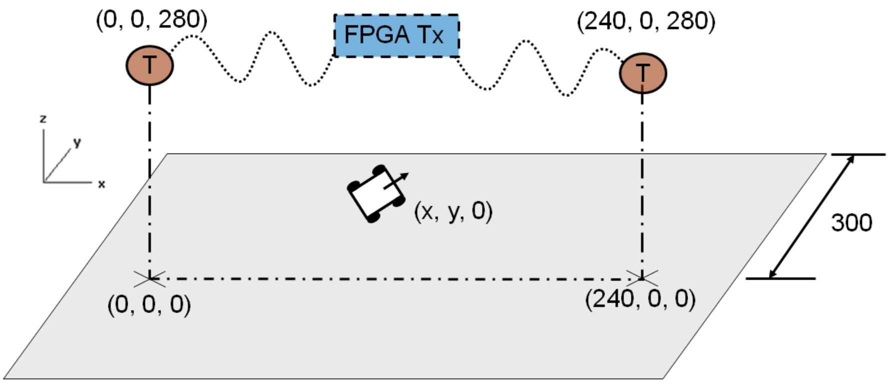

Fig. 2–8: Transmitters and receivers deployment

The robot (Fig. 2–9) is composed by three main layers, apart from the mechanical structure including the motors and their encoders. The first level is an analog board that implements all the auxiliary circuits, while the second contains the FPGA and is responsible of the implementation of all of the logic needed to determine the localization and orientation of the robot, apart from the control of the robot. The last layer contains the ultrasonic receivers, allowing them to be deployed with a right triangle distribution and at different distances for experimental tests.

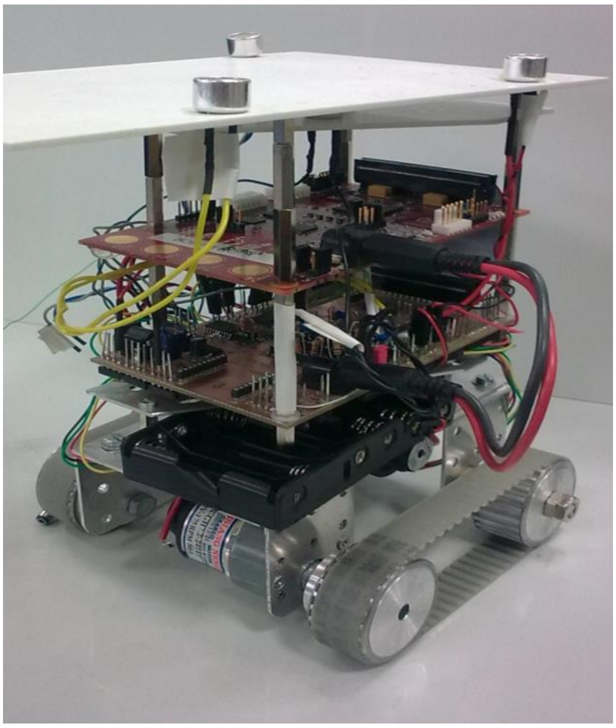

Fig. 2–9: Prototype robot

The first layer (Fig. 2–10) is an analog board with multiple functionalities. This board includes the voltage supply to convert the battery voltage to the FPGA supply voltage, manages the voltage conversion from FPGA to motors and allows the use of infrared sensor to detect obstacles. It also has an ADC to enable the connection of analog sensors and includes RF devices to establish connection between multiple robots or to a PC. But the main functionality of this board is the amplification and digitalization of the captured ultrasonic signal by the receiver (400SR120 model).

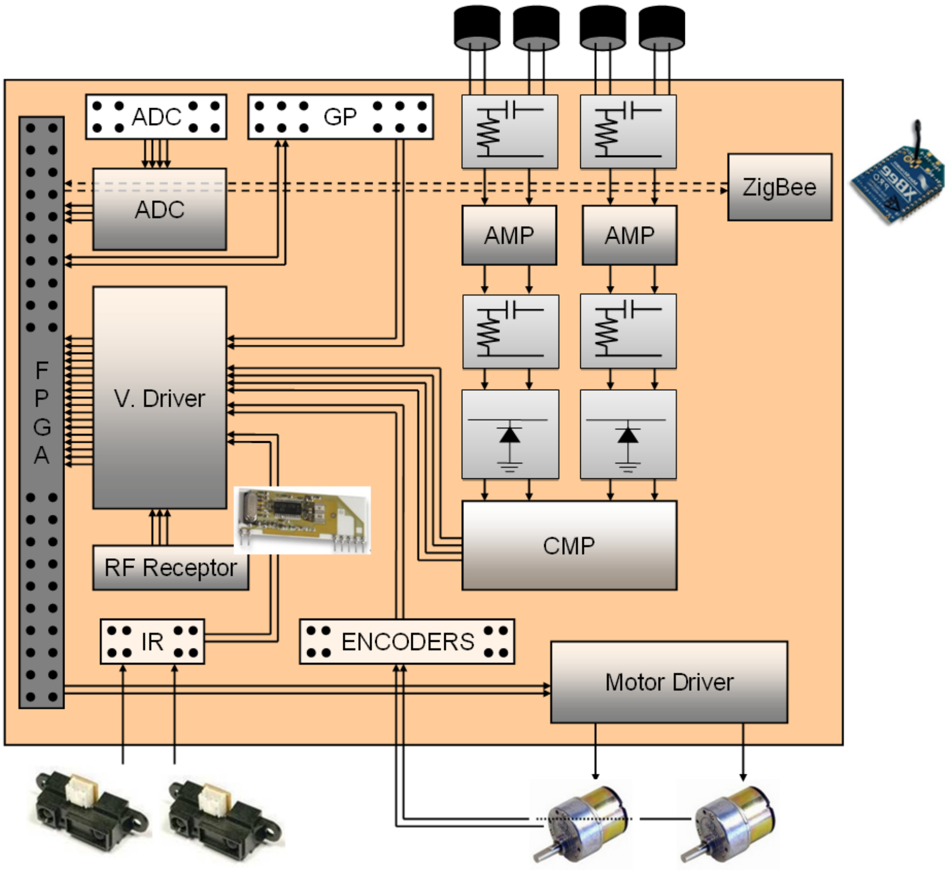

Fig. 2–10: Analog board

The digitalization phase consists in four stages. In the first one, the received signal is centered at 0 V with an RC filter. After this process, the signal is amplified using an instrumentation amplifier (model INA2331), so we can obtain high amplification from a weak source. The amplified output has a continuous component that depends of each receiver, so these signals are again connected to a high pass filter, implemented with another serial RC circuit. The output is filtered with a diode to eliminate the negative part. After the diode, a comparator device (model TLC352CP) is used to digitalize the signal. The output is a logic one when the amplified signal is over a certain value, and a logic zero when it is under that value, including all the negative semicycle. Therefore, the output is a digital signal which is almost a square signal at 40 kHz when the ultrasound signal is received, and a logic zero the rest of the time. In this way, the output of the circuit can be directly connected to an FPGA (or other digital circuit), avoiding the need of an analog-to-digital converter (ADC).

The second layer contains the FPGA (XilinxSpartan-3A) where the localization and orientation algorithm is implemented. In this FPGA, a MicroBlaze embedded microprocessor (running at 52 MHz) has been implemented and a custom peripheral has been developed to capture the DTOA measure. This peripheral has the architecture shown in Fig. 2–11.

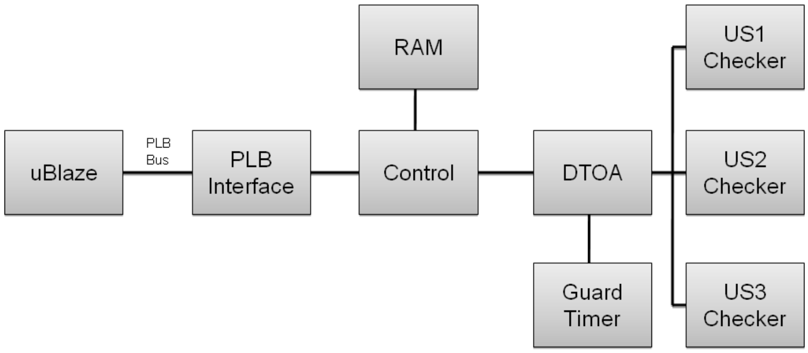

Fig. 2–11: Peripheral architecture

When any of the receivers captures a signal with enough intensity to generate at least three consecutive pulses at 40 kHz, the US (ultrasounds) Checker associated to the receiver initializes a counter in the DTOA module. When the ultrasonic wave arrives to a second receiver, the counter value is registered, but the counter keeps counting until the ultrasonic wave is detected in the last receiver. This last value of the counter is also stored. These two measures are adapted to inform of the measured delay from the auxiliary receivers to the reference receiver, independently of the reception order. The measures are stored in RAM and the value at a special RAM address is updated to indicate that a new measure has been captured.

A guard timer is activated after each measure in order to avoid detecting the rebounds of the ultrasonic signal as new measures.

The MicroBlaze microprocessor can read the RAM information through the PLB interface. It periodically polls the mentioned RAM special address to detect when a new measure is available. In that case, the microprocessor starts the localization and orientation algorithm (implemented in C-code).

2.5. Error Analysis

Multiple sources of error that affect the precision of the localization and orientation system have been detected. Some of the error sources are inherent to the electronic implementation of the localization system (like the differences in the delay of the amplification phase for each signal or the response time of each receiver), others are the results of problems in the mechanical implementation (like the incorrect position of the receivers or the incorrect parallelization of the ceiling with respect to the floor) and others are inherent to the system (like the fact of considering the received signal as a plane wave).

In this section, the most characteristic errors are theoretically analyzed by simulations using an environment with two transmitters, at positions (0, 0, 280) and (240, 0, 280) cm, like the one used in the experimental results (see Fig. 7). For this analysis, the robot is deployed at different positions, (x, y, 0), and it is always orientated to the system north. Experimental results are later presented in section 6.

The first error to be analyzed is the approximation of considering the received signal as a plane wave. This error can be appreciated in Fig. 2–2. The measured distance is considered as the cathetus of a right triangle, when the triangle has not a perfect 90º angle. This produces an error in the vertical angle estimation process that will affect the precision of the localization system. This error decreases if the distance between the receivers is small compared to the distance to the transmitter. An example of the position error for a distance between receivers of 30 cm is shown in Fig. 2–12.

Note: In all figures, the absolute localization error (represented in cm) is shown for each position.

Note: In all figures, transmitter positions are marked as red crosses.

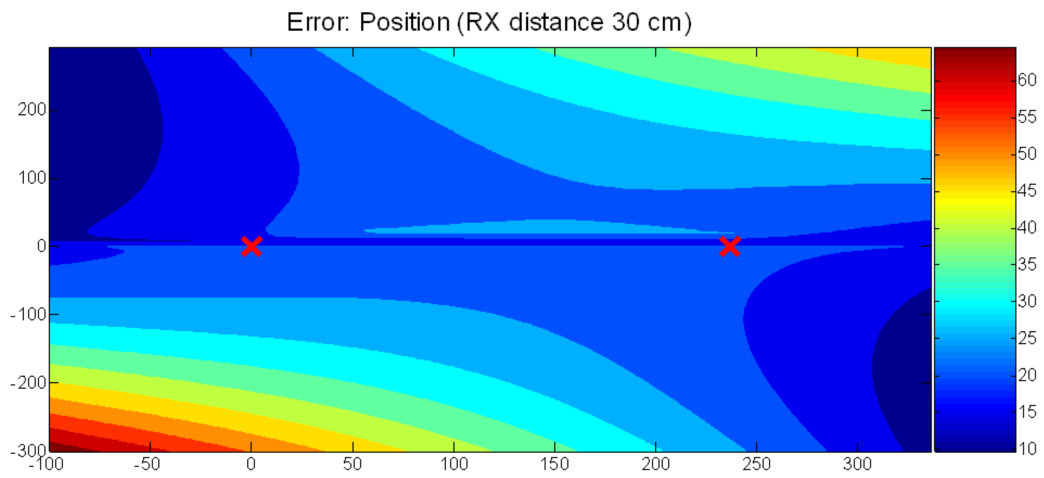

Fig. 2–12: Position error due to plane wave approximation (receivers distance 30 cm)

This error can be minimized reducing the distance between the receivers because, if the receivers are closer, the received wave will arrive to all receivers with a more similar angle. Fig. 2–13 shows the error when the distance between receivers is 3 cm.

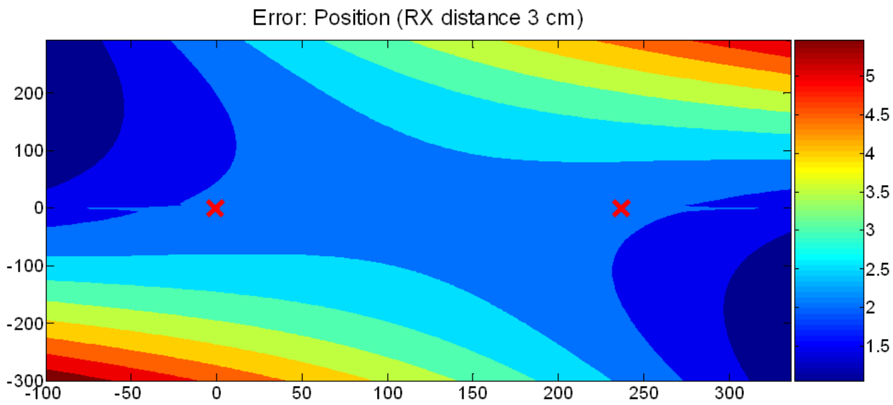

Fig. 2–13: Position error due to plane wave approximation (receivers distance 3 cm)

It can be observed that, although the distribution of error is similar in Fig. 2–12 and Fig. 2–13, the error magnitude of Fig. 2–13 is about ten times smaller than in Fig. 2–12, so this error is approximately proportional to the distance between receivers. The conclusion is that the smaller the distance between receivers, the smaller the error of approximation by a plane wave.

The second error to be analyzed is the error introduced at the amplification phase. As there are three receivers, there are three similar, but different, time responses. There are also three different paths from the receiver to the FPGA input pin. These three paths contain the same components, but as in the previous case, its temporal response is not identical. The result of this process is an error that will affect the time measured by the system. For example, if time estimation error is ±500 ns, the effect in the localization process when the distance between receiver is 3 cm is shown in Fig. 2–14 (all other errors sources are not considered).

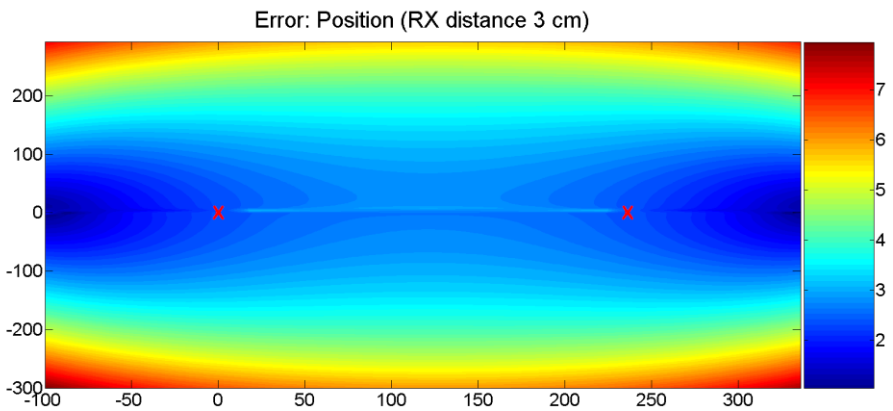

Fig. 2–14: Position error due to non ideal amplification phase (receivers distance 3 cm)

In order to reduce the effect of this error, the receivers must be placed as far as possible. When the distance between the receivers is reduced, the percentage of this error respect the total time measure will be bigger and the localization error will be increased too. To show this effect, Fig. 2–15 represents the localization error if, with the same estimation error (±500 ns), the distance between the receivers is reduced to only 1 cm.

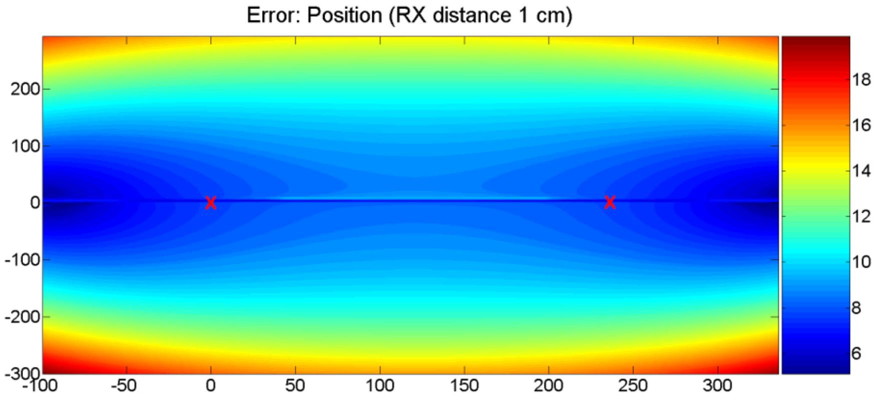

Fig. 2–15: Position error due to non ideal amplification phase (receivers distance 1 cm)

As it can be observed, the error distribution shown in Fig. 2–14 and Fig. 2–15 is similar, but error scale of Fig. 2–15 is three times greater than in Fig. 2–14.

So the error due to plane wave approximation increases with the distance between receivers, but the error due to non ideal amplification decreases. Therefore, there is an optimum in the distance between the receivers in order to minimize the global error. This optimum depends on the analog amplification phase precision and the height of the ceiling. In our implementation, the distance between receivers that showed the best localization results is 3 cm.

The third error to be analyzed is the error due to the incorrect parallelization of the ceiling with respect to the floor. Given that the transmitters are in the ceiling of the room but the receivers are on the floor, if the building has different inclinations in the floor and ceiling, this error will affect the localization precision of the system. To simulate this error, we consider that one of the transmitters is at the correct height while the other is 4.2 cm nearer to the floor (given that the distance between transmitters is 240 cm, the parallelization error is ~1º). This error in the deployment of the transmitters generates the localization error show in Fig. 2–16 when the distance between receivers is 10 cm:

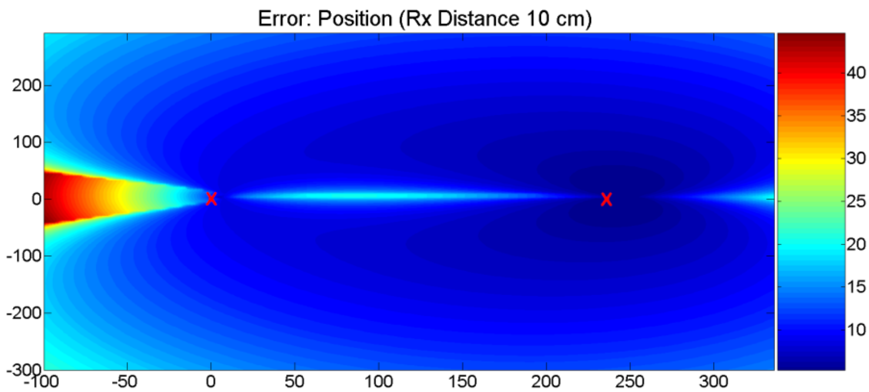

Fig. 2–16: Position error due to non ideal parallelization (receivers distance 10 cm)

This error doesn't depend on the relative distance between the transmitters and the receivers so strongly. To show this effect, if we reduce the distance between receivers to 3 cm, the error is similar as shown in Fig. 2–17:

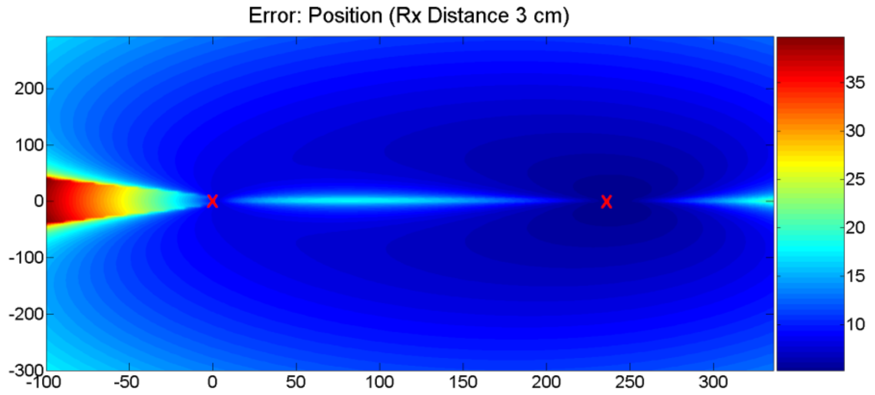

Fig. 2–17: Position error due to non ideal parallelization (receivers distance 3 cm)

To find the optimum distance between receivers, a characterization process of these errors must be performed. Fig. 18 shows the mean error (calculated in all the target area, -100 < x < 340 and -300 < y < 300) depending on the distance between receivers. The error due to plane wave approximation increases with the distance between receivers, as expected. However, the error due to non-ideal amplification decreases with the distance between receivers, while the error due to parallelization is almost independent of this parameter. As a consequence, the total error has a minimum around 3 cm of distance between receivers. This value would change depending on the amplification time error, which has been taken as 500 ns according to our experimental results. This time can change depending on the electronic implementation of the amplification phase, and the optimum distance between receivers would change accordingly: higher distance for higher time errors.

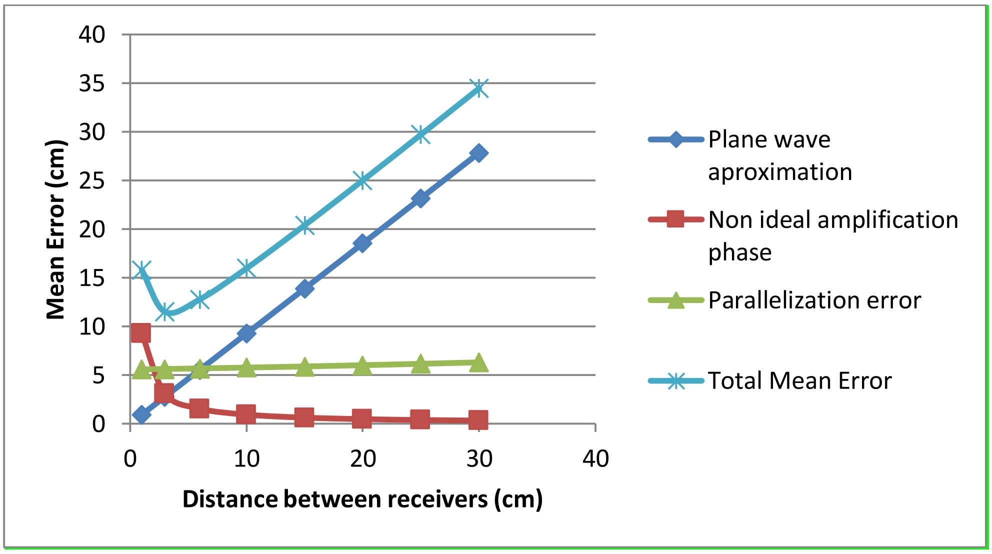

Fig. 2–18: Mean error versus distance between receivers

The last error that will be analyzed is the error of synchronization between receivers. As the robot has three receivers and each receiver is connected to a different amplification path, the reference signal at each receiver can arrive at the comparator with different intensity. This fact can cause that the comparator sends a valid signal of one receiver with an integer number of ultrasonic pulses of error. This error source can be observed in Fig. 2–19.

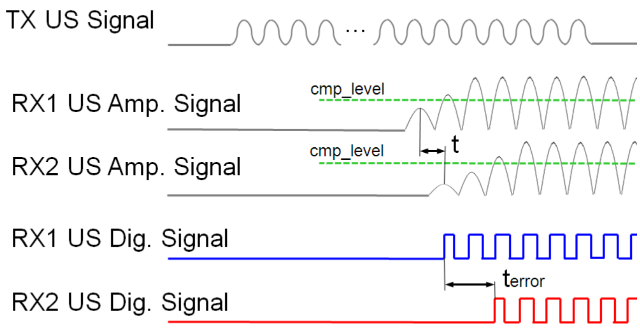

Fig. 2–19: Synchronization error

In Fig. 2–19, the same ultrasonic signal arrives to both receivers with a differential reception time 't', but as the ultrasonic signal from the first receiver is captured with more intensity, the signal is digitalized at the second cycle, while the signal from second receiver is captured at the third one, so the localization system will consider that the difference of arrival time will be 't_{error}' instead of 't'. This error would affect to the system with a similar distribution as the one shown in Fig. 2–14, but instead of consider 500 ns as the variation, the error in this case is 25 us (50 times greater).

This error is not acceptable, but can be discarded by software methods. The solution is to consider the previous position of the robot when obtaining its new localization. Like the error is due to the fact that the robot misses the first cycles of one of the signals, the error is always multiple of 25 us (the period of the ultrasonic signal), so if the new calculated position represents that the robot has moved more than a threshold (e.g. 1 meter), it starts a check process that consists in applying a ±25 us factor until the calculated position differs less than that threshold.

2.6. Experimental results

In order to test the proposed system, a prototype robot (Fig. 2–9) has been implemented. For this experiment, two transmitters were deployed at the ceiling of a room at positions (0, 0, 280) and (240, 0, 280) cm. The robot has three receivers at a distance of 3 cm between them and was deployed at the floor in three different positions:

- (100, 100, 0)
- (160, 100, 0)
- (160, 200, 0)

In each position, the robot was oriented with four different orientations (0º, 90º, 180º and 270º) and, for each orientation, 45 measures were taken with respect to both transmitters.

The first preprocess of the measures was to adjust them to the estimated position of the robot, adding or subtracting multiples of the ultrasonic period (T), 25 us, as explained in the previous section. Fig. 2–20 shows the correction factor that has been applied to the measures in function of the position of the robot.

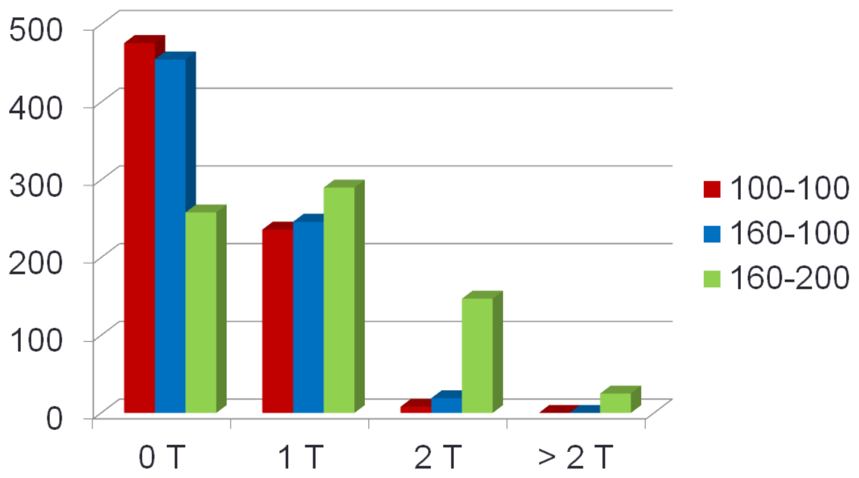

Fig. 2–20: US period correction factor

After removing this error from the measures, a median filter is applied to the estimated positions. The angle estimation error obtained for each resulting position and orientation is shown in Table 1, being Tx1 the first transmitter and Tx2 the second transmitter.

Table 1: Angle error after median filter

	Horizontal Angle Error Tx1	Horizontal Angle Error Tx2	Vertical Angle Error Tx1	Vertical Angle Error Tx2
100-100 0º	2.06º	0.13º	0.23º	2.74º
100-100 90º	0.45º	7.93º	1.07º	0.66º
100-100 180º	3.44º	0.03º	0.36º	1.22º
100-100 270º	0.14º	3.60º	0.60º	2.05º
160-100 0º	0.61º	2.32º	0.81º	0.03º
160-100 90º	1.68º	6.41º	1.76º	0.10º
160-100 180º	1.94º	1.12º	0.33º	0.04º
160-100 270º	0.47º	4.30º	2.96º	0.77º
160-200 0º	2.88º	0.78º	3.20º	1.25º
160-200 90º	0.47º	4.98º	0.62º	0.27º
160-200 180º	1.83º	2.15º	3.04º	2.07º
160-200 270º	0.11º	5.22º	1.08º	0.86º

This table shows directly the orientation error of the system, which goes from 0.13º up to 7.93º, but it doesn't represent the error in the localization system. The localization results obtained after applying the algorithm are shown in Fig. 2–21, Fig. 2–22 and Fig. 2–23, including each particular value and the median of the values for each orientation. The calculated positions are expressed in cm, and the ideal position (reference) is also represented for comparison purposes.

