IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 27, 2019, accepted June 29, 2019, date of publication July 3, 2019, date of current version July 19, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2926566

Evolutionary Greenhouse Layout Optimization for Rapid and Safe Robot Navigation

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This work was supported by the Cooperative Research Program for Agriculture Science and Technology Development, Rural Development Administration, South Korea, under Project PJ013871-02.

ABSTRACT There has been a rapid increase in demand for premium and safe agricultural products. Protected systems, such as greenhouses, are being adopted to meet demand. Ease in environmental regulation required for optimal plant growth is one of the advantages of protected systems. However, drawbacks such as poor ventilation in greenhouses can be fatal to the human workforce. This has led to the development of robots for hazardous tasks. Considering mobile robots are required to navigate down every aisle to perform a task in a greenhouse, and it is difficult to predict at which point the robot will need to return to the start point, to offload or refill for transportation and spraying schedules, respectively or battery charges. It will be commercially constraining to manufacture robots for every greenhouse specification. Efficient navigation can be done through path planning or layout design. In this paper, the greenhouse layout optimization problem was formulated to find optimal points on each bed to create an access path that would enable a reduction in the total travel time from all points in the greenhouse to the base point. The optimization problem was solved using differential evolution (DE), an evolutionary algorithm. Furthermore, we considered: 1) required space for inter-bed and rotary robot navigation; 2) standard bed specification; 3) area of the greenhouse; and 4) base point for starting and terminating navigation. The applicability of the proposed method was demonstrated by carrying out the experimental simulations on several greenhouse sizes.

INDEX TERMS Differential evolution, greenhouse, layout optimization, rapid and safe navigation, robots.

I. INTRODUCTION

The increasing demand for high quality and safe agricultural products combined with unpredictable climate variations have led to increasing use of protected production systems such as greenhouses [1]. Protected systems allow the regulation of macro and micro environments needed for optimal plant performance. In addition, extension of growing seasons, obtaining higher and better-quality yields by effectively controlling pests [2], [3] are other benefits of protected cultivation.

Greenhouse farming is a common form of protected cultivation which is a complex multiple-input multiple-output system [4]. Recently, research on greenhouse automation which is a vital component of mechanized cultivation, has been increasing globally [5]–[7] due to numerous benefits including reduction in the inhalation of chemicals which could be fatal or cause permanent damage to human health during spraying [8]–[11]; and precise and safe harvesting of agricultural products. In greenhouses, due to limited ventilation [10], [11] the risk of chemical inhalation during pesticide spraying is more likely. Autonomous pesticide spraying devices help in the precise application of pesticides and minimize human exposure to hazardous chemicals. The incorporation of harvesting robots also presents opportunities; for instance continuous long work hours as opposed to human labor that is prone to fatigue [12]. In addition, advanced recognition and control algorithms can better differentiate between ripened produce and harvest them with minimal or no damage to the produce compared to human labor. Also, application of robots will alleviate the need for expensive skilled labor [13]. Furthermore, the problems associated with

The associate editor coordinating the review of this manuscript and approving it for publication was Xiangtao Li.

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excess nutrient and pesticide runoff [14] from farms are greatly reduced and controlled in protected cultivation systems using accurate and precise robotic systems.

In greenhouses, various automation technologies are being employed for temperature and humidity control, soil preparation, and supply of water and nutrients [15]–[17]. Also, vital autonomous robotic systems are being adopted to perform tasks that are labor intensive and hazardous to humans due to the harsh conditions in greenhouses. These tasks include crop monitoring, treatment, harvesting and pest and disease detection. In automated greenhouses, a typical robotic application involves a single or multiple mobile robots navigating down the aisles reaching designated points for seeding, transplanting, harvesting, spraying pesticides [11] or crop monitoring. In a typical harvesting task, the harvesting robot is attached with a transportation robot with limited storage capacity. Once the transportation robot is full, it needs to go to the base station to empty the harvested produce and return to the harvesting robot. In addition to the various sizes and lengths of the greenhouses, due to the non-uniform spread of the yield and limited capacity of the robot, the points at which the transportation robot gets filled with produce is difficult to predict in advance. Similarly, in the case of pesticide application, the spraying robots have finite pesticide carrying capacity and must return to the base point to refill. The points from which the robots need to return to the base station is not known in advance. In addition, it is costly to manufacture robots for every greenhouse specification. Therefore, efficient robot navigation is crucial for successful robotic applications in greenhouses. Efficient robotic navigation can be achieved through- a) efficient path planning for the mobile robots for a given layout, and or b) designing a layout that would facilitate efficient robot navigation. In [18], a review of the common techniques for robot navigation in greenhouses was presented. In [19], [20], robotic manipulator motion planning was considered because of its importance in seeding, transplanting and harvesting automation. Path planning algorithms that include algorithms for direct displacement in the direction of the end-effector desired position have been explored in [21]–[24]. Further, the coverage path planning [25] for picking all the fruits on a scene or the time minimization [26] for moving from fruit to fruit are studied. Most of the research reported in literature considered path planning for a given layout without optimizing the layout for rapid navigation from point to point in the greenhouse. In [26] for example, designing a layout that would facilitate efficient robot navigation is not given as much importance as [25] where the path planning is done for a given layout.

