International Journal of Internet, Broadcasting and Communication Vol.16 No.4 255-264 (2024)
http://dx.doi.org/10.7236/IJIBC.2024.16.4.255

IJIBC 24-4-29

An Introduction to Numerical Modeling of Infrared Array-Based Object Detectors for Free-form Surface Installations

Joong Ho Lee

Assistant Professor, Department of Computer Engineering, Keimyung University, Korea
k28753969@kmu.ac.kr

Abstract

Infrared-based scanners are utilized as a promising method for detecting objects that contact on a surface. In this system, infrared transmitters and receivers are positioned at opposite ends of the plane, facing each other. Traditionally, this system employed a one-to-one scanning method, where a single infrared transmitter emits a light signal that is detected by a corresponding receiver on the opposite side. While this method offers advantages such as fast response times and system simplicity, it is limited by its inability to detect multiple objects simultaneously. To address this limitation, recent applications have adopted the one-to-many scanning. In this scanning method, a single infrared transmitter emits a light signal that is detected by multiple receivers on the opposite side. The results are then read in real-time to determine the position and size of the object. With the recent advancements in computing power, the response speed and accuracy of one-to-many scanning have significantly improved. However, in most cases, this method has been limited to object detection on simple planes, and there is no analytical method available to support performance prediction when considering various sensor installation configurations with various form-factors. In this study, we mathematically modeled an infrared sensor array system to predict the performance of various sensor configurations installed on two-dimensional planes or curved surfaces. Additionally, we assess the critical effect of inevitable positional errors (including orientation mismatches) on the system's performance. The unique approach introduced in this paper will provide highly reliable quantitative predictions, aiding in the design of sensor network form factors tailored for various applications in the future.

Keywords: *Infrared Sensor; array scanning; one-to-many scanning, 2D surface object detection.*

1. Introduction

There could be many methods to understand how the array scanning strategy might affect its functionalities [1][2][3]. In an effort to uncover a baseline, we concentrate on constructions of numerical models including not only LED emitters and IR receivers but also systemic structures of arrays. In the first part, we will focus on a series of analyses of infrared array scanning which will allow system designers to estimate functional

Manuscript Received: October. 3, 2024 / Revised: October. 8, 2024 / Accepted: October. 14, 2024
Corresponding Author: k28753969@kmu.ac.kr
Tel: +82-53-580-6689, Fax: +82-53-580-6689
Assistant Professor, Department of Computer Engineering, Keimyung University, Korea

performance for a given design condition. It is our belief that such is the best way to provide a basis for the design of infrared array scanning, rather than laying out a set of specs intended only for a particular type of sensor. We examined tolerances and clearance of emitters and receivers, installation errors of arrays, and topological patterns of array structures. We define the scope of guidelines to be addressed in order to design various types of array scanning systems. By combining the work done previously in the domains of multi-touch surface, we are able to provide a thorough examination of the issues of analytical investigation of the design of interactive large displays which support multi-touch functionality.

2. One-to-many scanning in infrared array-based object detectors

One-to-many scanning senses an object's position using a series of infrared LEDs and sensors mounted on the outside of what looks like an empty picture frame. Figure 1 shows an exemplary operation case of one-to-many scanning object detector. The LEDs create a grid of infrared beams that crisscross the space inside the frame. An object that enters the frame blocks some of the invisible beams, allowing the software to monitor the beams to track the movement of the object in real time. However, the “faster” scanning on the “larger” surface is still at issue. To lower the scanning time, Moeller et al. used only 26 transmitters for a medium-size touch screen. If they try to make the touch screen larger, the increased number of LEDs deteriorates scanning speed [4].

