Towards Mobile Robot Assisted Smart Containment

Tesfaye Wakessa Gussu and Yen-Chen Liu, *Member, RST*

Abstract—**In this work, we proposed an approach that enables achieving robot-assisted contagion-free public areas. Suppose a sign of contagion is detected due to sneezing, coughing, or droplets. In that case, the robot reorients itself towards the Direction Of Arrival (DOA) of the contagions and cleanse the identified Hot-Spot (HS) area. We utilized a ReSpeaker microphone array V.2 to capture the contagion's DOA. Assuming that the identification is carried out without a noticeable and disturbing change in the people's movement, the robot moves to the specified spot and performs cleansing. Therefore, we can set the goal of smart-containment (contagion-free spaces) of the room if the robot can continuously and efficiently identify the HS area and take those actions accordingly. Finally, we experimented with demonstrating the proof of concept. The result indicates that the proposed smart containment approach is achievable in a less costly way. Hence, we conclude that this targeted smart containment approach has an added value. It can significantly reduce the number of people infected, encourage people to travel, and help revive the affected economy. Overall, this work's practical implication is to inform end-users, policymakers, and robot developers to identify and appropriately develop mobile robots to advance society's well-being.**

Index Terms*—*Smart Containments, Mobile robots, Obstacle Avoidance, cough detector, sneezing detector, Kinematic analysis.

I. Introduction

THE current trend in the fight against the Covid-19 relies on widespread coronavirus testing, which is confronted by shortage ,and screening and quarantining of the infected peoples. In most countries, moderation, control, and complete containment of the spread of the Covid-19 is pending except for China [1] and may continue to last for months. As a result, salient plans are being practiced to raise awareness, adapt to the newly developed after effect habits, voluntary adherence to the enforced laws, and adjust to social norms changes. In general, the spread of the former Covid-19 virus is slowing down as population-level social distancing, an enhanced social distancing of the elderly, and suppression through epidemiological triggers are practiced [2], and the increasingly evolving technological throughputs and vaccines.

However, the longer those measures are in action, the economic fallouts, scarcity of resources, and budget shortage are forcing the societies to adapt and start to live their everyday lives as before the pandemic. Most of these responsive measures have little effect on easing the lock-down, encouraging people to freely travel and perform their worry-free day-today life activities, reducing anxiety and depression due to the pandemic. This, in turn, increases people's tendency to violate the stay-at-home and self-quarantine rules due to survival issues or feelings of boredness. Thus, such measures start to have a less significant effect on mobility.

These harmful effects of the Covid-19 crisis bring about changes in services, mostly carried out remotely or through social distancing [3]. The authors in [3] emphasized the underlying typology of the robotic service advances in catering and creating uplifting changes in the vulnerable groups' wellbeing suffering from social isolation. According to [4], there exists a conceptual linkage between global cities and epidemiology. There also exists a connection between urban pandemic management and the emerging fields of urban robotics [5]. However, these urban robots' particular appeal was to assist with delivery, enforcing policies, healthcare, and monitoring social distancing. This indicates that such robots are restrictive to mobility and are primarily based on pandemic control thoughts.

[6] discusses the robot's contribution in eradicating the Covid-19 transmission only when perceived in the context of containment in an unknown environment with Covid-19 patients and close contact pathogens. The robot searches for the victim based on the Robotic-Elephants Herding Optimization, which emulates better only if the search mission is started before the initial targets start to grow drastically. Most importantly, for the authors' approach to work effectively, the robot's speed must be higher than the viral spread speed. This makes the practical feasibility questionable. [7] proposed a cost-saving mobile platform-based automatic fever screening system. Their system is portable and allows taking the noncontact elevated body-temperature measurement. However, it exhibits lower specificity; its capability to capture asymptomatic patients and patients with other viral transmitters are not exact.

A contactless syndromic surveillance platform called FluSense [8] is developed as a cough recognition model. It consists of a novel edge-computing sensor system, models, and data processing pipelines to track crowd behaviors and influenza-related indicators, such as coughs. In this system, a microphone array, a thermal camera, and a neural computing edge are used to passively and continuously characterize speech and cough sounds along with changes in crowd density in a real-time manner. Although the FlueSense system is confined and

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Tesfaye Wakessa Gussu was with the Department of Mechanical Engineering, National Cheng-Kung University, Tainan 70101, Taiwan (e-mail: tesfayewakessa@gmail.com).

