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STUDY OF THE OPTIONS FOR IMPLEMENTING SAFE NON-CONTACT INTERACTIONS BETWEEN SERVICE ROBOTS AND PATIENTS WITH LIMITED MOBILITY

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Abstract

In this paper, we study the issues of developing a multimodal robotic system designed for automated patient monitoring in hospital wards. A significant portion of the time spent by junior medical staff in hospitals is devoted to delivering medications and fulfilling patients' requests, but also to monitor patient's condition. The primary objective of this project is to develop an autonomous platform capable of detecting and localizing critical patient events, such as coughing, respiratory distress, or physical movement under a blanket, without direct contact. To solve such problems, we have developed a sufficiently compact service tracked robot of the "AMUR" series service crawler equipped with a paired parallel manipulator. Our approach is to use this robot in a medical ward by supplementing the sensor system for AMUR with a simple Doppler system, combined with a microphone-based sound-direction-finding system, which makes it possible to assess the gestures of patients with limited mobility and respond to their needs more fully. To achieve this, we have developed a novel multimodal sensor fusion architecture that combines a 4-channel acoustic Time Difference of Arrival (TDoA) array with a 10 GHz Doppler motion sensor. Scenario is as follows: collaborative service robot enters the ward, stops (turns off the motors to eliminate acoustic noise), Microwave Doppler radar detects the patient's movement in the bed (even under the blanket!) and, as soon as the patient calls for help or coughs, the tilt-and-rotate device, using the azimuth received from the sensor, turns the robot directly towards the person, estimating the distance based on the curvature of the wavefront. By using a radio channel information is transferred to the Nurse on duty.

Keywords: mobile service robot for medical facilities; virtual prototyping; robot digital twin; acoustic and Doppler sensors.

1. Introduction

The primary objective of this project is to develop an autonomous platform capable of detecting and localizing critical patient events, such as coughing, respiratory distress, or physical movement under a blanket, without direct contact. We are in progress to solve such problems using a sufficiently compact service tracked robot of the "AMUR" series service crawler robot equipped with a paired parallel manipulator (Fig.1). The key features of such mobile robots [MR] are as follows: the size of the mobile platform at a weight of 11kg is 600x600x300mm; ground clearance is

190mm; distance between the manipulators is 400mm; the height of simultaneous lifting of the 2 grips of the manipulator range from 1050mm to -200mm; the built-in pallet for transporting the captured objects is 350x450mm []. Large objects weighing up to 55N must be grasped by the MR using both grippers, while small objects require only one of the grippers, designed for either compliant or rigid objects. The maximum traction force is approximately 70–90N, depending on the supporting surface. Accordingly, the mobile robot has an ability to climb inclined surfaces up to 25 degrees. The developed methodology for rapid prototyping and replication of various modifications of such MRs is based on laser and additive devices, the widespread use of mass-produced components, and the most readily available components and microprocessors []. The sensor equipment varies depending on the application scenarios: MR is used to handle transport and logistics functions, assist and establish contact with patients, and conduct room inspections/patrols with the possibility of accessing the facility's courtyard, etc. Considerations included MR navigation using AR-code navigation, identification of doors and door handles (based on data from the visual system), and the use of lidar and/or ultrasonic sensors to avoid obstacles []. A recognition system for limited set of voice commands and synthesizing of brief responses has been tested. The above indicates the MR's intentions and its understanding of the commands. All the described sensory and control systems were fundamentally built using a most simplified microprocessor-based calculators and local neural networks.