Figure 1. The one-to-many scanning system detects multiple objects

Figure 2 shows the overall construction of the one-to-many scanning system. The frame(a) possesses a PCB, Printed Circuit Board and IR receiver arrays of emitters(b) and receivers(c) which are mounted around the entire frame. Each IR module(d) consist of emitters or receivers. When the left side of the array is activated as an emitter, MCU(e) switches the right side of the array as a receiver to detect infrared light from the left side. Light detection information is transferred into MCU(e), which analyzes and converts the information into a data table(f) where a 1 indicates that light was successfully received and a 0 indicates detection failure. The size of the data table depends on the number of LED and IR sensor modules. The data table is converted to serialized TCP/IP protocol and LAN Port(g) transfers the data to PC(h) via LAN RJ45

The one-to-many scanning utilizes a point-to-point visual. By using individual infrared sensors and LEDs, rather than multi-point receivers such as cameras, this method wraps the entire screen in a continuous sensor that provides more complete information about the visual hull of any objects within the interaction area. By surrounding the area with infrared sensors, and pulsing infrared LEDs at given positions along the sensor, a more complete visual hull of the interaction area is generated. Adding hover detection is simply a matter of adding an additional layer of sensors atop the base frame. The arrangement raises the possibility of 3-

dimensional gestural interaction using point-to-point visual hull detection.

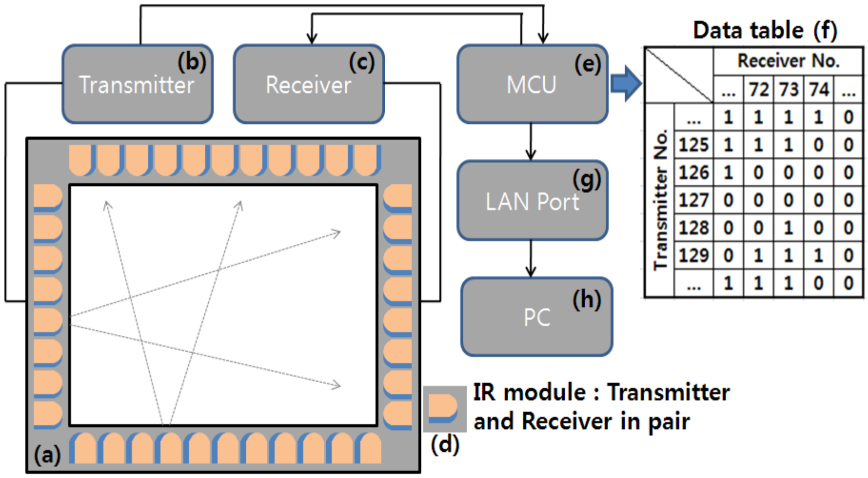


Figure 2. Framework of one-to-many scanning system

3. Modeling

The model is composed of sets of scan lines which could serve effective clues to the detection of objects. Then the mapping function converts the scan line domain into pixel domain, which generates a simulation of array scanning status. By using the domain mapping, designer can understand the density variations in certain areas and the design criteria with guide lines for the determination of important factors that influence system functionalities. In addition to an introduction of the array scanning model, a series of systemic analysis will estimate functionalities with regard to the simulated density of valid scan lines. A valid scan line is the virtual line that connects emitter and receiver with sufficient light strength. When an object is on that line, a shadow blocks the receiver's detection of light, which becomes a clue of an existence of an object. Density of valid scan lines is closely related to shadow effect, which precludes infrared array scanning from multi-touch detection. Low density of valid scan lines results in large shadows on the screen; as a consequence, ghost points may emerge. By analysis via simulation, potential performance of object detection on a given design condition can be evaluated.

The proposed array scanning model is useful for various design setups of array scanning, allowing not only a linear array, but also 3-dimensional structures such as spheres, as well as circular array patterns. Furthermore, various design tolerances and clearance factors were considered as well. First, emitter and receiver models will be introduced, which describe light variations along the emission angle. Second, an array scanning system model is introduced as a conditional probability set of valid scan lines which corresponds to density distribution per each sensor pixel. Finally, a blocking function is proposed. When an object is placed on a screen, its shadow blocks infrared light from a receiver. The blocking function model simulates its shadow so as to determine whether the shadow sufficiently depletes light received by receiver. With the blocking function, minimum detection size is estimated. When the minimum detection size is determined, the size of the object can be determined. The object is a sort of base unit of area that measures the existence of objects. The smaller pixel map is applied, the fine detection of object is possible. However, it would increase computation time, and so may result in slower detection speeds. That is the reason the optimization of pixel map resolution must be determined. The blocking function provides the guideline for determination of the proper value of pixel map resolution.