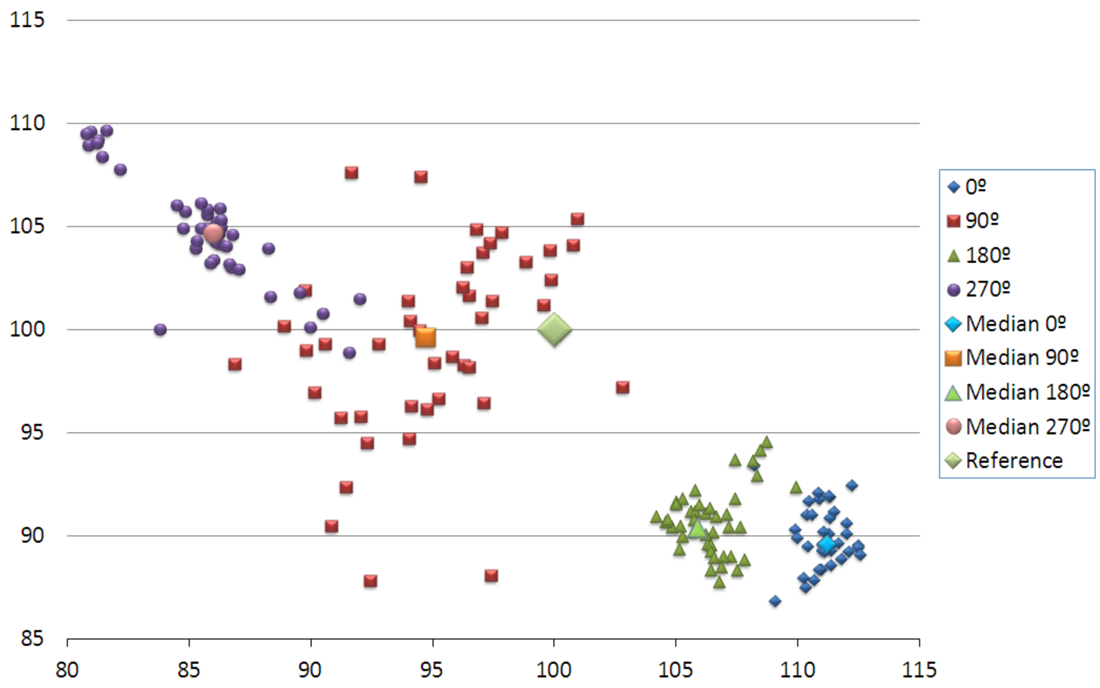

Fig. 2–21: Localization results at (100, 100, 0)

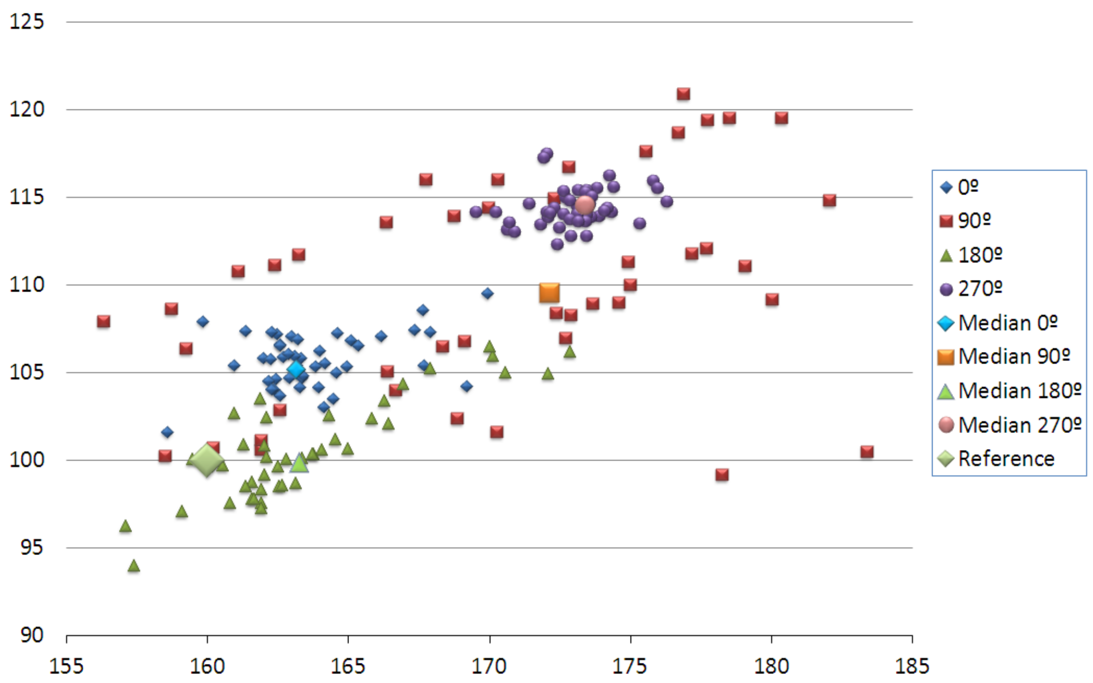

Fig. 2–22: Localization results at (160, 100, 0)

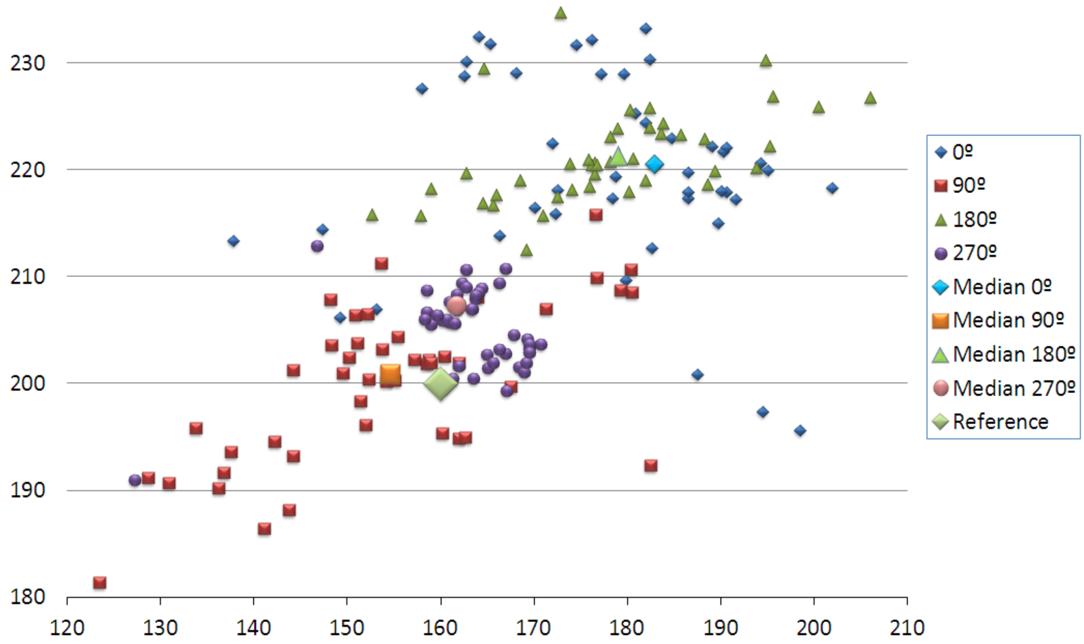

Fig. 2–23: Localization results at (160, 200, 0)

The localization error is summarized at Table 2:

Table 2: Localization Error Summary

	Error at Median Position	Mean Error	Standard Deviation
100-100 0º	15.33 cm	18.15 cm	8.17 cm
100-100 90º	5.27 cm	7.32 cm	4.48 cm
100-100 180º	11.28 cm	11.65 cm	1.56 cm
100-100 270º	14.73 cm	15.69 cm	4.16 cm
160-100 0º	6.07 cm	7.31 cm	2.56 cm
160-100 90º	15.46 cm	16.00 cm	8.44 cm
160-100 180º	3.27 cm	5.53 cm	4.46 cm
160-100 270º	19.77 cm	19.47 cm	1.40 cm
160-200 0º	30.84 cm	31.10 cm	8.52 cm
160-200 90º	5.36 cm	14.05 cm	9.42 cm
160-200 180º	28.62 cm	30.42 cm	12.08 cm
160-200 270º	7.45 cm	8.63 cm	4.76 cm

2.7. Conclusions

The results show that the proposed algorithm, ALO (Angle Localization and Orientation), is valid for indoor localization and orientation systems, allowing it to be implemented in low cost systems: less than 10 € for the electronic components of the reception system, and also for the transmission system, and any low cost processing element can be used as the formula have been simplified as much as possible.

The localization error is greater than the one obtained with other localization systems based on ultrasonic technology using TOA algorithms. For example, in [8], for a system that uses similar ultrasonic transducers, the mean error is about 3.5 cm, while the position error of the proposed system ranges between 5 and 30 cm.

The inferior obtained precision is due to the fact that an error in the estimation of the ultrasonic reception instant is less significant if the measured time is the time of arrival instead of the differential time of arrival. In TOA techniques, the time to be measured is in the order of 15 ms (a distance of 5 meters at 340 m/s), while in DTOA techniques the time to be measured is about 90 us (for a distance between receivers of 3 cm). Therefore, a fixed error (for example, 500 ns) is relatively much more important in DTOA than in TOA techniques. However, analyzing our system with respect to other ultrasonic TOA systems, we conclude that our system has three main advantages:

1. Apart from the localization information, we also obtain the orientation of the receiver.
2. Like other DTOA systems, the system doesn't need a synchronization signal between transmitters and receivers (i.e. no RF is needed).
3. The robot only needs to be in line of sight of two transmitters to obtain its localization, while TOA systems need at least three transmitters.

Comparing our system with others DTOA systems, the main advantages are:

1. The computational cost has been drastically reduced, making it comparable to TOA localization systems.
2. The number of receivers is only three, while other DTOA systems are usually implemented with more receivers.
3. It doesn't need a minimization method to solve the localization of the robot, simplifying its implementation.

2.8. References

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3. ALO4: ANGLE LOCALIZATION AND ORIENTATION SYSTEM WITH FOUR RECEIVERS

Abstract:

This paper presents a 2D indoor localization and orientation system based on a TDOA (Time Difference of Arrival) technique. It uses an array of receivers (four low cost ultrasonic resonant devices in a square distribution) to implement low computational effort DOA (Direction of Arrival) algorithms, based on assuming plane wave reception. The system only demands two transmitters at well-known positions at the ceiling of the room for obtaining the node position and orientation on the floor of the room. This system has been tested using a Xilinx Spartan-3A FPGA that implements a 52 MHz Microblaze. The experimental results include a total of 1,440 points, obtaining a mean localization error of 5.17 cm and a mean orientation error of 3.34º. For this system, the localization and orientation processes are executed in less than 50 us.

Keywords:

TDOA, location, orientation, ultrasonic, DOA

3.1. Introduction

Low cost and precise indoor localization systems are currently been highly demanded by new commercial robots. From robots that clean the floor of a room, to robots that emulate the behaviour of a waiter, the knowledge of the position and orientation of the node is one of the most important requirements to implement accurate navigation systems.

Nowadays, a robot can know its indoor localization with various technologies. From systems based on radiofrequency [1] to systems based on image processing [2, 3, 4], there are multiple systems that allow to know the position of an object. The decision depends on multiple factors as the resolution demanded by the application or the cost. Among all localization systems, one that allows a relatively high precision with an associated low cost is the one based on ultrasound technology [5].

Ultrasonic systems can be divided in two main groups in function of the propagation delay measurement. There are TOA (Time of Arrival) systems [6, 7, 8], that estimate the absolute distance between the node and the reference points, and there are TDOA (Time Difference of Arrival) systems, that use the difference of the propagation delay of a reference wave between multiple points.

Traditional TDOA systems use the intersections of hyperboloids to obtain the position of the node [9-14]. The main disadvantage of these systems is its high computational cost, so they usually implement minimization algorithms. There are also TDOA systems based on estimating the direction of arrival (DOA) of the reference wave [15-18]. As hyperboloids TDOA systems, these systems present a high computational cost as they need trigonometric and/or minimization functions.

In this paper, an evolution of a previous TDOA system (ALO (Angle Localization and Orientation) [19]) is proposed. The ALO system (ALO3 from now on) is characterized by its low computational cost, allowing the implementation of localization algorithms without minimization or trigonometric functions.

The evolution with respect to ALO3 consists in adding one additional receiver to the node, moving the reference point of the node to a point in the middle of the receivers. This fact almost removes the error of considering the arrival of the ultrasonic signal as a plane wave, significantly improving the system performance without increasing the computational effort. This new proposed system will be referenced as ALO4 from now on.

The rest of the paper is organized in eight main sections: "ALO4 System", describing the new TDOA system; "Computational Effort", analyzing the cycles needed by an embedded microprocessor to execute the localization and orientation processes; "ALO4 Error Analysis", where plane wave approximation error is analyzed using the new distribution; "Calibration", section that describes the process followed to improve the estimation of the direction of arrival; "Implementation", where the description of the implemented system can be found; "Deployment" where a description of how to deploy transmitters is shown; "Mobility Performance", where an analysis of the performance of the localization and orientation system is made when the node is moving; and "Results", where the experimental results are presented.

3.2. ALO4 System

The ALO4 system is based on the same principle as ALO3: estimating the direction of arrival of the reference wave measuring the propagation delay between receivers. Its only difference is that the node reference point is between its four receivers (Fig. 3–1).

This new approximation allows capturing a more precise measure of the propagation delay between receivers. When choosing one receiver as the reference point, as the signal does not arrive as a plane wave to the node, the distance measured (*dm*) will be always smaller than the ideal one (*d*).

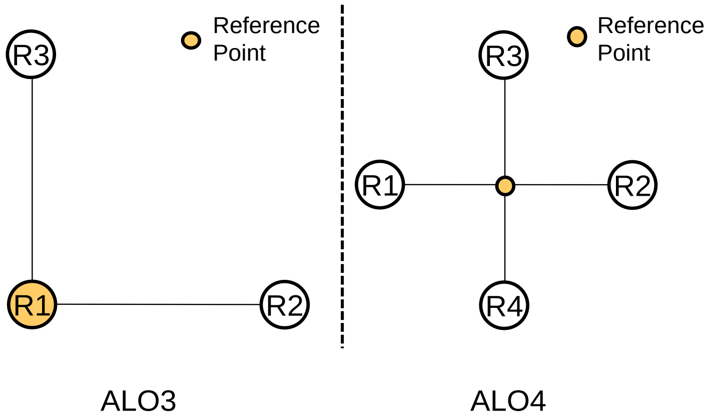


Fig. 3–1: ALO3 – ALO4 Reference Points

When the reference point is the midpoint between receivers, the reference signal will also arrive earlier to the nearest receiver, but it will arrive later to the second one so the measured distance will be more similar to the ideal one. This effect can be clearly observed when only two receivers are involved (Fig. 3–2), but the same effect exists between the configurations of ALO4 and ALO3.

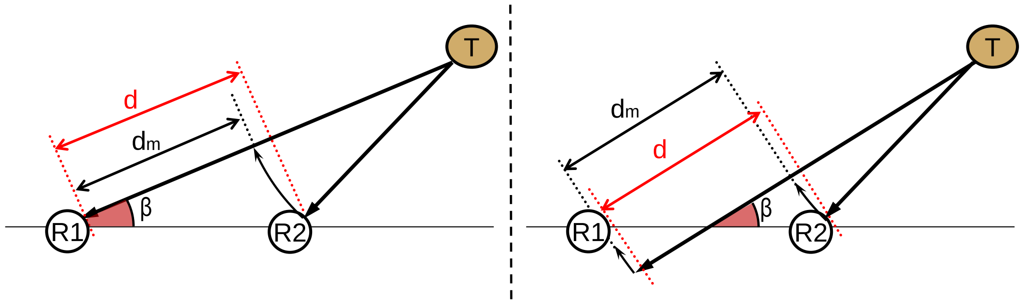


Fig. 3–2: Comparison of measured (*dm*) and ideal (*d*) distances in ALO3 and ALO4

Mathematically, ALO4 angle estimation (Fig. 3–3) formulae are "identical" to those of ALO3. As the reference point is in the middle of the receivers, the distance measured must be divided by 2 to consider this fact, but as the distance from the reference point to the receiver has also been divided by 2, the equations do not change.

$$\cos(\alpha) = \sqrt{\frac{(d_1/2)^2}{(d_2/2)^2 + (d_1/2)^2}} = \sqrt{\frac{d_1^{\,2}}{d_2^{\,2} + d_1^{\,2}}} \qquad (1)$$

$$\sin(\beta) = \sqrt{1 - \frac{(d_2/2)^2 + (d_1/2)^2}{(a/2)^2}} = \sqrt{1 - \frac{d_2^{\,2} + d_1^{\,2}}{a^2}} \qquad (1)$$

- d_1 = distance measured between R1 and R2
- d_2 = distance measured between R3 and R4
- a = distance between receivers

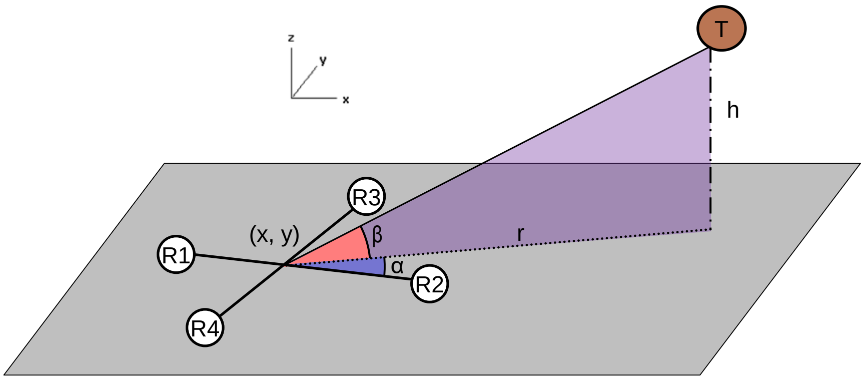


Fig. 3–3: ALO4 angles obtained with Equation (1)

With these angles, localization (Equations 2) and orientation equations () are identical for both systems.

$$r_1 = \frac{h}{\tan(\beta_1)} \qquad r_2 = \frac{h}{\tan(\beta_2)} \tag{2}$$

$$x = \frac{r_1^{\,2} - r_2^{\,2} + b^2}{2 \cdot b} \qquad y = \pm\sqrt{r_1^{\,2} - x^2} \tag{2}$$

- r_x = distance from the projection of transmitter X on the floor to the node.
- h = height of the ceiling
- b = distance between transmitters
- β_x= vertical angle measured to transmitter X

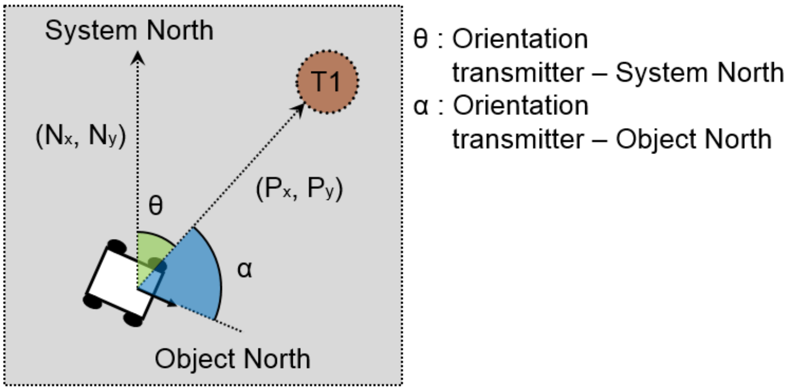


Fig. 3–4: ALO angles and vectors required for the orientation process

$$\cos(\theta) = \frac{P_x \cdot N_x + N_y \cdot P_y}{\sqrt{P_x^{\,2} + P_y^{\,2}} \cdot \sqrt{N_x^{\,2} + N_y^{\,2}}} \tag{3}$$

- (P_x, P_y)= vector from node position to the transmitter projection over the floor.
- (N_x, N_y)= vector that represents the system north.

3.3. Computational Effort

Computational cost associated to this system can be measured in the number of clock cycles needed by the microprocessor to execute the algorithm. In this case, the chosen microprocessor is MicroBlaze [20], which is an embedded microprocessor used in FPGAs.

The first consideration is that the use of ultrasonic signals reduces considerably the noise that is captured by the receivers, so the node does not need to implement any kind of filters or process the incoming signal [21] to deduce that a transmitter is emitting. The transmitter ID is deduced from the time between transmissions (see section 7 for more details), so this does not represent a computational cost too. The mainly computational cost is represented by the localization and orientation algorithms.

Analyzing the equations described in the previous section, the minimum number of cycles demanded by the system is:

- Localization needs 10 multiplications (h^2, a^2, b^2 and 2b are constants), 9 add-subtract operations, 3 divisions and 1 square root that represent a total of $10 \cdot 4 + 9 \cdot 4 + 3 \cdot 28 + 1 \cdot 27 = 187$ clock cycles
- Orientation needs, considering that system north is (0, 1), 2 multiplications, 2 add operations, 1 division and 1 square root, representing a total of 71 clock cycles.

Due to the fact of using resonant receivers, we have observed that measures can contain an error that is a multiple of the reference signal period (see section 9, Fig. 3–12, for more details about this error), which is treated as a variable offset. This offset generates a big error in the localization system, so in order to improve the localization performance the system iterates the localization process adding or subtracting one ultrasonic period to the measure until the node position is near to the previous one. This error is never over +/- 4 periods (Fig. 3–13) so, for the worst case, the system would need to perform 9 localization iterations to correct the offset (if the offset is greater, the measures will be discarded).

At the end, we must add some extra computational cost that represents the control process of the algorithm (a 20% of the calculated computational cost), obtaining a total of 2105 clock cycles. In our implementation, we use a Xilinx Spartan-3A FPGA that implements a Microblaze working at 52 MHz, so the localization and orientation processes only needs 40.5 us (less than two ultrasonic periods) to be executed.

This computational cost is negligible with respect to other DOA [17] or DTOA [22] systems, where minimization functions are used, allowing low cost implementations.

3.4. ALO4 Error Analysis

The only error source of the ones detailed in [19] that is affected by the new receivers deployment is the plane wave approximation error. This error is caused because, as the distance between transmitter and receiver is not infinite, the reference signal does not arrive to the node as a perfect plane wave. As the system considers plane wave arrival in order to simplify the localization and orientation algorithms, this simplification introduces an error on the final performance.

In this section, the effect of this error for the localization and orientation system is analyzed and compared with respect to the one obtained for ALO3.

3.4.1. Localization Errors

To measure the effect on the localization process of the plane wave approximation error, a simulation, using an environment with two transmitters, at positions (0, 0, 280) and (200, 0, 280) cm, and a node whose distance between receivers is 10 cm, has been executed. The node is deployed at different positions, (x, y, 0), and it is always orientated to the system north. The error between the position of the node and the one obtained after the localization process is shown in Fig. 3–5.

Note: In the simulation figures, the red squares represent the projection of the transmitters over the floor.

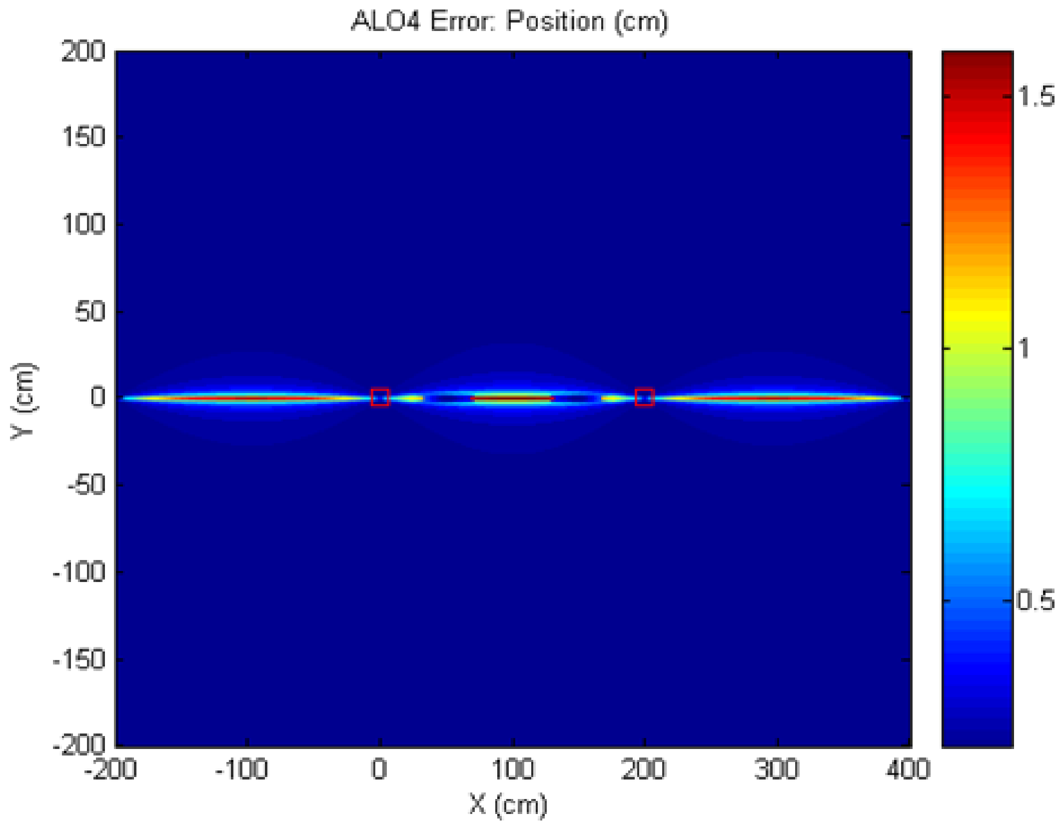


Fig. 3–5: ALO4 localization error caused by plane wave approximation

The mean error obtained for this simulation is 0.05 cm, 100 times lower than the error reported by the same simulation for ALO3.

3.4.2. Orientation Errors

The plane wave approximation also introduces errors in the orientation due to the fact that the measured and ideal distances (*dm* and *d* in Fig. 3–2) are not the same. This has an impact in the horizontal angle (α in equation 1), and therefore in the orientation. To measure its effect, a simulation of a node with its receivers deployed at 10 cm has been carried out (Fig. 3–6).

In this simulation, the node estimates the horizontal angle (α in equation 1) with respect to only one transmitter at (0, 0, 280). When more than one transmitter is available, there is redundant information, which can be used for minimizing the error. However, in this simulation only one transmitter is used in order to highlight the effect of the plane wave approximation.

The mean error obtained for this simulation is $5 \cdot 10^{-4}$ º, 10,000 times lower than the one obtained for ALO3.

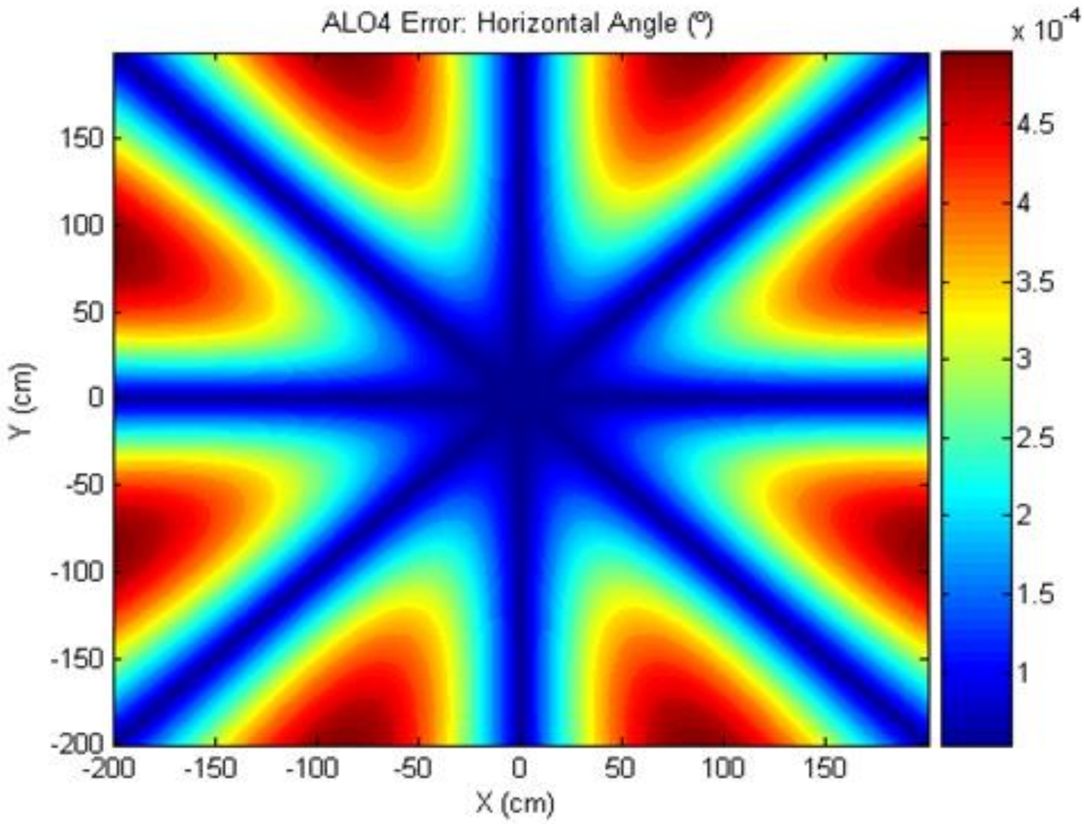


Fig. 3–6: ALO4 orientation error caused by plane wave approximation

3.5. Calibration

To obtain more accurate results on the ALO3 and ALO4 localization and orientation processes, a calibration procedure has been defined. The objective of this calibration process is to reduce the errors generated by an incorrect estimation of some parameters of the system (ceiling height, distance between receivers and transmitters or the sound propagation speed) and to compensate the error of the different propagation delays between the analog conditioning circuits used for each receiver.