Due to the reasons discussed above, for the harvesting and spraying tasks, the optimal consideration would be to develop a system that could simulate every greenhouse scenario where the travel time from any given point in the greenhouse to the base point is minimized. In conventional greenhouse layouts, this travel time during the harvesting and spraying operations is significantly high resulting in substantial loss of economic time. In literature, the authors have come across no study yet on greenhouse bed layout optimization considering the minimization of travel time for common tasks like harvesting and spraying or any other task for that matter. However, minimization in travel time has been investigated in warehouses using approaches like layout design, routing methods, order batching and zoning and storage assignment methods [27]–[29]. In [30], the warehouse layout was optimized functionally to the fluctuations in demand and inventory levels. The main goal was distance reduction and minimization in travel time. Strategies such as batching of orders in a parallel aisle warehouse has been investigated to minimize travel time [31]–[33]. However, in this study, the significant difference between warehouses, and greenhouses is that in warehouses the robots need not visit every bed during the order picking, whereas, in greenhouses, visits are required to each bed and plants on the bed [34], [35]. Unlike greenhouses, the location of the products in warehouses is always known and all that is required is a direct travel to the point-of-pick in a time-efficient way.

In this study, we optimized the accessibility of robots in greenhouse layouts by developing a system to find optimal and rapid navigation points. Beds were laid in parallel and the optimization problem was formulated to find optimal points on each bed to create an access path that would enable reduction in travel time from any point in the green house to the base point. The optimization problem was solved using Differential Evolution (DE) which is a popular evolutionary framework capable of handling complex optimization problems. In the developed system, the following considerations were included: – a) enough allowance for robot inter-bed and rotary movement considering robot size, b) standard bed specification for optimal plant growth, c) area of the greenhouse, and d) base point for robot starting and termination. These parameters can be changed to required specification. The travel times obtained by the proposed method were compared with the base-case of conventional layouts to demonstrate the effectiveness and quality of the designs obtained.

II. PROBLEM FORMULATION

Traditionally, greenhouses are rectangular with straight and parallel beds along the longest side and having adequate space between beds for robot and/or human movement referred to as picking aisles. The distance between the beds is usually standardized based on the requirements of the crop and/or the dimensions of the robots being considered. However, in large greenhouses, cross aisles that are right angles to the picking aisles are incorporated to facilitate better robot and/or human movement. Figure 1 provides the conventional greenhouse layout designs with and without cross aisles. In other words, conventional greenhouse layouts conform to these unspoken design rules - 1) picking aisles that allow the robot movement are straight and parallel, 2) cross aisles (if present) are straight and at right angles to the picking aisles. In conventional greenhouses where the primary work force comprises of humans, there are situations where items are