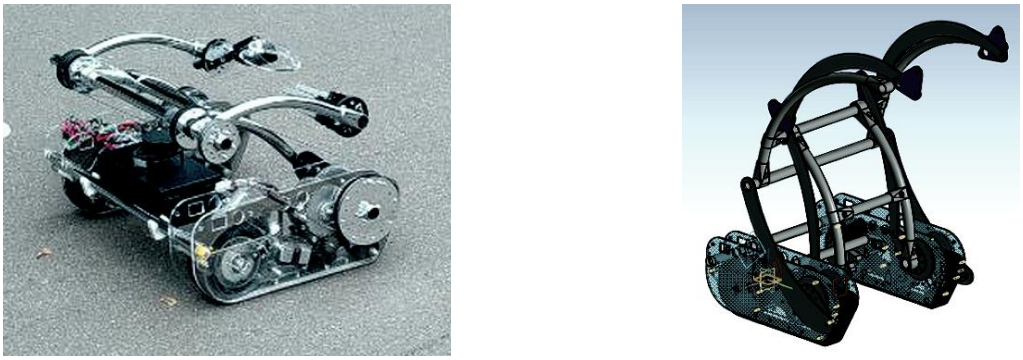


Fig. 1. Model of the Amur service robot with a paired parallel manipulator and its digital twin

2. Physics of the scenario

- Collaborative service robot AMUR enters the ward, stops (turns off the motors to eliminate acoustic noise),
- Microwave Doppler radar detects the patient's movement in the bed (even under the blanket!) and, as soon as the patient calls for help or coughs, the tilt-and-rotate device, using the azimuth received from the sensor, turns the robot directly towards the person, estimating the distance based on the curvature of the wavefront.
- By using a radio channel information is transferred to the Nurse on duty.



Fig.2. Collaborative service robot AMUR equipped with Microwave Doppler radar for motion detection and 4 microphones array direction finder

3. Data fusion sensor system description

From a hardware perspective (Fig.3), the system is driven by a LilyGO ESP32-S3 microcontroller. The acoustic front-end consists of four horn-loaded electret microphones digitized via two dual-channel PCM1808 I2S Analog-to digital converters, ensuring strict phase synchronization. To prevent signal distortion of the low-frequency Doppler shifts by the audio chip's internal high-pass filters, the Doppler sensor is routed directly to the MCU's internal SAR ADC (Successive-Approximation Register Analog-to-Digital Converter). Telemetry and alerts are transmitted to medical staff using an integrated LoRa 868 MHz transceiver. To maintain mobility through tight hospital spaces while providing a

wide baseline for spatial accuracy, the sensors are mounted on a custom deployable scissor-mechanism linkage array inspired by a traditional 5-blade fan structure. This allows the system to remain compact during transit and expand only when monitoring is initiated. The deployable scissor-mechanism array is integrated onto an Autonomous Mobile Robot (AMUR) platform. While the robot navigates the hospital ward, the mechanism remains folded to ensure mobility through tight spaces. Once the robot reaches the designated monitoring position near the patient's bed, the servo motor deploys the 5-blade array to establish a wide acoustic baseline and initiate multimodal tracking.

