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Techniques and Algorithms for Selection of Number and Locations of Temperature Sensors for Greenhouse

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ABSTRACT

Accurate measurement of spatial distribution of temperature and other micro-climatic parameters inside a greenhouse is important for their monitoring and control. To that end, suitable sensors in adequate number need to be appropriately distributed inside the greenhouse. Two new techniques, namely, Equal Temperature-Step (ETS) and Equal Segment-Area (ESA) techniques are proposed here for the selection of an optimal number of temperature sensors and their locations in a greenhouse with the objective of minimizing the Average Error (AVE), Root Mean Square Error (RMSE) and Maximum Temperature Error (MTE). These techniques were compared with TAE technique, reported earlier. Computational algorithms for the proposed techniques are also presented. Mathematical model of a typical temperature profile along the length of greenhouse has been developed and used for evaluation of the performance. The study shows that the minima of the three errors did not occur simultaneously for any number and locations of the sensors for TAE method. For ETS and ESA methods, the minima of all the three errors occured for the same number and locations of sensors and a smaller number of sensors needed to be used from error consideration. However, reduction in the errors with increase in the number of sensors was steeper for ETS technique as compared to ESA technique, thereby making ETS the best technique. This work can be readily adopted for the measurement of spatial distribution of any other parameter in a greenhouse.

Keywords: Average error, intelligent greenhouse, maximum error, profile, root mean square error, spatial distribution, wireless sensor network

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INTRODUCTION

Growth of plants inside a greenhouse depends on several factors, like temperature of the air inside the greenhouse, humidity, soil moisture, intensity of sunlight, carbon dioxide concentration, nutrient level in soil (Ahonen et al., 2008). But temperature is considered as most important among them. Moreover, the environment inside the greenhouse is often non-uniform and dynamic in nature (Pahuja et al., 2012). Hence, to get a good picture of the microclimate of the greenhouse, both spatial and temporal distributions of the selected parameters are important. As for the temperature, its average value inside the greenhouse is of prime importance in case a single crop is grown. In case multiple crops are being grown simultaneously, the profile of the temperature becomes important. To measure the average value and/or the profile of the temperature, adequate number of sensors appropriately located in the greenhouse will be required. Sensors need to be properly distributed along the length as well as the breadth of the greenhouse to obtain the average temperature and/or the temperature profile within acceptable accuracy limits. This calls for optimization of the number of sensors and their locations along both length and breadth of a greenhouse. Moreover, for the development of a cost-effective wireless sensor network (WSN) based measurement system, the deployment of sensor nodes in an Intelligent Greenhouse (IGH) needs to be considered. While an inadequate number of sensors would yield an incorrect measurement of average temperature and temperature profile inside the greenhouse, increasing their number would unnecessarily increase the cost of sensors and sensor nodes. Further, if, in line with the current trend, WSN based temperature measurement system were to be used, the WSN would also become unduly complex and expensive (Pahuja et al., 2013). In order to resolve these issues, it is essential to develop suitable techniques and computational algorithms for selecting an optimal number of sensors and their locations. No research paper focusing on the techniques or algorithms related to selection of number and locations of sensors in a greenhouse could be found in the literature. However, some papers obliquely related to this subject are briefly reviewed in the following paragraphs.

Balendonk et al. (2010) used low cost wireless sensors to investigate the horizontal distribution of temperature and relative humidity and to evaluate the number of sensors needed to accurately estimate the spatial and temporal climate distribution. Authors performed trials in four commercial greenhouses, for which 100 sensors were used. The sensors were placed *at equal distances*. They concluded that 9 sensors per hectare (±33 m spacing) could measure ΔT and ΔRH without missing a cold or wet spot.

Bendigeri and Mallapur (2014) proposed and simulated an energy efficient node placement algorithm (EENPA) for wireless sensor network. The authors worked on a circular node deployment technique instead of random placement of nodes. The simulation was carried out on Qualnet simulator. Simulation results revealed that the proposed algorithm did optimize the energy consumption in the network.

Pandey and Rizvi (2014) analysed certain strategies of node placement in wireless sensor networks. The authors have, in their paper, discussed static and dynamic positioning of nodes and compared various strategies of node positioning in wireless sensor networks. Both, role-based and objective-based placement strategies were considered in detail.

Ryu et al. (2014) conducted experiments in two greenhouses to investigate the spatial, vertical and temporal variability of ambient environment with two different crops. At every layer of measurement the sensors were equi-spaced on the assumption of spatial symmetry of the environmental conditions. The paper did not target on the optimizing the number and distribution of sensors.

Zorzeto et al. (2014) evaluated the homogeneity of distribution of two environmental parameters, temperature and humidity, using wireless sensors in a 1994 m^2 greenhouse with lettuce cultivation. Three sensors were installed in different positions in the greenhouse for 11 days and their hourly averages were collected. Authors concluded that, to assess the homogeneity of temperature and humidity with high accuracy, the number and the locations of the sensors needed to be considered as per application.

Lamprinos et al. (2015) studied the variability of the temperature and humidity inside a greenhouse of 160 m^2 area. The authors had developed a WSN of six nodes out of which three were sensor nodes, one router, one weather station and one coordinating node. In this paper also the distribution of the nodes considered was random.

Somov et al. (2018) developed an IoT system for an operational greenhouse. For the development of the WSN, authors used WaspMote sensor nodes in a mesh topology. The sensor nodes used were having pH, electric conductivity, solution flow, temperature, photosynthetically active radiation (PAR), humidity and CO_2 measuring sensors .The greenhouse had two zones zone A and zone B. Zone A was used for seed propagation and Zone B for growing plants. Two nodes per tray were deployed with one node in the beginning and the second at the end of each tray.