3.1. Array Scanning Model

We construct the mathematical model for array scanning system. At first, we describe a scan line set as follows:

$$\begin{aligned} \mathbf{V} &= \left\{ v_{ij} \mid 0 < i, j < n, \quad i, j \in \mathbf{N} \right\} \\ \mathbf{H} &= \left\{ h_{ij} \mid 0 < i, j < m, \quad i, j \in \mathbf{N} \right\} \end{aligned} \tag{1}$$

where v_{ij} and h_{ij} are cross emission intensities of infrared light which i[th] emitter emits to j[th] receiver. The $\mathbf{V}$ is vertical scan line set and the $\mathbf{H}$ is horizontal scan line set. The scan line sets are shown in Figure 3. The *b* is the width of the scan lines which corresponds to the width of emitter and receiver. The *d* is a gap distance between LED emitters on an array. To define the effective infrared sensor array, the set which is composed of valid scan lines are described as follows:

$$\begin{aligned} &\mathbf{V}_{Valid} = \left\{ \delta_{ij} \mid 0 < i, j < n, \quad i, j \in \mathbf{N} \right\} \\ &where \\ &\delta_{ij} = \begin{cases} 0 & if\ v_{ij} < T_v \\ 1 & otherwise \end{cases} \end{aligned} \tag{2}$$

$$\begin{aligned} &\mathbf{H}_{Valid} = \left\{ \delta_{ij} \mid 0 < i, j < m, \quad i, j \in \mathbf{N} \right\} \\ &where \\ &\delta_{ij} = \begin{cases} 0 & if\ h_{ij} < T_h \\ 1 & otherwise \end{cases} \end{aligned} \tag{3}$$

where the $\mathbf{V}_{Valid}$ and $\mathbf{H}_{Valid}$ are the sets of valid scan lines which have sufficient intensity of infrared light. T_v and T_h are threshold values for determination whether the pair has a sufficient intensity for scanning or not. Those values are determined to minimize the shadow effect. The $\mathbf{V}$ and $\mathbf{H}$ are belonging to the scan line domain. To investigate overall pattern of mesh net of scan lines, those set should be transformed to the pixel map domain. The pixel map domain is a matrix of pixels which indicate density of scanning along the detection area.

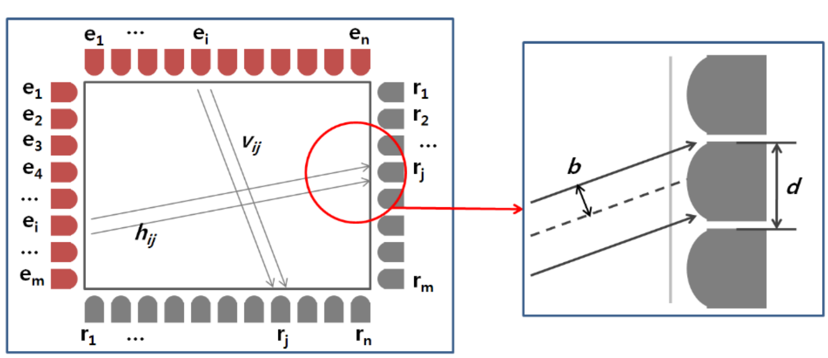
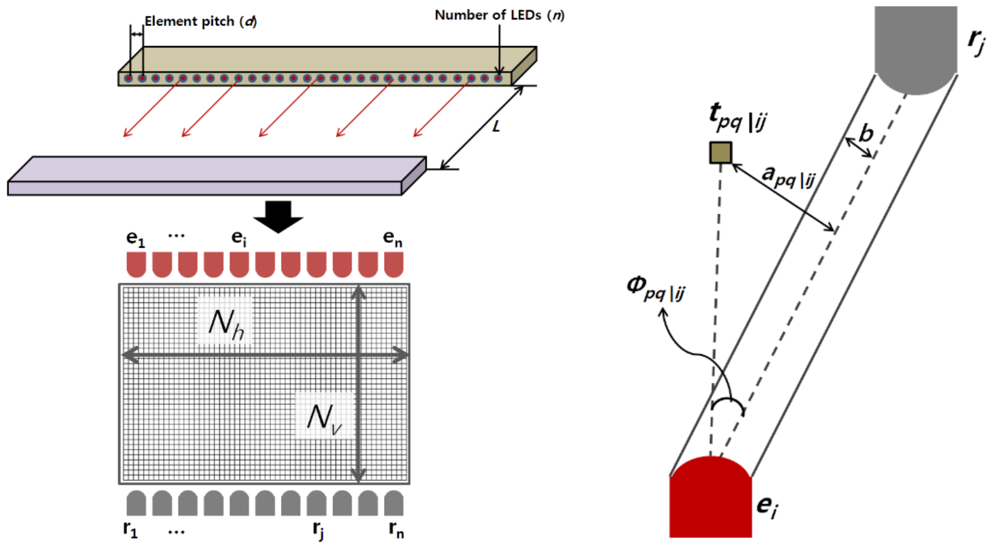