The calibration process includes the following steps:

1. Deploy the node in an arbitrary point of the map.
2. Capture the ALO3 and ALO4 differential times of arrival with respect to the system transmitters and with four different orientations (0º, 90º, 180º and 270º).
3. Remove the offset generated by ultrasonic resonant devices. This error is detailed in section 8 and Fig. 3–12. As all the captured measures are referenced to the same position, the localization results after removing this error offset shall be referenced to a small area.
4. When all localization points share the same area, modify the initial system parameters trying to minimize this area where the measures are represented (adjusting the ceiling height, sound propagation speed and the distance between receivers/transmitters).

To conclude, apply a fixed time to the measured propagation delay between the node receivers, trying to minimize the area where the measures are represented. The objective of this offset is to consider the error caused by the different propagation delays in the analog conditioning circuit for different receivers.

3.6. Implementation

The ALO4 system has been deployed using four transmitters in the ceiling of a room and a node that is placed on the floor area between transmitters (Fig. 3–7).

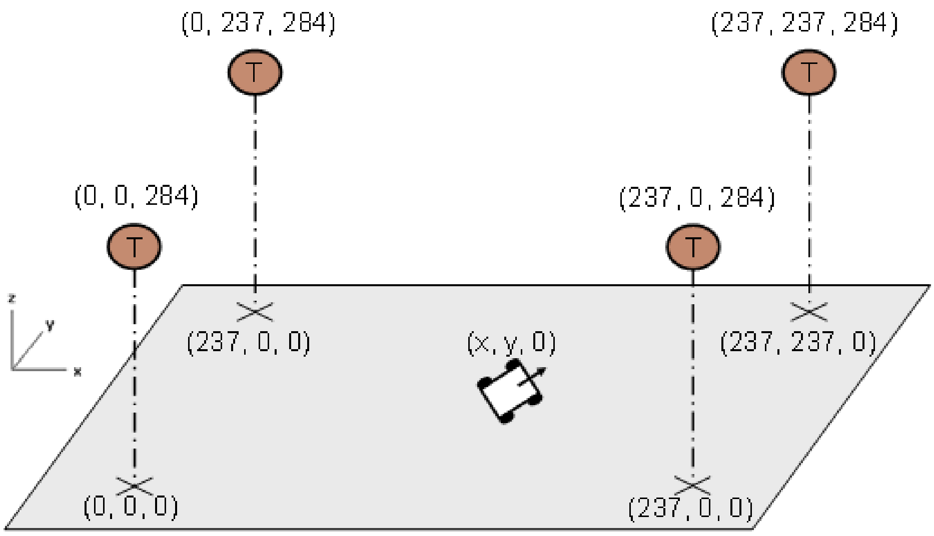


Fig. 3–7: General layout of the transmitters used in the experimental results

The prototype developed is shown in Fig. 3–8. It consists of three main layers: receiver board, analog conditioning board and FPGA board.

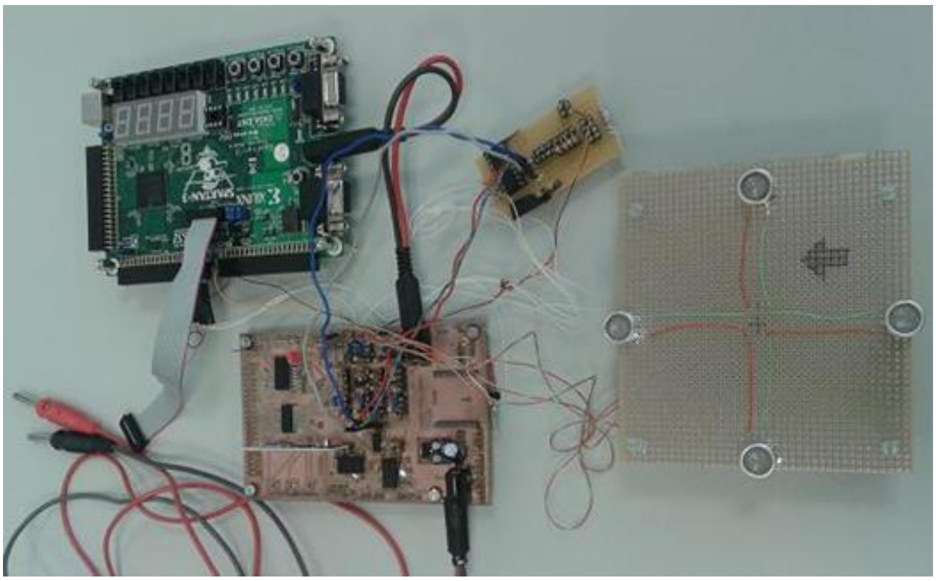


Fig. 3–8: Node implementation

The receiver layer consists of four ultrasonic receivers, model 400SR120, deployed in a square distribution with a diagonal of 10 cm.

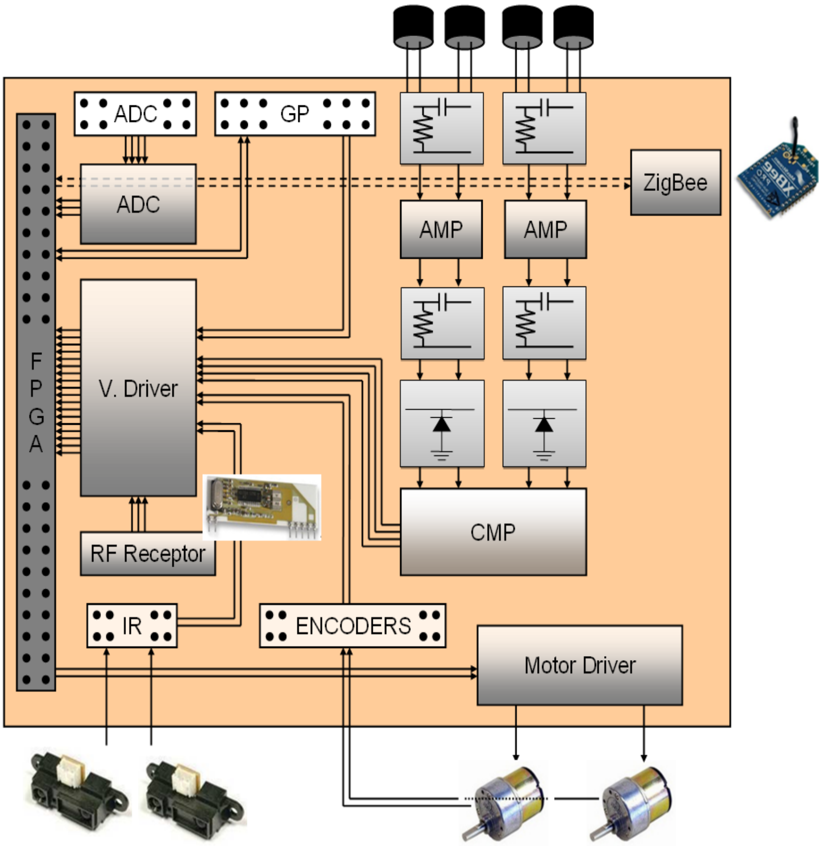


Fig. 3–9: General purpose board used for digitalization of the received signals

For the analog conditioning board we use a general purpose board designed not only for this experiment (Fig. 3–9). This is a general board providing multiple functionalities (ADCs, motor drivers, Zigbee…). The only part of this board requested by the system is the digitalization phase that consists in:

- A first RC filter: To remove the DC component of the received signal.
- An amplification stage: As the signal received is weak, it is amplified with an INA2331 amplifier.
- A second RC filter: Due to the high gain of the amplification stage, a continuous component appears at the output of the previous stage. This filter removes this component for each channel, setting the amplified signal mean value to 0V.
- A diode attached to GND: To prevent sending negative voltage signals to the input of the comparator stage, this diode removes all the negative part of the amplified signal.
- A comparator: To digitalize the signal, a comparator is used. In fact, this comparator (model TLC352CP) is included in a small separate board (see Fig. 3–8). The output of this stage is the input of the FPGA board.

The FPGA board is a Spartan-3 Evaluation Board from Digilent. The FPGA implements a MicroBlaze embedded microprocessor with a custom PLB peripheral. In this peripheral, the difference time of arrival is obtained. The MicroBlaze microprocessor accesses this peripheral to obtain this information and calculates the node position and orientation applying equations (1), (2) and (3).

The transmitter system is controlled by another Spartan-3 Evaluation Board. The FPGA generates trains of 15 pulses (with a frequency of 40 kHz) for each transmitter with the timing modulation detailed in section 7. Before the signal arrives to the transmitters, model 400ST120, the signal voltage level is converted from the range provided by the FPGA (0 - 3.3V) to a more effective range for the transmitters (0 - 20V) with a push-pull driver L293B.

3.7. Deployment

In order to adequately cover the localization are, the transmitters must be deployed according to the following principles:

- Transmitters are grouped in nine groups (ID, which is a number from 1 to 9) and are deployed following the structure shown in Fig. 3–10.
- Distance between transmitters is fixed and shall be calculated to guarantee that the signal generated by a transmitter can be correctly received on the floor point under any adjacent transmitter. This distance depends on the transmitter potency, the receiver sensitivity, the precision of the analog conditioning circuit in the node and the height of the ceiling.
- Transmitters of the same group transmit the signal at the same time, but as the distance between them is far enough, any receiver will only receive the signal from one transmitter of each group at a time.
- The time elapsed between transmission is defined as 55 ms + 2·ID ms. This gap guarantees that the time between any pair of transmitters of different groups is unique, and the node can identify the transmission group measuring the gap between received signals.

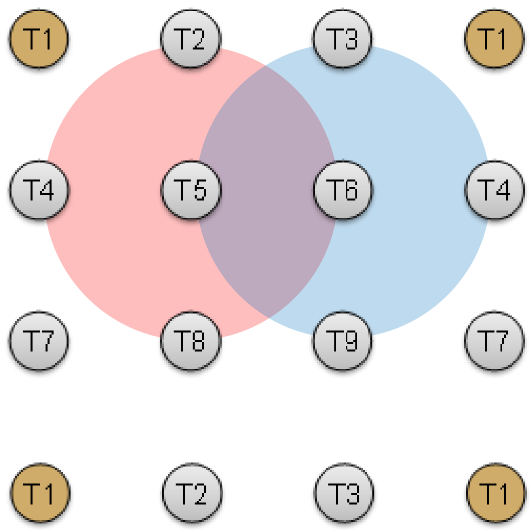


Fig. 3–10: Transmitters deployment and coverage area: red for transmitter T5 and blue for T6)

The node uses its previous position to discriminate between transmitters of the same group. Therefore, an initial position must be given, although it can be an approximate one, as it is only used to distinguish between very distant receivers (those of the same group which share ID).

This deployment guarantees that any area is covered by at least two transmitters, and all transmitters emit each second, so the node can update its position and orientation at this rate, without any initialization process. The only initialization requirement is that the initial position region must be known.

This deployment is valid for areas without obstacles. As ALO4 requires line of sight between the node and the transmitters, if the area contains multiple obstacles, the system will report big localization errors on the zones with bad coverage. To minimize this effect, transmitter shall be deployed closer, covering the area with obstacles with multiple transmitters from different angles.

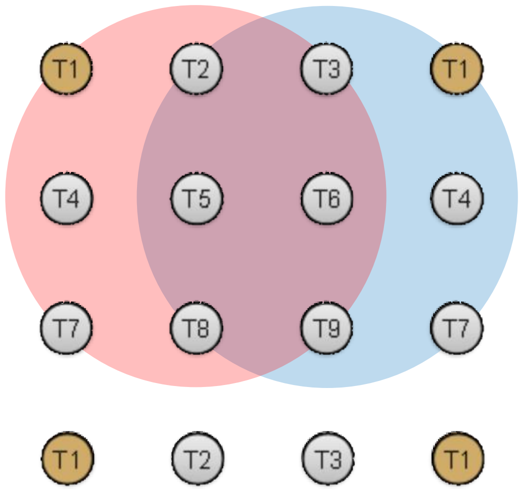


Fig. 3–11: Transmitters deployment (with extended coverage area: red for transmitter T5 and blue for T6)

For example, deploying the transmitters closer enough as shown in Fig. 3–11, enables that some areas are covered by more than 14 different pair of transmitters, increasing the possibilities that there is a line of sight between the node and a pair of transmitters.

The time modulation method requires that all transmitters are synchronized. In our implementation, this synchronization was provided by an unique FPGA board that controls all transmitters of the system.

As it can be seen the main drawbacks of the proposed system is that it needs direct line of sight and also deploying multiple transmitters in the ceiling. When direct line of sight is not possible in all zones, a multiple localization system should be used, adding some other method (i.e. wheel encoder). The advantage of the proposed method is that its error is non-cumulative (the error of each measure does not depend on the error of previous measures, like in wheel encoders, for instance) and it uses low cost resources. Both transmitters and receivers are low cost devices, and processing requirements are small, so they can be implemented with low cost microcontrollers.

3.8. Mobility Performance

In order to obtain a low cost implementation, ultrasonic resonant devices and simple conditioning circuits are proposed for both the transmitter and receiver. However, in this case different transmitters cannot emit simultaneously. If the node is moving, this will have an important impact in the localization, as the node position changes between the instant of receiving different transmitters signals. This error is affected by:

- Node movement direction.
- Position of the node.
- Time elapsed between transmitter emissions.
- Node speed.

Simulations with changes in all these parameters have been carried out using the deployment setting of section 6. The node was deployed at all points in a grid of 1 cm in the area covered by the transmitters. The results are summarized in **Table 1**.

Move Direction	Time between Transmissions	Node Speed	Localization Max. Error	Localization Mean Error	Orientation Max. Error	Orientation Mean Error
(1, 0)	700 ms	2 km/h	42.08 cm	22.63 cm	6.01 º	2.76 º
(0, 1)	700 ms	2 km/h	35.69 cm	16.52 cm	7.26 º	2.54 º
(1, 0)	70 ms	2 km/h	3.92 cm	1.98 cm	0.47 º	0.25 º
(1, 0)	700 ms	1 km/h	20.24 cm	10.51 cm	2.63 º	1.31 º

Table 1. ALO4 localization and orientation errors due to the fact that all transmitters do not emit simultaneously and the node is moving

As it can be seen, node speed and time between transmissions are the most critical aspects, as they both change the position of the node when different transmitters are received. An important conclusion is that non simultaneous transmitters are not suitable for localization while the node is moving. If localization when the node is stopped is not enough, then simultaneous transmitters should be used.
In order to achieve simultaneous emission of all transmitters, modulating the ultrasonic signal is necessary. However, this increases the complexity and cost associated to transmitters and receivers (low cost resonant devices cannot be used) and its conditioning circuits.
Even when all transmitters emit simultaneously, there is also an error when the node is moving, as the different receivers are not in the same position. This is affected by:

- Distance between receivers.
- Position of the node.
- Node movement direction.
- Node speed.

The errors on the vertical angle estimation will generate an error on the localization, while errors on the horizontal angle will affect the orientation. Simulating the effect of these errors on the environment defined in section 6, we have obtained the results summarized in **Table 2**.

Move Direction	Receivers distance	Node Speed	Localization Max. Error	Localization Mean Error	Orientation Max. Error	Orientation Mean Error
(1, 0)	10 cm	2 km/h	0.705 cm	0.184 cm	0.0162 º	0.0077 º
(0,1)	10 cm	2 km/h	0.705 cm	0.184 cm	0.0162 º	0.0077 º
(1, 0)	5 cm	2 km/h	0.703 cm	0.183 cm	0.0081 º	0.0039 º
(1,0)	10 cm	1 km/h	0.353 cm	0.092 cm	0.0081 º	0.0039 º

Table 2. ALO4 localization and orientation errors caused by node movement using simultaneous transmitters

These errors are inherent to the ALO4 system when the node is moving, so they cannot be easily removed. **Table 2** shows that the node speed is the most important parameter to be taken into account in this case, with an almost linear behaviour. However, the localization error is acceptable for typical indoor robot speeds.
After these simulations, we can conclude that ALO4 system is suitable for mobile nodes only if transmitters emit at the same time.

3.9. Results

To measure the precision of the ALO4 system, a comparison with the ALO3 system has been carried out. The node of Fig. 3–8 has been placed on different points in the environment defined in section 6. A total of 9 points have been analyzed and at each point, 10 different measures have been taken for four node orientations (0º, 90º, 180º and 270º) and for each transmitter, generating a total of 360 localization measures.

As we have four transmitters in the defined environment, and the system can calculate its position with respect to only two of them, the systems applies the localization algorithm with respect to each pair of transmitters that form a side of the square where they are deployed. This implies that four different positions are calculated for each measure (obtaining a total of 1,440 localization points).

Besides, the ALO3 system only needs three receivers to perform the localization process, but the node has four receivers so, for each measure, the localization process is applied four times (switching the reference point at the receiver), obtaining a total of 5,760 localization points.

As our implementation uses resonant devices, an offset error (Δ′ in Fig. 3–12) is sometimes added to the ideal time (Δ) between the captured signals. This error is caused because the reference signal does not arrive with the same strength and angle to all receivers, so the comparator will not always detect the signal after the same number of cycles. This error is always a multiple of the ultrasonic wave period ($\Delta = \Delta' \pm n \cdot T$), and it causes a great error on the localization results (i.e. an error of one ultrasonic period at any measure causes a localization error of up to 55.6 cm). However, it can be easily removed by a simple algorithm: the node only needs to add or subtract the ultrasonic period to the captured measures until the resultant position is near to the previous one.

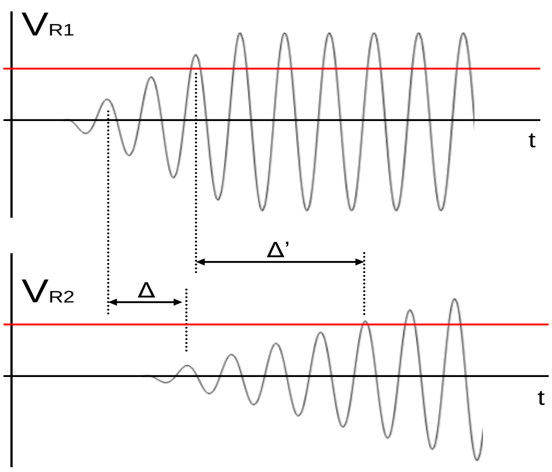
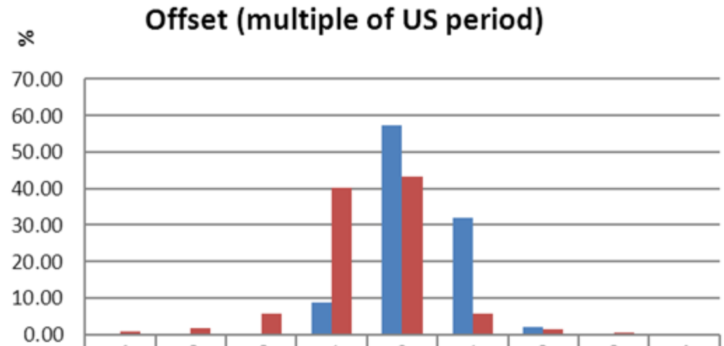


Fig. 3–12: Ultrasonic resonant devices offset error

The offset error detected and corrected on the captured measures (measured as an integer number 'n' of ultrasonic period 'T') is detailed in Fig. 3–13.



	-4	-3	-2	-1	0	1	2	3	4
ALO4	0.00	0.00	0.00	8.65	57.15	31.91	2.15	0.14	0.00
ALO3	0.75	1.70	5.89	40.30	43.26	5.87	1.41	0.54	0.30

Fig. 3–13: Ultrasonic signal period offset applied to the captured measures

After correcting this error, the node position results of the localization process are summarized in Fig. 3–14 (ALO3 system) and Fig. 3–15 (ALO4 system).

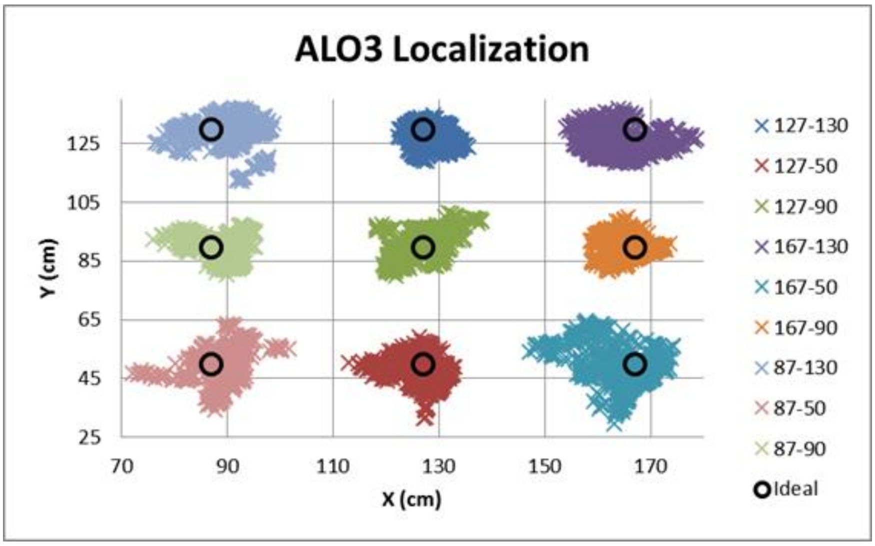


Fig. 3–14: ALO3 localization results

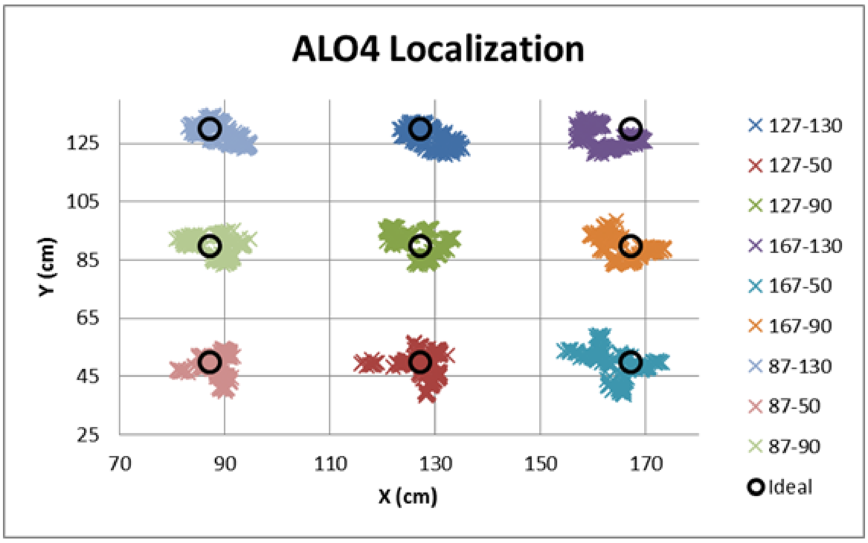
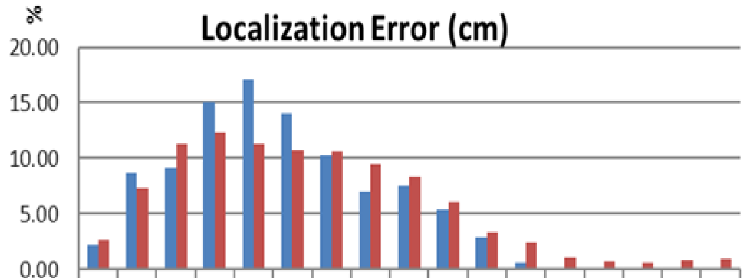


Fig. 3–15: ALO4 localization results

As it can be seen, the ALO4 system has higher positioning accuracy and lower positioning jitter. To measure these effects, the absolute error between the ideal point (where the node was deployed) and the point reported by the localization process has been calculated for both systems, and these results are shown in Fig. 3–16.



	<1	<2	<3	<4	<5	<6	<7	<8	<9	<10	<11	<12	<13	<14	<15	<16	>16
ALO4	2.2	8.7	9.1	15	17	14	10	7	7.5	5.3	2.9	0.6	0.1	0.1	0	0	0
ALO3	2.6	7.3	11	12	11	11	11	9.5	8.3	6.1	3.4	2.4	1.1	0.8	0.6	0.8	1

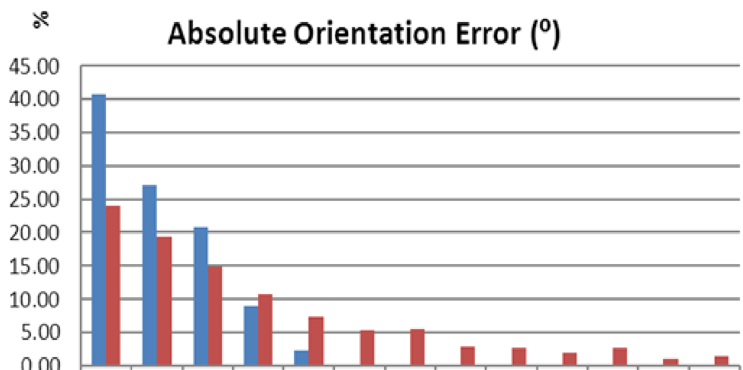
Fig. 3–16: Localization error for ALO3 and ALO4

ALO3 has obtained a maximum positioning error of 20.89 cm (with a mean error of 5.89 cm and a standard deviation of 3.30 cm) while the ALO4 maximum error is 13.03 cm (its mean error is 5.17 cm and its standard deviation is 2.51 cm). The mean error corresponds to the positioning accuracy, and the standard deviation to the positioning jitter.

Comparing the ALO3 localization results with respect to the results obtained by ALO3 when no calibration was carried out [19], it can be concluded that the calibration process is very important for these systems as it reduces the localization error more than 33%.

Other important comparison is with respect to other similar localization systems. The precision results are very similar or even better than those of other TDOA systems (about 10 cm in [23]), but using much simpler localization algorithms. On the other hand, TOA systems can obtain some further accuracy (3 cm in [24]), but they need an auxiliary synchronization system (usually RF) between node and transmitters, which is avoided in TDOA implementations such as ALO4.

Both ALO3 and ALO4 systems also report the node orientation with respect to the system north. The errors in the reported absolute orientation, in degrees, are shown in Fig. 3–17.



	<1	<2	<3	<4	<5	<6	<7	<8	<9	<10	<11	<12	>12
ALO4	40.7	27.0	20.8	9.03	2.29	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ALO3	23.9	19.4	14.9	10.8	7.38	5.30	5.57	2.93	2.73	1.88	2.62	1.08	1.35

Fig. 3–17: Orientation error for ALO3 and ALO4

The ALO3 system obtains a mean orientation error of 3.34º (its maximum error is 16.27º and its standard deviation 3.01º) while ALO4 obtains a mean error of 1.53º (with a maximum of 5.88º and a standard deviation of 1.09º).

3.10. Conclusions

This paper presents an inexpensive localization and orientation system for indoor environments based on ultrasound transceivers. It uses a TDOA technique, but with very simple algorithms, suitable for embedded systems. It is based on estimating the reception angle of an ultrasonic signal, calculated measuring the difference in the time of arrival between four receivers.

This system is an evolution of a previous system (ALO3), which used three receivers instead of four. With this new receiver, the localization and orientation performance is increased but keeping the localization and orientation algorithm as simple as its predecessor.

Analytically, the ALO4 system can estimate more precisely the arrival angle because it reduces the error of considering the received signal as a plane wave. The current implementation of ALO4 obtains high localization and orientation errors when node is moving, but these errors can be reduced drastically emitting all transmitters at the same time, making the system suitable for mobile nodes.

The experimental results show that ALO4 reduces the mean and maximum localization error on a 12.22% and 37.63%, respectively, and the mean and maximum orientation error on a 54.19% and 63.86% with respect to its predecessor, and its precision is comparable to other TDOA and DOA systems that implement more complex algorithms.