Lata and Verma (2017) proposed and successfully investigated two approaches namely equal sensor spacing method and trial and error method for the selection of number and locations of temperature sensors in a greenhouse. The trial and error method proved a superior as it offered better accuracy with fewer sensors.

Two new techniques Equal Temperature-Step (ETS) method and Equal Segment-Area (ETA) method are proposed for optimizing the number and locations of temperature sensors from the consideration of various measurement errors and are compared with the Trial-and-Error (TAE) method reported in Lata and Verma (2017).

For each method, a computational algorithm has been developed for determining the optimal number and locations of the sensors. Performance of each technique is investigated in terms of Percentage Average Error (%AVE), Percentage Root Mean Square Error (%RMSE), and Maximum Temperature Error (ΔT_{max}).

Evaluation of the two new techniques and their comparison with the TAE technique are carried out for temperature measurements along the length of the greenhouse only.

The organization of rest of the paper is as follows: A typical temperature profile inside a greenhouse is considered in the next section, while the section thereafter discusses the parameters used for evaluation of the proposed techniques. Subsequent sections are devoted to the description of principles and the algorithms for the proposed techniques, results of evaluation and discussions thereon. Conclusions and scope of future work are presented in the last section.

MATHEMATICAL MODEL OF TEMPERATURE PROFILE INSIDE GREENHOUSE

The greenhouse and the temperature profile inside it have been taken from Lata and Verma (2017) to facilitate comparison of the proposed new techniques with the trial and error method reported in that reference. Thus the greenhouse considered is of 20 m length and W width. It has a door of 2 m height located at the centre of one of the width- wise walls and an air cooler placed at the opposite wall. A layout of the greenhouse is given in the Figure 1.

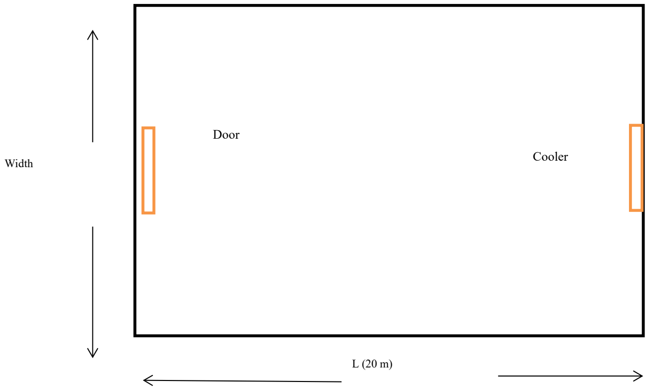

Figure 1. Greenhouse Layout

The temperature profile was developed under following three assumptions:

When the door is closed the temperature just inside the door is 30˚C and temperature outside is 40˚C.

When the door is opened there is a sudden rise in temperature near the door and it decreases exponentially along the length of the greenhouse.

One cooler is kept on opposite side of the door and the temperature at this wall is 20˚C.

The linear component of the profile y_1 is represented by the equation

$$y_1 = mx + c \tag{1}$$

where x = distance from the door along the length of the greenhouse

y_1= temperature varying as a function of x

m= slope of the temperature profile and

c = intercept on the temperature axis.

Applying the assumptions (i) and (iii) listed above, the values of m and c are -0.5˚C/m and 30˚C respectively.

The exponentially component of the temperature profile y_2 is given by

$$y_2 = a\,e^{-x/b} \tag{2}$$

where y_2 = temperature rise at a distance x from the door

a= temperature rise at the door

b= space constant for the exponential decay curve.

As per the assumption (i) outside temperature is 40°C, the temperature near the door on opening would abruptly rise from 30°C to 40°C. Thus, a =10°C. Further it is further it is assumed that space constant ‘b’ for the exponential decay is 2m.

The overall temperature profile inside the greenhouse from the door to the air cooler is obtained by addition of equations 1 and 2, and putting the values of various constants

$$T(x) = y_1 + y_2$$

$$= (mx + c) + (a\,e^{-x/b}) \tag{3}$$

$$T(x) = (-0.5x + 30) + 10e^{-0.5x} \tag{4}$$

This temperature profile is shown in Figure 2.

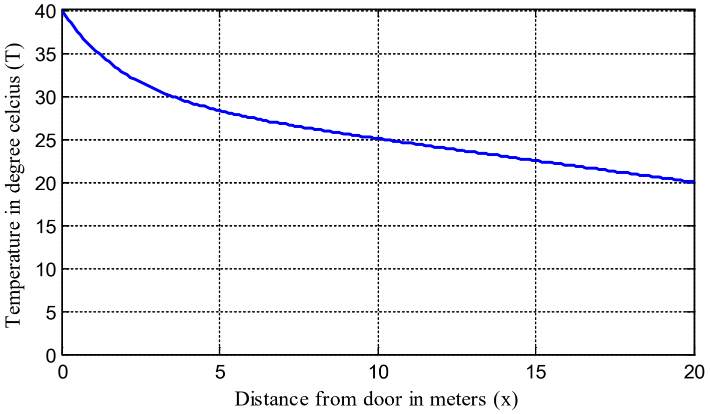

Figure 2. Overall Temperature Profile inside Greenhouse

EVALUATION PARAMETERS

The actual (assumed) temperature profile along the length of GH, T(x), mathematically represented by equation 4, is again shown in Figure 3 (a). For explaining the evaluation process, let the temperature profile curve be broken into four segments (the basis of segmentation is different for the three techniques of selecting the number and locations of sensors). Let a temperature sensor be placed at the middle of each segment and the temperature measured by the sensor be assumed as valid over that segment. The stepped temperature profile so obtained from the sensor measurements, *$T_m(x)$,* and the variation of square of error with distance from the door are shown in Figure 3 (a) and (b) , respectively. Mathematically, *$T_m(x)$,* can be expressed by the following relations:

$$T_m(x) = \left. \begin{matrix} T_1 & for\ 0 < x < x_1 \\ T_2 & for\ x_1 < x < x_2 \\ T_3 & for\ x_2 < x < x_3 \\ T_4 & for\ x_3 < x < x_4 \end{matrix} \right\} \quad (5)$$