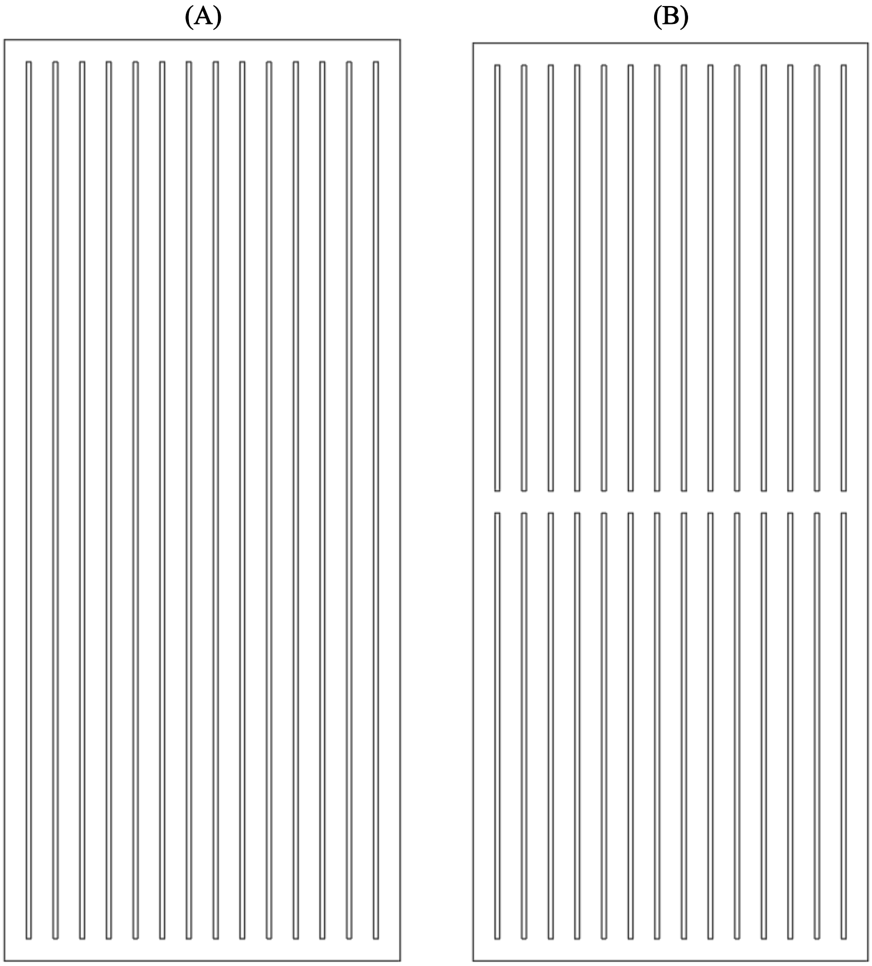

FIGURE 1. Conventional greenhouse design with different accessibility points; layouts without (A) and with (B) cross-aisle.

passed across to coworkers over the beds or in some instances, under the beds. However, in automated greenhouses, this is not practical with the presence of robots. Thus, conventional designs following the rules above reduce the free movement (accessibility) of the robots and increase their travel time. For example, as mentioned earlier, in a harvesting task, the transportation robot needs to empty its filled-up basket at the base point. In addition, the point at which the basket will fill up is not known in advance. Consequently, it is essential to find an optimal layout of beds that can facilitate easy robot movement and minimize the travel time from any given point to the start point. Recently, due to the increase in greenhouse automation, the incorporation of robots in greenhouses is gaining prominence thus making the design of optimal layout of beds crucial.

In warehouses, it is claimed that flying V layouts (Figure 2) offer a travel time reduction of 10% thus enabling a better robot movement [34]. The difference between the layouts in Figure 1(b) and Figure 2 is the position of the through point on each bed to enable the robot's movement across the beds. In other words, the accessibility or the travel time reduction depends on the position at which the individual beds are cut.

Therefore, in the current problem formulation, in accordance with literature, we assumed a rectangular shaped greenhouse where the beds of length (l) are placed parallel to each other along the longest side. Then, the aim was to identify the optimal position to cut each bed that would minimize the travel time from any point in the greenhouse to the base point. As shown in Figure 2, we used the following notations:

Bp – base point where the transportation robot empties or spraying robots refills its tank.

a- distance between beds (depends on the crop requirements and/or dimensions of the robots being considered)

b_i – position at which bed i is cut

w – half the width of cut on the beds (fixed for all beds)

nr = number of beds to the right of Bp

nl = number of beds to the left of Bp

br = location of beds to the right

bl = location of beds to the left

With loss of generality, we derive the expected travel time or travel cost considering the right side of the base point (Bp). Then, it is extended to the beds on the left side of the base point (Bp).