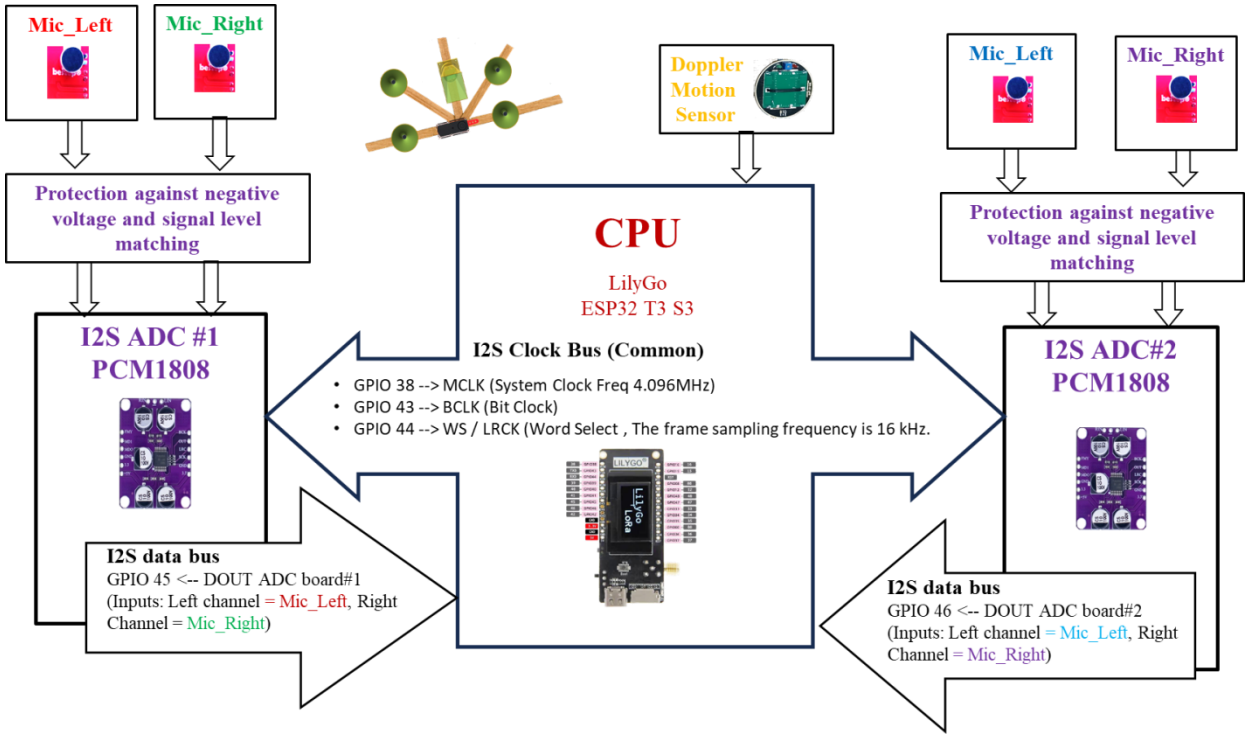
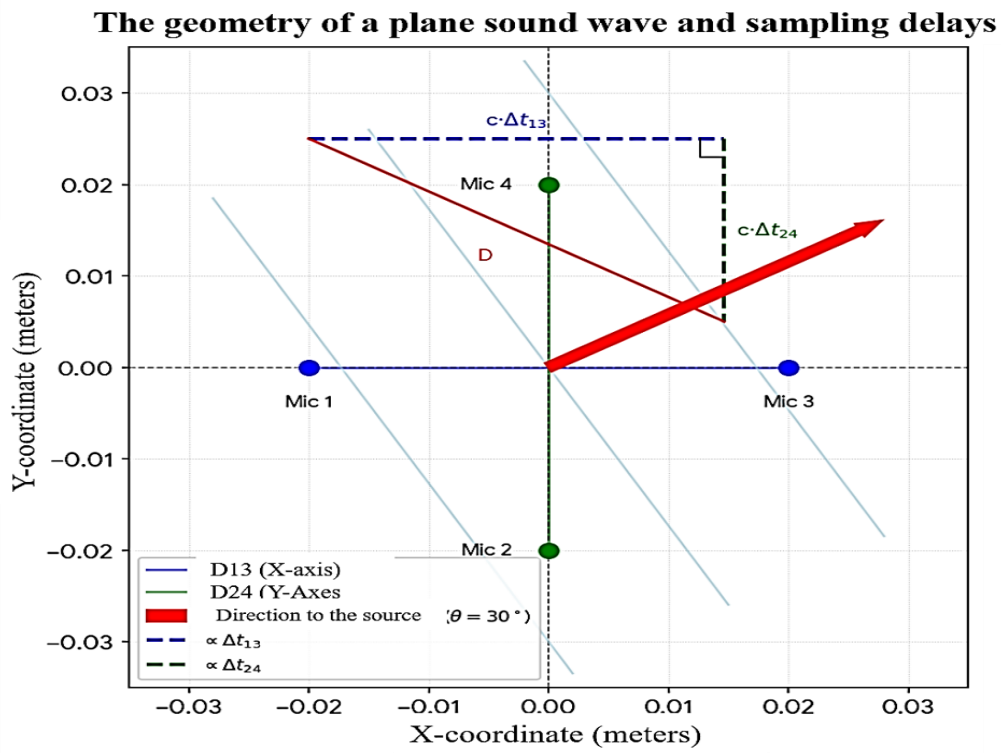


Fig. 3. Functional diagram of the motion direction finder and sound source direction-finding system.