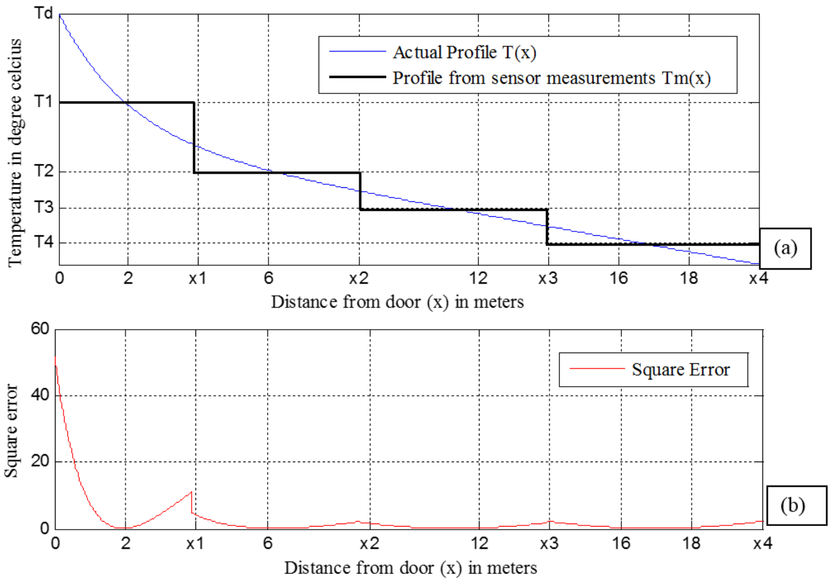

Figure 3. (a) Temperature profiles and (b) Variation of square error with distance from door

For obtaining a temperature profile from sensor data exactly matching with the actual temperature profile, an infinite number of sensors would be required. As per established engineering practices, a small mismatch should always be acceptable. The mismatch can be quantified in terms of certain errors. For that purpose, Percentage average error, Percentage RMS error and Maximum error are used as bases for the evaluation and comparison of the three techniques.

Calculation of Percentage Average Error (%AVE)

The average value of measured temperature along the whole length, T_{avm}, can be obtained by averaging $T_{m(}$x) over 0 to L. That is,

$$T_{avm} = 1/L \int_0^L T_m(x)\ dx \tag{6}$$

Similarly, the theoretical average value of the temperature along the whole length, T_{avth}, can be obtained by averaging T(x), that is

$$T_{avth} = 1/L \int_0^L T(x)\, dx \tag{7}$$

Therefore, the %AVE in the measured profile can be written as

$$\%AVE = \frac{(T_{avm} - T_{avth})}{T_{avth}} * 100 \tag{8}$$

Calculation of Percentage RMS Error (%RMSE)

The error at a distance x in the measured profile is given by

$$\varepsilon(x) = T_m\ (x) - T(x) \tag{9}$$

The squared error at a distance x will be

$$\mathrm{\varepsilon^2(x) = [T_m\ (x) - T(x)]^2} \tag{10}$$

So the RMSE along the whole length of GH (L) is given by

$$RMSE = \sqrt{\frac{1}{L}\left[\int_0^L [T_m - T(x)]^2\ dx\right.} \tag{11}$$

In order to indicate the closeness of the measured profile, $T_m(x)$, to the actual temperature profile, T(x), another unit-less percentage error is defined here. It is taken as the ratio of RMSE to the theoretical value of average temperature along the whole length (T_{avth}), expressed in percentage. Thus

$$\%RMSE = \frac{(RMSE)}{T_{avth}} * 100 \tag{12}$$

Calculation of Maximum Error | ΔT_{max} |

The maximum temperature error | ΔT_{max} | at any point along the profile is yet another indicator of the deviation of the measured profile from the theoretical one, and can be evaluated using the following equation:

$$|\Delta T_{max}| = Max\ [T_m\ (x) - T(x)] \tag{13}$$

DESCRIPTION OF TECHNIQUES

The TAE method proposed in Lata and Verma (2017) and the two newly proposed techniques are described in the following subsections.

Trial-and-Error (TAE) Method

The principle of TAE method proposed in Lata & Verma, 2017 is illustrated in Figure 4 for four sensors (n=4). The minimum number of sensors, n_{min} is assumed as 3 and the minimum spacing between any two sensors is assumed as 2.0m. Therefore, for L=20 m the maximum number of sensors, n_{max} is 20.0/2.0 or 10. The locations of the two extreme sensors are fixed at a distance of $L/2n_{max\,=}$ 1.0 m from the door and cooler side walls, respectively.