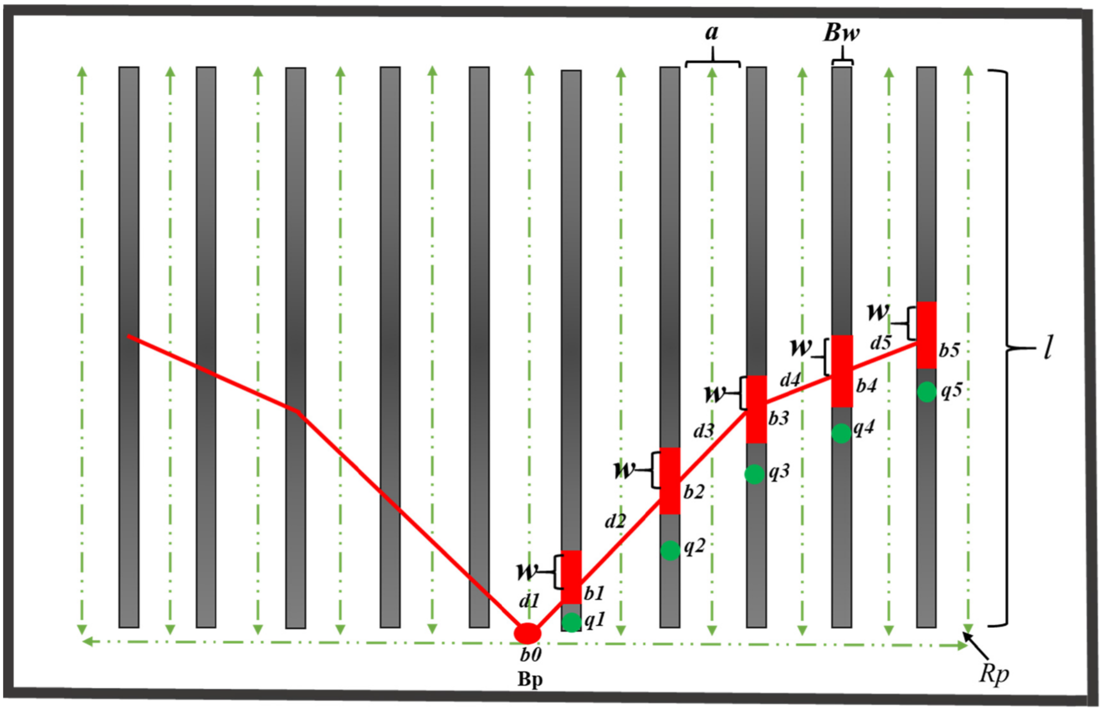

FIGURE 2. A representation of the approach used in this study to minimize the travel time to the base point from any location (where *Bw:* bed width, *a*: distance between beds, Bp: base point,*Rp*: regular path,*l*: length of beds, b_i: position at which bed *i* is cut, *w*: half the width of cut on the beds, d_i: robot travel distances, q_i: point on bed *i* at which the robot is not sure of traveling either along the bottom path or up, along the cross beds and down).

As shown in Figure 2, let vector $\boldsymbol{br} = \{b1, \ldots, b\text{nr}\}$ be the locations where the beds on the right of Bp are cut to provide a cross-aisle of width $2w$ on each bed. Then, by Pythagoras' theorem, the distances d_i can be calculated as

$$d_i = \sqrt{a^2 + (b_i - b_{i-1})^2} \tag{1}$$

where $b_0 = 0$ and is located at the base point (Bp). Let $q_i < \text{b}_i$ be a point on bed i at which the robot is not sure of traveling either along the bottom path or up, or along the cross beds and down as shown in Figure 2. Therefore,

$$ia + q_i = b_0 + \sum_{k=1}^{i} d_k + (b_i - q_i) \tag{2}$$

$$q_i = \frac{1}{2}\left(b_0 + \sum_{k=1}^{i} d_k + b_i - ia\right) \tag{3}$$

The access paths were divided into three regions that corresponded to different shortest paths to return to the base point (Bp) depending on the position of the robot (y). For $\text{y} < q_i$, the shortest path would be down and along the bottom cross aisle. For $q_i \leq \text{y} \leq \text{b}_i$, the shortest path corresponds to travelling up and along the cross aisle. For $\text{y} \geq b_i$, it is suggestable to travel down and along the cross aisle. Let $\text{C}_i(\text{y}, \boldsymbol{br})$ be the travel cost or travel time for the robot to reach the base point from a uniformly distributed point (y) in aisle i.

Thus, the expected travel cost, from a point in aisle $i \geq 1$ is

$$\begin{aligned}
E[C_i(\boldsymbol{br})] &= \frac{1}{h-2w}\int_o^h C_i(y, \boldsymbol{br})\, dy \\
&= \frac{1}{h-2w}\left[\int_o^{q_i} C_i(y, \mathbf{br})\, dy + \int_{q_i}^{b_i-w} C_i(y, \boldsymbol{br})\, dy \right. \\
&\quad \left. + \int_{b_i+w}^{h} C_i(y, \boldsymbol{br})\, dy\right] \\
&= \frac{1}{h-2w}\left[\int_o^{q_i} (ia+y)\, dy \right. \\
&\quad + \int_{q_i}^{b_i-w} (b_o + \sum_{k=1}^{i} d_k + b_1 - y) dy \\
&\quad \left. + \int_{b_{i+w}}^{h} (b_o \sum_{k=1}^{i} d_k + y - b_i) dy\right] \\
&= \frac{1}{h-2w}\left[q_i\left[ia + \frac{1}{2}q_i\right] + (b_i - w - q_i)\right. \\
&\quad \times \left[b_o + \sum_{k=1}^{i} d_k + \frac{1}{2}(b_i + w - q_i)\right] \\
&\quad \left. + (h - b_i - w)\left[b_o + \sum_{k=1}^{i} d_k + \frac{1}{2}(h - b_i + w)\right]\right]
\end{aligned}$$

where d_i and q_i were obtained in Equations (1) and (3), respectively. The expected travel cost from a point in aisle 0 does not depend on vector $\boldsymbol{br}$ as there is no travel along the cross aisle. Hence, for travel from any point in aisle 0 to the base point, the expected travel cost is simply the travel from the center of aisle:

$$E\left[C_0\right] = \frac{h}{2} \tag{4}$$

Therefore, given $\boldsymbol{b} = \{\boldsymbol{br}, \boldsymbol{bl}\}$ with nr beds on the right and nl beds on the left of the base point (Bp), the expected travel cost from any point in the entire space is given by

$$E\left[C\left(\boldsymbol{b}\right)\right] = E[C_0] + \sum_{i=1}^{nr} E[C_i\left(\boldsymbol{br}\right)] + \sum_{i=1}^{nl} E[C_i\left(\boldsymbol{bl}\right)] \tag{5}$$

where $\boldsymbol{bl} = \{b1, \ldots, b\text{nl}\}$. In addition, the condition $q_i \leq$ bi – w needs to be met. Consequently, the optimization problem was to find an optimal $\boldsymbol{b}$ that

$$\begin{aligned} &\text{Minimizes } \; E[C(\boldsymbol{b})] \\ &\text{Subject to } \; w + q_i \leq b_i \text{ for all } i \\ &\qquad\qquad\quad b_i \leq h - w \text{ for all } i \end{aligned} \tag{6}$$