Yen-Chen Liu is with the Department of Mechanical Engineering, National Cheng-Kung University, Tainan 70101, Taiwan (e-mail: yliu@mail.ncku.edu.tw).

optimized to work in a noisy and crowded public space like a hospital waiting room in a privacy-sensitive way and can capture viral transmitters, it lacks mobility.

According to [9], robotizing the social sphere helps automatize individuals' activities and changes in society's social processes. Hence, making robots an integral part of such spaces allows us to leverage services such as guidance, monitoring, information, and safety precaution retrieval about the virus. For instance, robots like Promobot can autonomously navigate and performs contact-less thermo-control of a passerby for an elevated covid-19 like temperature control. However, this robot can't screen contagion and take any form of mitigation action.

Despite the differences in geographical locations and society's living standards, we believe that mobile robots could securely isolate and contain the HS/subjects and reduce the spread of the viral transmissions. These days, the various efforts being practiced had little effect on the restoration of social life and revival of the affected economy. The lockdowns and strict social distancing rules remain practical for unknown periods. This urges for systematically identifying and practicing a smart containment strategy. In this regard, we proposed a methodology to achieve robot-assisted contagion free public areas.

We foresee that the proposed approach dramatically reduces the added costs due to the complexity of contagion area identification and cleansing of the identified HS areas. To perform the aforementioned cyclic cleansing task, the robot must know the contagion location and navigate to that hotspot (HS) area. Hence, having a mobile robot capable of roaming in public areas, repeatedly identifying contagion signs, and cleansing the identified HS turns the site into a smartly contained space. However, performing the aforementioned cyclic cleansing task, the robot must know the contagion location and navigate to that hotspot (HS) area. Thus, we mounted an array of Respeaker microphone array V2.0 on the mobile robot to triangulate the HS's location with contagion signs such as coughing and sneezing, thereby commanding the robot reorient itself towards the DOA and perform the cleansing.

The rest of the paper is organized as follows. The problem definition and the proposed methodologies are described in Sect. 2 and Sec. 3. In Sect. 3, the adopted navigation and obstacle avoidance approach, the software, and the experimental hardware setup is described. Experimental results of different use scenarios and the corresponding results are discussed in Sect. 4. Finally, Sect. 5 concludes the paper.

II. DESCRIPTION OF PROBLEM STATEMENTS

Many containment strategies are being adopted in public market areas, waiting rooms, tourism sites, and likes. Fig. 1 shows some of the currently practiced containment strategies existing to-date. Such containment strategies play a crucial role in reviving the economy and reducing the spread of harmful contagion. However, its effectiveness depends on people's adherence to the social distancing policy and their will to obey it, necessitating extra monitoring and surveillance systems. Furthermore, the occurrence of high-pitched dialogues, sneezing, or coughing during mobility (see Fig. 2) results in an increased possibility of droplets/viral transmissions. Such cases, together with a lack of reliable mitigation methods, necessitates seeking effective, smarter, cost-effective, and well-targeted containment strategies to suppress the spread of the pandemic.

Irrespective of the public spaces' location, people use their free-will to sneeze, cough, or talk while moving (See Fig. 2). The absence of a vaccine, the lock-downs, and the intervention rules set by the World Health Organization (WHO) are putting us into a state of frustration since nobody is sure when the pandemic is going to be fully moderated, controlled and contained [1] thoroughly. Either due to adaptation or survival issues (particularly in developing countries), there is increased mobility in public areas. Hence, the possibility of droplets or viral transmissions might significantly increase due to the accompanying vital signs such as talking, sneezing, or coughing. These critical signs could speed up the spread of the viral or other contagions even if every individual has gone through screening at every public-place entrance.

(a) Public Market. (b) Public area. (c) Tourism.

Fig. 1: Various containment strategies.

