ULTRASONIC ARRAY SENSOR FOR INDOOR PRESENCE DETECTION

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ABSTRACT

Reliable detection of user presence is key in realizing energy-efficient occupancy-adaptive indoor lighting systems. We present an ultrasonic array sensor for reliable presence detection in indoor spaces. Short bursts of sinusoidal pulses are transmitted periodically from the sensor. The objective is to then determine presence of a user within the sensing region by processing the received echoes at the receiver array. Zones of movements are identified with coarse range and direction-of-arrival estimates using moving target indicator processing and conventional beamforming. Tracking is further applied on the resulting zone estimates to improve reliability of detection. Using a prototype implementation, we show that the proposed ultrasonic array sensor achieves better detection results compared to a state-of-art passive infrared sensor.

Index Terms— Ultrasonic array sensor, indoor presence detection

1. INTRODUCTION

Indoor lighting constitutes about a third of the electrical energy consumption in buildings [1]. Occupancy-adaptive lighting control, for e.g. keeping lighting on only when an office space is occupied by a user and turning off otherwise, brings about substantial energy savings. The reliable detection of users is key in these systems. A missed detection, leading to lights turning off while a user is in the office, causes considerable user inconvenience. A large number of false alarms on the other hand lead to lower energy savings. To enable more predictable lighting control behavior, reliable presence detection is required. Towards this end, we present an ultrasonic array sensor.

Passive infrared (PIR) sensors are commonly used as occupancy sensors in indoor spaces [2] but are known to suffer from poor detection performance. RF-Radar based techniques [3] are unsuitable for in-room presence detection due to through-wall propagation properties, while ultrawide-band radars [4] remain expensive. More complex camera sensors are attractive when analyzing people interactions and in surveillance applications [5], [6], but are expensive as presence detectors and moreover sensitive to varying indoor lighting conditions.

Our proposed ultrasonic array sensor comprises of a broad-beam transmitter and co-located array of receiver elements. Short bursts of sinusoidal pulses are periodically transmitted. This signal is reflected from the environment and the echoes are received at the receiver array. We are interested in low-complexity receiver processing algorithms to enable implementation on a low-cost micro-controller platform. Moving target indicator processing [7, Chapter 3] is first used to discriminate user movement given static objects within the sensing region. A difference signal is obtained by subtracting the echoes corresponding to consecutive transmission bursts. Since echoes due to static objects are almost identical, their contribution in the difference signal is close to zero. Echoes from a moving user, on the other hand, lead to a non-zero difference signal component. This is used for determining an initial zone with user movement, where the pair of group range and direction-of-arrival (DoA) define a zone. To keep the complexity low, we use a group range, which is a collection of consecutive ranges, and fixed conventional beamforming [8] in defining zones. The largest of the power values over the zones is then computed. If it exceeds a pre-determined threshold, an occupant is declared to be observed in the corresponding zone. To improve presence detection, a tracking algorithm is used. The premise of this tracking is that user motion follows temporal continuity, i.e. a future zone of a user is dependent on (and in the vicinity of) a current zone. Based on individual zone estimates, a tracking score is updated. We finally declare presence if the tracking score exceeds a certain threshold.

The combination of the proposed array sensor design and algorithmic blocks result in a reliable presence detector. We evaluate the detection performance of our sensor using different types of motion along the guidelines in [9], and benchmark with a commercial PIR sensor. We find that our sensor solution is substantially superior in detecting tiny and minor motion that are the common sources of missed detection and in turn user dissatisfaction with lighting systems.

2. ULTRASONIC ARRAY SENSOR

The designed ultrasonic array sensor has a broad-beam transmitter with center frequency f_c and a co-located linear array of M receiver elements, with half-wavelength inter-element separation. A prototype implementation is depicted in Fig. 1. The use of a transmitter with broad-beam radiation pattern ensures a sufficiently large sensing region and limiting array processing to the receiver side allows reuse of commercially available sensor components. An array at $f_c = 40$ kHz with half-wavelength inter-element spacing of ≈ 4.3 mm is feasible using commercially available components due to their dimensions at the receiver side, but not at the transmitter side. The sensor is installed in the ceiling, typically centrally and away from obvious obstructions, in order to monitor presence in an office space. Localized presence sensing with an ultrasonic array sensor installed in a wall-mounted configuration was considered in [10]. Note that the sensor installation-configuration influences the view of an object observed by the sensor.