The problem formulation in Equation (6) can be represented as

$$\mathbf{F(b)} = E(C(\boldsymbol{b})) + \sum\nolimits_{i=1}^{n} \left(R_i \left\langle v_i\right\rangle^2 + P_i \left\langle u_i\right\rangle^2\right) \tag{7}$$

where, F($\boldsymbol{b}$) is the overall objective function to be minimized. The constraint violations corresponding to the two inequality constraints in Equation (6) are v_i and u_i with R_i and P_i being the penalty factors for v_i and u_i, respectively and n, the total number of beds in the whole space (nr + nl).

The optimization problem formulated in Equation (7) was solved using Differential Evolution (DE) [36], which is a stochastic population-based evolutionary optimization algorithm. Like other evolutionary algorithms, DE starts with a randomly and uniformly initialized population of solutions in the search space bounded by minimum and maximum values of the parameters. In DE, the evolution experienced by each individual in a population is through the sequential application of operators referred to as mutation, and crossover on each randomly selected individual from the population at any time. The result of this variation is a new candidate solution referred to as offspring and the offspring replaces the original solution in the population if its objective value defined in Equation (7) is better or the same. For more detailed description regarding DE, refer to [36-38].

As discussed above, the difference between conventional greenhouses (Figure 1) and the proposed model is the position of the cross-aisles. In a conventional greenhouse without any cross-aisle (Figure 1a) and with a perpendicular cross-aisle to the beds (Figure 1b), the expected travel cost would be the same. Assuming the uniform distribution of the point (y) where the transportation robot gets filled, the expected travel cost (time) from a point in aisle $i \geq 1$ is

$$E\left[C_i(y)\right] = \frac{1}{h}\int_o^h C_i(y)dy = \frac{1}{h}\left[\int_o^h (ia + y)dy\right] = \frac{h}{2} + ia \tag{8}$$

The expected travel cost from any point in aisle 0 would be same as Equation (4)

$$E[C_0(y)] = \frac{h}{2} \tag{9}$$

Then, the expected travel cost from any point in the whole space in conventional greenhouse layout is given by

$$E\left[C\left(y\right)\right] = E\left[C_0\left(y\right)\right] + \sum_{i=1}^{nr} E[C_i(y)] + \sum_{i=1}^{nl} E[C_i(y)] \tag{10}$$

$$E\left[C\left(y\right)\right] = \frac{h}{2} + \left[nr * \frac{h}{2} + a \times \frac{nr\left(nr+1\right)}{2}\right] + \left[nl * \frac{h}{2} + a \times \frac{nl\left(nl+1\right)}{2}\right] \tag{11}$$

III. EXPERIMENTAL SET-UP AND SIMULATIONS

The run time taken by the algorithm was dependent on the search space and could be between minutes to hours. The simulations were done on 7 GHz Intel Core i5 processor, 8 GB random access memory and 128 GB solid-state drive with Windows Version 10 operating system (Microsoft Corporation, Redmond, WA). In this work, the parameters of the optimization algorithm, that is, DE were set as:

Population size (NP) - 500
Mutation strategy – DE/rand/1
DE-step size – 0.5
Crossover strategy – Binary Crossover
Crossover rate – 0.9
Maximum number of iterations (stopping criterion) – 30000
Ri, Pi = 10^{12}

Two set-ups were simulated to investigate the percentage improvement of the new layouts with created access routes over conventional layouts as shown in Figure 3. The first set-up had the base point (start and end point) in the middle of the layout while the base point was one fourth to the right in the second set up.

IV. PERCENTAGE IMPROVEMENT BETWEEN LAYOUTS WITH CREATED ACCESS POINTS AND CONVENTIONAL LAYOUTS

In the layouts having the access routes created in the middle, there were varied patterns in the percentage improvement (Figure 4). At 20 m length, the percentage improvement in travel time started a sharp continuous decline at 10 beds (20 m width) and reached no improvement at 200 beds (362 m width). At 50 m length, the improvement in accessibility increased rapidly to 10 beds (20 m width) and stabilized at 50 beds (100 m width) followed with continuous decrease from 50 beds (100 m width) to 200 beds (362 m width). At this length, the simulated results showed the importance of the bed orientation. Choice to be designated as width or length affected the accessibility. At a length of 100 m, there was a steady improvement in accessibility from 10 beds to 100 beds. Also, the improvement between 50 and 100 beds was not as drastic (about 2%) as that of 0 to 50 beds