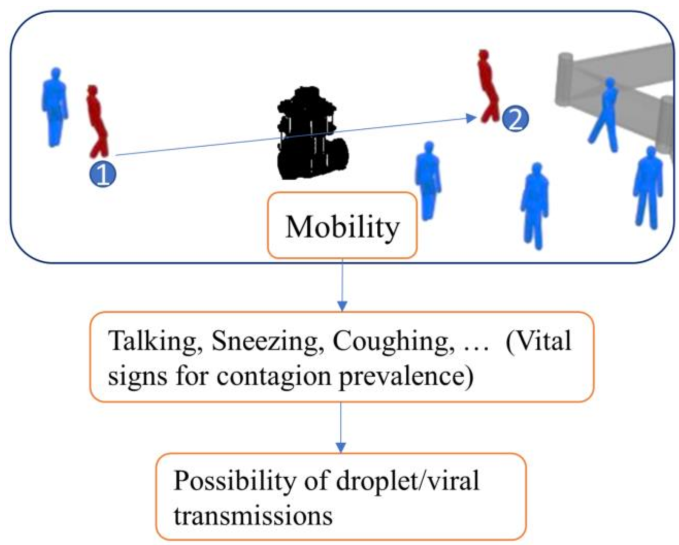


Fig. 2: Effect of mobility and contagion expansion.

For instance, assume that the person in red in Fig. 2 is a victim and moves from point 1 to point 2. The possibility of droplets or viral transmissions among the group of people at area 2 is higher due to the possibilities of conversations, sneezing, or coughing. These vital signs could speed up the spread of the viral or another contagion transmission even if every individual has gone through screening at every public place entrance. Furthermore, after every individual (an asymptomatic/ uninfected person) entering the public spaces are checked-in clear, the robot and the people (in motion or standing/sitting) could be anywhere inside the public areas.

Suppose a sign of droplets due to sneezing, coughing, talking, or any possible reason is detected without any noticeable and disturbing change among the travelers. The robot's priority to move to area 2 and takes actions like cleaning, mopping, and disinfecting is higher. Therefore, we can set the goal of smart containment (contagion-free spaces) of the room if the robot can continuously and efficiently identify the spotted area and take those actions accordingly. As a result, the room becomes contagion-free.

III. PROPOSED APPROACH

While the approach adopted in this work is carried out in three steps, Algorithm 1 shows the working principle of the proposed containment process. The mobile robot moves within the public area and checks for HS with increased vital signs or contagion droplets in this approach. When multiple HS regions are identified, the robot controller performs prioritization and commands the robot to move to the area with higher importance and complete the cleansing task. As a result, the public spaces are kept contagion-free at all times.

Algorithm 1 The psuedocode assumes that the public area is suitable for smooth maneuverability of mobile robot.

▷ Initialize the robot to move inside the public area
▷ Capture the body temperature of in and outgoing persons inside the public spaces
if $Body_{temp} <= 37.5°$ **then**
  pass
else
  Inform to Security/Alarm
end if
▷ Initialize the robot to move inside the public area
Check for hotspot area with sign of contagion droplets or viral transmission
if Multiple area detected **then**
  Prioritize based on RSSI
  Obtain the location information
  The robot moves towards the HS area with higher RSSI
  if Obstacle detected **then**
    Reorient the robot to avoid the obstacles
    if Robot reached the HS area **then**
      stop the robot and perfom cleansing the area
      if cleansing completed **then**
        Repeat Checking for the HS area
      end if
    end if
  end if
end if

Step 1 is the screening step. Every individual entering the public area is assumed to undergo contact or contact-less screening for vital signs such as elevated body temperature, fever, coughing, etc. However, there is a possibility that an asymptomatic traveler/person could pass the entrance; and once cleared, mobility within the public area is not restricted.

Step 2 is a vital sign detection step. While step 1 only takes place at the entrance, we plan to place the vital sign detector on top of the mobile robot and adopt the Flusence [8] concept to track the possibilities of contagion droplets characterization. The robot has an additional camera for checking the presence of droplets and the cleanliness of the floor.