3.11. Acknowledgments

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4. ANGLE LOCALIZATION AND ORIENTATION SYSTEM WITH 4 RECEIVERS AND BASED ON AUDIBLE SOUND SIGNALS

Abstract:

This paper presents a 2D indoor localization and orientation system based on a TDOA (Time Difference of Arrival) technique. It uses an array of receivers to implement low computational effort DOA (Direction of Arrival) algorithms. The system is implemented in the audible bandwidth (reference signal frequency is 11 kHz) with low cost microphones and speakers and its performance is compared to the same system but implemented with ultrasonic devices.

Keywords:

TDOA, location, orientation, sound, DOA

4.1. Introduction

Indoor navigation systems is a research area that is currently being studied by multiple groups around the world. Nowadays, there is not any method that provides an indoor navigation capacity to a node whose performance discards the rest of proposals, so the final application must choose between one of them in function of its requirements.

All navigation systems are based on three main parts: mapping, position and orientation. With mapping the node knows the environment, with position the node knows its location and with orientation the node can travel to its destiny. In this paper, a low cost localization and orientation system is presented.

Indoor localization systems are currently divided in function of multiple factors. They can be grouped by the technology used in their implementation: From systems based on radiofrequency [1] to systems based on image processing [2, 3, 4], there are multiple options. The decision of the technology used at the system depends on multiple factors as the cost constraints, the node computational capacity or the precision demanded by the system. One technology that allows a relatively high precision with an associated low cost is the one based on ultrasound technology [5].

Ultrasonic systems base their localization on measuring the distance between known points. The low propagation speed of the ultrasonic wave (~340 m/s) makes it possible to estimate this distance with a high precision, and due to its simply analog adaptation stage and the low frequency of the ultrasonic signal (20 – 40 kHz), the cost associated to these systems is low when comparing it to radiofrequency or image processing system.

Other fact that categorizes localization systems is based on the principle of their localization algorithm. There are TOA (Time of Arrival) systems [6, 7, 8], that estimate the absolute distance between the node and the reference points, and there are TDOA (Time Difference of Arrival) systems [9, 10], that use the difference of the propagation delay of a reference wave between multiple points. Other localization method, no such common, is DOA (Direction of Arrival) [11, 12, 13, 14] that is based on estimating the received or transmitted signal angle.

TOA systems have associated low computational effort algorithms (based, commonly, on intersection of spheres) but require a high synchronization between transmitters and receivers. TDOA and DOA systems are the opposite: require a high computational effort (because they are, commonly, based on intersection of hyperboloids or trigonometric functions) but they do not require synchronization between transmitters and receivers.

In this paper, a TDOA system based on ALO (Angle Localization and Orientation) [15] algorithm is presented, but instead of using ultrasonic signals as the reference signal, audible sound signals (of a frequency of 11 kHz) are used. The objective is to check the behavior of the ALO system with this technology and analyze the effect of the inherent errors on audible signals.

Ultrasonic ALO system presents an error that is caused by the use of resonant devices. As the signal does not arrive with the same angle and strength to the receivers, some receiver reaches the threshold level before the others, adding and offset to the time measured. In this implementation, the system tries to minimize and remove this offset, switching the ultrasonic resonant devices by microphones and speakers.

It is important to take into account that sound localization systems may not be valid for multiple environments, such as those where robots share the space with persons, but they provide a good comparison system against the one based on ultrasonic technology.

The rest of the paper is organized in five main sections: "ALO System", presenting the TDOA system; "ALO Error Sources", analyzing the some errors that affect to ALO systems and the solution proposed to these errors, "Implementation", where the description of the implemented system can be found; "Results", where the experimental results are presented; and finally, "Conclusions".

4.2. ALO System

The ALO system implemented in this paper is based on the ALO4 version [16]. The localization algorithm is based on estimating the direction of arrival of the reference wave, measuring the propagation delay between four receivers (Fig. 4–1):

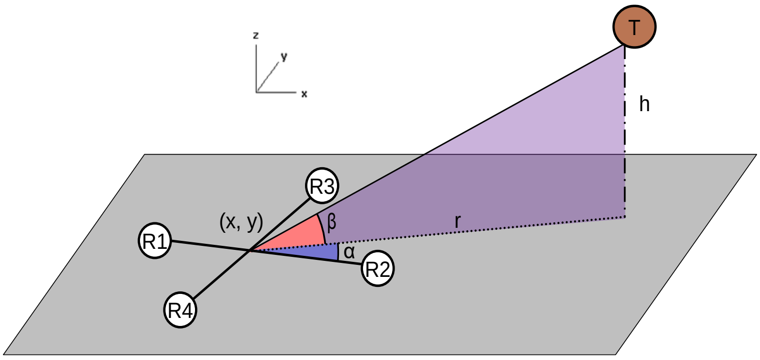

Fig. 4–1: ALO4 System

Mathematically, ALO4 angle estimation is obtained applying the following procedure:

$$\cos(\alpha) = \sqrt{\frac{(d_1/2)^2}{(d_2/2)^2 + (d_1/2)^2}} = \sqrt{\frac{d_1{}^2}{d_2{}^2 + d_1{}^2}} \quad (1)$$

$$\sin(\beta) = \sqrt{1 - \frac{(d_2/2)^2 + (d_1/2)^2}{(a/2)^2}} = \sqrt{1 - \frac{d_2{}^2 + d_1{}^2}{a^2}} \quad (1)$$

- d1 = distance measured between R1 and R2
- d2 = distance measured between R3 and R4
- a = distance between receivers

With these angles, localization (Equations 2) and orientation (Fig. 4–2 and Equation 3) can be deduced.

$$r_1 = \frac{h}{\tan(\beta_1)} \qquad r_2 = \frac{h}{\tan(\beta_2)} \quad (2)$$

$$x = \frac{r_1{}^2 - r_2{}^2 + b^2}{2 \cdot b} \qquad y = \pm\sqrt{r_1{}^2 - x^2} \quad (2)$$

- r_x = distance from the projection of transmitter X on the floor to the node.
- h = height of the ceiling
- b = distance between transmitters
- β_x= vertical angle measured to transmitter X

$$\cos(\theta) = \frac{P_x \cdot N_x + N_y \cdot P_y}{\sqrt{P_x{}^2 + P_y{}^2} \cdot \sqrt{N_x{}^2 + N_y{}^2}} \quad (3)$$

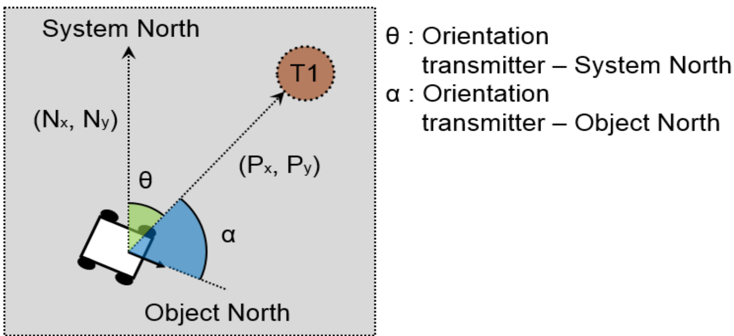

Fig. 4–2: ALO Orientation angles

4.3. ALO Error Sources

ALO system has been previously implemented using resonant ultrasonic devices [15, 16]. The use of resonant devices involve that the signal that arrives to a receiver can be captured with more strength than the signal of other receivers (receivers tolerance, difference on the reception angle or difference on the distance to the transmitter are factors that explain this behavior). This difference in the strength of the captured signal is translated to the voltage provide at the output of the receiver, so when this signal is filtered by a threshold (red line in Fig. 4–3), the system obtains an undesired offset (Δ').

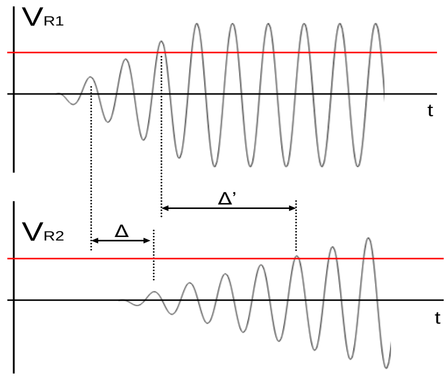

Fig. 4–3: Resonant devices error

This error is always a multiple of the period (T) of the reference signal (Δ = Δ' ± n·T). The factor 'n' that affects to this error depends on the distance between the node and the transmitter, the orientation of the node, the distance between receivers… so it cannot be removed by calibration. On the previous implementation of ALO systems, this error was discarded considering the previous position of the node: As the offset is always a multiple of the ultrasonic period, and the position error generated by this error is very large, the localization algorithm calculates different positions for the node up to the resultant position is near to the previous node position.

One way to remove this error from the captured measures is reducing the distance between receivers, constraining the maximum delay that can be measured between any pair of receivers to the half of the period of the reference signal. With this approximation, if the delay measured is greater, the measure is discarded and the system waits until signal is received on both receivers to capture it (Fig. 4–4).

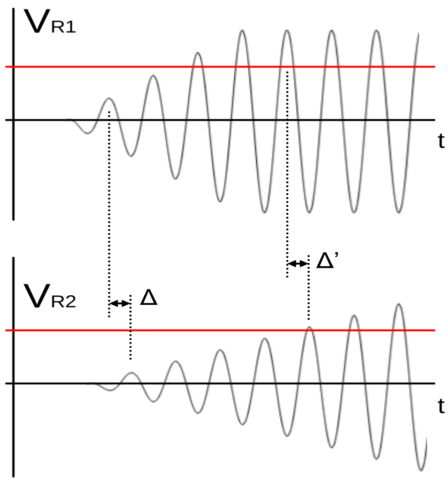

Fig. 4–4: Resonant devices error solution

The problem of this solution is that reducing the distance between receivers causes that small errors on the estimation of the delay (due to not identical timing response of the receivers or the analog circuit) causes great errors on the localization results. To illustrate it, if we consider a fixed error of 2 us (this error is the one reported at [15] when distance between receivers was 3 cm), the mean localization error that the system obtains in function of the distance between receivers is the one shown in Fig. 4–5.

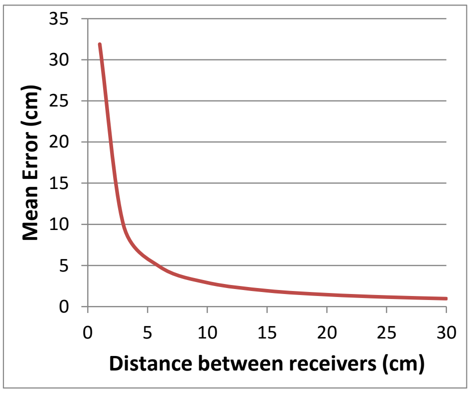

Fig. 4–5: 2 us offset error versus receiver distance

Reducing the distance between receivers to 4.25 mm [340 m/s / (2 • 40 kHz)] will cause that the localization error is so great that invalidates the system.

Keeping the distance between receivers, the only way to guarantee that the maximum delay measurable is less than the half of the period is reducing the frequency of the reference signal (to 1.7 kHz for a distance between receivers of 10 cm). This implies that the system needs to replace the ultrasonic devices by microphones and speakers.

Reducing this frequency so much causes other source of error to increase. To estimate the delay between two receivers, the system searches the instant of the peak value of the received signal. The estimation of this instant will have a tolerance that depends on the noise of the environment and the period of the signal. For example, if we have a tolerance of 1% when obtaining the instant of the peak value, for a 40 kHz ultrasonic signal this error will be of 250 ns, while the same error on a 2 kHz sound signal will be of 5 us.

Due to this fact, in this paper a mixed solution has been implemented. The distance between receivers has been fixed to 10 cm, while a signal of 11 kHz is generated at the transmitters.

4.4. Implementation

The transmission system is implemented using low cost commercial speakers (model HERCULES. XPS 2.1 20 ARC WHITE) connected to a computer. The satellite speaker is used to implement the transmitters of the localization system (Subwoofer is placed in a far place and covered to do not affect to the system behavior). They are deployed at a height of 224 cm and the distance between the two speakers is 161 cm. The node will only be deployed in the floor between both receivers.

Although this solution allows to modulate the transmitter identifier on the reference signal and it allows that all transmitters emit simultaneously with different frequencies, in this implementation only one transmitter emit at a time and no modulation is added to the reference signal.

The node consists on a device with four commercial microphones (model FOX-2214) deployed in a square distribution with a diagonal of 10 cm. These microphones are connected to the following adaptation circuit (Fig. 4–6).

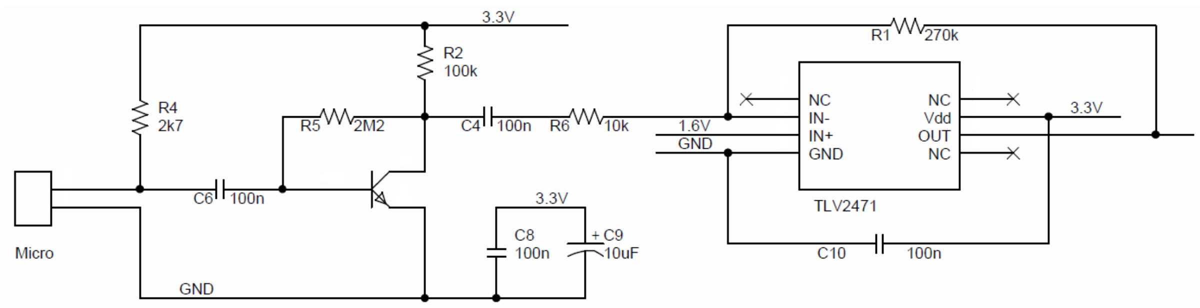

Fig. 4–6: Microphone adaptation circuit

The output of this stage goes to a comparator (model TLC352CP) that converts the analog signal in a train of pulses when the signal voltage reaches a threshold. The output of this comparator enters in an FPGA with a system-on-chip based on MicroBlaze. The FPGA measures the delay between the receivers and applies the equations of section 2 to obtain the node position (more details can be found in [15]).

The algorithm implemented on the FPGA only considers the first pulses of the received signal to avoid capturing incorrect measures due to multipath or rebounds.

4.5. Results

We have compared the sound implementation against our previous ultrasonic system [16], deploying the ultrasonic transmitters on the same positions as the speakers.

The sound and ultrasonic nodes have been placed on four different points. At each point, ten different measures have been taken for four node orientation (0º, 90º, 180º and 270º) and for each transmitter, generating a total of 320 localization measures for each system. For both systems, no noise sources were used when the measures were captured.

Analyzing the measures captured, sound system shows that no offset is needed to be applied to correct its measures, while ultrasonic system needs to correct 41.72% of the measures by ±1 period and 1.25% by ±2 period. This improvement is associated to the use of microphones instead of resonant devices, whose timing response is more accurate.

Before calculating the position of the node, we have tried to minimize the error caused by the non ideal amplification stage for the four receivers. As we have four orientation for each position, we have applied a fixed calibration factor on the measures captured by the system up to the localization points associated to these measures converge on the same area. For the sound system, the calibration factor applied was of up to 8.3 us and for the ultrasonic system 3.1 us. The effect of this calibration factor can be observed on Fig. 4–7.

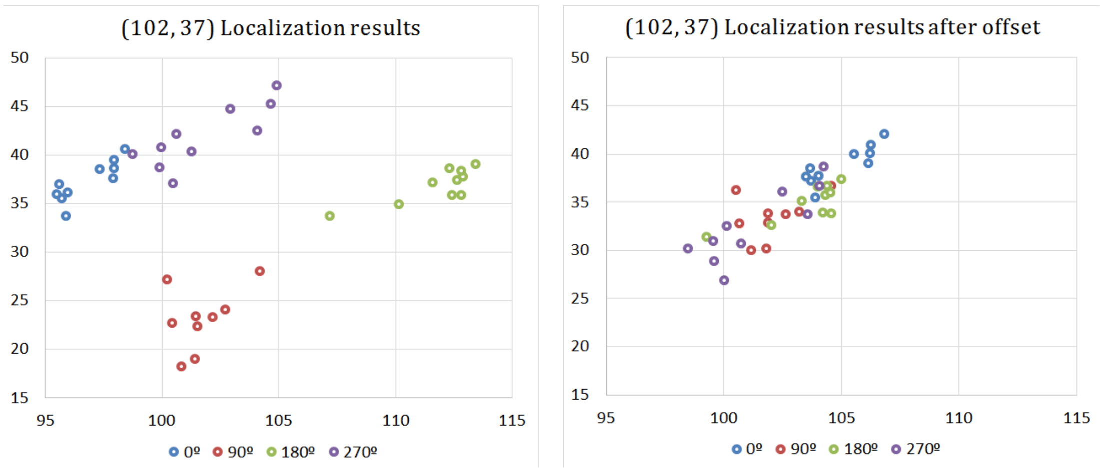

Fig. 4–7: Offset error correction effect at (102,37) for sound system

The results of the localization process are shown in Fig. 4–8 (Sound system) and Fig. 4–9 (Ultrasonic system).

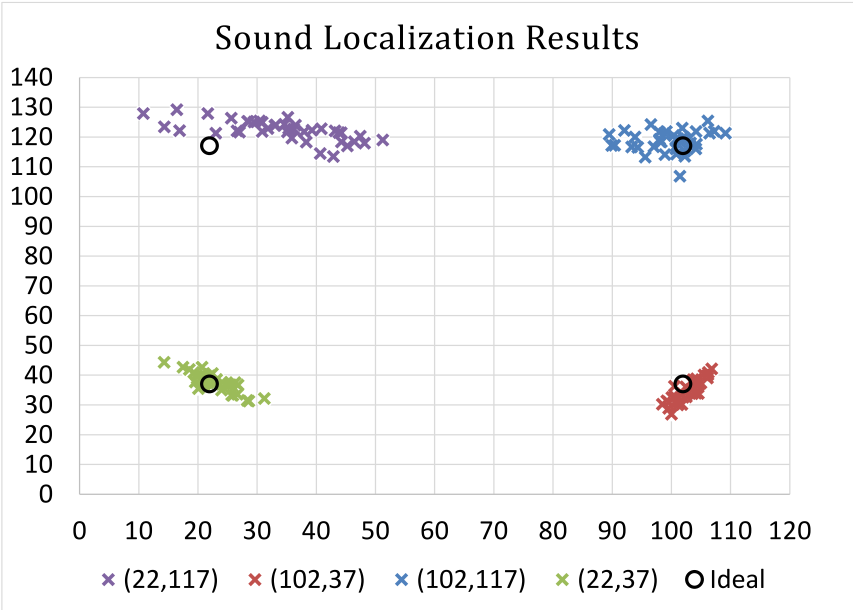

Fig. 4–8: Sound localization results

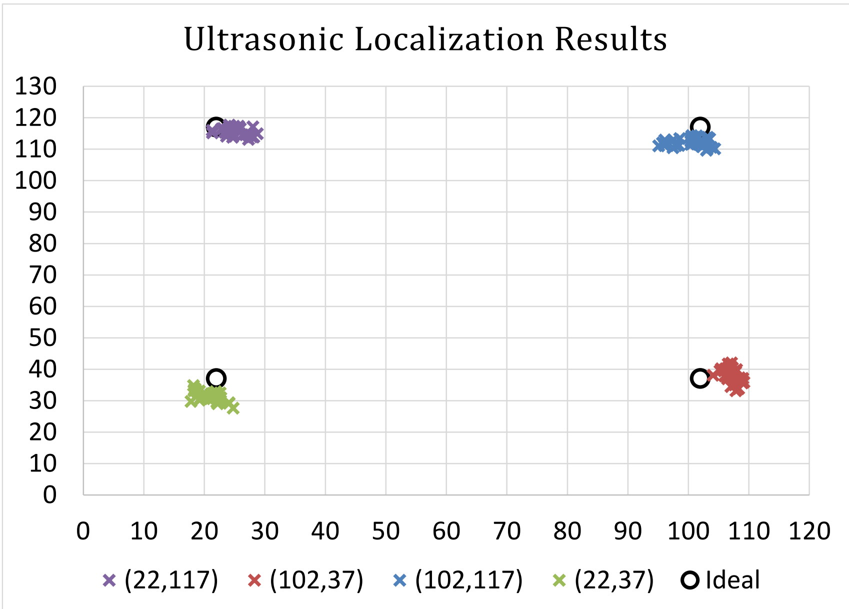

Fig. 4–9: Ultrasonic localization results

The first conclusion that can be extracted from these results is that ultrasonic system offers localization results more concentrated than the results obtained by the sound system. To measure this behavior, the distance from the mean point of the localization points at each position has been calculated and it has been measure the distance from this point to the rest of localization points, obtaining the results shown in Fig. 4–10.

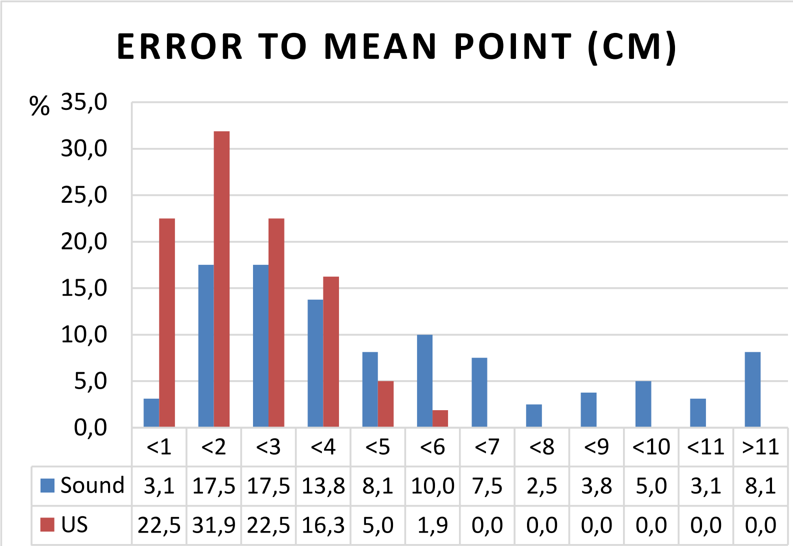

Fig. 4–10: Error to mean point

The greater divergence observed from the sound system is due to the lower frequency used at the reference signal.

The ultrasonic system has also more precision in the localization results. To measure this effect, the error between the ideal point (where the node was deployed) and the result of the localization process has been calculated for both systems, and these results are shown in Fig. 4–11.

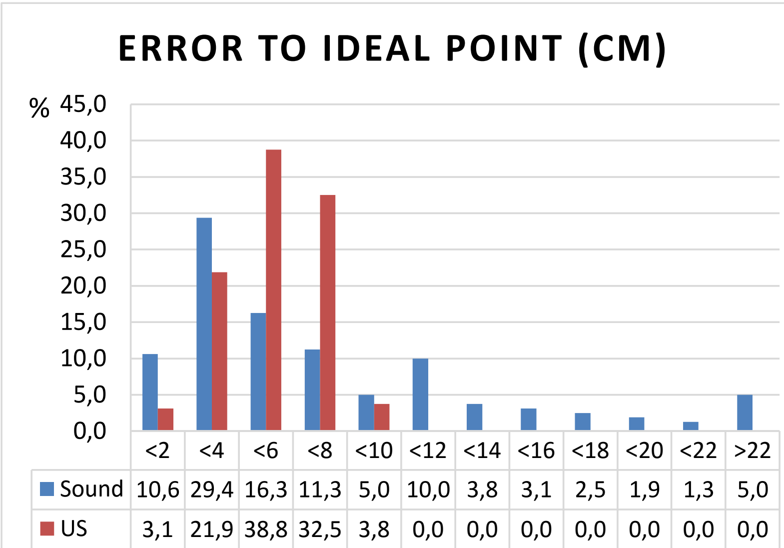

Fig. 4–11: Localization Error

The sound system has obtained a maximum localization error of 29.3 cm (with a mean error of 7.26 cm and a standard deviation of 6.13 cm) while the ultrasonic maximum error is 9.82 cm (its mean error is 5.21 cm and its standard deviation is 1.73 cm).

For both systems the node orientation has been calculated. The error with respect to the ideal node orientation is summarized in Fig. 4–12.

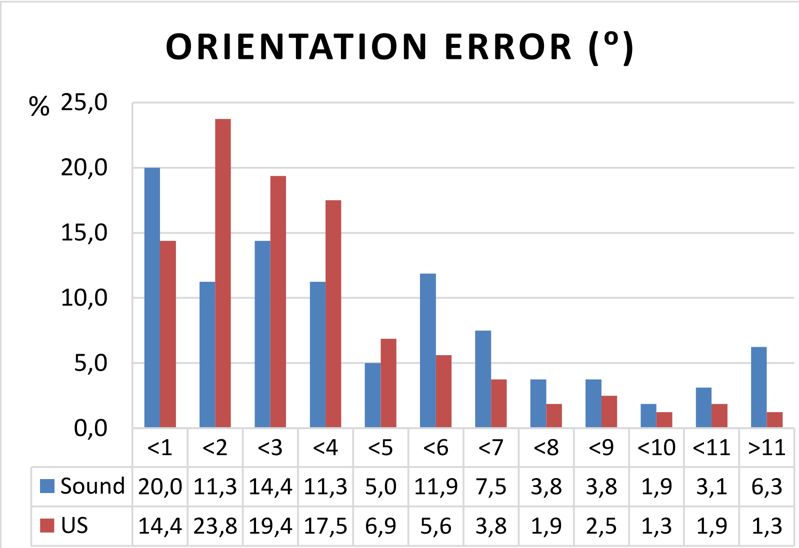

Fig. 4–12: Orientation Error

The sound system obtains a mean orientation error of 4.27º (its maximum error is 17.22º and its standard deviation 3.54º) while ultrasonic system obtains a mean error of 3.22º (with a maximum of 15.02º and a standard deviation of 2.59º).

4.6. Conclusions

This paper presents an inexpensive localization and orientation system for indoor environments, based on microphones and speakers at audible frequencies, that minimizes the offset error measured at the signal at the receivers that it is typical when using ultrasonic resonant devices.

It uses a very simple TDOA technique that is based on estimating the reception angle of a signal, calculated measuring the difference in the time of arrival between four receivers.

The system presents a mixed solution, reducing the maximum number of period associated to the delay measurable between receivers but trying to keep a relatively high frequency on the reference signal.

The experimental results show that sound system does not need to correct the received measures applying the signal period offset, while more than 42% of the ultrasonic measures need to be fixed. This behaviour is caused by the used of microphones instead of resonant devices.

However, the sound system reports greater mean and maximum localization and orientation errors than the one obtained with the ultrasonic solution. This worse behaviour is caused by the lower frequency of the reference signal. The precision on the estimation of the delay between the signal captured at the receivers depends on the reference signal period, and as for the sound system this frequency is lower, the precision on the angles estimated by the ALO system are worse, fact that reduces the localization and orientation precision.

As a final conclusion, is the final application allows to eliminate the offset error via software (the difference between two consecutive node positions is small), it is recommended to use ultrasonic signals instead of audible ones.

4.7. Acknowledgment

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5. HALO4: HORIZONTAL ANGLE LOCALIZATION AND ORIENTATION SYSTEM WITH 4 RECEIVERS AND BASED ON ULTRASOUNDS

Abstract:

This paper presents a low cost ultrasonic localization and orientation system based on the DTOA (Differential Time Of Arrival) technique. The proposed system consists in deploying any number of autonomous nodes at the floor of a room and place some transmitters at the ceiling. Each node shall have four ultrasonic receivers to obtain the basic measures for the localization and orientation systems, and the coverage area of the system is defined by any region covered by at least three transmitters. The localization system is based on an estimation process of the horizontal angle of the node with respect to the transmitters. This implementation allows deploying the transmitters at different heights and ignores the error introduced by an incorrect estimation of the ultrasonic signal speed. The computational effort of the proposed system is greater than other ALO (Angle Localization and Orientation) systems, needing a minimization process to obtain the localization results, but it is smaller than in other typical techniques, like those based on the intersection of hyperboloids.

Keywords:

DTOA, location, ultrasonic, angle, DOA

5.1. Introduction

Each year, new robots for indoor applications are developed, and one of the most characteristic differences that fix their market value is their navigation system, or in other words, the capacity of the robot to know its position and orientation, and its ability to map and navigate through the environment.

The mapping and navigation accuracy of the robot are limited by the precision of the localization and orientation system, and that is why these systems are being deeply studied.

There are a lot of technologies that allow knowing the position of a node in an indoor environment, as the systems based on radiofrequency [1] or the systems based on image processing [2, 3] or the system based on searching references points [4]. Each of them has advantages and disadvantages, and the selection is done in function of the computational capacity, the accuracy and the cost demanded by the application.

Among all localization systems, one that allows a relatively high precision with an associated low computational requirement and low cost is the one based on ultrasound technology [5].