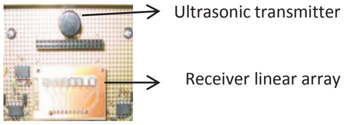

Fig. 1: Prototype of ultrasonic array sensor.

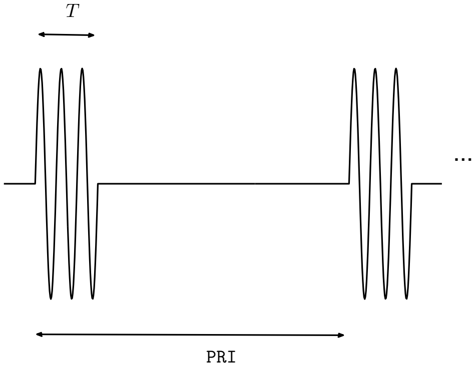

Fig. 2: Transmitted waveform.

The transmitted waveform, depicted in Fig. 2, is a burst of sinusoidal pulses of duration T and pulse repetition interval of `PRI`. The duration T should be small enough to allow for sufficient spatial resolution. The period `PRI` should be chosen large enough so as to receive all echoes from within the sensing region.

The transmitted signal is reflected from various objects within the sensing region resulting in echoes at the receiver array. We now describe the algorithmic blocks at the receiver side to determine user presence. The algorithm design choices are made with a view towards a low complexity implementation, as compared to the more complex processing techniques described in [10].

3. RECEIVER ARRAY PROCESSING

At each receiver element, we obtain a difference signal by subtracting the received echoes corresponding to consecutive transmitted bursts. Zones are defined as pairs of group range and DoA, and the power values in each zone using the difference signal at zero frequency is computed. A zone with observed movement is identified as one that has the largest power exceeding a pre-defined threshold. Finally, a tracking algorithm provides a score, related to the confidence of user movement in a zone, using which presence detection is decided.

3.1. Moving target indicator processing for movement detection in zones

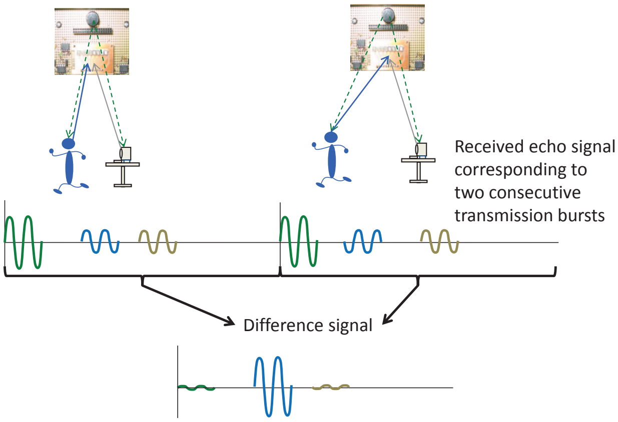

Fig. 3: Illustration showing difference signal obtained by taking difference of received echo signals corresponding to consecutive transmission bursts with a static object and moving user in the sensing region.

Let $u_m^{(k)}\left(\tilde{t}\right)$ be the received signal at the m-th receiver at time $\left(k\mathtt{PRI} + \tilde{t}\right)$ where $\tilde{t}$ is the relative time with respect to the beginning of the pulse during the k-th transmission burst. Note that any echo coming from a static object is the same for any two consecutive signals $u_m^{(k-1)}\left(\tilde{t}\right)$ and $u_m^{(k)}\left(\tilde{t}\right)$. Thus, if we subtract both signals, then only those echoes coming from moving objects remain [7], [10] (see Fig. 3).

We calculate the difference signal $\Delta u_m^{(k)}\left(\tilde{t}\right)$ as

$$\Delta u_m^{(k)}\left(\tilde{t}\right) = u_m^{(k)}\left(\tilde{t}\right) - u_m^{(k-1)}\left(\tilde{t}\right).$$

The difference signal $\Delta u_m^{(k)}\left(\tilde{t}\right)$ is at frequency f_c and is continuous, so we need to preprocess it. The preprocessing comprises digitizing, filtering and down-mixing the signal to zero frequency. Let the sampling rate for digitizing the signal be f_s and the number of samples over which the signal is filtered be Γ. We will refer to each filtered group of samples as a range $\rho = 1, \ldots, R$, where

$$R = \left\lfloor \frac{\texttt{PRI}.f_s}{\Gamma} \right\rfloor$$

is the total number of ranges.