Step 3 is the cleansing state. At this stage, hotspot (HS) area identification, prioritization, and robot commanding tasks are carried out. To achieve these actions, we proposed two more assumptions:

Assumption 1: The robot motion and the cleansing action are governed by local distance information between the robot and the hots-spot area. While the distance information is obtained from the direction of arrival (DOA) of the vital signs, the hotspot's choice (the target area) is based on the prioritization in the event of multiple area identification. Fig. 3, shows that the robot can start cleansing from Area1 on-wards without interfering or obstructing the mobility of the peoples in that public area. However, if Area2 has more people than Area1 and the people inside this area are not moving, the robot carries out the cleansing and containing action without violating public privacy. Thus, we propose a subsequent assumption to address this issue.

Assumptions 2: If the person in the prioritized area is not moving, the robot must not violate public privacy by any means. Therefore, we propose a safe bounding area, as shown by the dotted lines in Fig. 3. The robot considers anything crossing the bounding region as an obstacle.

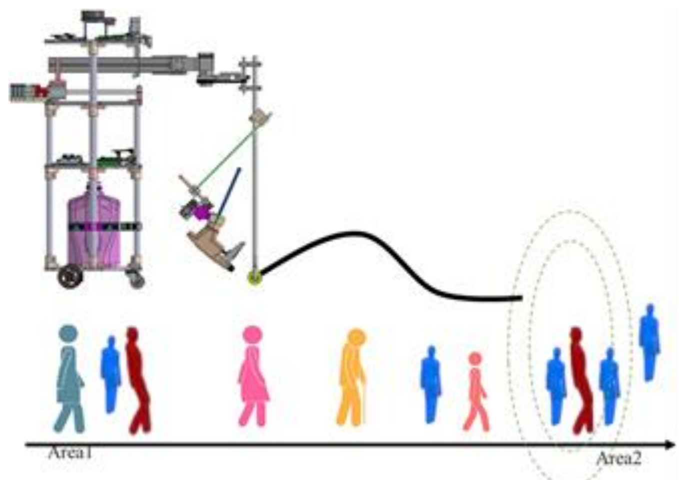


Fig. 3: Robot safe cleansing area.

IV. NAVIGATION AND OBSTACLE AVOIDANCE

In scenarios where humans and robots coexist together, it is a requirement that our modified waffle robot be able to autonomously navigate through its environment while avoiding obstacles to reach the HS location and cleansing. Methods such as homotopy optimal trajectory [10] and homotopy continuation methods [11] would allow the robot to precisely reach the goal position. However, the modified waffle robot has no prior knowledge of the location of the HS. Hence such approaches are computationally not feasible as the robot can recognize its surroundings using onboard sensors and instantaneously decides and reacts to obstacles based on predefined range.

We implemented the navigation and obstacle avoidance using an extra skirt of ultrasonic sensors and the Laser Distance Sensor (LDS). As a result, the robot can navigate and perform the cleansing task in a known and structured indoor environmental setup. The first step to prove the cleaning robot concept was to study the test platform's software and hardware architecture.

A. Hardware System Architecture

The modified turtlebot3 waffle's hardware components consist of two major sections: the mobile platform and the cleanser arm section. In addition to While keeping the majorities of the hardware and the onboard sensors that came with the original turtlebot3 waffle, we made the following changes. The modified waffle is five times taller in height, and the Intel-Joule $570x$ Single Board Computer is replaced with Raspberry pi $4, 64\ bit$, $8\ GB$ RAM SBC (Single Board Computer. In general, the primary hardware modules that are added to the mobile platform section include:

- ReSpeaker Microphone Array (version 2.0): A microphone array with 4 microphones and a built-in high-performance chipset.
- Seek CompactPRO: A thermal camera able to capture thermal images with a $320x240$ pixel resolution and a 32° field of view.
- Intel Neural Compute Stick 2: A computing hardware that uses Intel Movidius Myriad X Vision Processing Unit for efficient deployment of deep learning models on the edge. Item Raspberry Pi 4 MODEL B, $64\ bit, 8\ GB$ RAM: This serves as the control platform to synchronize all the attached sensors and devices.
- Skirt of 8 HC-SR04 ultrasonic sensors.