Principle of Operation & Sensor Configuration

The core localization technique is based on the Time Difference of Arrival (TDoA) method.
Microphone Array Geometry:
The system features 4 electret microphone modules equipped with acoustic horns, mounted on the blades of an automatically deploying fan mechanism.
Spatial Tracking: Rather than calculating absolute 2D/3D coordinates via hyperbolic intersection (near-field model), the system utilizes a plane-wave approximation (far-field model). This is due to the baseline distance between microphones (D = 33.3cm) being significantly smaller than the distance to the acoustic source (the patient).
Therefore, the array acts as an acoustic direction finder, computing the precise AoA (Angle of Arrival / Azimuth θ of the sound source. See Fig.4.



Fig, 4. Spatial Coordinate, X (m) / Spatial Coordinate, Y (m) Incident Plane Wavefront (Cough/Acoustic Event) Direction of Arrival (DoA) Vector / Propagation Path Array Diagonal 1-3 (D_{13}) and Array Diagonal 2-4 (D_{24}) Spatial Path Difference $\Delta d_{13} = c \cdot \Delta t_{13}$

Mathematical method of calculation: Digitization

The DMA (Direct Memory Access) buffer receives a parallel 32-bit stereo stream. The data is normalized by dividing by the maximum measuring amplitude 2^{31}(2147483648.0)
Mutual cross-correlation (TDoA): The search for time delays Δt_X and Δt_Y is carried out by discrete integration of the signal product in a sliding window of lags from -12 to +12 samples. Sub-sample accuracy is achieved by parabolic interpolation of the peak using the Knapp–Carter method based on three points.[4].
Azimuth (Angle): The direction cosines of the wavefront are calculated as the ratio of the difference in the sound path to the base of the scissor-mechanism array.

$$d = 0.333 \text{ м}: \quad cos(\alpha) = \frac{\Delta t_X \cdot C}{d} \; : \; cos(\beta) = \frac{\Delta t_Y \cdot C}{d}$$

The final circular azimuth is determined using the four-quadrant arctangent function atan2(cos_beta, cos_alpha).
Distance (Range): Assessed by the curvature of the spherical front (Fresnel approximation) via the difference in projection delays:

$$R = \frac{d^2}{2 \cdot C \cdot |\Delta t_X - \Delta t_Y|}$$

If the object is infinitely far away, the delays are equal, and $R \to \infty$ (plane wave).

Step-by-Step Time Delay of Arrival (TDoA) Calculation Flow

Step 1: Signal Acquisition & Time Delay Estimation
Four audio channels are sampled synchronously via I2S.
When a sudden acoustic event (e.g., a cough) occurs, the absolute time delays between opposing microphone pairs on the fan diagonals are computed using the Generalized Cross-Correlation with Phase Transform (GCC-PHAT) algorithm:

$$\Delta t_{1\text{-}3} = t_3 - t_1$$
$$\Delta t_{2\text{-}4} = t_4 - t_2$$

Step 2: Conversion to Spatial Path Difference Using the constant speed of sound ($c \approx 343$ m/s 20∘C), the time differences are translated into physical path differences:

$$\Delta d_{1=3} = \Delta t_{1=3} \cdot c$$
$$\Delta d_{2=4} = \Delta t_{2=4} \cdot c$$

Step 3: Resolving the Angle of Arrival (AoA) The geometrical projections of the incoming plane wave along the array diagonals relate to the true azimuth angle θ as follows:

$$\Delta d_{13} = D \cdot \cos(\theta)$$
$$\Delta d_{24} = D \cdot \sin(\theta)$$

To eliminate quadrant ambiguity across a full 360° plane, the exact direction is resolved using the two-argument arctangent function:

$$\theta = \text{atan2}\,(\Delta d_{24}, \Delta d_{13}) = \text{atan2}\,(\Delta t_{24}, \Delta t_{13})$$