Figure 3. The set of cross-emission intensity of each emitter-receiver pair is described.



(a) (b)

L : Distance between an emitter array and a receiver array

d : Element pitch of LED emitters or IR receivers

n : Number of LED emitters or receivers

N_h : Number of pixels along horizontal direction (horizontal resolution)

N_v : Number of pixels along vertical direction (vertical resolution)

Figure 4. The pixel map domain consists of $N_v \times N_h$ numbers of pixels(a). A pixel which is located in the band *b* has a value of 1 (b).

As shown in Figure 4(a), The pixel is defined as a basic unit to identify object area. On the pixel domain, we can find object area with shadows. When all the valid scan line set draws scanning meshes on the pixel map domain, the initial state of 2D surface is fixed. We define a matrix for the pixel map domain as follows:

$$\mathbf{M} = \begin{bmatrix} t_{11} & t_{21} & .. & t_{N_h 1} \\ t_{12} & .. & .. & .. \\ .. & .. & .. & .. \\ t_{1N_v} & .. & .. & t_{N_h N_v} \end{bmatrix} \tag{4}$$

where $t_{N_h N_v}$ is pixel detected. When N_h is the number of pixels in horizontal direction of pixel map and N_v is that of vertical direction, $\mathbf{M}$ is a matrix whose dimension is $N_h \times N_v$, which represents detection resolution. The initial state matrix of array scanning $\mathbf{M}_0$ can be described as follows:

$$\begin{aligned} &\mathbf{V}_{Valid} \xrightarrow{f} \mathbf{M}_V \\ &\mathbf{H}_{Valid} \xrightarrow{f} \mathbf{M}_H \\ &\mathbf{M}_0 = \mathbf{M}_V + \mathbf{M}_H \end{aligned} \tag{5}$$

where *f* is a mapping function which converts the scan line domain into the pixel map domain. When the system uses vertical scanning only, $\mathbf{M}_0$ can be equivalent to $\mathbf{M}_V$.

3.2. Blocking Function

There is correlation between the scan line domain and the pixel map domain in terms of dimensions. For example, in a vertical scanning, the height of a pixel unit is $\frac{L}{N_v}$ and the width is $\frac{d \times n}{N_h}$. To transform $\mathbf{V}_{Valid}$ into $\mathbf{M}_0$, a series of calculations is defined as follows:

$$\phi_{pq|ij} = \tan^{-1}\left(\frac{L - q\frac{L}{N_v}}{p\frac{d \times n}{N_h} - i \cdot d}\right) - \tan^{-1}\left(\frac{L}{d \cdot (j-i)}\right) \tag{6}$$

$$a_{pq|ij} = \sqrt{(p\frac{d \times n}{N_h} - j \cdot d)^2 + (L - q\frac{L}{N_v})^2} \times \sin(\phi_{pq|ij}) \tag{7}$$

$$t_{pq|ij} = \begin{cases} 0 & if\ a_{pq|ij} > b \\ \\ 1 & otherwise \end{cases} \tag{8}$$