Although both the LDS and the ultrasonic sensor skirts were used to detect and avoid an obstacle, the robot navigates to the HS location using the sensory information obtained from LDS. The additional skirts of ultrasonic sensors give the extra capability to avoid smaller obstacles that the LDS cannot cover. As a result, the robot performs collision free navigation and performs cleansing. While the Dynamixel motors (XM430-210) is powered by a $12\ V$ Li-Po battery, the raspberry pi 4B is powered by an external power bank. Thus, the robot continues receiving the sensory information from the onboard sensors, communicates with the Raspberry Pi 4B, and attempts to reach the HS area. The second section of the modified waffle robot is the cleansing module. This section consists of a reciprocating section and a rotary section. While the reciprocating action is sought to move the mopper in a backward-forward motion, the mopper arm's extra rotary movement prevents damage if the robot simultaneously undergoes both turning and cleansing tasks

B. Software System Architecture

Leveraging the available $8\ GB$ RAM on the Pi SBC, we installed the Desktop version of Ubuntu 18.04 operating system and ROS melodic. Then we developed a three-stage algorithm for autonomous navigation of the robot and a cleansing of the HS area. Fig. 4 shows the three stages that constitute our approach as denoted by A, B, and C, respectively.

At stage A, the robot undergoes initialization using command line input by the operator., such as bringing up the robot on the SBC, provide the local position information from the onboard sensors, and command the robot to move forward until the viral contagion signs are detected. Stage B follows stage A.

At stage B, the robot moves toward the HS area while avoiding obstacles and comes to a complete stop upon reaching the area requiring cleansing.

Stage C involves checking the states of the mobile robotic platform and activating the cleansing section. Three seconds after the mobile robotic platform comes to a complete stop; the cleaning task is performed for 1min before the cleansing section's actuators go back to an idle state. The onboard realsense camera checks for the floor's cleanliness and sends feedback of either success or repeat the cleansing command to the SBC. Hence, the mobile platform motion and cleanser section's cyclic action is executed to yield a contagion free public space.

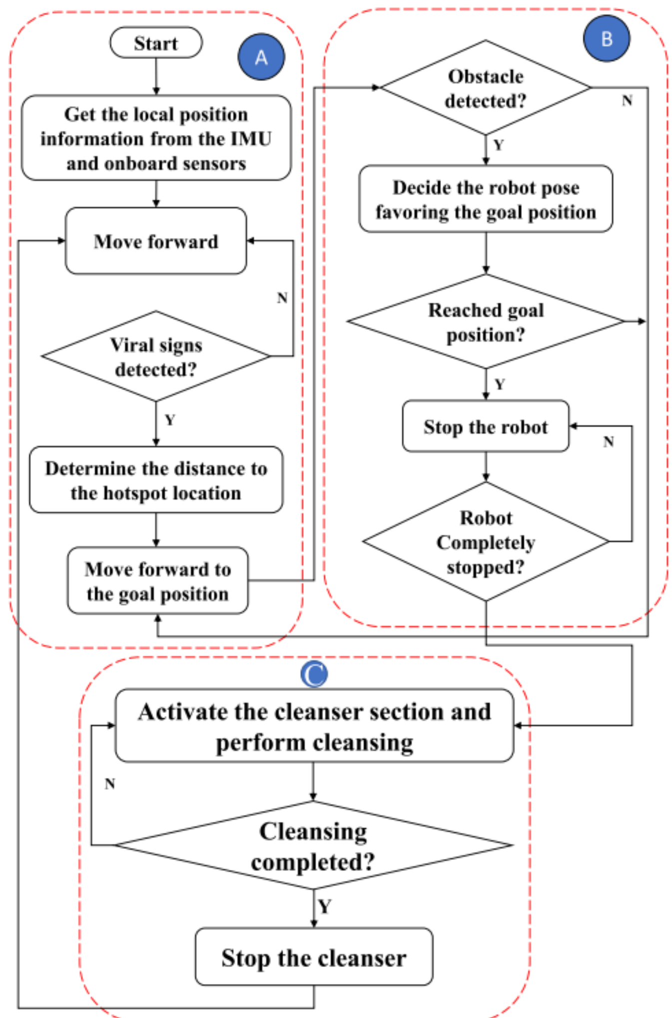


Fig. 4: Decision Making approach to cleansing and obstacle avoidance.