Hardware Architecture & Signal Chain



- Microcontroller Unit (MCU): LilyGO T3S3 (powered by an ESP32-S3 dual-core processor).
- Audio Digitization: Two dual-channel PCM1808 (or similar) stereo ADCs connected via the I2S (Inter-IC Sound) protocol, ensuring tightly synchronized, multi-channel audio sampling.
- Front-End Protection: The electret microphone amplifier outputs are routed through Schottky diodes to clamp negative voltage spikes, protecting the ADC inputs from clipping and electrical damage.
- Multimodal Sensor Fusion: A 10 GHz Doppler radar module with a directional horn is mounted on the central blade to detect micromovements (chest wall movement, shifting under blankets), complementing the acoustic TDoA array.
- Telemetry: Data dissemination to medical staff is handled via an integrated LoRa 868 MHz long-range transceiver.

Physical Advantages of the Horn-Loaded Array

- Standard Time Delay of Arrival (TDoA) relies on omnidirectional microphones, which suffer in highly reverberant environments (like hospital rooms). Integrating acoustic horns solves two critical issues:
- Multipath Rejection (Eco Suppression): The directional horns attenuate acoustic reflections coming from the floor, ceiling, or walls. The microphones primarily capture the direct-path line-of-sight (LOS) signal, keeping the cross-correlation sharp and error-free.
- Spatial Masking & Validation: Sound originating from behind a horn is significantly attenuated. This creates an amplitude disparity that acts as a validation layer: if the calculated TDoA indicates a forward-facing angle, but the rear microphone registers a highly dampened amplitude, the algorithm can flag and reject the reading as a false positive reflection.

What can be seen when demonstrating the operation of the system mock-up

For programming the LilyGo T3S3 microprocessor we are using an ARDUINO IDE 1.8.19 portable version. The processor has an embedded OLED display, which we programmed to display the direction, azimuth and distance measured in real time. We can also display live results on the monitor or plotter of Arduino IDE
On the Plotter: If the sound source is located at distance of 1 meter, the green line on the plotter will be fixed at around the 50 marks. If to move back 2 meters, the line will rise to the 100 marks. Blue and red lines on the plotter are differential signals between the cross-microphone pairs (see Fig.5.).
On the OLED screen: the direction vector is dynamic. The dynamic radius variable is configured so that when the sound source approaches the loudspeakers, the vector line on the screen will gradually lengthen, reaching the edges of the circle. When the source moves far into the room, the vector contracts to the central point, indicating that the target has moved away. Display also reflects range and azimuth on the screen in digits. However not very clear yet.

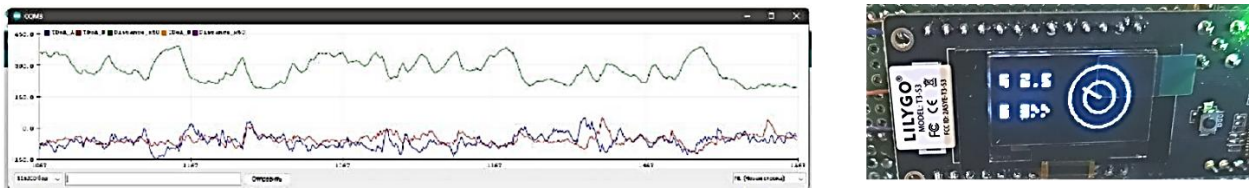


Fig. 5. Arduino IDE plotter and OLED display of the LilyGo T3S3 processor.

Evolution of the Project & Future research plans

We started our project from interfacing three I2S MEMS INMP441 microphones with analog-to digital converter onboard to the two maximum possible I2S interfaces of the LilyGoT3S3 microcontroller. Because I2S is a stereo-pair standard, first two microphones did have equal amplitude, however the third microphone taken alone from the second stereo pair degraded essentially and we were unable to compare time delays in such configuration. Besides, three microphones provide only 2D direction finding without horns. Our next step was using four same microphones, which were working satisfactory, but we could not separate microphones to a distance longer than 5.6cm because of the common synchronization signals of I2S protocol. Then we decided to implement two analog-to-digital boards namely PCM1808 ADC, which are also interfaced to a processor via I2S, but in this case we could apply analog electret microphones modules and separate them to at least 33cm. However, we again used three microphones and interfaced a Doppler motion detector sensor to a second input of the second ADC1808. This configuration worked, bur we again came back to a four- microphone configuration and interfaced Doppler sensor to a normal pin of the processor due to a very low frequency of the Doppler signal. This is a configuration being described in this paper.
Future work foresees expansion of the Doppler motion detection of the patient by using 3 horned Doppler motion detectors at different physical frequencies: ultrasound 40KHz and two radio frequencies: 3.2GHz and 10.5GHz, Data fusion of such combination and implementation algorithms of fuzzy logic seems promising for us from the point of excluding false detections (Fig. 7).