In Figure 4(b), $\phi_{pq|ij}$ is the relative angle between scan line from i^{th} emitter to j^{th} receiver and the pixel $t_{pq|ij}$. And $a_{pq|ij}$ is the normal distance between the pixel $t_{pq|ij}$ and the scan line. Thus, $\mathbf{M}_0$ can be calculated as follows:

$$\begin{aligned} &\mathbf{M}_0 = \left\{ \mathrm{t}_{pq} \,\middle|\, 0 < p < h,\ 0 < q < w \right\} \\ &where \\ &t_{pq} = \sum_{i,j=0}^{n} t_{pq|ij} \end{aligned} \tag{9}$$

Since $\mathbf{M}_0$ is the initial state matrix of array scanning system, which means the status that there is no object on a detection surface, all t_{pq} on the surface should have even level. Otherwise, non-uniformity may deteriorate reliability of object sensing. For the given area, the uniformity σ can be described as follows:

$$\begin{aligned} &\forall t_{pq}\ \ where \\ &p_{left\,end} \le p \le p_{right\,end} \\ &q_{top\,end} \le q \le q_{bottom\,end}, \\ &\sigma = Max(t_{pq}) - Min(t_{pq}) \end{aligned} \tag{10}$$

System designer defines an effective range of detection area. For all pixels on given range (e.g. from top-left to bottom-right of the surface), σ should be small enough to avoid excessive non-uniform density in scan lines. Large σ means that there will be relatively poor sensitive area. It is dependent on mounting pattern of emitters and receivers and scanning angle.

4. Object Detection Simulation

When objects are located on the detective area, shadows occur to block several scan lines. The blocked scan line set $\mathbf{V}_B$ and $\mathbf{H}_B$ can be described as follows:

$$\begin{aligned} \mathbf{V}_B &= \left\{ bv_{ij} \mid 0 < i, j < n,\ bv_{ij} < T_v,\quad bv_{ij} \in \mathbf{V}_{Valid} \right\} \\ \mathbf{H}_B &= \left\{ bh_{ij} \mid 0 < i, j < m,\ bh_{ij} < T_h,\ bh_{ij} \in \mathbf{H}_{Valid} \right\} \end{aligned} \tag{11}$$

where bv_{ij} and bh_{ij} are the blocked scan line intensity which drop down under the threshold value. Thus, we can derive resultant pixel domain as follows:

$$\begin{aligned} \mathbf{V}_R &= \mathbf{V}_{Valid} - \mathbf{V}_B \\ \mathbf{H}_R &= \mathbf{H}_{Valid} - \mathbf{H}_B \end{aligned} \tag{12}$$

Thus,

$$\begin{aligned} &\mathbf{V}_R \xrightarrow{f} \mathbf{M}_{VR} \\ &\mathbf{H}_R \xrightarrow{f} \mathbf{M}_{HR} \\ &\mathbf{M}_R = \mathbf{M}_{VR} + \mathbf{M}_{HR} \end{aligned} \tag{13}$$

where $\mathbf{V}_R$ and $\mathbf{H}_R$ are scan line set after object blocks several valid scan lines. $\mathbf{M}_R$ is the resultant pixel map matrix of the area. Now we can define the matrix $\mathbf{M}_{Shadow}$ as follows:

$$\mathbf{M}_{Shadow} = \mathbf{M}_0 - \mathbf{M}_R \tag{14}$$

The pixel map which their values are decreased under the detection threshold are considered to be included in object area. The opposite case is considered to be the shadow trace mentioned in the problem statement. The matrix $\mathbf{M}_{Touch}$ can be determined by the object detection threshold as follows:

$$\mathbf{M}_{Touch} = \left\{ t_{pq} \mid t_{pq} < T_T,\ t_{pq} \in \mathbf{M}_{Shadow} \right\} \tag{15}$$

where T_T is the detection threshold value. T_T has to be designed so that $Area(\mathbf{M}_{Touch})$ is approximately equivalent to the size of the object. $Area(\mathbf{M}_{Touch})$ can be defined as follows:

$$\begin{aligned} &Area(\mathbf{M}_{Touch}) = \sum_{p=0}^{N_h} \sum_{q=0}^{N_v} \delta_{pq} \frac{L}{N_v} \frac{d \times n}{N_h} \\ &where \\ &\delta_{pq} = \begin{cases} 0 & if\ \ t_{pq} < T_T \\ 1 & otherwise \end{cases} \end{aligned} \tag{16}$$

Figure 5 shows the initial state matrix of the array scanning $\mathbf{M}_0$, the shadow area matrix $\mathbf{M}_{Shadow}$, the point matrix $\mathbf{M}_{Touch}$.. When the object is detected by the array scan, the pixel map changes as shown in Figure 6(single object detection) and 7(multi objects detection).

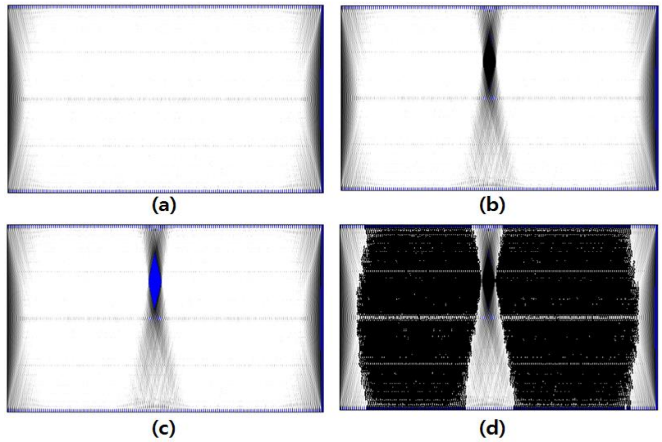


Figure 5. The detection area should be differentiated from shadow by the T_T. (a) shows the initial state matrix of the array scanning $\mathbf{M}_0$ and (b) shows the shadow area matrix $\mathbf{M}_{Shadow}$. (c) shows detection area $\mathbf{M}_{Touch}$ with blue color. The remaining shadow is shown as (d).

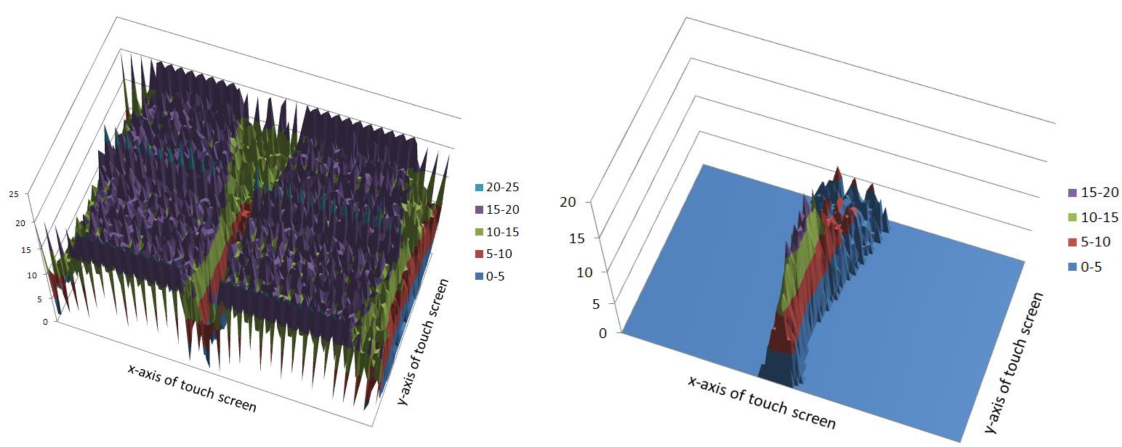


Figure 6. 3D diagram of the resultant pixel matrix $\mathbf{M}_R$ (a) and $\mathbf{M}_{Shadow}$ (b) with single object.