Localization systems are based on estimating their position with respect to reference points whose positions are known. In function of the kind of the measure used, systems can be categorized as:

TOA (Time Of Arrival): These systems estimate the absolute distance between the node and the reference points [6, 7, 8]. These systems usually reach the higher precision on localization process and their associated computational cost is very small (they generate spheres at the reference points and intersect them). Their main problem is that they demand a high synchronization between the reference points and the node (system based on ultrasounds usually use a radiofrequency signal to reach this requirement, fact that increases the cost of the system)

DTOA (Difference Time Of Arrival): These systems estimate the difference in the distance between known points with respect to a signal generated at the reference points [9]. They usually reach less precision than TOA systems and their computational cost is also higher (they need to intersect hyperboloids [10, 11, 12, 13, 14, 15]). Their main advantage is that as known points are usually deployed at the same node, synchronization is easier (ultrasound systems do not need any auxiliary signal) making the systems more autonomous.

DOA (Direction Of Arrival): These systems base the localization process on the knowledge of the direction where the reference point is deployed [16, 17]. Knowing the direction among multiple reference points, trigonometric functions can be applied to know the position of the node. These systems present a high computational cost and, as DTOA systems, they don't need any synchronization process. These systems have been substituted by TOA and DTOA systems because they usually reach higher precision.

In this paper, an evolution of the ALO4 system [18] is presented. ALO systems implement a localization process based on TOA algorithms (intersection of spheres), but is based on using multiple receivers (as DTOA systems) to obtain the direction of arrival (as DOA systems) of the reference wave. The computational cost is similar to TOA systems but it does not require a high synchronization between transmitters and receivers.

HALO4 bases the localization on the estimated horizontal angle, fact that changes the localization process (making it more complex) but allowing deploying the transmitters at different heights and making the system immune to errors on the estimation of the ultrasonic speed, so it obtains a better precision on the localization and orientation processes.

The rest of the paper is organized in six main sections: "ALO4 System", where a summary of the previous ALO system is presented; "HALO4 System", where the new system is detailed; "HALO4 Minimization Process", in this section the minimization process is described and its computational cost analyzed; "HALO4 Errors", where some of the most typical errors that affect the precision of the system are analyzed; "Implementation", where the implementation of the system can be found; and "Results", where the experimental results are presented.

5.2. ALO4 System

ALO4 system (Fig. 5–1) bases the estimation of the received angle in the measure of the propagation delay of a reference wave between 4 receivers deployed at the node in a square distribution. The node is located in the floor while the transmitters are in the ceiling.

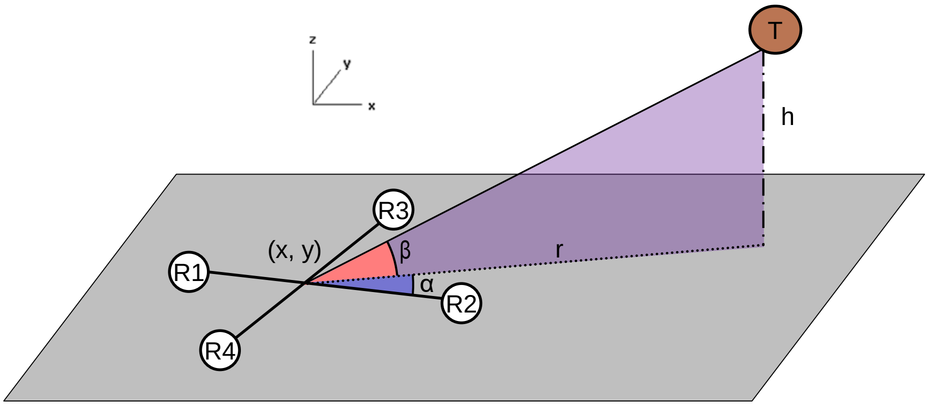


Fig. 5–1: ALO4 system showing the node with 4 receivers and a transmitter

In this system, the height of the ceiling (*h*) is fixed, so the difference in the time of arrival to each receiver depends on both the horizontal distance to the transmitter (*r*) and the orientation of the node.

With the measured delays, ALO4 system obtains the direction of arrival of the ultrasound signal applying the following formulas (distances in (1) are the result of multiply the measured delays by the propagation speed of the reference signal). The details on how to obtain these formulas can be found in [9] and [18], but the general idea is that if the signal arrives in all the transmitters almost at the same time it is because node is below the transmitter, so all the receivers have a similar distance to the transmitter, and therefore the vertical angle β approaches 90°. On the contrary, if the horizontal distance *r* increases, the difference in the time of arrival to each receiver will increase.

$$\sin(\beta) = \sqrt{1 - \frac{d_2^{\,2} + d_1^{\,2}}{a^2}} \qquad \cos(\alpha) = \sqrt{\frac{d_1^{\,2}}{d_2^{\,2} + d_1^{\,2}}} \qquad (1)$$

- d_1 = measured distance between R1 and R2
- d_2 = measured distance between R3 and R4
- a = distance between receivers

With a single distance to a transmitter it is impossible to know the location of the node. However, knowing the distance to two transmitters the location can be deduced as the intersection of two circumferences. In fact, there would be two possible solutions, but using the orientation of the node (which nodes receive the signal first), the exact location can be deduced. Therefore, merging the measured vertical angle with respect to two transmitters, the system is able to obtain the localization of the node as:

$$r_1 = \frac{h}{\tan(\beta_1)} \qquad r_2 = \frac{h}{\tan(\beta_2)} \qquad (2)$$

$$x = \frac{r_1^{\,2} - r_2^{\,2} + b^2}{2 \cdot b} \qquad y = \pm\sqrt{r_1^{\,2} - x^2} \qquad (2)$$

- r_x = distance from the projection of transmitter X on the flour to the node.
- h = height of the ceiling
- b = distance between transmitters
- βx= vertical angle measured to transmitter X

And with the horizontal angle with respect to one transmitter and the position of the node, it obtains its absolute orientation.

5.3. HALO4 System

The HALO4 system uses the same receivers and measures to obtain the same angles as ALO4 (Fig. 5–1), but instead of using the vertical angle for the localization process it only uses the horizontal angle. Once the node location is obtained, the node obtains its orientation in the same way as in ALO4 implementations.

This new approximation makes the system immune to errors on the estimation of the reference wave speed: Equations described in (1) are expressed in distances, but the node does not measure distances, it measures propagation delays, transforming these formulas in:

$$\sin(\beta) = \sqrt{1 - \frac{(t_2 \cdot v_s)^2 + (t_1 \cdot v_s)^2}{a^2}} \qquad (3)$$

$$\cos(\alpha) = \sqrt{\frac{(t_1 \cdot v_s)^2}{(t_2 \cdot v_s)^2 + (t_1 \cdot v_s)^2}} = \sqrt{\frac{t_1^{\,2}}{t_2^{\,2} + t_1^{\,2}}} \qquad (4)$$

- t_1 = time measured between R1 and R2
- t_2 = time measured between R3 and R4
- v_s = estimated propagation speed of reference wave.

To calculate the vertical angle β (3), the system converts the time that the reference signal need to travel the distance between receivers (t_2 and t_1) to a distance using the estimated propagation speed of the ultrasonic signal. As the system cannot obtain the propagation speed of the reference wave at each instant, it considers a propagation speed established by a calibration process and considers that this propagation speed as a constant. Ultrasound propagation speed depends on multiple factors, as the temperature or the humidity of the environment, so it usually changes frequently, demanding a constant calibration process or an error will be introduced in the estimation of the vertical angle.

The horizontal angle α (4) only depends on the time measure by the system, so the propagation speed can be removed from the formula without introducing any error on the estimation. Besides, if the localization process only needs the horizontal angle, the transmitters can be deployed at different heights, and the localization error introduced by the incorrect parallelization between the floor and the ceiling of the room is reduced too.

To obtain the position of a node only requesting the horizontal angle, the node must obtain the angle with respect to two transmitters (φ at Fig. 5–2).

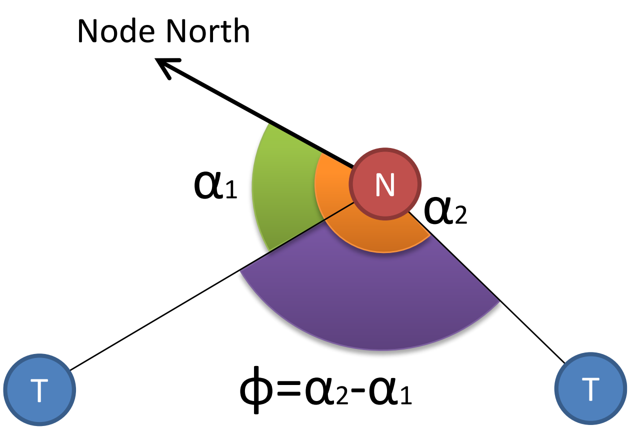


Fig. 5–2: HALO4 ϕ angle in function of the horizontal angle of the node with respect to two transmitters

Knowing the angle φ with respect to three transmitters, the node position is constrained to only one point, as shown in Fig. 5–3:

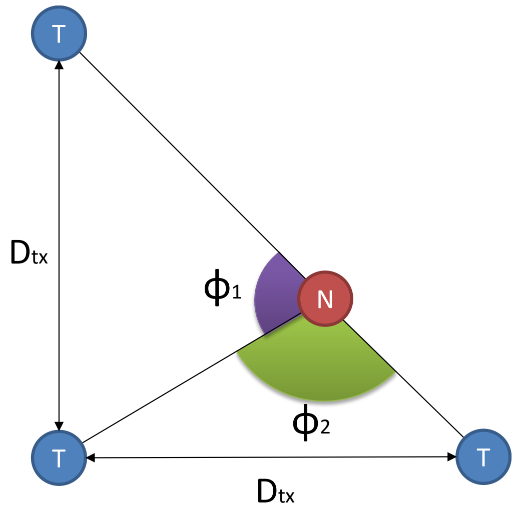


Fig. 5–3 HALO4 necessary angles to implement the localization algorithm

If we analyze the possible points that are defined by a pair of transmitters [at (0,0,*h*) and (250,0,*h*)] and a measured angle φ, the Fig. 5–4 is obtained.

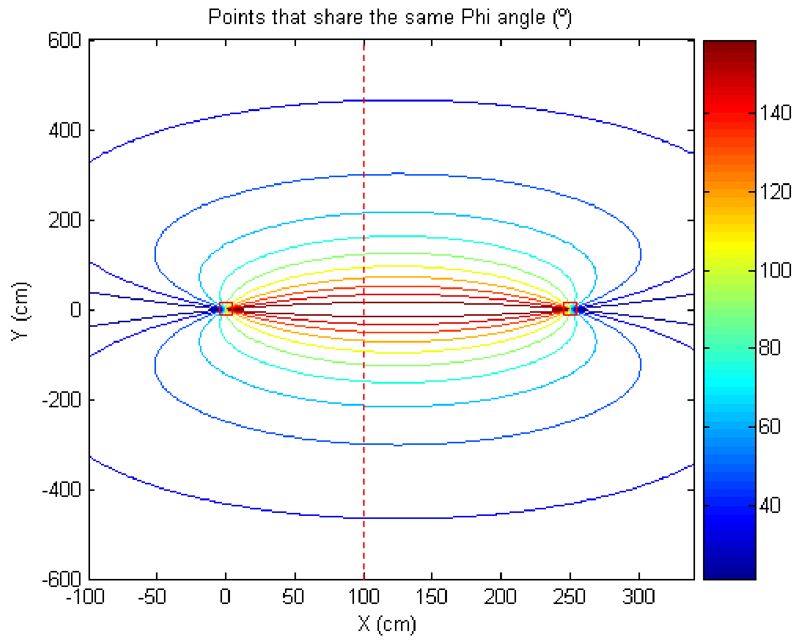


Fig. 5–4 Points that share the same ϕ angle. ϕ angle at the vertical red line in the figure is detailed in Fig. 5–7.

Combining two of these curves, the position of the node is defined.

Mathematically, the solution of the problem is very complex (has an associated high computational cost).

To show an example of this complexity, if we define three transmitters at (0, 0), (300, 0) and (0, 300) and the node is at (200, 50), the points that share the two measured horizontal angles with respect to the three transmitters are the ones that exist in the two curves, (5) and (6), of Fig. 5–5.

$$2 \cdot 300^2 = x^2 + y^2 + 1.8159xy \qquad (5)$$

$$300^2 = \left(\frac{x^2 - y^2}{-1.5185x - 0.8333y}\right)^2 + x^2 + 1.5185\frac{x^2 - y^2}{-1.5185x - 0.8333y}y \qquad (6)$$

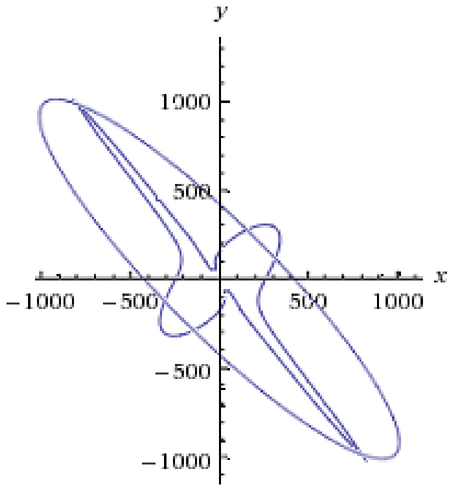


Fig. 5–5: Graphical representation of the mathematical solution (positions expressed in cm)

With this process, the node obtains 8 points: 6 of them are discarded as the node can know its region in function of the horizontal angles measured (Fig. 5–6), and as the node knows the angle associated to each pair of transmitters, only one solution is obtained.

In order to discern between regions 2 and 3, the following reasoning can be used. In region 2, the φ angle with respect to the transmitters deployed at the X axis is found counter clockwise with respect to the φ angle obtained with respect to the transmitters deployed at the Y axis, while at region 3 this order is inverted (clockwise). A similar reasoning can be used to discern between regions 1 and 4, where one φ angle is smaller and included in the other φ angle.

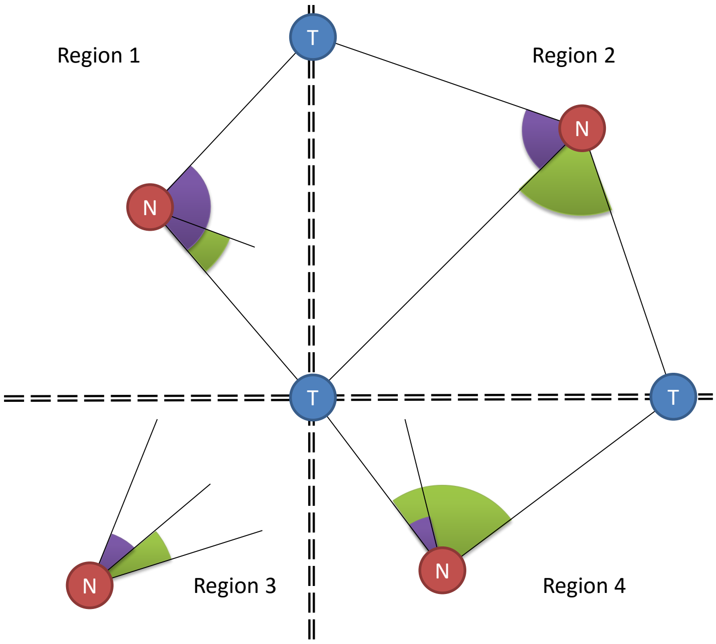


Fig. 5–6: ф angles in function of the node position and region

5.4. HALO4 Minimization Process

Instead of using a complex algorithm that solves the localization system, a minimization process has been implemented.

This process is based on the next principle: as it can be observed in Fig. 5–4, in the region limited by two transmitters, if we trace a line perpendicular to the line that joins the transmitters (as the red line in the figure), the points nearest to the transmitters have a greater angle associated, while the points at a greater distance have an associated smaller angle. For example, if we only draw in a figure the ϕ angle evolution for the points of Fig. 5–4 that share X=100 cm, Fig. 5–7 is obtained.

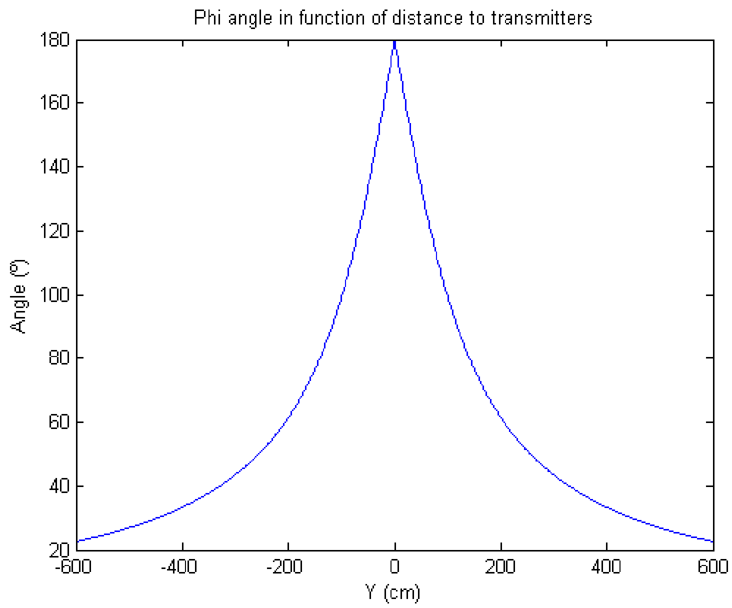


Fig. 5–7: ϕ angle evolution as a function of the distance to the line joining the transmitters for X=100 (see Fig. 5–4)

Based on this fact, the minimization algorithm consists in:

1. Capturing the two angles that are generated between the node and the transmitters (ϕ_1 and ϕ_2)
2. Place an imaginary node in the center of the map and calculate the theoretical angles with respect to all transmitters (ϕ_{1i} and ϕ_{2i})
3. Compare ϕ_1 and ϕ_2 with ϕ_{1i} and ϕ_{2i}.
4. Select the angle that diverges more.
5. Move the imaginary node in the direction perpendicular to the transmitters that involves this angle. *
6. Recalculate ϕ_{1i} and ϕ_{2i} for the new position.
7. If imaginary and captured angles are "identical" stop the process, else iterate from step 3.

* The node starts moving 50 cm every iteration (the distance between transmitters divide by 5), but each time that the direction associated to any angle switches, this movement is divided by 2 up to a minimum of 0.1 cm. Starting with a higher step (more than 50 cm) would be better for positions near the corners of the map, but worse for positions near the center. This is a good trade-off between the necessary number of iterations and accuracy.

When the imaginary node position goes outside the region between transmitters, the direction of minimization must be changed by the line that joins the imaginary node position with the mid-point of the transmitters.

This minimization process requires a higher computational cost than other ALO systems. To illustrate the computational cost of HALO4 system, a MATLAB simulation has been done. In this simulation, transmitters were placed at the ceiling of a room at (0,0,280), (0,250,280) and (250,0,280) and the node was placed in the floor between (0.5,0.5) and (249.5,249.5) in all points of a grid of 0.5x0.5 centimeters (generating a total of 249000 measures). The minimization process stops when the difference between imaginary and calculated angles is less than 0.001 rad. For these conditions, the minimization algorithm needs the number of iterations shown in Fig. 5–8.

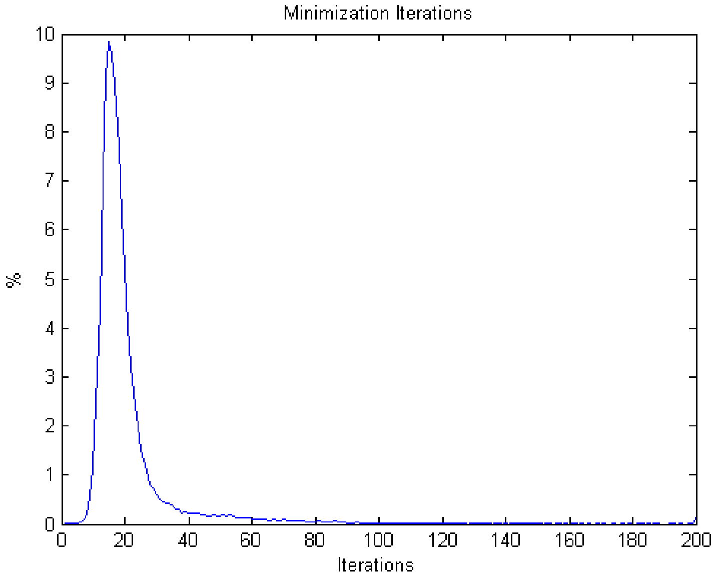


Fig. 5–8: Number of iterations for the minimization process

The mean number of iterations needed to localize a node via this minimization algorithm for the detailed environment is 20.54.

The time requested by Matlab to execute this localization process has been measured with different computers and operating systems (no parallelization techniques have been implemented to solve the algorithms). The results are summarized in Table 1:

Table 1. Computational Cost - Localization Algorithms

System	Num. Measures	Execution Time (min)	Mean Time per Measure (ms)
HALO4 (CPU1)	249000	0.2863	0.0690
ALO4 (CPU1)	249000	0.0237	0.0057
HALO4 (CPU2)	249000	0.6057	0.1460
ALO4 (CPU2)	249000	0.0318	0.0077
DTOA with Gauss- Newton minimization algorithm [19] (CPU3)	160000	3.7333	1.3999
DTOA with Cayley-Menger minimization algorithm [19] (CPU3)	160000	43.1833	16.1937

** CPU1: Intel Core i5-2500K processor (working at 3.30 GHz with 8GB of RAM) with Windows 7 (64 bits)*

** CPU2: Intel Core 2 Duo E8200 processor (working at 2.66 GHz with 2GB of RAM) with Windows XP (32 bits)*

** CPU3: Intel Core 2 Duo 2.00 GHz [19]*

It can be deduced that HALO4 has a computational cost between 10-20 times higher than ALO4 systems, but comparing it with other DTOA minimization systems, its cost has been significantly reduced.

5.5. Implementation

HALO4 system has been implemented using an FPGA platform. We have used four transmitters in order to cover a wider area. They are placed on the ceiling of a room, and they take turns to transmit. The distance between the transmitters is 237 cm. The possible points where the object can be placed are defined in the floor of the room. The ceiling height is 284 cm. This distribution allows the implementation of ALO4 and HALO4 systems (Fig. 5–9).

For the transmitter system, a state machine has been implemented in a Xilinx Spartan3 FPGA. The transmitter module consists in the generation, each 200 us, of a train of 20 pulses at 40 kHz. This signal is sent to a driver that increases the voltage of the signal from 3.3 V to 20 V, and this amplified signal is the input of the ultrasonic transmitters (model 400ST120-PROWAVE).

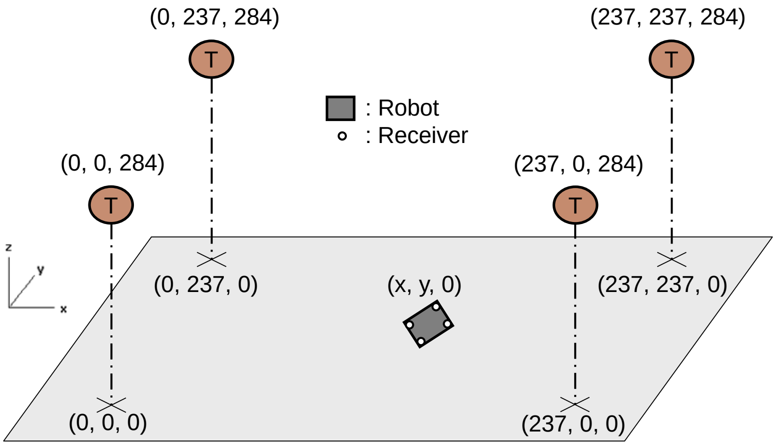


Fig. 5–9: System deployment (positions are expressed in cm)

The receiver module (Fig. 5–10) consists of four ultrasonic receivers (model 400SR120-PROWAVE) in a square distribution. The diagonal of this square is 10.15 cm.

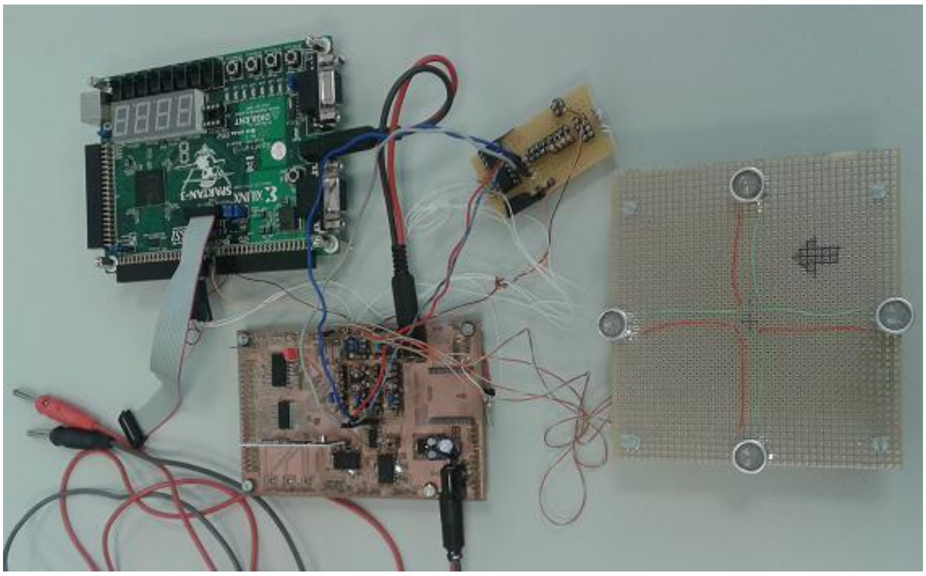


Fig. 5–10: Receiver implementation

The analog conditioning circuit and the digital processing system of the receiver are explained in detail in [9].

5.6. HALO4 Errors

The main error sources that affect HALO4 localization algorithm are the errors introduced in the minimization algorithm and the errors generated by an incorrect estimation of the horizontal angle (mainly, the error introduced by the non-ideal amplification phase).

To show the effect of these errors, the same environment as in the previous sections has been used. Different simulations have been executed and in each one only one of the previous errors listed has been analyzed.

HALO4 system precision is also affected by other error sources, as the incorrect parallelization between the receivers and the ceiling. This section only includes the error sources whose effect is very different in HALO4 and ALO4 systems.

5.6.1. Minimization error

The implemented minimization algorithm has two main error sources: The first limitation is the maximum error defined between the measured angles and the estimated angles. The second error is that the algorithm limits the number of iterations to 200. This represents the maximum time between measures that the algorithm has to obtain its position. Although this number is ten times greater than the mean number of iterations show in Fig. 5–8, the 0.053% of the analyzed points need more iterations to reach the requested precision. The effect of these errors is shown in Fig. 5–11.

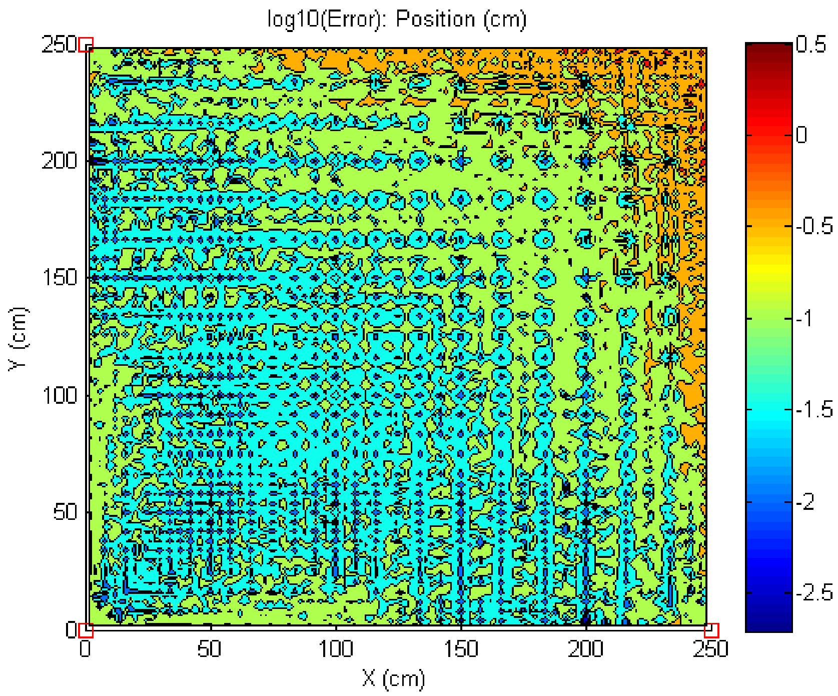


Fig. 5–11: HALO4 minimization error (represented in a logarithmic scale)

In the zone at a greater distance from transmitters, the error is higher. This effect is due to that in this zone, the measured angles are smaller than in the rest of regions, so the maximum error between imaginary and measured angles represents a higher percentage error than in the rest of zones. For this simulation, the maximum localization error obtained is 6.72 cm while the mean error is 0.16 cm.