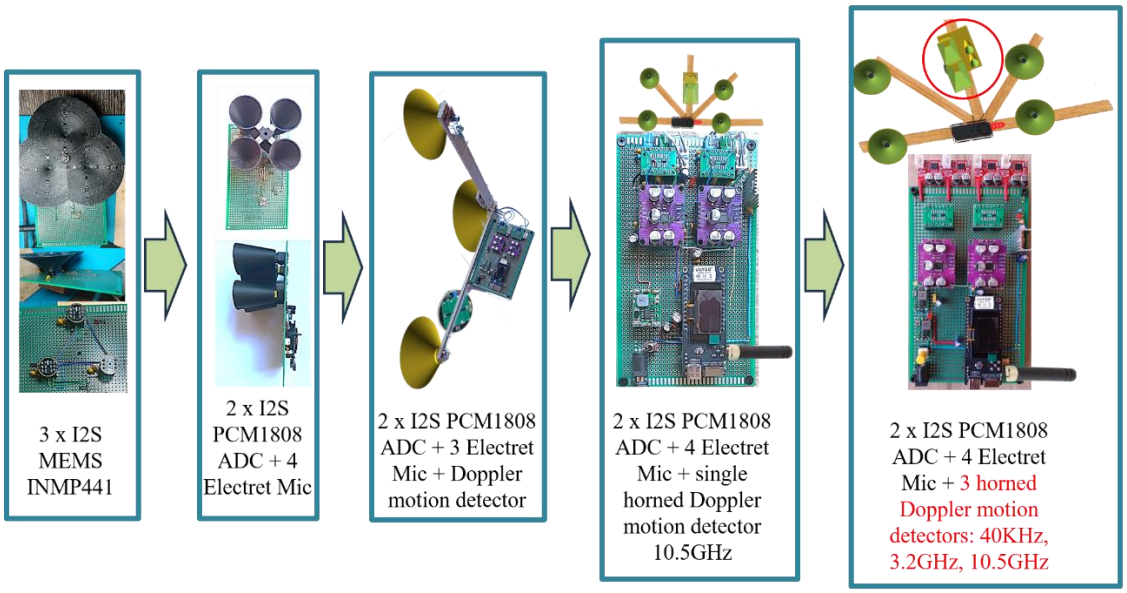


Fig. 7. Evolution of the Project & Future work of our motion detection and direction-finding project

5. Conclusion

- The proposed system introduces a practical approach to non-contact clinical monitoring. Our spatial localization algorithm successfully operates across two distinct physical domains.
- Within a range of up to 10 meters, the system leverages wavefront curvature (the spherical wave model) via cross-shaped orthogonal microphone pairs to estimate both the direction and the absolute distance to the patient. Beyond this 10-meter threshold, the system seamlessly transitions to a planar far-field approximation to resolve the azimuth angle.
- A cornerstone operational feature of our platform is the Acoustic Silence Protocol. To completely eliminate parasitic structural vibrations and ego-noise from the robot's drivetrains, all motors and actuators are completely powered down the moment the fan mechanism is fully deployed. This time-division approach ensures a pristine signal-to-noise ratio and prevents any interference with the sensitive GCC-PHAT cross-correlation and Doppler tracking.
- Currently, the core sensor array and its deployment mechanics have been successfully validated in our laboratory workshop.
- The next immediate step of this project is the physical integration of the deployed array onto the Autonomous Mobile Robot (AMUR) platform and subsequent field testing in a simulated clinical environment.

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