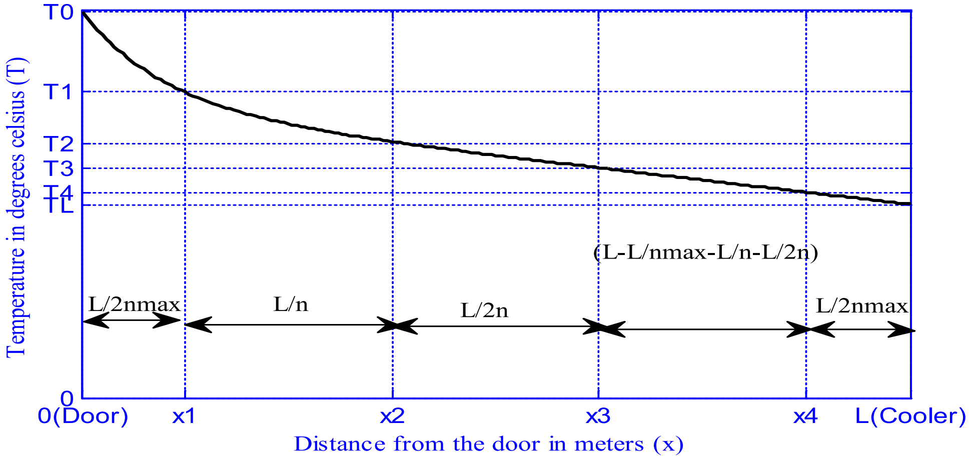

Figure 4. Principle of TAE Method illustrated for Four Sensors

In first trial, the second sensor (S2) from the door side was placed at a distance of L/2n, subject to the condition that it should not be less than 2m from the first sensor S1 and moved further in steps of 1m in the subsequent trials/options. The successive sensors were separated by a distance of L/n. Such trials were made with different number of sensors (3, 4, and so on) and with different placement options. For each option, the average temperature that would be measured by the sensors was calculated and compared with the theoretical average temperature given by equation (7) and the %AVE is determined from equation (8). Similarly, %RMSE and Maximum Error were calculated from equations (11) (12) and (13) respectively.

Equal Temperature-Step (ETS) Method

This method aims at optimizing the number and locations of sensors by segmenting the profile curve on the basis of equal temperature steps. As in the earlier methods, the minimum number of sensors is taken as 3 and the minimum spacing between any two sensors as 2.0m.

ETS Principle

In this approach, whole length of GH (L) is divided into 'n' segments and a sensor is placed at the middle of each segment such that the weighted average of the temperatures measured by the sensors has minimum error with respect to the theoretical average value. The nature of segmentation for n=4 is illustrated in Figure 5, where the first segment is narrowest and the last segment is the widest, and there is a progressive increase in the width in between.

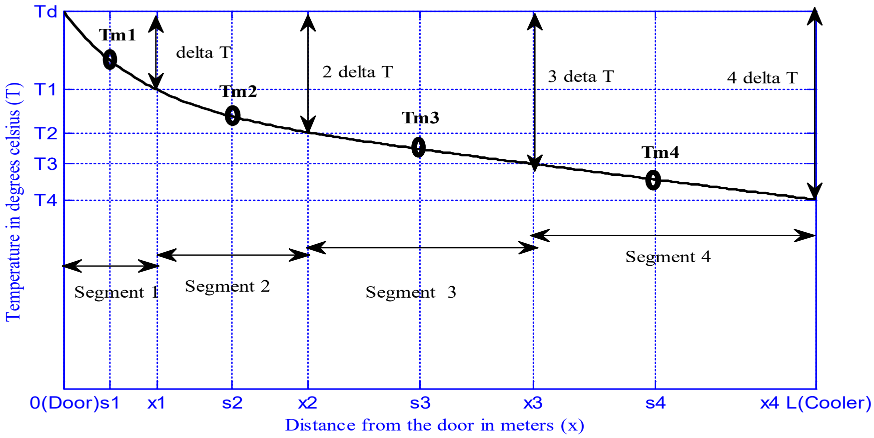

Figure 5. Sensor locations for ETS Method

The principle used here is that the drop from door side temperature (T_d) to cooler side temperature (T_c) is divided into equal steps of ΔT, such that

$$\Delta T = (T_d - T_C)/4 \tag{14}$$

For any general value of n, the relation (14) will become

$$\Delta T = (T_d - T_C)/n \tag{15}$$

The temperatures measured by sensors placed at the middle points of the segments are indicated in the Figure 5 as T_{m1}, T_{m2}, T_{m3} and so on. The weighted average temperature calculated from these values is given by

$$T_{avm} = \frac{1}{L}\sum_{j=1}^{n} T_{mj}\left(x_j - x_{j-1}\right), \qquad x_0 = 0 \tag{16}$$

The percentage error in the measured average temperature can be determined using equation (8), %RMSE using equations (11) and (12) and maximum error using equation (13).These errors are calculated using the above process for different values of 'n' within the limits suggested above, i.e. 3 to 10. The value of 'n' that results in minimum errors is finally selected as the optimal number of sensors to be used. The corresponding locations of the sensors S_1, S_2, S_3 etc. become the optimal locations of these sensors.

Computational Algorithm for ETS

Based on the optimization principle enumerated above, following are the computational steps (algorithm):

Step 1. Calculate the theoretical average temperature from equation (7).

Step 2. Take n=3 (the minimum suggested number of sensors).

Step 3. Calculate temperature step ΔT from equation (15).

Step 4. Calculate the temperatures at the end points of segments from

$$T_j = T_d - j\Delta T, j = \{1,2,3,--- -n\} \tag{17}$$

Step 5. For each value of the temperature $T_{j,}$ j= {1, 2, 3, -----n}, determined in step 4, solve equation 4 numerically to find the corresponding distance x_j (end of j^{th} segment), so that

$$T_j = T(x_j), j = \{1,2,3,-- -n\} \tag{18}$$

(18) **Step 6.** Calculate the locations of sensors (distance from door) s_1, s_2 etc. from the equation:

$$s_j = (x_j - x_{j-1})/2 \quad , \qquad j = \{1,2,3,-- -n\}, x_0 = 0 \tag{19}$$

Step 7. Calculate the temperatures measured by various sensors from equation 4 by substituting s_j for x, so that

$$T_{mj} = T(s_j), \qquad j = \{1,2,3,-- -n\} \tag{20}$$

Step 8. Calculate the weighted average of measured temperatures using equation (16).