Switching the maximum number of iterations and the threshold of the maximum angle divergence, a higher precision can be reached, but the computational cost of the algorithm is increased. Anyhow, the minimization process is subject to future optimizations using other minimization algorithms, but the basic idea is that the minimization process necessary in HALO4 is not a high computational demanding one, which can be solved using a simple minimization process with less computational resources than other state of the art localization algorithms, as shown in section 4.

5.6.2. Non-ideal amplification phase error

This error consists in that as there are four analog paths from the different receivers to the input of the processing system, there is a difference in the propagation delays of the generated signals. In our experiments, the error of this type measured was up to 2.1us. To show the effect of this error in the HALO4 system, a simulation where only one of the measures captured contains this error has been executed. The simulation results are shown in Fig. 5–12.

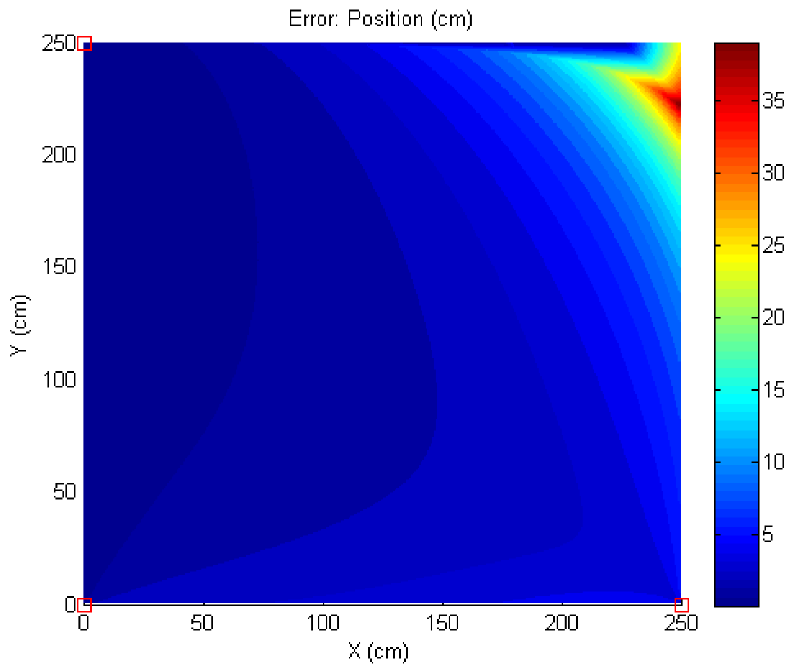


Fig. 5–12: Non-ideal amplification error

This error has a great repercussion on the localization performance of the system, with a maximum error of 39.06 cm and a mean error of 3.15 cm. To minimize this effect, it is recommend that the paths from receivers to FPGA pins should be almost identical and the robot should execute the calibration process detailed at [18] before start the localization algorithm.

5.7. Results

In order to test the proposed system, a prototype robot has been used, the same as the one detailed in [18]. The experiment consists on placing the robot on different points in the environment defined in section 5. The robot was calibrated following the algorithm described in [18], before the localization process starts.

After this calibration process, the system parameters for the experiment are the ones defined in section 5, except the following: sound propagation speed was 346.6 m/s, and the offset applied was up to 2.1 us between two different receivers.

A total of 9 points have been analyzed and at each point, 10 different measures have been taken for each node orientation (0°, 90°, 180° and 270°) and for each transmitter, generating a total of 360 localization measures.

The same measures are used to obtain the node position and orientation applying the ALO4 and HALO4 algorithms.

As our implementation uses resonant devices, an offset error (Δ′ in Fig. 5–13) is sometimes added to the ideal time (Δ) between the captured signals. This error is caused because the reference signal does not arrive with the same strength and angle to all receivers, so the comparator will not always detect the signal after the same number of cycles. This error is always a multiple of the ultrasonic wave period (Δ=Δ′ ± n·T), and it causes a great error on the localization results. It can be easily removed by a simple algorithm: the node only needs to add or subtract the ultrasonic period to the captured measures until the resultant position is nearer to the previous one.

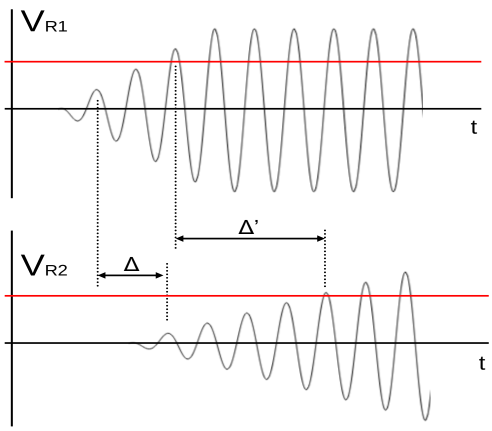


Fig. 5–13: Ultrasonic resonant devices offset error

The correction factor applied to the experimental measures is summarized in Fig. 5–14.

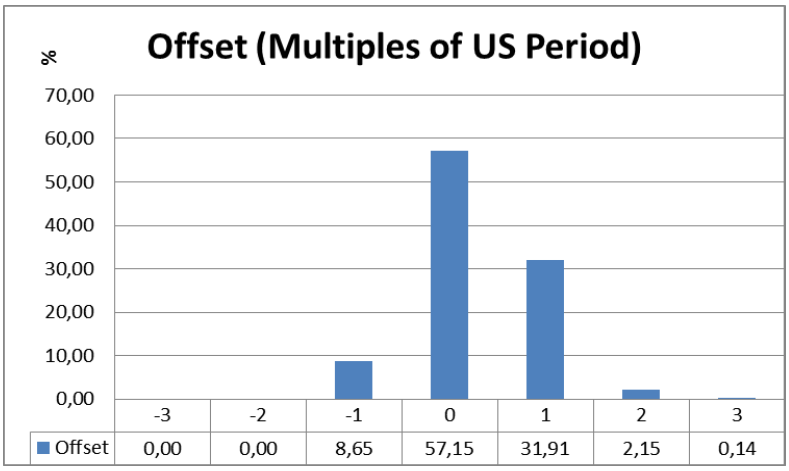


Fig. 5–14: Offset generated by resonant receivers

As the environment has four transmitters and the ALO4 system can calculate its position with respect to only two of them, the systems applies the localization algorithm with respect to each pair of transmitters that form a side of the square where the transmitters are deployed. The HALO4 system needs three transmitters, so it uses the four possible combinations that involve the three transmitters in a right triangle distribution.

This implies that four different positions are calculated for each measure (obtaining a total of 1440 localization points).

The results of the localization process are summarized in Fig. 5–15 (ALO4 system) and Fig. 5–16 (HALO4 system):

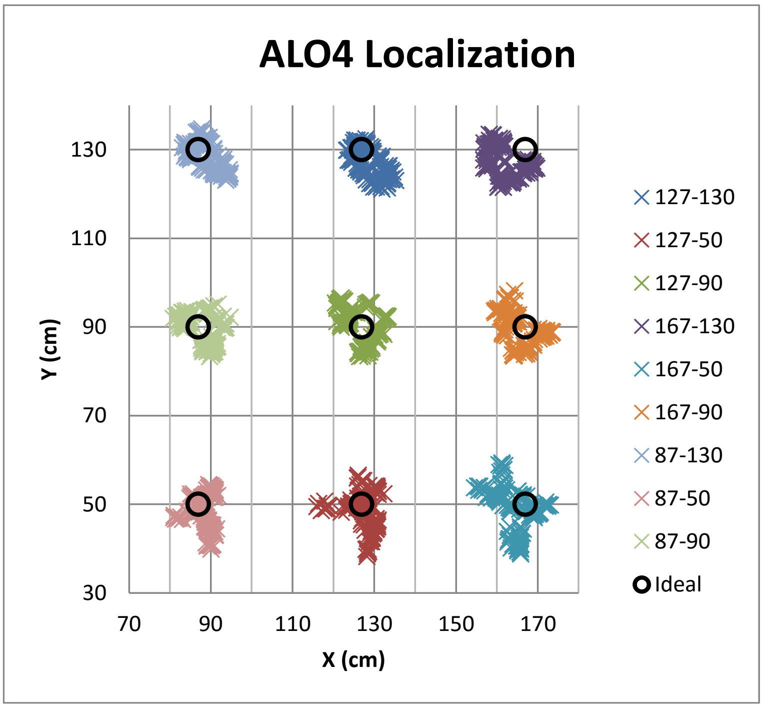


Fig. 5–15: ALO4 localization results

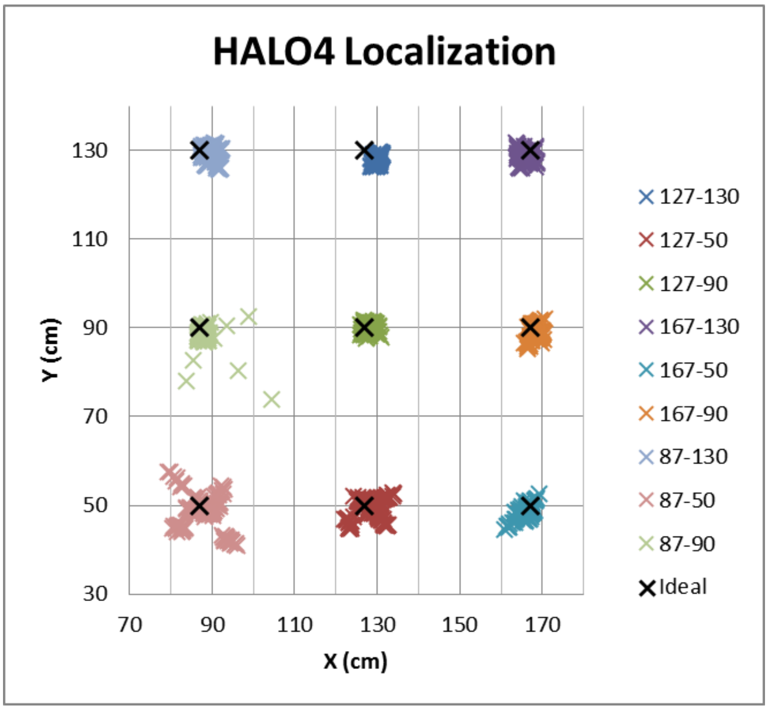
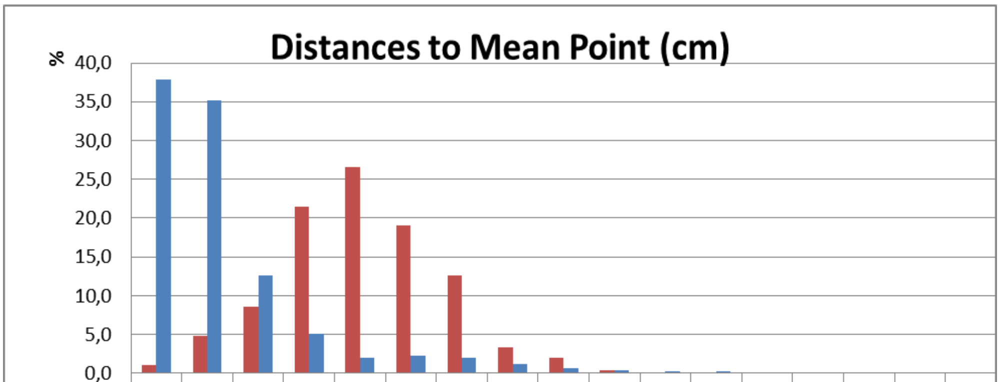


Fig. 5–16: HALO4 localization results

The first conclusion is that the HALO4 system obtains localization results with less dispersion than ALO4 system with one consideration. If one of the measures captured has an amplification error different than the value obtained by calibration (resonant receiver responds a bit faster/slower because a previous noise has charged the receiver, for example), the error introduced with HALO4 algorithm is bigger than the effect of the same error source on ALO4.

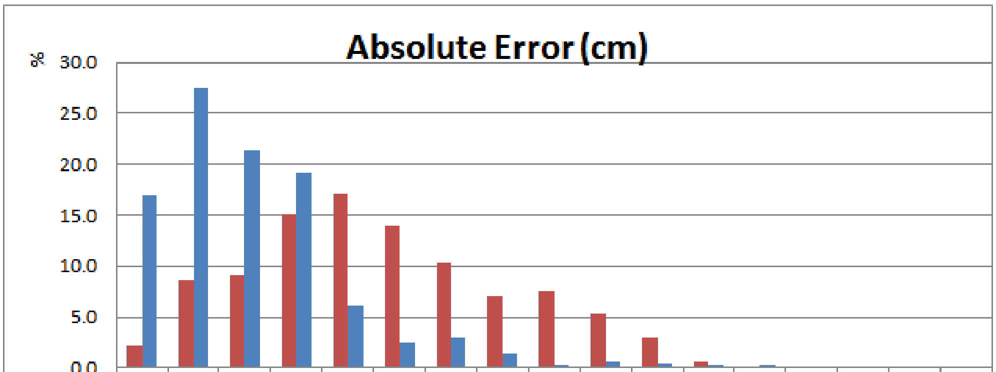
The mean point of each localization area has been calculated and the distances of each point to this reference point have been measured. These distances have been summarized in a histogram (Fig. 5–17). ALO4 has a mean distance of 4.55 cm with a maximum distance of 10.06 cm (the standard deviation is 1.57 cm) while HALO4 reaches a mean distance of 1.85 cm, but its maximum distance is 21.94 cm (its standard deviation is 1.89 cm).



	<1	<2	<3	<4	<5	<6	<7	<8	<9	<10	<11	<12	<13	<14	<15	<16	>16
ALO4	1,0	4,9	8,6	21,5	26,5	19,1	12,6	3,3	1,9	0,3	0,1	0,0	0,0	0,0	0,0	0,0	0,0
HALO4	37,8	35,1	12,6	5,1	1,9	2,2	1,9	1,3	0,7	0,4	0,3	0,3	0,1	0,0	0,0	0,0	0,1

Fig. 5–17: Histogram of the distances to the mean point, reflecting the dispersion of each method

HALO4 system has also more precision in the localization results. To measure this effect, the error between the ideal point (where the node was deployed) and the result of the localization process has been calculated for both systems, and these results are shown in Fig. 5–18.



	<1	<2	<3	<4	<5	<6	<7	<8	<9	<10	<11	<12	<13	<14	<15	<16	>16
ALO4	2.2	8.7	9.1	15.1	17.1	14.0	10.3	7.0	7.5	5.3	2.9	0.6	0.1	0.1	0.0	0.0	0
HALO4	16.9	27.4	21.3	19.2	6.1	2.5	2.9	1.5	0.3	0.6	0.5	0.3	0.3	0.1	0.0	0.0	0.1

Fig. 5–18: Histogram of the localization absolute error (distance between the localization result and the node real position)

As with the distance to the mean point, ALO4 obtains a smaller maximum error (20.06 cm with respect to 23.77 cm of HALO4 system) but HALO4 reaches a better mean error (2.65 cm with respect to 5.18 cm obtained by ALO4).

Both ALO4 and HALO4 also give the orientation apart from the localization. The errors in the absolute orientation, in degrees, are shown in (Fig. 5–19).

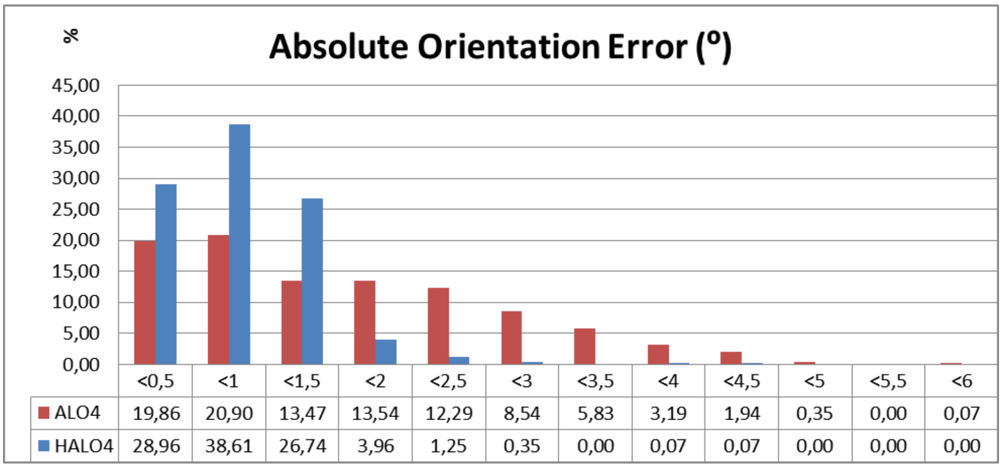


Fig. 5–19: Histogram of the absolute orientation error

The HALO4 system improves the precision of localization system due to the higher localization precision reached, obtaining a mean orientation error of 0.80º (its maximum error is 4.02º and its standard deviation 0.48º) while ALO4 obtains a mean error of 1.53º (with a maximum of 5.88º and a standard deviation of 1.09º).

5.8. Conclusions

This paper presents a new algorithm to obtain the position and orientation of a robot, HALO4. It is based on the direction of arrival of signals generated by three transmitters. The estimation of the direction of arrival is the same as in the ALO4 system, but the localization algorithm differs from this one, using the horizontal angles instead of the vertical angles to obtain the position of the robot.

Using the horizontal angles allows deploying the transmitters at different heights and making the system immune to errors generated by an incorrect estimation of the ultrasonic signal speed. The disadvantage of HALO4 with respect to ALO4 is that the localization algorithm has a greater complexity, needing a minimization process to obtain the position of the node, representing a computational cost that is up to 20 times higher, but it is less than other DTOA minimization algorithms based on hyperboloid intersections.

Experimental results that share the same measures to obtain the orientation and position of the node have been carried out. HALO4 can estimate more precisely the position and orientation of the node than ALO4, reaching a mean error of 2.65 cm with respect to the ideal point (while ALO4 obtains 5.18 cm) and a mean orientation error of 0.80º (ALO4 obtains 1.53º), therefore showing the advantage of using the horizontal angles instead of the vertical ones at a cost of more computational effort.

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6. CAL4: CEILING ANGLE LOCALIZATION SYSTEM WITH 4 TRANSMITTERS BASED ON ULTRASOUNDS

Abstract:

This paper presents an ultrasonic localization DTOA (Difference Time of Arrival) system, based on ALO4 (Angle Localization and Orientation with 4 receivers). The proposed system consists in only one receiver per node and four transmitters deployed in a square on the ceiling of the room. This approximation denies the possibility of obtaining the orientation of the node but increases the precision on the localization result, obtaining errors comparable to the one reported by TOA (Time Of Arrival) systems. The localization algorithm is similar to its predecessor, so its computational cost is lower than the traditional DTOA systems based on the intersection of hyperboloids.

Keywords:

DOA, DTOA, location, ultrasonic

6.1. INTRODUCTION

The navigation capacity is one of the critical systems for robots or mobile nodes in wireless sensor networks [1]-[2] to guarantee a correct behavior of these devices when executing their programmed tasks. Navigation systems are based on three pillars: localization, orientation and mapping. Multiple technologies allow obtaining the information necessary to implement the localization and orientation algorithms, but the only technology that provides a high precision at a low cost is the one based on ultrasounds.

There are two main groups of ultrasonic localization systems depending on the measures used for the localization algorithm. TOA systems [3]-[4] use the absolute distance between transmitters and receivers, while DTOA use the difference in the distance measured at multiple receivers.

DTOA systems need a higher computational cost (as they are based on the intersection of hyperboloids [5]-[8] or trigonometric functions [9]-[10]) and usually reach a lower precision than TOA systems, but they do not need any synchronization between receivers and transmitters.

Between all DTOA systems, a low cost DTOA system is the one called ALO4 [11]. The main advantage of the ALO systems with respect to other DTOA systems is its low computational cost that can be compared with TOA systems. As all DTOA systems, its main disadvantage is its low precision, reporting (for a 2D environment) a localization error up to 13 cm (with a mean error of 5.17 cm), while, in a 3D environment, the TOA system detailed in [12] has a precision about 3 cm.

This paper presents a conceptual evolution of the ALO4 system. Instead of using four receivers in the robot to obtain the estimated reception angle of the reference wave, this system only uses one receiver and estimates the angle of emission of a hypothetical wave generated in the mid point of four transmitters. As transmitters are deployed on the ceiling, the distance between them is not constrained to the size of the robot, and as the robot only has 1 receiver, its cost and size are reduced too.

The rest of the paper is organized in seven main sections: “ALO4 System”, where a summary of this system is presented; “CAL4 System”, where the new system is exposed; “Plane Wave Approximation error”, where this error is analyzed and a method to reduce it is defined; “Non Ideal Amplification Error”, section that describes the effect of this error on the system; “Offset Error”, where the main error of the CAL4 system is studied;, “Implementation”, where the implementation of the system can be found; and “Results”, where the experimental results are presented.

6.2. ALO4 System

ALO4 system (Fig. 6–1) bases the estimation of the received angle in the measure of the propagation delay of a reference wave between 4 receivers deployed in a node in a square distribution.

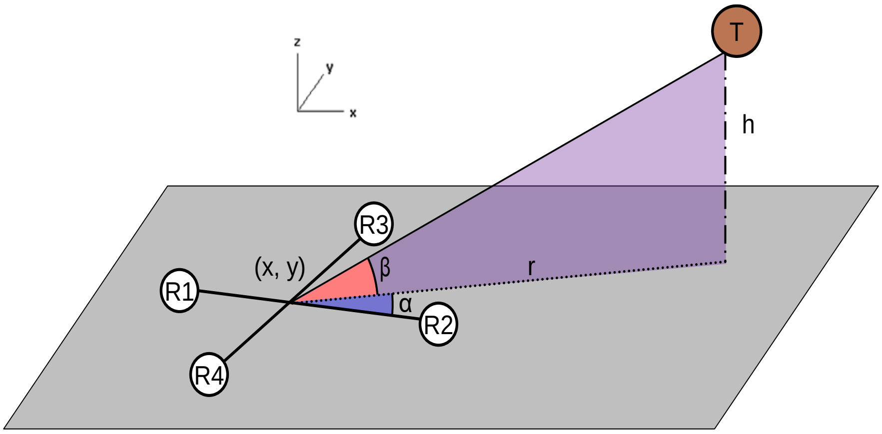


Fig. 6–1: ALO4 system

With the delays measured, ALO4 system obtains the direction of arrival of the ultrasound signal applying the following formulas:

$$\cos(\alpha) = \sqrt{\frac{d_1^{\,2}}{d_2^{\,2} + d_1^{\,2}}} \qquad \sin(\beta) = \sqrt{1 - \frac{d_2^{\,2} + d_1^{\,2}}{a^2}} \qquad (1)$$

- d_1 = distance measured between R1 and R2
- d_2 = distance measured between R3 and R4
- a = distance between receivers

Merging the vertical angle measured with respect to two transmitters, the system is able to obtain the localization of the node as:

$$r_1 = \frac{h}{\tan(\beta_1)} \qquad r_2 = \frac{h}{\tan(\beta_2)} \qquad (2)$$

$$x = \frac{r_1^{\,2} - r_2^{\,2} + b^2}{2 \cdot b} \qquad y = \pm\sqrt{r_1^{\,2} - x^2}$$

- r_X = distance from the projection of transmitter X on the floor to the node.
- h = height of the ceiling
- β_X = vertical angle measured to transmitter X

And with the horizontal angle with respect to one transmitter and the position of the node, it obtains its absolute

6.3. CAL4 System

The CAL4 system is based on the same principle as ALO4, but instead of estimating the angle depending on the "delay between receivers", its principle is based on the "delay between transmitters" (Fig. 6–2).

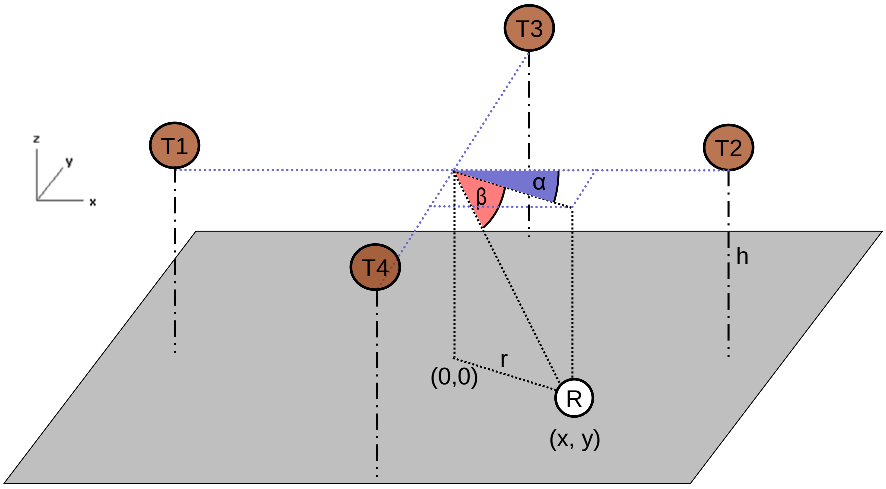


Fig. 6–2: CAL4 system

Although all transmitters emit simultaneously, the signal generated by each transmitter arrives with a different delay to the node. If the node estimates these delays, the time measured is the same as the delays captured when one transmitter is placed on the node position and four receivers are placed on the transmitter positions. Therefore, the same formulae (1) can be used for obtaining the vertical and horizontal angles at the mid point between the transmitters. With these angles, the node obtains its position using:

$$r = K \frac{h}{\tan(\beta)} \quad (3)$$

$$x = \pm r \cdot \cos(\alpha) \qquad\qquad y = \pm r \cdot \sin(\alpha)$$

- r = distance from the projection of centre of the transmitters on the floor to the node
- h = height of the ceiling
- K = constant that reduces the error due to the plane wave approximation (detailed in section 4)
- β = estimated vertical angle
- α = estimated horizontal angle

The system chooses one of the four possible points in function of the delay used to estimate the angles. Example:

- If node detects that is nearer T2 → x > 0
- If node detects that is nearer T1 → x < 0

The trigonometric functions of the equations (3) have a simple equivalence defined in (1), so the node does not need to implement trigonometric functions to obtain its position.

6.4. Plane Wave Approximation Error

ALO systems base its low computational cost on the simplification that the waveform is received as a plane wave.

Although ALO4 reduces the plane wave approximation error [11], this error has a great dependence on the distance between receivers. In CAL4, the distance between "receivers" can be much larger than in ALO4 implementations, fact that introduces a very significant error on the localization process. To show this effect, a hypothetical case where the ceiling is at 280 cm, and the transmitters are placed in the vertices of a square with a side of 240 cm has been simulated, obtaining the errors of Fig. 6–3 (transmitters are represented as red squares in the vertices of the figure):

The error mainly affects the precision on the estimation of the vertical angle and has a great dependence on the distance between the node position and the mid-point between the transmitters

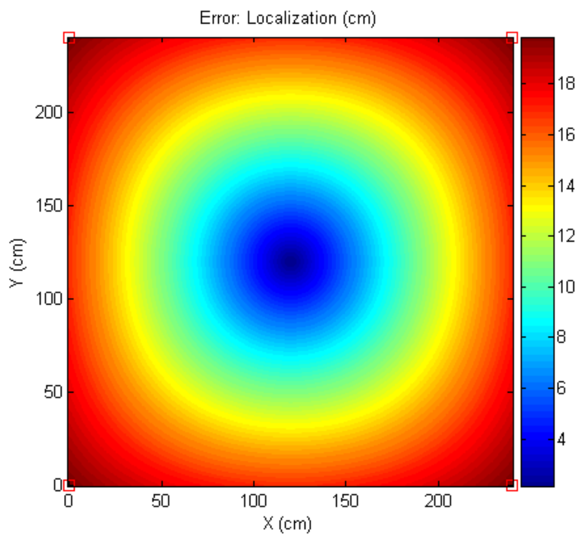


Fig. 6–3: CAL4 plane wave localization error (K=1)

To minimize this effect, a K factor is introduced in 'r' as shown in equations (3). This factor was obtained with a successive approximation process executed on a computer that emulates the environment where the node will be moving. This factor is only calculated one time during the deployment of the system, so it does not affect to the computational cost demanded by the node.

This factor reduces up to 10 times the plane wave localization errors, as shown in Fig. 6–4.