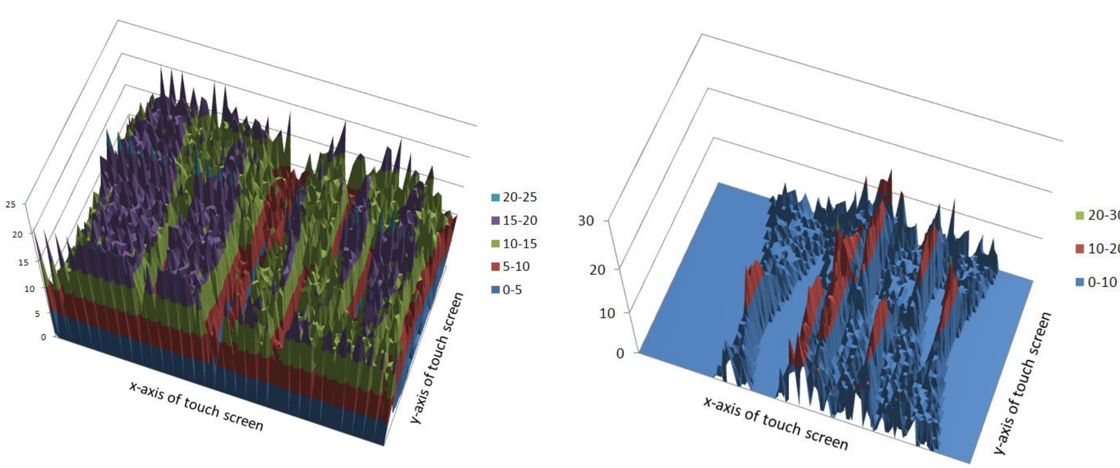


Figure 7. 3D diagram of the resultant pixel matrix $\mathbf{M}_R$ (a) and $\mathbf{M}_{Shadow}$ (b) with multi objects.

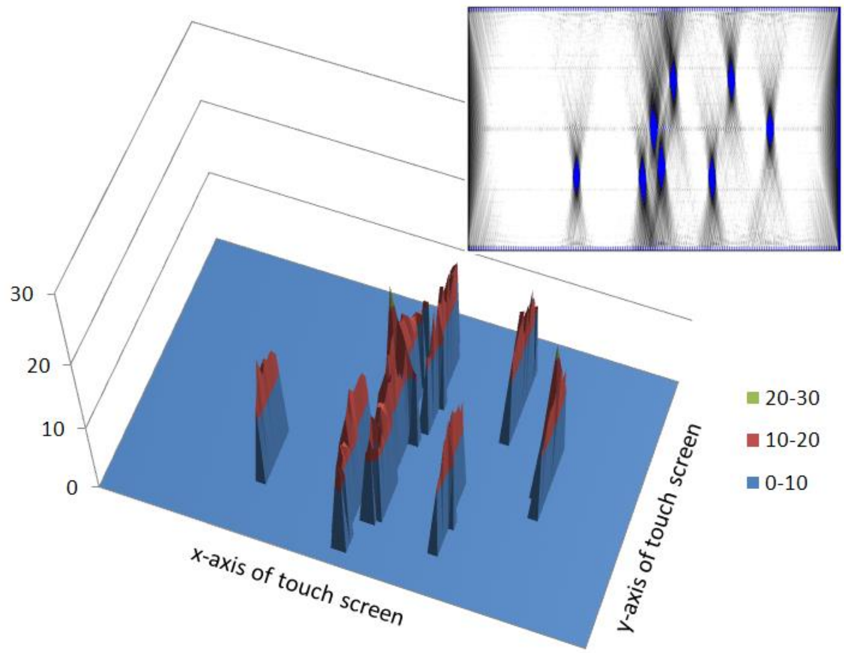


Figure 8. 3D diagram of the point matrix $\mathbf{M}_{Touch}$ with multi-object point.