Step 9. Calculate %AVE using equation (8).

Step 10. Calculate the profile from the sensor measurements $T_m(x)$ as per equation (5).

Step 11. Calculate RMSE using equation (11) and % RMSE using equation (12).

Step 12. Calculate the maximum temperature error using equation (13).

Step 13. Repeat steps 2 to 12 for n=4, 5 etc. up to the maximum suggested number of sensors or until minima on the modulus of percentage average error versus 'n' curve is achieved.

Step 14. Identify the value of 'n' that gives minimum percentage average error. This is the optimal number of sensors.

Step 15. Take the positions of the sensors corresponding to the optimal value of 'n' from step 6 as the optimal locations of the sensors.

Equal Segment Area (ESA) Method

The method involves optimization of number of locations of sensors by splitting the total area under the profile curve into segments of equal areas.

ESA Principle

The whole area under the temperature versus distance graph along the length of the greenhouse is divided into segments of equal areas and a sensor is placed at the middle of each segment such that the weighted average of the temperatures measured by 'n' sensors has a minimum error with respect to the theoretical average value of the temperature along the length. The limits on the number of sensors are the same as taken in the ETS method. The principle of EAS method on temperature versus distance graph is illustrated in Figure 6 for n=4.

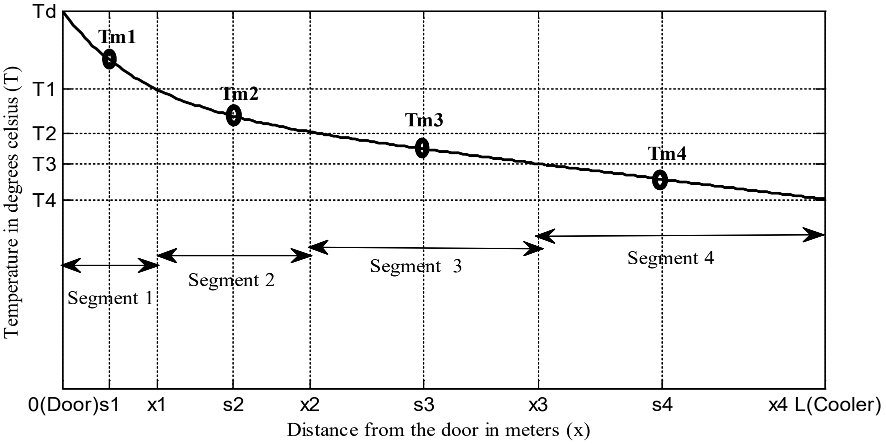

Figure 6. Sensor Locations for ESA Method

The whole area under the graph, A, is split into A_1, A_2, A_3 and A_4 such that

$$A_1 = A_2 = A_3 = A_4 = A/4 \tag{21}$$

For any general value of 'n', relation (21) becomes

Area of each segment = A/n (22)

Total area under the complete curve, A, is calculated as under:

$$A = \int_0^L T(x)\ dx \tag{23}$$

The end points of various segments x_1, x_2, etc. are then successively determined from the following relations:

$$A_1 = \int_0^{x_1} T(x)\ dx = {}^{A}/_{4};$$

$$A_2 = \int_{x1}^{x_2} T(x)\ dx = {}^{A}/_{4} \qquad \text{and so on} \tag{24}$$

Once the end points of various segments had been determined, the sensors were located at the midpoints along the length of the greenhouse. The temperatures measured by the sensors are indicated in Figure 6 as T_{m1}, T_{m2}, T_{m3} etc. The weighted average temperature was then calculated from these measured values using equation (16), the theoretical average temperature from equation (7) and percentage average error from equation (8). Like the ETS method, the calculations were repeated for different values of 'n' within the suggested limits and optimal number of sensors was identified from the minimum values of the average errors. The corresponding locations of sensors are their optimal locations.

Computational Algorithm for ESA

A computational algorithm for determining the optimal number and locations of sensors based on ESA approach is given below. It is identical to that for ETS approach except at steps 3 and 4.

Step 1. Calculate the theoretical average temperature from equation (7).

Step 2. Take n=3 (the minimum suggested number of sensors).

Step 3. Calculate total area under the curve, A, from equation (23).

Step 4. Calculate end points of various segments x_1, x_2 etc. one by one from the nonlinear equations (24) using an iterative numerical method.

Remaining steps are identical to those of the algorithm for equal temperature-step method.

RESULTS AND DISCUSSIONS

Three techniques TAE, ETS and ESA have been evaluated in respect of the Average, RMS and Maximum errors. The results for each technique along with discussion of the same are given in the following subsections.

TAE Evaluation

The Trial and error process has been applied by varying the number of sensors from 3 to 5. The results for various number of sensors and placement options are given as follows.

Results for Three Sensors (TAE)

In this exercise, three sensors were placed in the greenhouse. The positions of the two extreme sensors (S_1 & S_3) were fixed at 1.0m and 19.0m. In the first option, the second sensor S_2 was placed at a spacing of L/2n=20/6=3.33m from S_1. In subsequent options, this spacing was increased in steps of 1.0m. For example, in option 2, the three sensors are placed at1.0m, 5.33m and 19.0m, respectively, from the door. Various temperature errors are calculated for each option and are given in Table 1.

A graph of these three errors vs. option number is shown in Figure 7. It is observed that %AVE reduces with the increasing option number, but the minima for %RMSE is obtained at option number 5 and the minima for $|\Delta T_{max}|$ occurs at option number 2. However the average error reduces linearly as the option number is increased from 1 to 10.The minima for |%AVE | is for option 10.