The down-mixed and filtered signal at range ρ is denoted by vector

$$\hat{\boldsymbol{u}}^{(k)}(\rho) = \left[\hat{u}_1^{(k)}(\rho), \quad \hat{u}_2^{(k)}(\rho), \quad \ldots, \quad \hat{u}_M^{(k)}(\rho)\right]^T,$$

where

$$\hat{u}_m^{(k)}(\rho) = \frac{1}{\Gamma} \sum_{\nu=(\rho-1)\Gamma+1}^{\rho\Gamma} \Delta u_m^{(k)}\left(\frac{\nu}{f_s}\right) e^{-2\pi j \frac{\nu f_c}{f_s}}, \qquad m = 1, 2, \ldots, M, \ \rho = 1, 2, \ldots, R.$$

We implement a low complexity algorithm for range and DoA estimation. The array response matrix associated with a linear array of M receivers has M independent steering vectors. Thus, we can reduce complexity by monitoring M DoA angles, defined by the set

$$\mathcal{A} = \left\{\Theta_1, \ \Theta_2, \ \ldots, \ \Theta_M\right\},$$

with M discrete values for DoA where

$$\boldsymbol{a}(\Theta_q) = \left[1, \, e^{j\pi \sin(\Theta_q)}, \, \ldots, \, e^{j\pi(M-1)\sin(\Theta_q)}\right]^T$$

is the response of the linear array to a signal coming from angle Θ_q [11].

In order to further lower complexity, we combine P consecutive ranges into a single group range. Let the group range n comprise the ranges $[(n-1)P+1, nP]$. Hence, we have

$$N = \left\lceil \frac{R}{P} \right\rceil$$

group ranges.

We calculate the received power per group range n and angle Θ_q as

$$\Lambda^{(k)}(n, \Theta_q) = \sum_{\rho=(n-1)P+1}^{\min\{R, nP\}} \left| \boldsymbol{a}(\Theta_q)^H \hat{\boldsymbol{u}}^{(k)}(\rho) \right|^2. \tag{1}$$

The largest peak of (1) corresponds to the zone of the strongest echo (a possible occupant). Let the pair $\{n^\star, \Theta_{q^\star}\}$ be the zone with the largest received power. We calculate the signal-to-noise ratio (SNR) for this zone as

$$F^{(k)}(n^\star, \Theta_{q^\star}) = \frac{\Lambda^{(k)}(n^\star, \Theta_{q^\star})}{\sigma^2(n^\star, \Theta_{q^\star})}$$

where $\sigma^2(n^\star, \Theta_{q^\star})$ is the noise power level at zone $\{n^\star, \Theta_{q^\star}\}$. The noise power level is measured at periods when the room is unoccupied.

If the SNR is larger than a predefined threshold, C_d, i.e.

$$F^{(k)}(n^\star, \Theta_{q^\star}) \geq C_d, \tag{2}$$

then we declare observation of an occupant in the zone $\{n^\star, \Theta_{q^\star}\}$.

3.2. Tracking and detection rule

We implement a simple tracking algorithm to improve the performance of presence detection. We consider that an occupant's movement must satisfy some constraints on temporal motion continuity [12], i.e. the current zone of the occupant depends on the occupant's previous zone.

Hence, we assign to each zone $\{n, \Theta_q\}$ a score $\Psi_{n,q}$ to indicate the confidence that an occupant is present in zone $\{n, \Theta_q\}$ given its previous observed locations. This scores accumulates with each new observation from the occupant's zone.

Let $\boldsymbol{\Psi}^{(k)}$ be the matrix of size $N \times M$ with scores $\left\{\Psi_{n,q}^{(k)}\right\}$ during the k-th transmission. Each element in the score matrix $\boldsymbol{\Psi}^{(k)}$ depends on the previous score matrix $\boldsymbol{\Psi}^{(k-1)}$. We consider that if an occupant during current transmission k is observed at zone $\{n^\star, \Theta_{q^\star}\}$, then the likelihood that the same occupant during previous transmission $k-1$ was at a given zone decreases monotonically with distance. This is captured by the weighting function