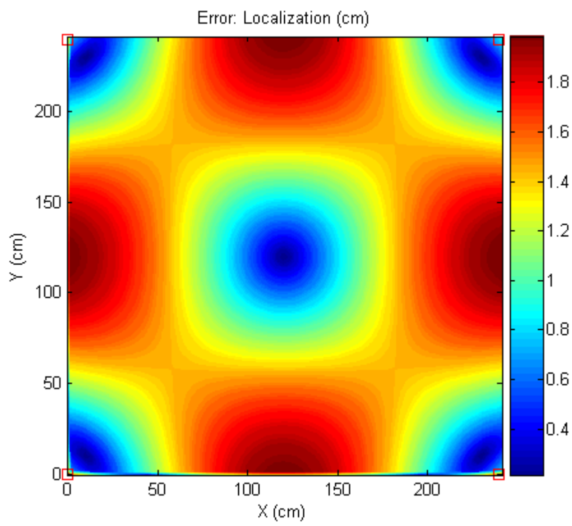


Fig. 6–4: CAL4 plane wave localization error (K=1.1388)

6.5. Non-Ideal Amplification Error

The second error to be analyzed is the delay caused by the different devices used during the implementation of the system. In [11] this error is mainly caused by the four different amplification paths from the four receivers to the ADC.

As in CAL4 there is only 1 receiver, there is only one path from the receiver to the ADC, so no errors are inserted in the node. However, CAL4 has four transmitters, each one with its own delay, and when the system measures the delay between the reference points, it measures the valid measure plus this error.

This error can be modeled as a constant error, so its effect is greater when the distance between the reference points used to estimate the angle is smaller (for smaller distances, the total time measured is smaller and, proportionally, the effect of this error is greater).

In ALO4, this error is one of the most important error sources of the system (for a distance between receivers of 10 cm and an error of 4 us, the mean localization error generated by this effect is ~3cm), but in CAL4 system, as the distance between transmitters is much larger, this error is negligible (for the previous simulation, the effect of this error is ~0.9 mm).

6.6. Offset Error

When using resonant devices, there is an inherent error in all measures reported by these components. This error consists in that resonant devices response depends on the intensity and direction of the received wave. The received analog signals rise faster or slower, so they reach the threshold value (line red at Fig. 6–5) after different delays that are always a multiple of the reference wave period.

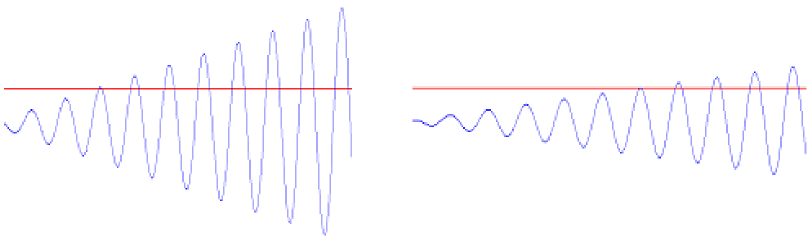


Fig. 6–5: Ultrasonic resonant devices offset error

In ALO4 system, this error can be easily removed by software: As the receivers are close, this offset is usually zero or one period, and errors of one period generates a mean localization error of ~30 cm. Knowing the previous position of the robot and localizing the node frequently, this error can be deduced and removed.

In CAL4, due to the larger distance between transmitters, the range of the offset error is increased and cannot be removed via software because an error of one period only generates a localization error of less than 1 cm.

For the simulation environment defined in the previous section, an offset error of up to six ultrasonic periods at one of the captured measures causes an error on the node position between 5 cm and 8 cm.

As it can be observed, this error is the main error source of the system and is inherent to the technology used to implement the localization system. The only way to reduce this error is to replace the resonant ultrasonic receiver and transmitters by ultrasonic microphones and speakers, fact that would increase the cost of the system.

6.7. Implementation

The localization system implemented is the same as the one described in [11].

Summarizing the implementation, the environment is composed of four transmitters on the ceiling and one robot, with four receivers, deployed at the floor of the room, as shown in Fig. 6–6.

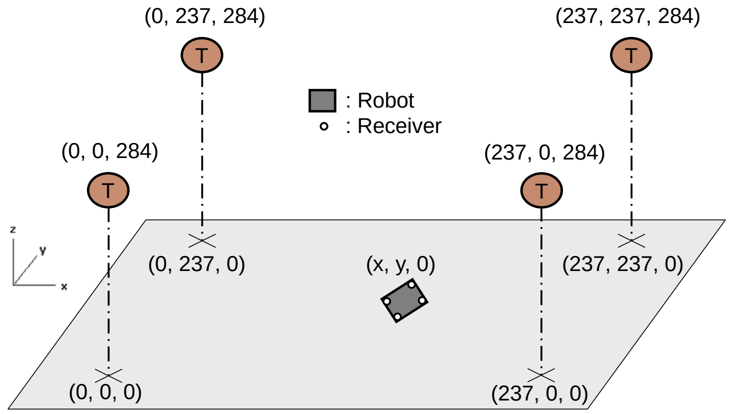


Fig. 6–6: General layout of the transmitters used in the experimental results

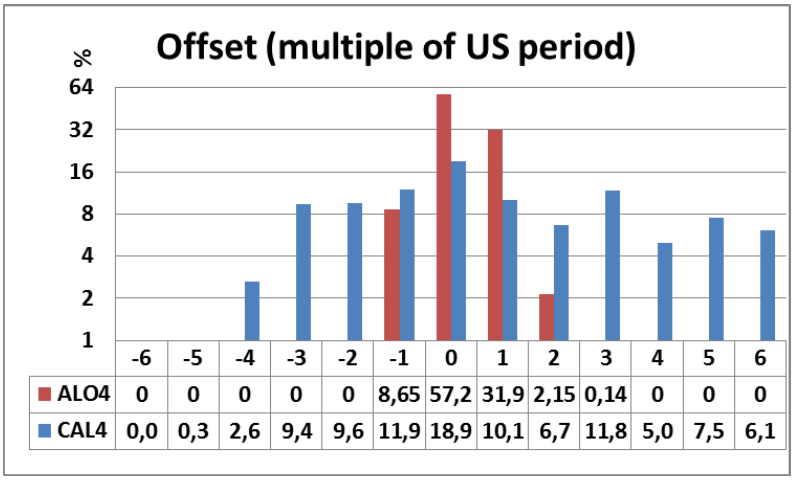
The robot implements four ultrasonic receivers deployed at a square distribution with a side distance of 10 cm, allowing us to compare CAL4 system performance (giving one independent localization for each receiver) against ALO4 system (localizing the mean point between receivers) with the same measures for both cases.

The system has been calibrated as described in [11] before obtaining the experimental results of the next section.

6.8. Results

In order to test the proposed system, the node defined in section 7 has been placed on different points in the environment defined in Fig. 6–6. A total of 9 points have been analysed and at each point, 10 different measures have been taken for each node orientation (0º, 90º, 180º and 270º) and for each receiver, generating a total of 360 localization measures.

The offset error for both systems, caused by resonant receivers, is summarized in the histogram shown on Fig. 6–7. The offset error for ALO4 has been removed, however, CAL4 offset error has been considered when obtaining the localization of the node.



	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
ALO4	0	0	0	0	0	8,65	57,2	31,9	2,15	0,14	0	0	0
CAL4	0,0	0,3	2,6	9,4	9,6	11,9	18,9	10,1	6,7	11,8	5,0	7,5	6,1

Fig. 6–7: Offset at ALO4 and CAL4

The localization results obtained by both systems are summarized in Fig. 6–8, Fig. 6–9, Fig. 6–10 and Fig. 6–11.

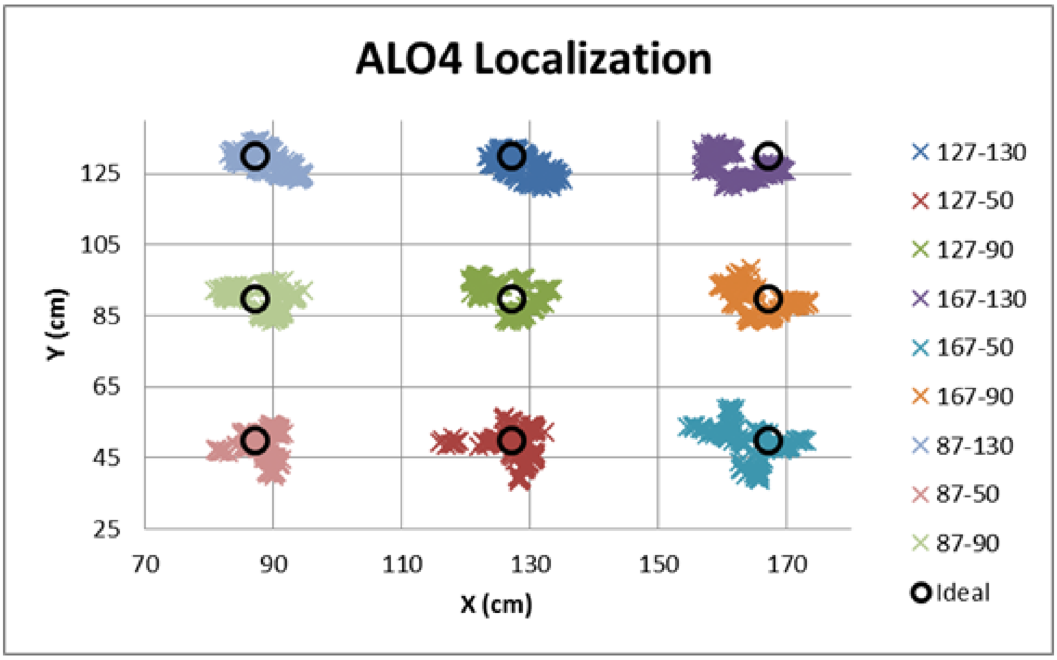


Fig. 6–8: ALO4 localization results

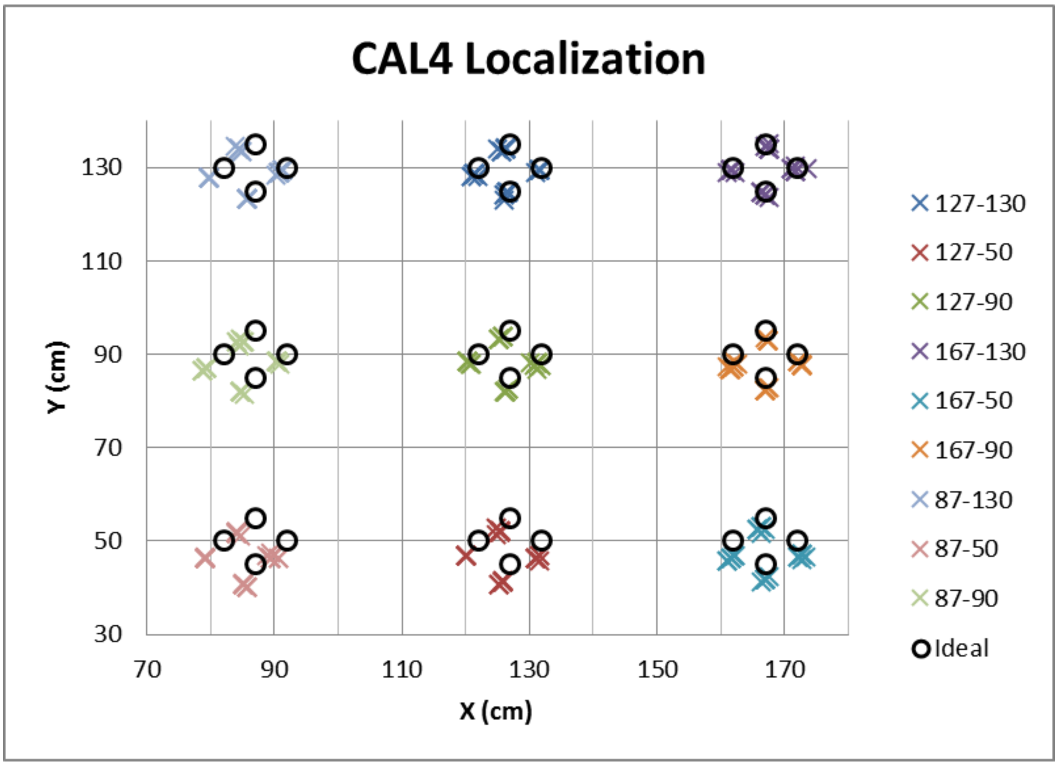


Fig. 6–9: CAL4 localization results

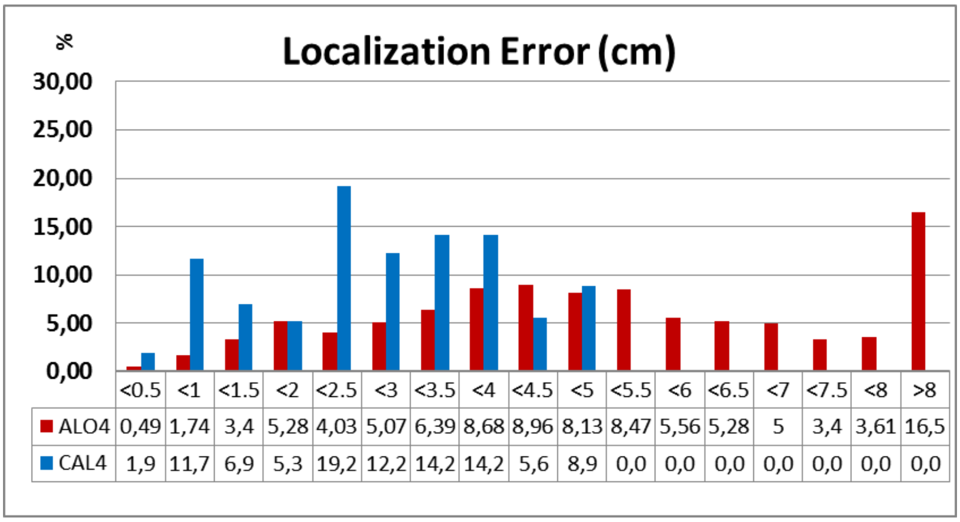


Fig. 6–10: Localization error for ALO4 and CAL4

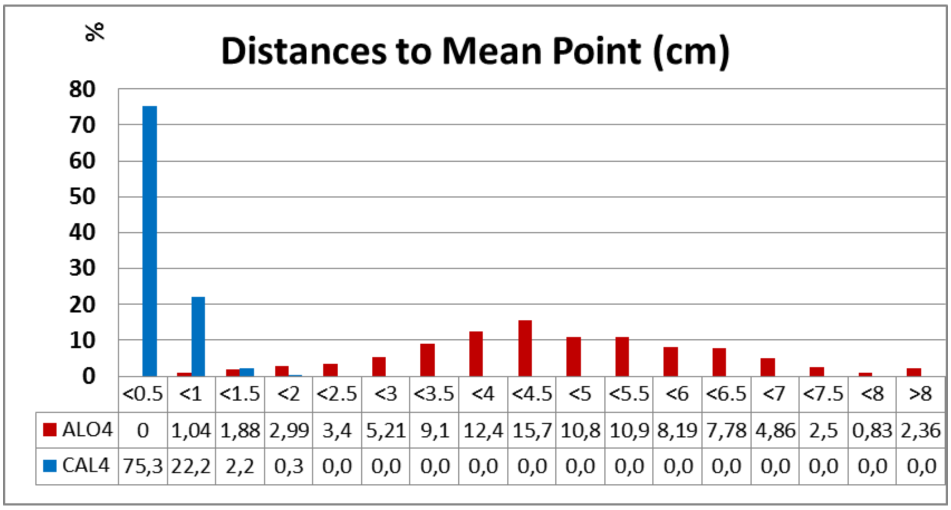


Fig. 6–11: Distances to mean point (dispersion measure)

6.9. Conclusions

This paper presents a change of concept of the ALO4 system, switching from using 4 receivers and 1 transmitter to using 4 transmitters and 1 receiver without increasing the low computational cost of the ALO4 system (that is similar to the computational cost of TOA systems).

Analytically, this new approach is immune to small variations on the captured measures, but it reports a higher error due to the approximation of the reference signal as a plane wave and due to the offset error caused by the resonant ultrasonic devices.

Although analytically CAL4 does not provide a great improvement with respect to ALO4, experimental results show that captured measures have a smaller variation in the node position (with a variation of less than 1 cm) and although localization errors depend on the position of the node (positions nearer the centre of the transmitters have smaller errors) CAL4 obtain a better localization precision with respect to ALO4, with a mean error of 2.30 cm (while ALO4 reaches a 5.18 cm) and a standard deviation of 1.22 cm (ALO4 has a standard deviation of 2.51 cm). This error is similar to the error obtained with TOA systems [12].

6.10. Acknowledgment

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7. RESULTADOS

7.1. Resumen de Resultados

En el presente capítulo se recoge un resumen de los resultados obtenidos al comparar las diferentes alternativas utilizadas a lo largo del desarrollo de esta tesis, con el fin de poder compararlas bajo unas mismas condiciones.

7.1.1. Resultados en función de la tecnología utilizada

A lo largo del desarrollo de esta tesis se han utilizado tecnologías basadas en sonido y ultrasonido para implementar el sistema ALO4 (capítulos 3 y 4). Para comparar las prestaciones obtenidas al utilizar ambas tecnologías, se desplegaron 2 transmisores de ultrasonido y 2 altavoces en el techo de una habitación (compartiendo la misma posición) y se situó el nodo, con los receptores, en 4 posiciones en el suelo, siguiendo la distribución mostrada en la Fig. 7–1.

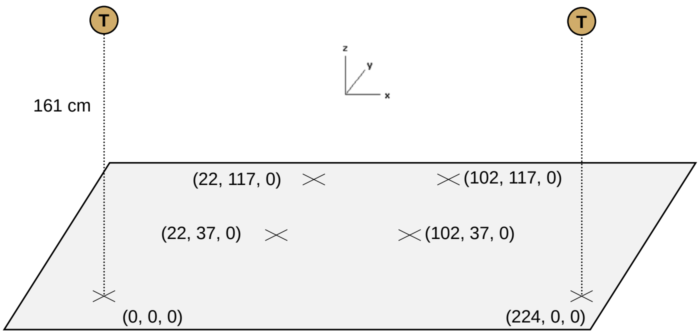


Fig. 7–1: Distribución utilizada para obtener los resultados experimentales para la comparación de la tecnología utilizada

En cada una de las posiciones en las que se situó el robot, se tomaron medidas hasta poder calcular la posición del nodo 10 veces respecto a 4 orientaciones diferentes (0º, 90º, 180º y 270º), obteniendo un total de 40 puntos de localización por posición analizada. El sistema de ultrasonido utilizó una señal de 40 kHz como señal de referencia mientras que el sistema de audio transmitía una señal de 11 kHz.

Antes de obtener la posición del robot, el sistema se calibró siguiendo el procedimiento detallado en la sección 3.5. Además, se eliminó el error de offset de las medidas capturadas (el error de offset corregido se detalla en la Tabla 1).

Tabla 1: Offset corregido para cada tecnología (en múltiplos del periodo de la señal de referencia)

Tecnología	Offset 0 T (Sin error)	Offset 1 T	Offset 2 T
Sonido	100,00 %	0,00 %	0,00 %
Ultrasonido	57,03 %	41,72 %	1,25 %

Con las medidas capturadas (y corregidas) respecto a los diferentes transmisores, se procedió a obtener la posición y orientación del objeto, obteniendo los resultados mostrados en la Fig. 7–2:

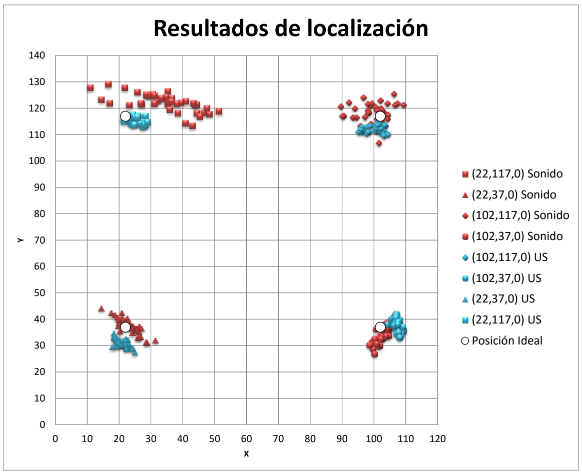


Fig. 7–2: Resultados de localización utilizando sonido y ultrasonidos

Analizando el error absoluto respecto al punto ideal, se obtiene el histograma de la Fig. 7–3:

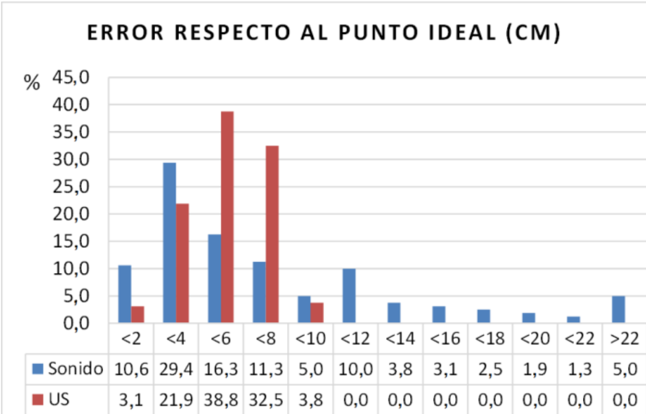


Fig. 7–3: Histograma del error en la localización respecto al punto ideal (sonido / ultrasonidos)

El histograma de la Fig. 7–4 muestra el error en la orientación calculada por el sistema respecto a la orientación real del nodo en función de la tecnología utilizada:

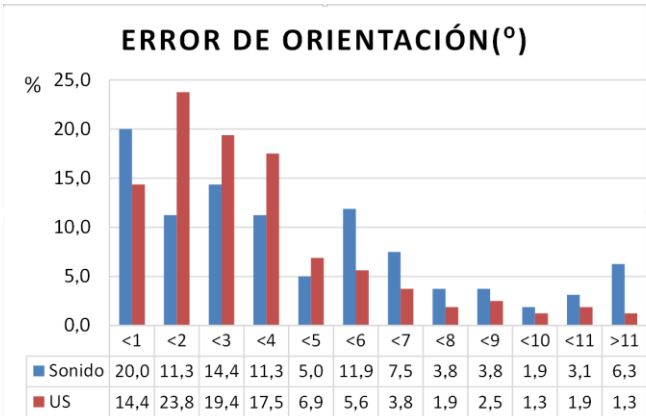


Fig. 7–4: Histograma del error en la orientación del nodo (sonido / ultrasonido)

Tecnología	Máximo error de localización	Error medio de localización	Máximo error de orientación	Error medio de orientación
Sonido	29,3 cm	7,26 cm	17,22º	4,27º
Ultrasonidos	9,82 cm	5,21 cm	15,02º	3,22º

Tras los peores resultados obtenidos con el sistema basado en sonido, se descarta su uso y el resto de sistemas propuestos en la presente tesis no se implementan con esta tecnología.

7.1.2. Resultados en función del sistema de localización / orientación utilizado

Para comparar las prestaciones de los sistemas propuestos durante el desarrollo de esta tesis, se desplegó en el techo de una habitación 4 transmisores y un robot con 4 receptores. Debido a los problemas obtenidos al utilizar sistemas de audio convencionales (detallados en el capítulo 6), dicha tecnología se descartó para estas pruebas y se decidió utilizar transductores de ultrasonidos, desplegándolos con la topología mostrada en la Fig. 7–5:

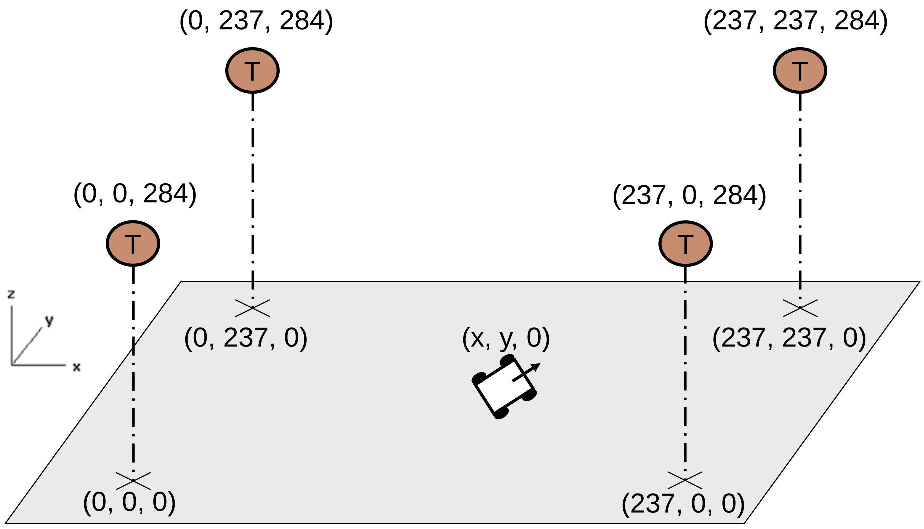


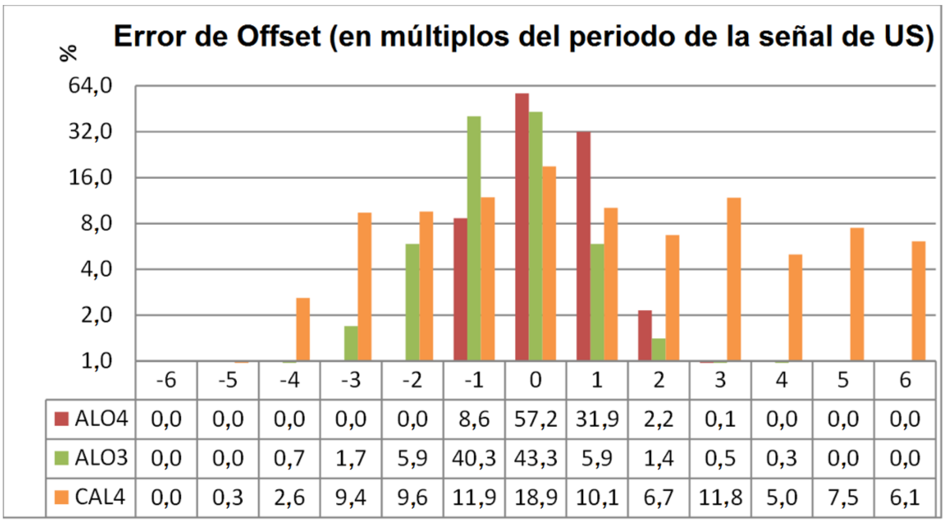
Fig. 7–5: Topología utilizada para obtener los resultados experimentales para la comparación de los sistemas de localización

Los receptores se desplegaron en los vértices de un cuadrado cuya diagonal era de 10,15 cm.

En este entorno, se situó el robot en 9 posiciones distintas, orientándolo en cada posición en 4 direcciones diferentes (0º, 90º, 180º y 270º). Para cada posición y orientación, se capturaron 10 medidas respecto a cada transmisor.

Antes de capturar las medidas, el sistema se calibró siguiendo el procedimiento detallado en el capítulo 3.5. Además, para los algoritmos ALO3, ALO4 y HALO4 se eliminó el error de offset (el cual se detalla en el capítulo 2) antes de obtener la posición y orientación del objeto. Para el algoritmo CAL4, este efecto no se eliminó ya que es muy difícil definir una condición que permita detectar este caso.

La distribución del error de offset en las medidas capturadas es la que se muestra en la Fig. 7–6 (al utilizar los sistemas ALO4 y HALO4 los mismos receptores, el error de offset es idéntico para ambos casos).



	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
ALO4	0,0	0,0	0,0	0,0	0,0	8,6	57,2	31,9	2,2	0,1	0,0	0,0	0,0
ALO3	0,0	0,0	0,7	1,7	5,9	40,3	43,3	5,9	1,4	0,5	0,3	0,0	0,0
CAL4	0,0	0,3	2,6	9,4	9,6	11,9	18,9	10,1	6,7	11,8	5,0	7,5	6,1

Fig. 7–6: Error de offset tras aplicar los diferentes algoritmos

Con las medidas capturadas (y corregidas) respecto a los diferentes transmisores, se procedió a obtener la posición y orientación del objeto aplicando los diferentes algoritmos descritos en los capítulos anteriores, lo que permite analizar las prestaciones de cada uno de estos algoritmos con el mismo error introducido por la etapa analógica encargada de capturar y adaptar la señal de ultrasonidos.