Table 1

Placement options along with evaluation errors for three sensors

Option Number	S_1 (m)	S_2 (m)	S_3 (m)	%AVE of TAE	%RMSE of TAE	$\lvert\Delta T_{max}\rvert$ of TAE
1	1.0	4.33	19.0	9.0366	15.7056	8.4818
2	1.0	5.33	19.0	7.8167	14.6369	7.5343
3	1.0	6.33	19.0	6.8246	13.8868	8.3082
4	1.0	7.33	19.0	5.9706	13.4205	8.9743
5	1.0	8.33	19.0	5.2005	13.2240	9.5750
6	1.0	9.33	19.0	4.4811	13.2885	10.1316
7	1.0	10.33	19.0	3.7925	13.6011	10.6732
8	1.0	11.33	19.0	3.1227	14.1413	11.1965
9	1.0	12.33	19.0	2.4642	14.8839	11.7093
10	1.0	13.33	19.0	1.8126	15.8000	12.2176

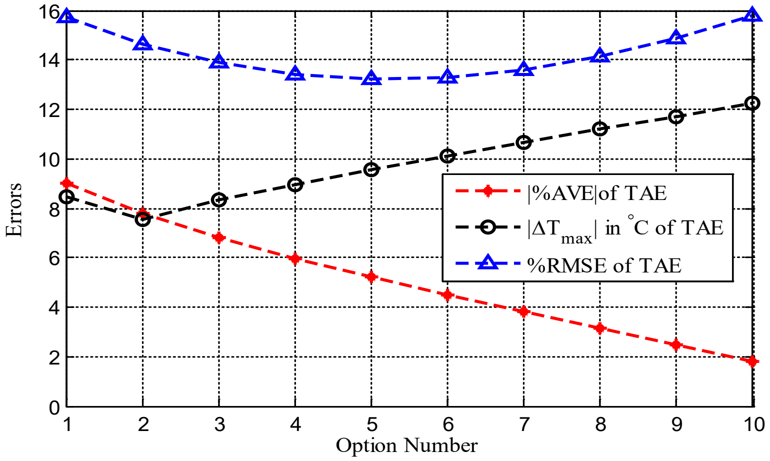

Figure 7. Errors vs. Option number for Three Sensors for TAE

Results for Four Sensors (TAE)

The locations of the two extreme sensors were taken the same as for three-sensor placement options. In the first option, S_2 was placed at a spacing of L/2n=20/8=2.5 m from S_1. This spacing was increased in steps of 1.0 m again. Sensors S_2 and S_3 were separated by a distance of L/n= 20/4 = 5m. Various errors calculated for the 8 options are given in Table 2 and are plotted against the sensor placement options in Figure 8.

Table 2

Placement options along with evaluation errors for four sensors

Option Number	S1 (m)	S2 (m)	S3 (m)	S4 (m)	%AVE of TAE	%RMSE of TAE	$\|\Delta T_{max}\|$ of TAE
1	1.0	3.5	8.5	19.0	7.6408	10.4051	5.5776
2	1.0	4.5	9.5	19.0	5.9679	9.9195	6.7613
3	1.0	5.5	10.5	19.0	4.5748	9.7979	7.6760
4	1.0	6.5	11.5	19.0	3.3516	9.9633	8.4276
5	1.0	7.5	12.5	19.0	2.2313	10.3646	9.0801
6	1.0	8.5	13.5	19.0	1.1735	10.9632	9.6727
7	1.0	9.5	14.5	19.0	0.1535	11.7255	10.2288
8	1.0	10.5	15.5	19.0	-0.8434	12.6224	10.7628

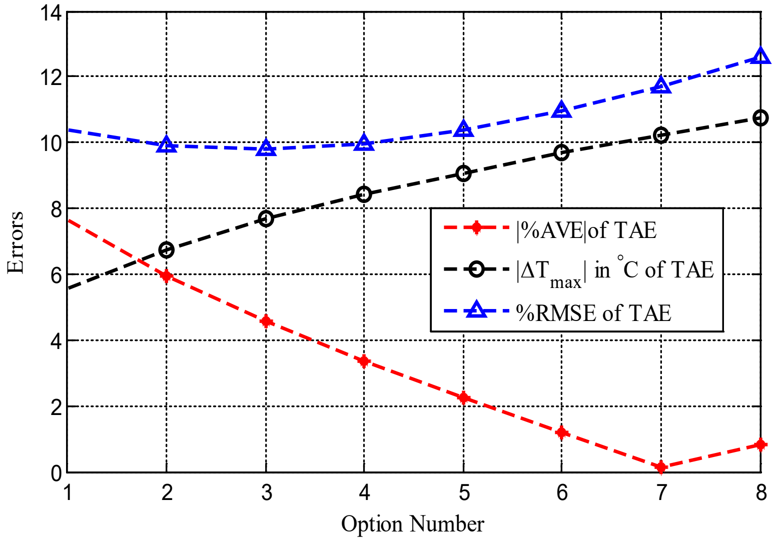

Figure 8. Various Errors vs. Option Number for Four Sensors for TAE

Least %AVE is 0.1535% for option 7, whereas the least %RMSE is 9.7979% for option 3 and the least values of $|\Delta T_{max}|$ is 5.5776 ˚C for option 1. Thus it had been observed that the three errors did not have simultaneous least values for any of the options. For n=4, $|\Delta T_{max}|$ is equal to 5.5776˚C for option 1 and gradually increases to 10.7628˚C for option 8.

Results for Five Sensors (TAE)

The positions of extreme two sensors were again fixed at 1.0 m and 19.0 m. Spacing of S_2 from S_1 is L/2n =20/10=2.0m in the first option, which was increased in the steps of 1.0 m in successive options. S_2, S_3, and S_4 were interspaced by L/n=20/5=4.0m. Various placement options along with the calculated errors given in Table 3 and graphs between various errors and sensor placement options are shown in Figure 9.