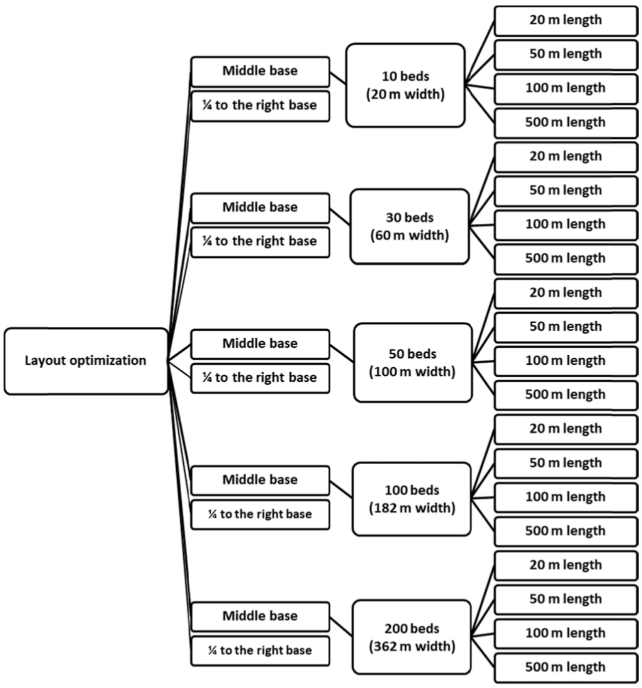

FIGURE 3. Experimental simulation set-up for different land areas.

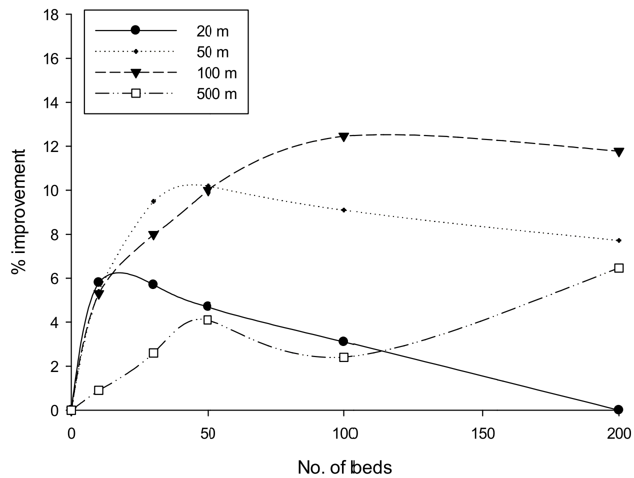

FIGURE 4. Percentage improvement between new layout with created access routes and conventional layout with base point in the middle.

with 10% improvement recorded. However, with increase in beds (width) the percentage improvement decreased about 1%. Despite this, there was still an overall improvement between the new layout and the conventional layout at all the beds averaging 9.2% improvement in all the investigated cases at 100 m length. At 500 m length, a different trend was recorded with a continuous improvement in accessibility from 0 to 50 beds and steep decline at 100 beds followed with increment in the percentage improvement between the new layout with created access routes and conventional layout at 200 beds. Thus, it can be concluded that improvements will be recorded if the length is more than the width of the greenhouse. This assertion can be backed with the principles from the Pythagoras' theorem.

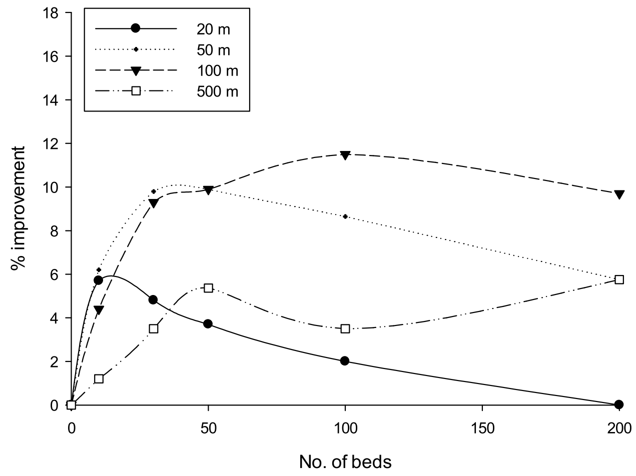

FIGURE 5. Percentage improvement between new layout with created access routes and conventional layout with base point at one fourth to the right.

As in the layouts having the base point at the center, the layouts with the base point one fourth to the right had a similar trend in most cases with varied patterns in the percentage improvement in travel time between the new layout with created access routes and conventional layout with base point one fourth to the right (Figure 5). At 20 m length, like the layouts with base in the middle of the greenhouse, the percentage improvement started a sharp continuous decline at 10 beds (20 m width) and reached no improvement at 200 beds (362 m width). Additionally, the improvement in accessibility increased rapidly to 10 beds (20 m width) and stabilized at 50 beds (100 m width) at 50 m length. This was followed with continuous reduction from 50 beds (100 m width) to 200 beds (362 m width). At a length of 100 meters there was a steady improvement in accessibility from 10 to 100 beds. However, as in the previous case with the base point at the center, the improvement was about 2% between 50 and 100 beds showing a less significant improvement compared to the 10% improvement recorded at 0 to 50 beds. Furthermore, with increase in beds (width) the percentage improvement decreased about 1%. Regardless of this, there was still an overall improvement between the new layout and the conventional layout for all the beds. Also, similar to the previous case, at 500 m length, a different trend was recorded with a continuous improvement in accessibility from 0 to 50 beds and steep decline at 100 beds followed with increase in the improvement at 200 beds.