$$\delta(n_i - n_j, \Theta_i - \Theta_j) = \begin{cases} 1, & \text{if } n_i - n_j = 0 \\ & \quad \text{and } \Theta_i - \Theta_j = 0 \\ 0.5, & \text{if } |n_i - n_j| \leq \alpha_1 \\ & \quad \text{and } |\Theta_i - \Theta_j| \leq \alpha_2 \\ 0, & \text{otherwise.} \end{cases}$$

which indicates the confidence that the occupant is observed at location $\{n_i, \Theta_i\}$ given that it was at location $\{n_j, \Theta_j\}$. The factors $\alpha_1 \geq 0$ and $\alpha_2 \geq 0$ are propagation factors. Hence, we update the element $\Psi_{n^\star, q^\star}^{(k)}$ as follows

$$\Psi_{n^\star, q^\star}^{(k)} = \max\Bigg(0, \frac{F^{(k)}(n^\star, \Theta_{q^\star})}{C_d} + \max_{\zeta, v}\left\{\Psi_{\zeta, v}^{(k-1)} \delta(n^\star - \zeta, \Theta_{q^\star} - \Theta_v)\right\}\Bigg).$$

Other elements of the score matrix are updated with

$$\Psi_{n,q}^{(k)} = \max\Bigg(0, \frac{F^{(k)}(n^\star, \Theta_{q^\star})}{C_d} \delta(n^\star - n, \Theta_{q^\star} - \Theta_q) \quad \Psi_{n,q}^{(k-1)} - \beta\Bigg), n \neq n^\star \text{ and } q \neq q^\star,$$

where $\delta(n^\star - n, \Theta_{q^\star} - \Theta_q)$ indicates the confidence that the occupant is at location $\{n, \Theta_q\}$ given that it is observed at location $\{n^\star, \Theta_{q^\star}\}$. The factor $\beta \geq 0$ ensures that those zones wherein no occupant is longer observed decrease their tracking confidence score with time.

When a score element in the matrix $\boldsymbol{\Psi}^{(k)}$ is larger than tracking threshold C_{Th}, then presence is declared. Presence is detected as long as new observations of the occupant's zone are obtained, i.e. as long as (2) is satisfied. The region is declared as unoccupied when none of the scores exceed C_{Th}, i.e.

$$\Psi_{n,q}^{(k)} < C_{Th}, \quad n = 1, 2, \ldots, N, \quad q = 1, 2, \ldots, M,$$

for a period larger than K_{Th} transmissions. The parameter K_{Th} has to be chosen larger than the expected maximum number of transmissions without detection of the occupant (i.e. no movement of the occupant).

4. PERFORMANCE EVALUATION

A prototype implementation of the ultrasonic array sensor was installed in a ceiling-mounted configuration in an office room as depicted in Fig. 4. The dimensions of the room were: length $l = 6$ m, width $w = 4$ m and height $h = 3$ m. The sensor was located at the center of the ceiling of the room, i.e. $\{x = 0, y = 0, z = 3\}$. The transmitter was of model 400EP14D [13] at central frequency $f_c = 40$ kHz, bandwidth of 2 kHz and with a broad-beam profile. The co-located linear array consisted of four receivers of model SPM0404UD5 [14] with inter-element separation of 4.3 mm. Furthermore, the linear receiver array was parallel to the length of the room. The parameters of the transmitted waveform were $T = 2$ ms and $\texttt{PRI} = 32$ ms. This choice of parameters corresponds to a sensing range D of around 5 m, which is large enough for covering typical cellular offices.

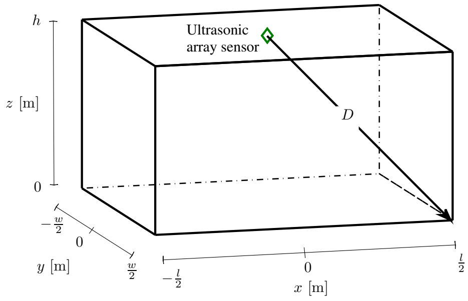

Fig. 4: Ceiling-mounted sensor configuration in office room.

The design parameters in the receiver array processing are summarized in Table 1. We average the signal over $\Gamma = 200$ samples (i.e. 1 ms at sampling rate $f_s = 200$ kHz). This corresponds to filtering out all echoes with a Doppler frequency larger than 1 kHz (i.e. filter out all moving sources with a radial speed larger than 4 m/s). We further combine 5 consecutive ranges into a single group range in order to decrease the complexity of the algorithm. A further simplification is achieved by monitoring 4 independent DoA angles. Using these parameter values, the tracking matrix is reduced to a matrix of size 6×4. An occupant between consecutive transmission can only change the position between adjacent group ranges ($\alpha_1 = 1$ group range) and/or adjacent DoA angles ($\alpha_2 = 45°$).