Table 3

Placement options along with evaluation errors for five sensors

Option Number	S_1 (m)	S_2 (m)	S_3 (m)	S_4 (m)	S_5 (m)	%AVE of TAE	%RMSE of TAE	$\lvert\Delta T_{max}\rvert$ of TAE
1	1.0	3.0	7.0	11.0	19.0	6.2617	7.8754	4.834
2	1.0	4.0	8.0	12.0	19.0	4.3287	7.6993	6.2119
3	1.0	5.0	9.0	13.0	19.0	2.7023	7.9697	7.2445
4	1.0	6.0	10.0	14.0	19.0	1.2619	8.5152	8.0674
5	1.0	7.0	11.0	15.0	19.0	-0.0658	9.2356	8.7633
6	1.0	8.0	12.0	16.0	19.0	-1.3251	10.0760	9.3821

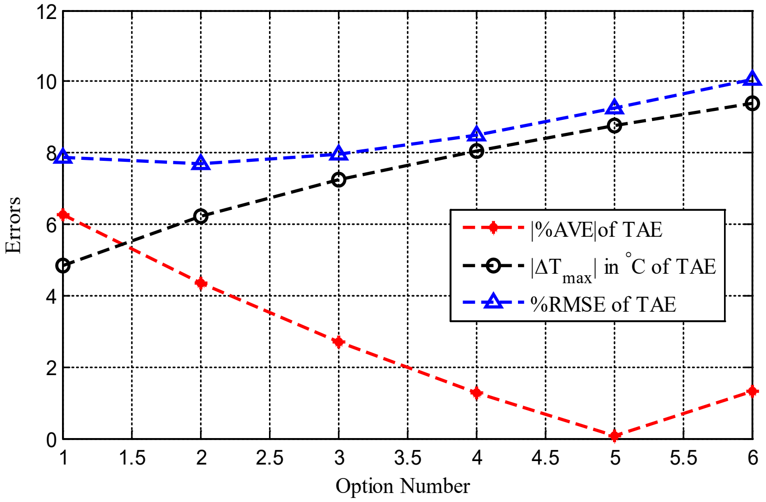

Figure 9. Various Errors vs. Option number for Five Sensors for TAE

It is observed that option 5 gives the least average error of 0.0658%, while option 2 gives the least value of RMS error (7.6993%). Maximum temperature error is lowest for option 1 and increases from option 1 to option 6.

Discussion of Results (TAE)

Based on the above trial-and-error exercise, the least values of %AVE for various number and placement options of sensors are summarized in Table 4 with the corresponding %RMSE and maximum temperature error.

Table 4

Least %AVE for various numbers of sensors along with corresponding %RMSE and $|\Delta T_{max}|$

Number of Sensors	Sensor Locations (Distances from door in m)	Least %AVE of TAE	%RMSE of TAE	$\|\Delta T_{max}\|$ of TAE
3	1.0, 13.33, 19.0	1.8126	15.8000	12.2176
4	1.0, 9.5, 14.5, 19.0	0.1535	11.7255	10.2288
5	1.0, 7.0, 11.0, 15.0, 19.0	-0.0658	9.2356	8.7633

It was observed that five sensors, located at 1.0 m, 7.0 m, 11.0 m, 15.0 m and 19 m, yielded a minimum error of 0.0658% in the measurement of average temperature, but the RMSE percentage was 9.2356% for this case, which was not the least. Hence this cannot be considered as the best choice of sensor placement. Least values of %RMSE for various number and placement of sensors are summarized in Table 5 with the corresponding values of %AVE and maximum temperature error. It was observed that five sensors, placed at 1.0m, 4.0m, 8.0m, 12.0m and 19.0m from the door gave %AVE of 4.3287% but corresponding %RMSE was 7.6993% which was quite large. Hence this option is not the best one.

Table 5

Least %RMSE and corresponding %AVE and $|\Delta T_{max}|$ *vs. number of sensors*

No. of Sensors	Sensor locations (Distances from door in m)	Least %RMSE of TAE	%AVE of TAE	$\|\Delta T_{max}\|$ of TAE
3	1.00,8.33,19.00	13.2240	5.2005	9.5750
4	1.00, 5.50, 10.50, 19.00	9.7979	4.5748	7.6760
5	1.00, 4.00,8.00,12.00,19.00	7.6993	4.3287	6.2119

ETS Evaluation

A software program was written in MATLAB as per the algorithm. The results of the computation are summarized in Table 6.

Table 6

Errors vs. number of Sensors for ETS method

No. of Sensors	Locations of Sensors (Distances from door in m)	%AVE of ETS	%RMSE of ETS	$\|\Delta T_{max}\|$ of ETS
3	0.8673, 4.4699, 7.2051	-0.5276	7.2831	7.2126
4	0.5829, 2.3284, 6.8088, 15.0637	-0.3375	5.5470	5.2875
5	0.4400, 1.5940, 3.8373, 8.7075, 16.0246	-0.2131	4.4036	4.1604

It may be noted that the percentage error in the average temperature for n = 4 is -0.3375%, root mean square error is 5.5470% and maximum temperature error is 5.2875˚C. For n=5, no significant reduction in these errors has been observed. Thus the optimal number of sensors can be selected as four and the optimal location of these sensors are 0.5829m, 2.3284m, 6.8088m, and 15.0637m from the door. It is important to note that the minima for all the errors occur for the same number and locations of sensors. A graph between various errors and the number of sensors is given in Figure 10.