There is a striking resemblance in the percentage increase curves between the layout with the base in the middle and one fourth to the right at 50 and 100 m length. However, the percentage improvement curves peaked at approximately 6% for 20 and 500 m lengths. Furthermore, the peaks were recorded at 10 and 50 beds for 20 and 500 m respectively unlike the previous case (central base point) where the percentage peaks were recorded at 6 and 4% for 20 and 500 m respectively.

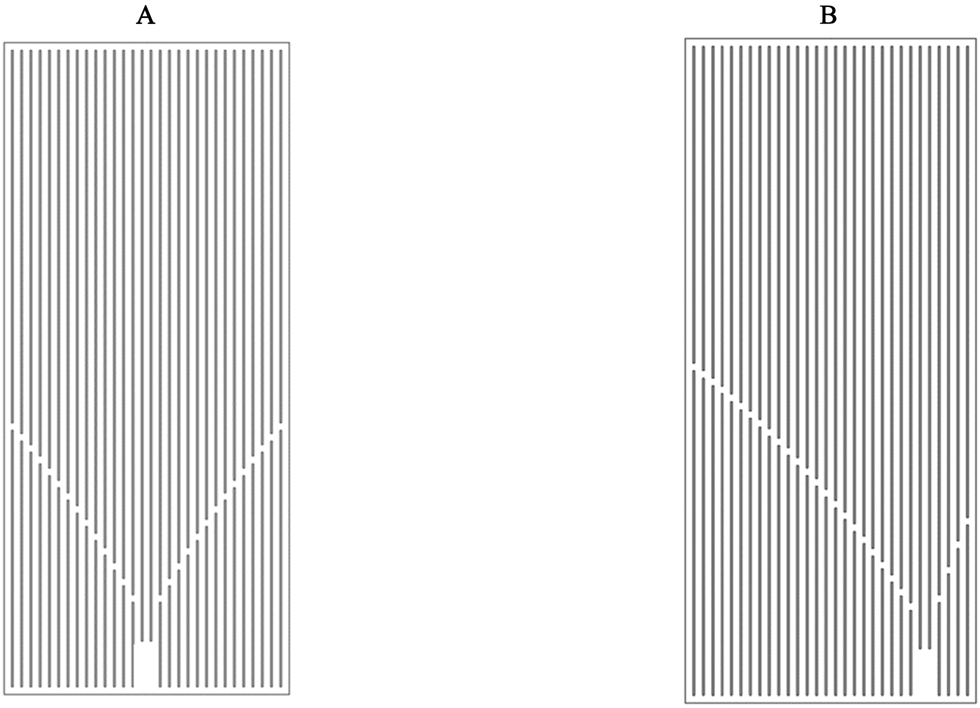

FIGURE 6. Layout configurations with base point at middle (A) and one fourth to the right (B) for 30 beds (60 m width) and 500 m length.

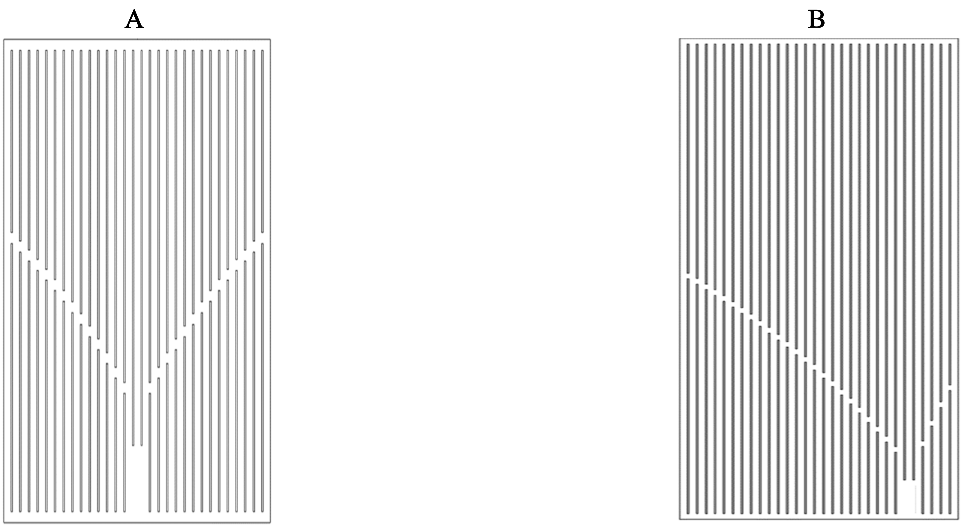

FIGURE 7. Layout configurations with base point at middle (A) and one fourth to the right (B) for 30 beds (60 m width) and 100 m length.