Figure 8 shows resultant detection areas which are determined by the detection threshold value T_T . The detection information can be described with two factors, the position and the size. The size can be represented by bounding square which encloses each separated groups of the area. For example, the areas can be segmented as certain groups of detection areas which have no connectivity among them. These groups can be described with squares as shown in figure 9. And the position can be calculated as a center of mass for each separate bounding square.

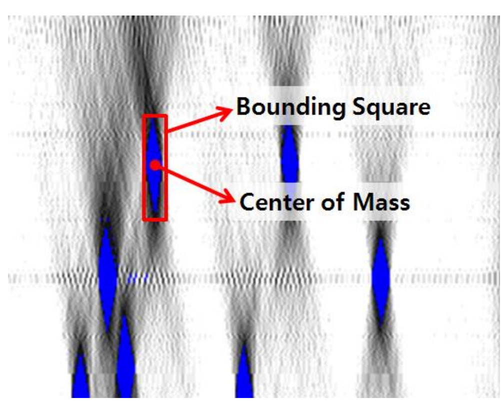


Figure 9. Bounding square and center of mass can be a description of detection information

5. Conclusion

There could be many methods for allowing us to understand how the array scanning strategy we have described might affect multi-object detection. In an effort to uncover a baseline, we concentrate on constructions of numerical models including not only LED but also systemic structures of arrays. There exists a myriad of mechanisms for detecting objects[5][6][7]. We suggested a series of analyses of infrared array scanning which will allow system designers to estimate functional performance for a given design condition. This study would provide a basis for the design of infrared array scanning system, rather than laying out a set of specs intended only for a particular type of 2D array sensor.

Acknowledgement

Followings are results of a study on the “Convergence and Open Sharing System” Program through the National Research Foundation of Korea(NRF) finded by the Ministry of Education.

References

[1] K.H. Lee, R. Ehsani, “Comparison of two 2D laser scanners for sensing object distances, shapes, and surface patterns”, Computers and Electronics in Agriculture, Volume 60, Issue 2, 250-262, 2008, https://doi.org/10.1016/j.compag.2007.08.007.

[2] G.C. Stockman, P. Morawski, “2D object acquisition using circular scanning”, Pattern Recognition, Volume 17, Issue 3, Pages 321-330, 1984, https://doi.org/10.1016/0031-3203(84)90082-7.

[3] Mihálik, Michal, Marian Hruboš, P. Vestenický, P. Holečko, D. Nemec, B. Malobický, J. Mihálik, "A Method for Detecting Dynamic Objects Using 2D LiDAR Based on Scan Matching" Applied Sciences 12, no. 11: 5641. 2022, https://doi.org/10.3390/app12115641

[4] J. Moeller, A. Kerne, S. Damaraju. “ZeroTouch: a zero-thickness optical multi-touch force field.” In CHI '11 Extended Abstracts on Human Factors in Computing Systems (CHI EA '11). Association for Computing Machinery, New York, NY, USA, 1165–1170. 2011. https://doi.org/10.1145/1979742.1979710

[5] K. Kim, S. Lee, “Development of Structured Light 3D Scanner Based on Image Processing. International Journal of Internet, Broadcasting and Communication”, 11(4), 49–58. 2019, https://doi.org/10.7236/IJIBC.2019.11.4.49

[6] H. Kim, “Surface Parameterization Based on Circular Centering Property”, International Journal of Internet, Broadcasting and Communication, 11(1), 54–59. 2019, https://doi.org/10.7236/IJIBC.2019.11.1.54

[7] J. Kim, “Single Image Fog Removal based on JBDC and Pixel-based Transmission Estimation”, International Journal of Advanced Smart Convergence, 9(3), 118–126. 2020, https://doi.org/10.7236/IJASC.2020.9.3.118