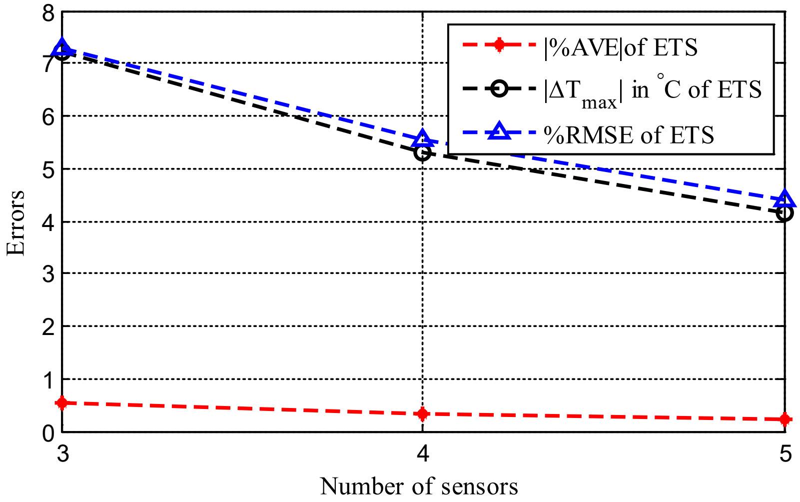

Figure 10. Various Errors vs. Number of Sensors for ETS method

It was observed that the trends for the errors against the number of sensors was similar. For the ETS technique, the minima of all the three errors occured for the same number and locations of sensors. Moreover, as the number of sensors was increased from 3 to 4 in the given situation, there was a significant reduction in each error. But as the number was further increased from 4 to 5, further reductions in the errors were only marginal. Hence instead of five sensors, only four sensors were sufficient. Thus, using ETS technique, cost of one sensor can be saved as compared with the TAE approach.

ESA Evaluation

The proposed ESA algorithm was implemented using MATLAB software. The evaluation was done using same theoretical temperature profile and parameters as used for the ETS and TAE methods. A summary of the results is given Table 7.

Table 7

Errors vs. number of sensors for equal segment-area method

No. of Sensors	Locations of Sensors (Distances from door in m)	%AVE of ESA	%RMSE of ESA	$\lvert\Delta T_{max}\rvert$ of ESA
3	2.6994, 8.7560, 16.0566	-0.9867	7.7687	8.7565
4	1.9440,6.2588,11.2934,16.9787	-0.5798	5.9874	6.6324
5	1.5116,4.8417, 8.6744, 12.8946, 17.5503	-0.3780	4.8483	6.0595

From the Table 7, it can be observed that the least value of all the three errors is corresponding to the same number of sensors, that is, n=5. Again, no significant improvement in %AVE, %RMSE and maximum temperature error is achieved by increasing the number of sensors from 4 to 5. Graphs of all the errors against the number of sensors are shown in Figure 11. For this technique too, the trends for the various errors are similar.

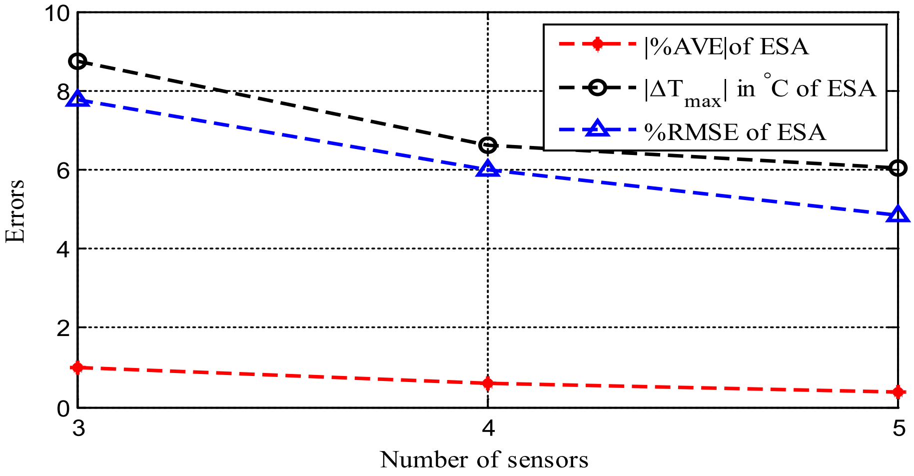

Figure 11. Various Errors vs. Number of Sensors for ESA Method

CONCLUSIONS AND FUTURE WORK

Two new techniques for the selection of an optimal number of temperature sensors and their locations in a greenhouse have been proposed and presented along with computational algorithms. These techniques have been compared with TAE method with respect to various errors. One clear advantage of the newly proposed techniques is that the process of selection of number and location of sensors can be automated using the algorithms developed and reported here. On the contrary, the TAE method which is not based on any logic cannot be automated and needs to be handled manually. Further it is also observed that the minima of the errors do not occur simultaneously for any number and locations of the sensors in TAE Method. On the other hand the minima of all the three errors for the two proposed techniques occur for the same number and locations of the sensors. The reduction in the errors with increase in the number of sensors is not as steep for ESA method as it is for ETS method. Hence it is concluded that the ETS is the best of the three techniques.

The present work has been carried out for the measurement of temperature profile alone and that too along the length of a greenhouse. As a future extension of this work, the proposed techniques can be applied for optimal selection of the number and locations of temperature sensors along the breadth as well. However, the constraint on the minimum number of sensors should to be relooked as per the width of the greenhouse. The resulting arrangement of the sensors will be a two-dimensional matrix. Moreover the techniques can be considered for the measurement of spatial distribution of other micro-climatic parameters in a greenhouse like humidity, luminosity, carbon-dioxide, soil moisture etc., and their performance may be evaluated and compared for different profiles.

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