El sistema de localización ALO3 (definido en el capítulo 2) obtuvo los resultados mostrados en la Fig. 7–7:

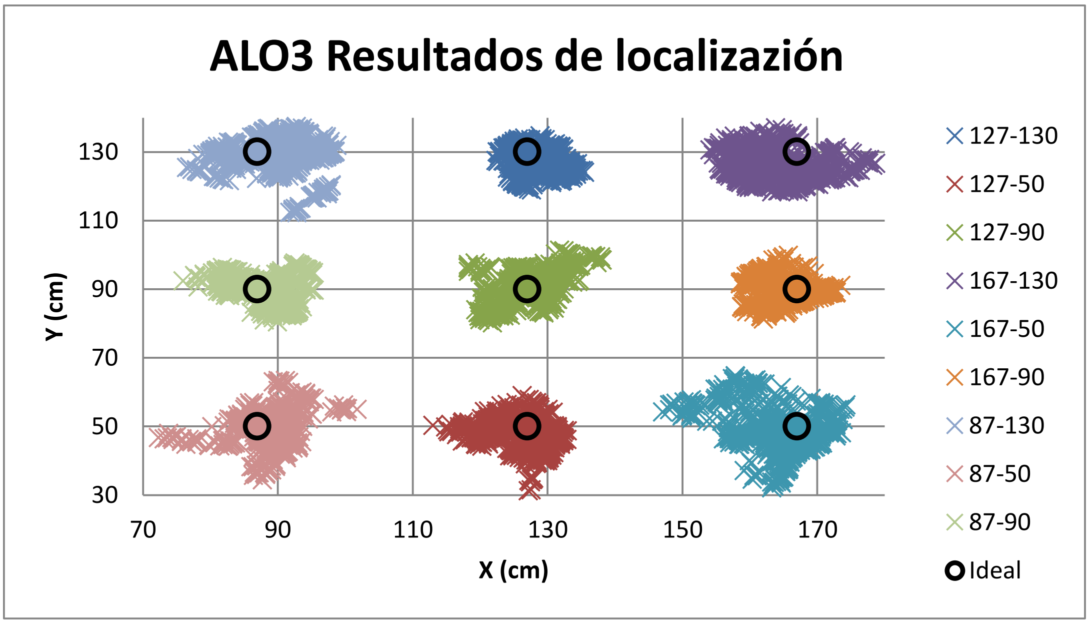


Fig. 7–7: ALO3 resultados de localización

Al aplicar el algoritmo ALO4 (detallado en el capítulo 3), el sistema reportó las posiciones de la Fig. 7–8:

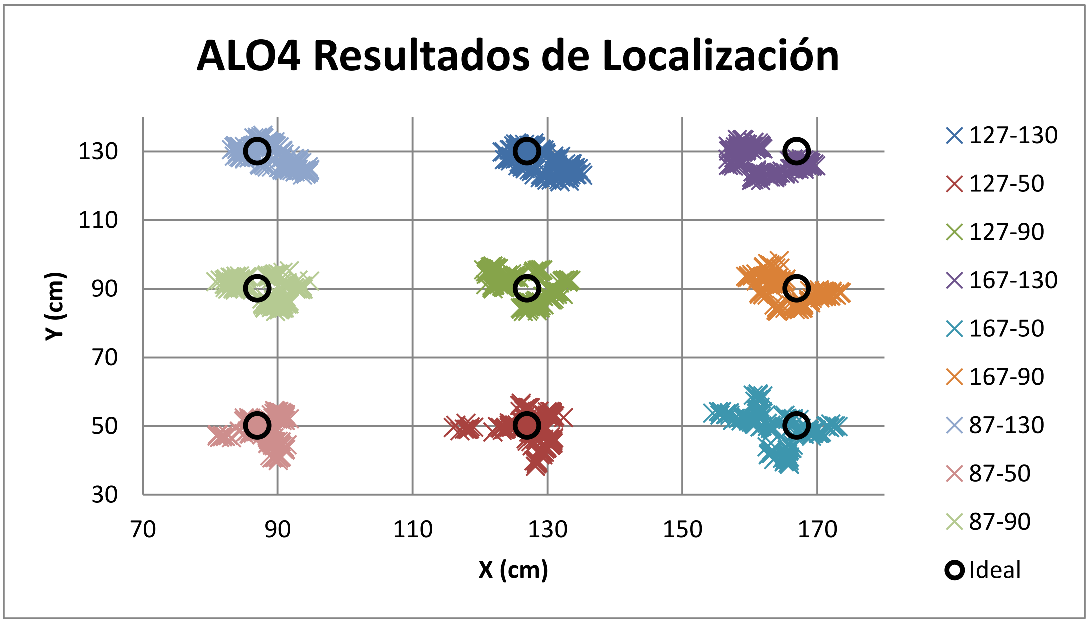


Fig. 7–8: ALO4 resultados de localización

Utilizando la aproximación de HALO4 (descrita en el capítulo 5) se obtienen los resultados de la Fig. 7–9:

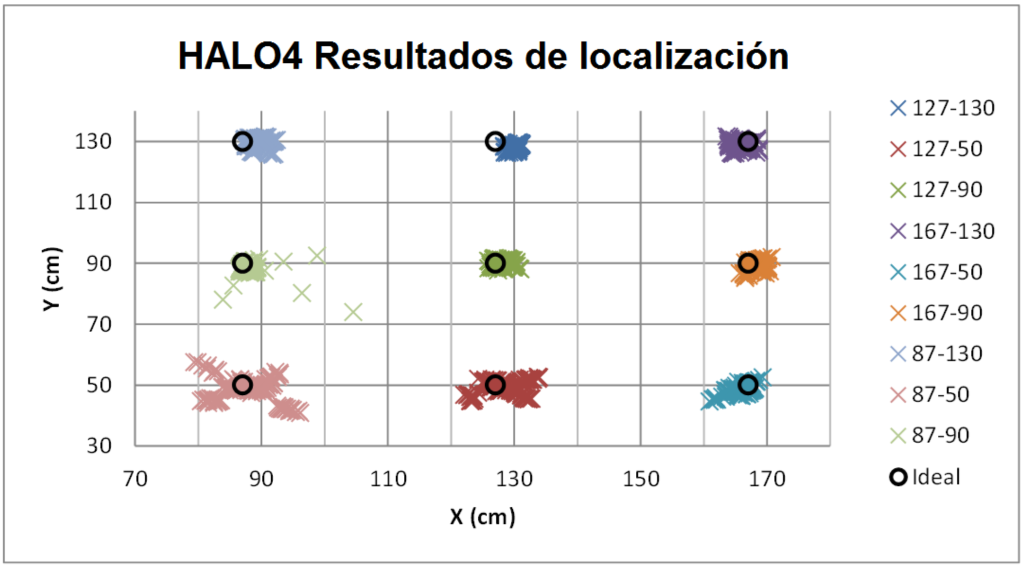


Fig. 7–9: HALO4 resultados de localización

El algoritmo CAL4 (definido en el capítulo 6) cambia las bases del sistema, necesitando 4 transmisores y un solo receptor para obtener la posición del objeto. Como se comparten las medidas respecto al resto de algoritmos, dichas medidas se tomaron para que el punto de referencia del objeto (el centro del cuadrado) no cambiase al rotar el objeto. Como en CAL4 el punto de referencia es uno de los receptores situados en los vértices del cuadrado, dicho punto cambia para las 4 orientaciones del robot, obteniendo para cada posición 4 puntos de referencia distintos según se muestra en la Fig. 7–10.

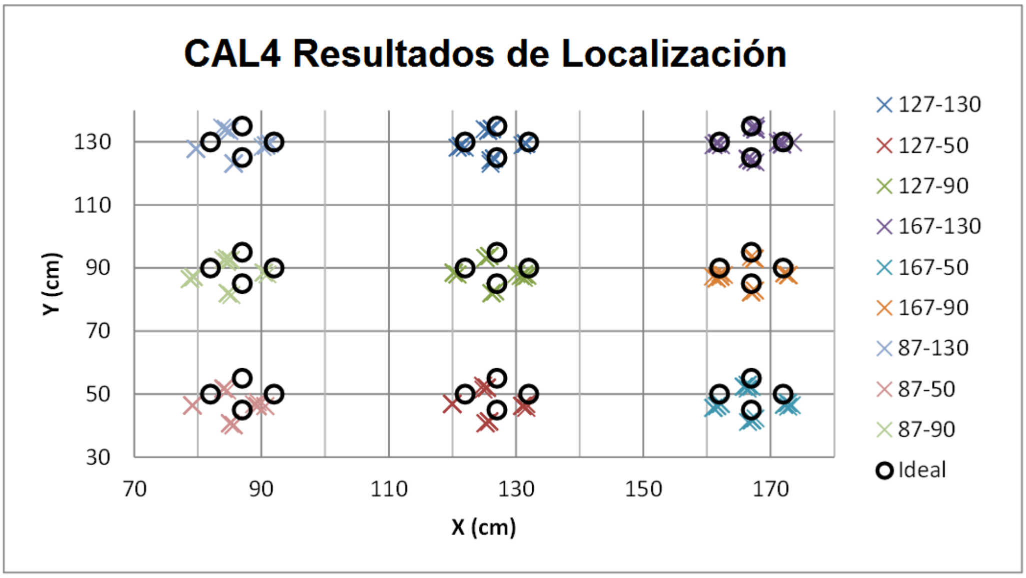
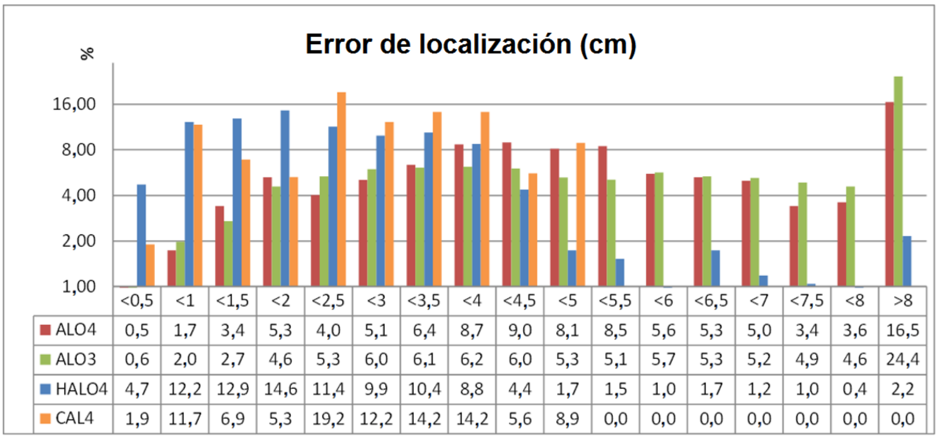


Fig. 7–10: CAL4 resultados de localización

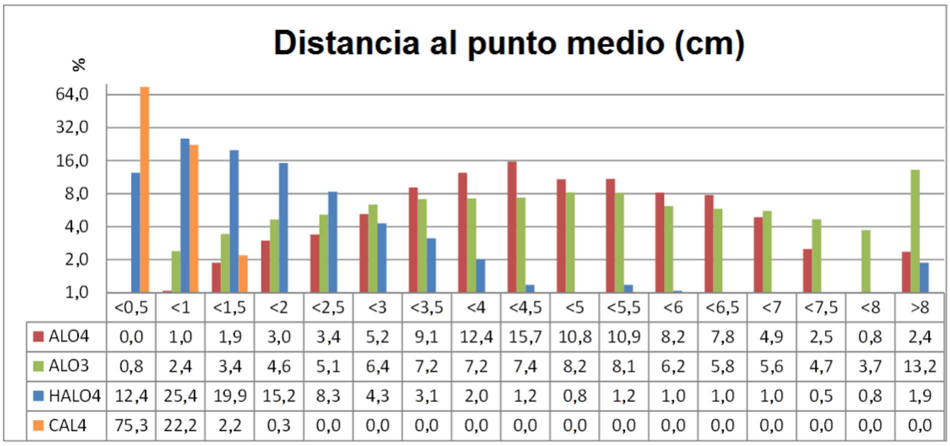
En base a estos resultados, los errores respecto a la posición ideal del objeto para cada uno de los diferentes algoritmos se muestra en el histograma de la Fig. 7–11.



	<0,5	<1	<1,5	<2	<2,5	<3	<3,5	<4	<4,5	<5	<5,5	<6	<6,5	<7	<7,5	<8	>8
ALO4	0,5	1,7	3,4	5,3	4,0	5,1	6,4	8,7	9,0	8,1	8,5	5,6	5,3	5,0	3,4	3,6	16,5
ALO3	0,6	2,0	2,7	4,6	5,3	6,0	6,1	6,2	6,0	5,3	5,1	5,7	5,3	5,2	4,9	4,6	24,4
HALO4	4,7	12,2	12,9	14,6	11,4	9,9	10,4	8,8	4,4	1,7	1,5	1,0	1,7	1,2	1,0	0,4	2,2
CAL4	1,9	11,7	6,9	5,3	19,2	12,2	14,2	14,2	5,6	8,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Fig. 7–11: Histograma con el error en la localización de los diferentes algoritmos

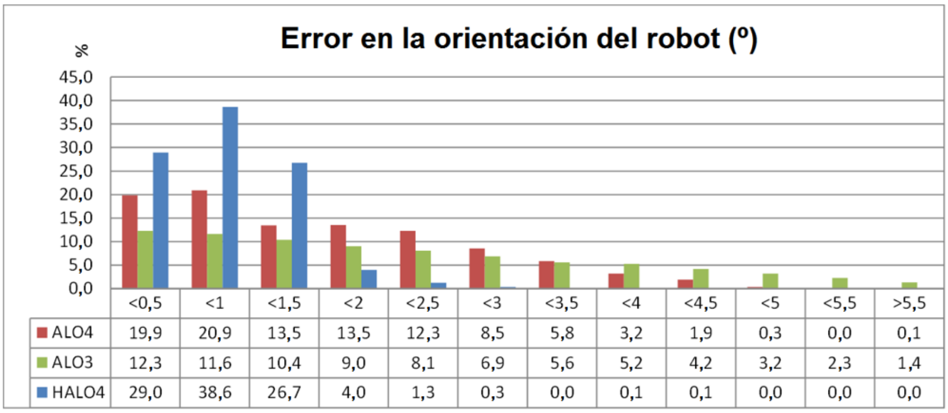
Como medida de dispersión de los resultados de localización obtenidos, se calculó el punto medio de las posiciones obtenidas y se midió el error respecto a estos puntos, obteniendo el histograma de la Fig. 7–12:



	<0,5	<1	<1,5	<2	<2,5	<3	<3,5	<4	<4,5	<5	<5,5	<6	<6,5	<7	<7,5	<8	>8
ALO4	0,0	1,0	1,9	3,0	3,4	5,2	9,1	12,4	15,7	10,8	10,9	8,2	7,8	4,9	2,5	0,8	2,4
ALO3	0,8	2,4	3,4	4,6	5,1	6,4	7,2	7,2	7,4	8,2	8,1	6,2	5,8	5,6	4,7	3,7	13,2
HALO4	12,4	25,4	19,9	15,2	8,3	4,3	3,1	2,0	1,2	0,8	1,2	1,0	1,0	1,0	0,5	0,8	1,9
CAL4	75,3	22,2	2,2	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Fig. 7–12: Histograma con las distancias al punto medio de las posiciones obtenidas por los diferentes algoritmos

Analizando la precisión del sistema de orientación de los diferentes algoritmos, se obtiene el histograma de la Fig. 7–13 (al no proporcionar el sistema CAL4 la orientación del sistema, este no aparece reflejado en el histograma).



	<0,5	<1	<1,5	<2	<2,5	<3	<3,5	<4	<4,5	<5	<5,5	>5,5
ALO4	19,9	20,9	13,5	13,5	12,3	8,5	5,8	3,2	1,9	0,3	0,0	0,1
ALO3	12,3	11,6	10,4	9,0	8,1	6,9	5,6	5,2	4,2	3,2	2,3	1,4
HALO4	29,0	38,6	26,7	4,0	1,3	0,3	0,0	0,1	0,1	0,0	0,0	0,0

Fig. 7–13: Histograma con el error en la orientación obtenida por los diferentes algoritmos

7.2. Análisis de Resultados

En este apartado se analizarán todas las versiones del sistema ALO recopiladas en esta tesis, presentando los pros y contras de cada una de ellas. Además se comparan sus prestaciones respecto un sistema TOA [1], ajeno a la presente tesis, desarrollado por el mismo grupo de investigación.

Nota: El sistema TOA [1] se basa en utilizar ultrasonidos como señal de referencia, y radiofrecuencia para garantizar el sincronismo entre transmisores y receptores.

La Tabla 2 presenta, a modo resumen, las características y prestaciones de los sistemas presentados en esta tesis doctoral.

Nota: El error de localización y orientación definido en esta tabla es el que se corresponde con los resultados mostrados en el apartado 0, a excepción de los presentados para el sistema TOA [1], los cuales han sido extraídos del artículo en donde se define el sistema (en un entorno parecido al del resto de sistemas).

Tabla 2: Resumen de características y prestaciones

Sistema	Nº TX	Nº RX	Error localización	Error Orientación	Pros	Contras
TOA [1]	2	1	Media: 2,00cm Desv. Std.: 1,34cm Max: 7,25cm	Media: - Desv. Std.: - Max: -	Demanda computacional reducida. Alta precisión.	Requiere sincronizar transmisores y receptores. No proporciona la orientación del nodo.
ALO (ALO3) Capítulo 2	2	3	Media: 5,89cm Desv. Std.: 3,30cm Max: 20,89cm	Media: 3,34º Desv. Std.: 3,02º Max: 16,27º	Demanda computacional reducida.	Muy baja precisión.
ALO4 Capítulo 3	2	4	Media: 5,18cm Desv. Std.: 2,51cm Max: 13,03cm	Media: 1,53º Desv. Std.: 1,09º Max: 5,88º	Demanda computacional reducida.	Baja precisión.
HALO4 Capítulo 5	3	4	Media: 2,65cm Desv. Std.: 1,99cm Max: 23,77cm	Media: 0,80º Desv. Std.: 0,48º Max: 4,02º	Alta precisión. Sistema inmune a la velocidad de propagación de la señal de referencia.	Alta demanda computacional. Presenta problemas de precisión frente a *outlayers*.
CAL4 Capítulo 6	4	1	Media: 2,30cm Desv. Std.: 1,22cm Max: 4,96cm	Media: - Desv. Std.: - Max: -	Alta precisión. Fácil implementación en el nodo. Demanda computacional reducida (además, no requiere eliminar el error de offset).	No proporciona la orientación del nodo. Difícil despliegue de los transmisores para garantizar la cobertura.

Si tomamos como referencia el sistema TOA [1], debido a que tradicionalmente este tipo de sistemas han permitido alcanzar mayores precisiones que los sistema DOA y DTOA, únicamente los sistemas HALO4 y CAL4 logran obtener precisiones parecidas a las logradas por este sistema, mientras que los sistemas ALO3 y ALO4 obtienen una error en la localización cercano al doble que el presente en los anteriores sistemas.

El principal punto negativo del sistema CAL4 es su alta demanda de transmisores para poder proporcionar la posición del objeto, lo que dificulta el despliegue del sistema. Sin embargo, el sólo demandar un receptor en el nodo y no requerir una alta capacidad de computación para implementar el algoritmo de posicionamiento, posibilita proporcionar capacidades de navegación a pequeños robots autónomos.

Por otro lado, el sistema HALO4 tiene como punto a favor la capacidad de proporcionar la orientación del objeto y de ser inmune a la velocidad de propagación de la señal de referencia, lo que simplifica enormemente el proceso de calibrado tras el despliegue del sistema. Como contrapartida tenemos que el sistema demanda una alta capacidad computacional para poder proporcionar la posición y orientación del nodo, lo que dificulta su uso en robots autónomos de bajo coste.

El algoritmo ALO4 presenta peores prestaciones que las arrojadas por el sistema HALO4 pero demanda un coste computacional mucho menor utilizando el mismo hardware que el sistema HALO4. Esto hace que este sistema sea idóneo como primera aproximación para conocer la posición y orientación del objeto. Dicha posición puede ser utilizada directamente (en caso de que el sistema no requiera mucha precisión para la región por la que se mueve el robot) o como punto de partida del sistema HALO4 con el fin de minimizar el número de iteraciones requeridas por el sistema para obtener la posición y orientación del objeto.

Por último, pese a que el sistema ALO3 es el que peores prestaciones ofrece, el hecho de sólo requerir 3 receptores para poder obtener la posición y orientación del objeto hacen que sea un sistema a considerar para aumentar la fiabilidad del conjunto: Un sistema ALO4 / HALO4 podría tener en memoria una variación del algoritmo de posicionamiento / orientación para que en caso de que uno de los receptores se estropease, permitir retornar al robot a una posición conocida en donde repararlo.

7.3. Conclusiones

La solución propuesta en la presente tesis permite desarrollar nodos que:

- Obtienen su posición y orientación dentro de un edificio.
- No necesitan recurrir a una unidad de procesamiento ajena al propio nodo para poder implementar el algoritmo de posicionamiento y orientación.
- Permite alcanzar prestaciones equivalentes a las ofrecidas por los sistemas TOA, sin necesitar sincronizar los transmisores con los receptores (una de las principales limitaciones de estos sistemas).

Las diferentes versiones del sistema ALO presentadas permiten al usuario utilizar la que más se adecue a las necesidades de su proyecto, desde crear robots con una alta capacidad computacional y altos requisitos de precisión, a proporcionar las bases del sistema de navegación a pequeños robots de bajo coste. De entre las soluciones propuestas, cabe destacar dos de ellas:

- El sistema CAL4 proporciona una precisión equivalente a la ofrecida por los sistemas TOA con unos requisitos en el nodo móvil muy parecidos a los demandados por estos sistemas. Su principal limitación, la de demandar un mayor número de transmisores para poder localizar al objeto, debería mitigarse al implementar encoders en las ruedas del robot (algo imprescindible en cualquier sistema de localización actual), por lo que el nodo podría recurrir a esta información en las regiones en las que no tenga cobertura de los 4 transmisores.

- El sistema HALO4 también permite obtener una precisión equivalente a la proporcionada por los sistemas TOA. Además, el sistema reporta la orientación del objeto junto con la posición del mismo, lo que aumenta las capacidades de navegación del nodo en el que se implemente este sistema. El principal inconveniente de este sistema es que demanda una alta capacidad computacional.

Del resto de sistemas propuestos, el sistema ALO4 permite proporcionar la posición y orientación del objeto, utilizando el mismo hardware que el sistema HALO4, demandando un menor coste computacional pero con una menor precisión. Esto hace que este sistema sea el idóneo cuando el nodo no dispone de la capacidad computacional requerida por el sistema HALO4, o cuando la los requisitos de precisión del entorno no son tan exigentes.

Por último, el sistema ALO3 permite proporcionar un sistema de localización que permite seguir funcionando al robot cuando uno de los receptores del sistema ALO4 / HALO4 falla, a costa de incrementar el error en la posición y orientación del nodo.

7.4. Referencias

[1] A. Sanchez, S. Elvira, A. de Castro, G. Glez-de-Rivera, R. Ribalda, and J. Garrido, Low cost indoor ultrasonic positioning implemented in FPGA, Proceedings of the 35th Annual Conference of IEEE in Industrial Electronics, IECON (2009) 2709-2714.

8. Conclusiones y Trabajo Futuro

8.1. Conclusiones

La presente tesis presenta un sistema de localización y orientación para interiores basado en una aproximación DOA, mostrando diferentes versiones del sistema, cada una de ellas con sus propias características y prestaciones.

De los sistemas presentados, destacan dos de ellos (los sistemas CAL4 y HALO4). El uso del resto de sistemas se restringe a sistemas auxiliares del sistema HALO4:

- ALO3 permite proporcionar la posición y orientación de un objeto utilizando tres receptores con una baja precisión. Esto hace que su uso sólo se recomiende como sistema de prevención para considerar el caso de que uno de los receptores del sistema HALO4 falle, permitiendo al nodo seguir funcionando para retornar a una posición conocida en donde repararlo.
- ALO4 permite obtener la posición y orientación de un objeto utilizando el mismo hardware que el sistema HALO4 pero con un menor coste computacional. Debido a que su precisión dista de la alcanzada por el sistema HALO4, su uso debería restringirse a cuando el nodo no dispone de la suficiente capacidad computacional para implementar el sistema HALO4, cuando la demanda de precisión del entorno no es muy elevada o como sistema de inicialización del sistema HALO4 (con el fin de reducir el proceso iterativo utilizado para obtener la posición del objeto).

De entre los sistemas destacados, no hay ninguno que ofrezca unas prestaciones superiores a las del resto, ya que la mejora en la precisión ofrecida por ellos viene ligada a una limitación en su uso, lo cual hace que no puedan imponerse en todas las situaciones:

- HALO4 permite conocer la posición y orientación de un objeto situando en el objeto 4 receptores y necesitando línea de visión directa respecto a 2 transmisores. La precisión proporcionada por este sistema es semejante a la obtenida por los sistemas TOA y permite obtener junto con la posición del objeto su orientación, a costa de demandar una mayor capacidad computacional que los sistemas TOA.
- CAL4 requiere que el objeto se equipe con sólo un receptor y que exista línea de visión directa respecto a 4 transmisores. Proporciona una precisión similar a la obtenida por HALO4 pero demanda una menor capacidad computacional (equivalente a los sistemas TOA). Este sistema no proporciona la orientación del objeto y dificulta el despliegue de los transmisores, al demandar una alta sincronización entre ellos y que deba existir una cobertura de 4 transmisores (en vez de 2) en todo momento para poder proporcionar la posición del objeto.

Pese a las limitaciones ofrecidas por los sistemas aquí propuestos, el hecho de que no deba existir sincronización entre transmisores y receptores reduce la complejidad del sistema respecto a los sistemas TOA, eliminando la necesidad del uso de dispositivos de radiofrecuencia o de relojes precisos para alcanzar dicho sincronismo, lo que hace que estos sistemas sean una buena solución para implementar las bases de un sistema de navegación para interiores.

8.2. Trabajo Futuro

Tras los resultados obtenidos por los diferentes sistemas recogidos en la presente tesis, las líneas de investigación recogidas en este apartado podrían iniciarse con el fin de aumentar las prestaciones del sistema.

8.2.1. HALO4 demanda computacional

El principal inconveniente del sistema HALO4 es su alta demanda computacional. Esta demanda viene definida por el algoritmo de minimización necesario para resolver la ecuación matemática utilizada para obtener la posición del objeto.

Si dicha ecuación se consiguiese resolver de forma que no se necesitase este proceso de minimización, la demanda computacional del sistema se reduciría considerablemente, haciendo el sistema accesible para robots basados en microprocesadores de bajo coste.

Otra posible solución a este problema sería combinar diferentes sensores para trazar el movimiento del robot por el entorno. El sistema de minimización propuesto no considera la posición previa del objeto ni cuánto ni en qué dirección se ha movido el robot, por lo que si dispusiese de esta información, el número de iteraciones requeridas por el algoritmo podría reducirse considerablemente, reduciendo la demanda computacional del sistema.

Por último, el sistema podría cargar, como posición inicial del sistema de minimización, la posición proporcionada por el sistema ALO4 (el cual demanda el mismo hardware que el sistema HALO4). Esta posición, pese a tener un error elevado, está próxima a la posición real del sistema, por lo que dicha información podría servir para minimizar el número de iteraciones demandas por el algoritmo de minimización utilizado por el sistema HALO4.

8.2.2. CAL4 error de offset

La principal fuente de error de este sistema es que al utilizar dispositivos resonantes de ultrasonidos, el sistema es incapaz de determinar una marca de referencia en las señales generadas por los transmisores de forma precisa. Esto se traduce en que el sistema tiende a cometer errores múltiplos del periodo de la señal de ultrasonidos en el tiempo medido cuando el nodo está más cerca de un transmisor que de otro. Si se eliminase este problema, el sistema mejoraría enormemente su precisión, llegando a proporcionar precisiones del orden de milímetros.

Para lograr este objetivo, se debería valorar sustituir el uso de dispositivos resonantes por micrófonos y altavoces de ultrasonidos, con los cuales ser capaces de modular de forma eficaz un patrón en la señal de ultrasonidos que permita medir con precisión la diferencia del tiempo de vuelo de la señal de ultrasonidos sin introducir ningún error de offset.

8.2.3. Robot en movimiento

Las soluciones planteadas en esta tesis siempre consideran que el robot está parado mientras captura las medidas respecto a los transmisores. Esto hace que el sistema sea poco útil, ya que lo más común cuando más se requiere que el sistema de localización y orientación sean precisos es cuando el objeto se esté desplazando.

Para solucionar este problema, sería recomendable el uso de micrófonos y altavoces de ultrasonidos con los cuales se permita transmitir y recibir de forma simultánea las señales de referencia utilizadas por los diferentes transmisores, aproximación que eliminaría este error introducido debido a que el nodo esté en movimiento.

8.2.4. Uso de radiofrecuencia

Pese a que la tecnología basada en ultrasonidos permite obtener una alta precisión al posibilitar estimar el tiempo de vuelo de la señal de forma sencilla y con una alta resolución, su uso en dispositivos comerciales es bastante limitado debido al escaso alcance que proporcionan (menor que la decena de metros) y a que la señal no atraviesa obstáculos como paredes o puertas.

Esta limitación hace que sea necesario desplegar un gran número de transmisores en el entorno, lo cual constriñe en gran medida su uso en entornos industriales y lo excluye del ámbito doméstico.

Para eliminar este inconveniente, se debería valorar la precisión obtenida al utilizar dispositivos basados en radiofrecuencia. Las señales de radiofrecuencia no tienen las limitaciones de las señales acústicas, pero requieren de un sistema de procesamiento de señal mucho más complejo que podría hacer que la precisión del sistema no fuese muy elevada.