We consider that an occupant is observed when the received power is at least $C_d = 5$ times the power noise level. Further, we require at least 3 consecutive observations of the occupant to declare a presence ($C_{Th} = 3$). Before declaring a room as unoccupied, we require at least $K_{Th} = 600$ transmissions (around 20 s) without any observation of movement.

Table 1: Parameters of algorithm

Parameter	Value
f_s	200 kHz
M	4
Γ	200 samples
R	32 ranges
C_d	5
C_{Th}	3
K_{Th}	600
$\mathcal{A}$	$\{-45°, 0°, 45°, 90°\}$
α_1	1 group range
α_2	45°
β	1
P	5 ranges
N	6 group ranges

We used the guidelines for testing occupancy sensors in [9] to evaluate sensor performance, with a user making different types of movements. In addition to the major motion (corresponding to movements like walking) and minor motion (corresponding to movements like slowly waving hands) tests specified in [9], we additionally used a tiny motion test to capture user behavior under situations like reading, typing etc.

We compared the detection performance of the proposed sensor with a commercial PIR sensor type IRS-A330ST02 [15]. Both sensors were mounted in close vicinity in the ceiling. The ratio of detections reported by the sensor to the total number of decisions made, as percentage, was used as the detection performance metric. Two sets of experiments were considered. One in which the user was below the sensors and the other in which the user was about 2.5 m away from the sensors. The performance comparison of the two sensors is shown in Figs. 5 and 6. The “none” case corresponds to the scenario when the room was empty, thus the percentage of detections translate to false alarms. For both sensors, no false alarms were reported. For major motion, both the PIR sensor and the ultrasonic array sensor show comparable performance, as is to be expected. The detection of the PIR sensor degrades rapidly for smaller movements (minor and tiny motion types). The ultrasonic array sensor exhibits good sensitivity in detecting these challenging motion types.

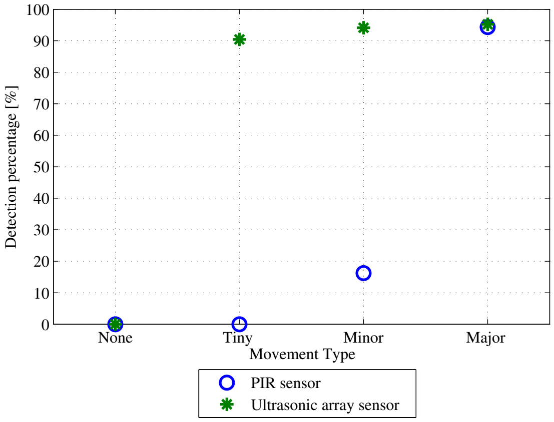

Fig. 5: Comparison of detection performance for user below the sensors.

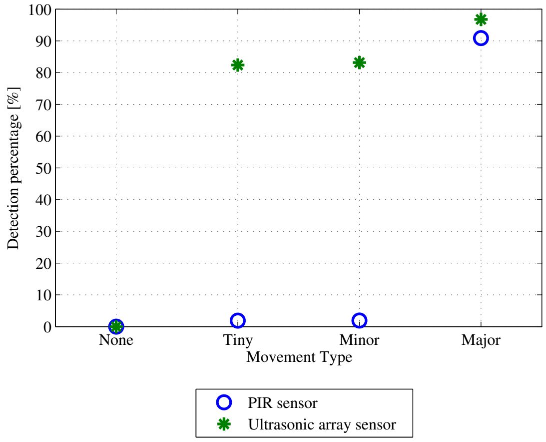

Fig. 6: Comparison of detection performance for user 2.5 m away from the sensors.

5. CONCLUSIONS

We presented a prototype ultrasonic array sensor for reliable presence detection under low-complexity algorithmic requirements. Our solution comprised of determining an initial zone with largest power due to user movements, where a zone was defined by a group range and DoA angle. Tracking of user movement over zones was used to improve detection performance. Further enhanced sensing functionalities like user localization and tracking are enabled by the ultrasonic array sensor and are topics under current investigation.

6. REFERENCES

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