C. Hotspot Area and Contagion Source Indentification

According to our assumptions, the vital sign source could be either in motion, standing, or sitting. The robot performs the aforementioned cyclic cleansing task; it has to know the viral contagion location and navigate to that HS area. However, the Rsespeaker microphone array will not provide the HS's exact location. Hence, the incoming sound's source position is used as a target point for the robot. Suppose that the victim is within a range of 5m from the robot. The ReSpeaker Microphone array $V2.0$ can only return feasible readings of voice activity direction and the DOA, and we use triangulation to determine the location of a contagion sign transmitter. Fig.5a shows the arrangement of the three ReSpeaker microphone array $V2.0$ on the modified waffle robot. Then, we calculated the (x, y) coordinate position of the source using only the DOA readings obtained from the three ReSpeaker Microphone array $V2.0$.

Fig. 5b illustrates the adopted triangulation approach for contagion source or the HS location. To pinpoint the location of the HS, we considered several scenarios and presented the derivation of the distance to the person with vital sign of coughing or sneezing as follows:

$$d_1 = d1\left(\frac{\sin(\alpha3)\sin(\alpha2)}{\sin(\alpha3 + \alpha2)}\right) \quad (1)$$

$$d_2 = d2\left(\frac{\sin(\alpha3)\sin(\alpha1)}{\sin(\alpha3 + \alpha1)}\right) \quad (2)$$

where $d1$ and $d2$ are obtained from geometrical location of the three ReSpeaker microphone array $V2.0$. Applying cosine law, we obtain:

$$\begin{aligned} {d_1}^2 = & \ (d1)^2 + (x - x3)^2 + (y - y3)^2 \\ & -2(d1)\sqrt{(x - x3)^2 + (y - y3)^2} \end{aligned} \quad (3)$$

$$\begin{aligned} {d_2}^2 = & \ (d2)^2 + (x - x1)^2 + (y - y1)^2 \\ & -2(d1)\sqrt{(x - x1)^2 + (y - y1)^2} \end{aligned} \quad (4)$$

Substituting (1) and (2) into (3) and (4), respectively yields (5).

$$\begin{aligned} 4\begin{bmatrix} x1 - x3 \\ y1 - y3 \end{bmatrix}^T \begin{bmatrix} x \\ y \end{bmatrix} = & \ (x1)^2 + (x3)^2 + (y1)^2 + (y3)^2 \\ & -(d1)^2\left(\frac{\sin(\alpha3)\sin(\alpha2)}{\sin(\alpha3 + \alpha2)} + 1\right)^2 \\ & -d2)^2\left(\frac{\sin(\alpha3)\sin(\alpha1)}{\sin(\alpha3 + \alpha1)} + 1\right)^2 \end{aligned} \quad (5)$$

Equation (5) represents the (x, y) position of the contagion with respect to the position of the ReSpeaker microphone array $V2.0$, where $\alpha1$, $\alpha2$ and $\alpha3$ are functions of the DOA and are determined according to the Algorithm 3.

After obtaining the goal pose (x, y, θ) of the robot, the cleansing action requires determining the safe distance d and comparing the result with the minimum geometrical constraint for avoiding collision with the human-subject. (see Fig. 5a). Thus:

$$d_{safe} \geq d_{min} + R \quad (6)$$

D. Obstacle Avoidance Approach

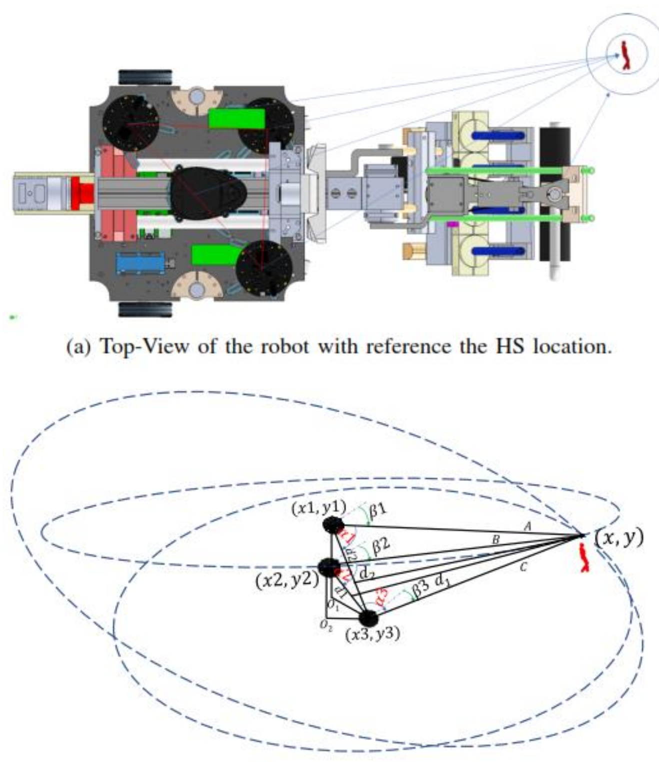
In stage B of Fig. 4, the robot navigates to the HS by detecting and avoiding obstacles. The eight HC-SR04 ultrasonic sensors that form a skirt on the modified robot body enables the robot to detour away from smaller objects whose heights are below 0.6m. Whereas the onboard LDS enables the robot to detour away from obstacles of a larger height. Thus, the robot instantly detects and avoids obstacles by moving away and reorienting itself towards the goal position.

The LDS that comes with the original robot scans the environment from 0° to 360°. Both the LDS and the ultrasonic sensor skirt returns the measurements data-point in the form of ranges reflecting the position of an obstacle in degrees, forming a field of view and distance. Hence, we categorized the critical region to the front and ±30° to the left and to the right side for the LDS. These regions correspond to the left/right turn in place, left/right tight turn, and left/right wide turn for ultrasonic range sensing is considered. Overall, the obstacle avoidance approach is developed according to the Algorithm 3.

The measurement data for each region are in turn consists of Long Range (LR) and Short Range (SR) distances, which are bounded by the R_{min} and R_{max}, respectively. (6) expresses the relationship between d_{min} and d_{safe} signifying that obstacles in SR are weighted more compared to those in LR while the robot is moving forward towards the HS.

V. PROOF OF CONCEPT

To prove the applicability and feasibility of the proposed approach, we conducted an experiment by considering varying combination scenarios for incoming sound direction. In addition, the numerical values were obtained from the geometrical relationship between the robot body and the location of the three ReSpeaker microphone array $V2.0$ through direct measurement and presented Table I. This table shows the dependency of the source position with the DOA as received by the three ReSpeaker microphone array $V2.0$.



(a) Top-View of the robot with reference the HS location.

(b) Triangulation based sound source localization approach

Fig. 5: (a) Top-View of the robot (b) approach to determination of source position by triangulation.

Algorithm 3 Psuedoalgorithm for obstacle avoidance using the LDS and ultrasonic sensor skirt.

Obtain the goal position d
Set the safe distance from the geometry of the robot $\ni$ $d_{safe} \leq d_{min} + R$
Set the LR and the SR with lower and upper bound range as R_{min} and R_{max}
Get distance readings and store in array form
distance[]= index(of all ultrasonic sensors and LDS)
distanceIndex[]=distance[0..j]
for $i = 0$ to $len(distanceIndex)$ **do**
  if $distance[j] \leq SR$ **then**
    remove zero readings of ultrasonic sensors
    Robot moves towards either of the regions A-E
  end if
end for
while $distance[j] \geq LR$ **do**
  Moveforward to the hotspot area
  if Robot reach hotspot area **then**
    break
    Start cleansing
  end if
end while

VI. CONCLUSSION

This paper proposed a method for achieving a more targeted smart containment approach using a mobile robot and an array on ReSpeaker microphone array V2.0. We begin by presuming that the proposed targeted approach is less restrictive on people's mobility, assists in an economic revival, and brings the socioeconomic norm back to before pandemic like states. To achieve smart containment's objective, we tested our approach utilizing a mobile robot equipped with cleansing devices and a less costly apparatus for processing the incoming contagion signs. This realization was met under the assumption that every individual entering the public area is checked-in clear for Covid-19, the robot and the crowd mobility is not restricted.

TABLE I: Experimental parameter values.

ReSpeaker position on the robot			Sound direction of arrival (DOA)	Souce position	Directional cosine
i	x_i	y_i	β_i	(x, y)	α_i
$i = 1$	-17.8	86.13	$\beta 1 = 0°$		$60°$
$i = 2$	149.56	83.02	$\beta 2 = 0°$		$62°$
$i = 3$	147.28	93.55	$\beta 3 = 0°$		$62°$
			$\beta 1 = 0°$		$\alpha 1 = 60°$
			$0 <° < \beta 2 < 30°$		$62° + \beta 2$
			$0 <° < \beta 3 < 30°$		$62° + \beta 3$
			$\beta 1 = 0°$		$\alpha 1 = 60°$
			$-30° < \beta 2 < 0°$		$62° - \beta 2$
			$-30° < \beta 3 < 0°$		$62° - \beta 3$
			$\beta 1 = 0°$		$\alpha 1 = 60°$
			$0 <° < \beta 2 < 30°$		$62° + \beta 2$
			$-30° < \beta 3 < 0°$		$62° - \beta 3$
			$\beta 1 = 0°$		$\alpha 1 = 60°$
			$-30° < \beta 2 < 0°$		$62° - \beta 2$
			$0 <° < \beta 3 < 30°$		$62° + \beta 3$

Therefore, if a sign of contagion resulting from coughing, sneezing, or talking is identified, a triangulation principle is used to locate the person's location in that identified area. An array of the three Respeaker microphone array V.2 captures the contagion's DOA, which are later used to triangulate and obtain the HS location, which is the robot position on the (x, y).

The robot reorients itself and starts to move towards the HS and cleans the area for 1min. After accomplishing the task, the robot begins to roam inside the public spaces and identify contagion signs without a noticeable and disturbing change in people's state of movements. If an indication of droplets is being detected again due to sneezing, coughing, talking, or any possible reason, the robot moves towards the specified spot and performs cleansing. Therefore, we can set smart-containment (contagion-free spaces) goals if the robot can continuously and efficiently identify the spotted area and take the cleansing actions accordingly. As a result, the room becomes contagion-free.

In conclusion, having a robot capable of roaming in public spaces and continue tracing the vital contagion signs, and cleansing the area has an added value in easing and further flattening the expansion curve of the Covid-19 like pandemic/epidemic in a less costly way. Overall, this work's practical implication is to inform the end-users, the policymakers, and the robot developers to identify and appropriately develop mobile robots to advance society's well-being.

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Tesfaye W. Gussu received the *B.S. degree in mechanical engineering* from Jimma University, Jimma, Ethiopia, in 2007, and the *M.S. and Ph.D degree in mechanical engineering* from *National Taiwan University of Science and Technology*, Taipei, Taiwan, in 2014 and 2017, respectively. He was with NCKU (National Cheng Kung University) under the supervision of Prof. Yen-Chen Liu. His research interests include control of mobile robotic systems, mobile robot design and development, human-robot interaction, and robotic application for factory automation.

Liu Y. Chen (M' 12-SM' 19) received the *B.S. and M.S. degrees in Mechanical Engineering fr*om *National Chiao Tung University*, Hsinchu, Taiwan, in 2003 and 2005, respectively, and the *Ph.D. degree in Mechanical Engineering* from the *University of Maryland*, College Park, MD, *USA*, in 2012. He is currently an Associate Professor with the *Department of Mechanical Engineering*, *National Cheng Kung University* (NCKU), *Tainan*, *Taiwan*. His research interests include control of networked robotic systems, bilateral teleoperation, multi-robot systems, mobile robot network, and human-robot interaction. Dr. Liu was the recipient of the Ta-You Wu Memorial Award, Ministry of Science and Technology (MOST), Taiwan, 2016, Kwoh-Ting Li Researcher Award, National Cheng Kung University, Taiwan, 2018, and Young Scholar Fellowship - Columbus Program, MOST, Taiwan, 2019.