New Layout Configurations With Created Access Points: For the layout configurations, the point from which the access routes were created, and the patterns were different despite the areas being the same. The layout with the base at the middle (Figure 6(A)) had the access point cut starting from a lower position compared to the layout with the base point one fourth to the right. From the Pythagoras' theorem [39], it will take a shorter time to reach the base point from any area in the greenhouse when the base is at the middle of the layout than at one fourth to the right as shown in Figure 4 and 5. Consequently, the algorithm searches to minimize the travel time from any point, thus creating two unequal routes in the layout with the base one fourth to the right (Figure 6(B)).

Figure 7(A) and (B) had an opposite drift compared to Figure 6. The created access point started at a lower position in Figure 7(B) compared to Figure 7(A) in the layout. However, the created access points started at a similar point in Figure 8(A) and (B). This scenario was also recorded in Figure 9(A) and (B).

The shape of the cut in Figure 8(A) and 9 (A) mimicked a typical flying-V design where [34] argued that cross aisles

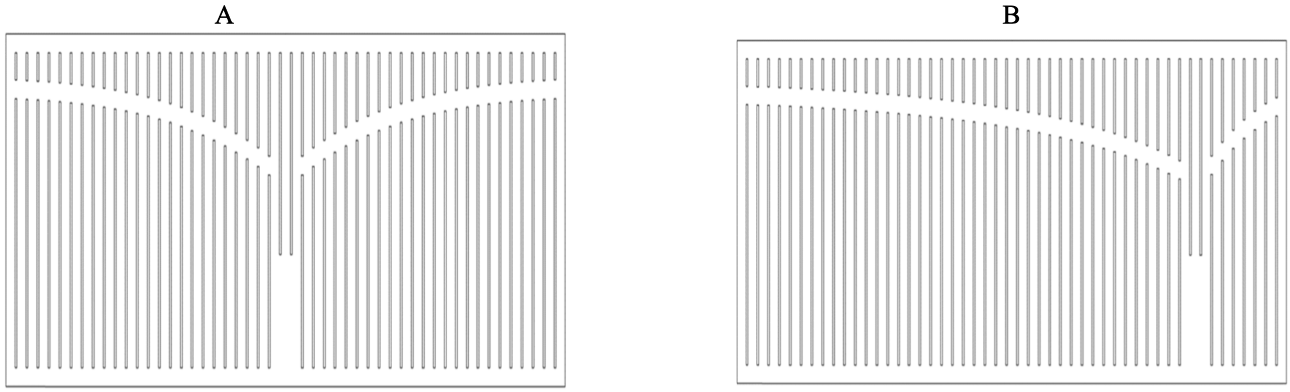

FIGURE 8. Layout configurations with base point at middle (A) and one fourth to the right (B) for 50 beds (100 m width) and 50 m length.

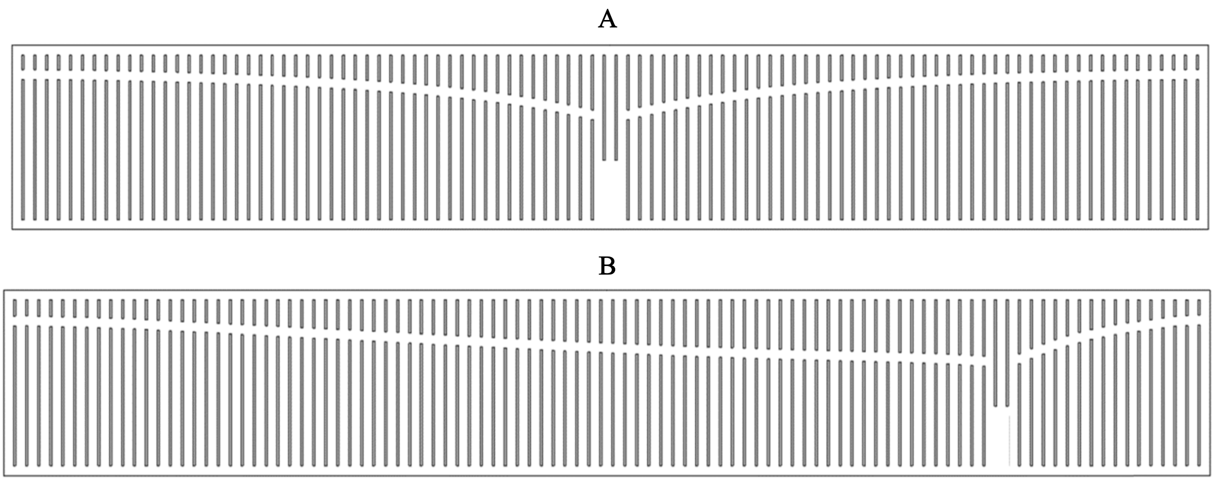

FIGURE 9. Layout configurations with base point at middle (A) and one fourth to the right (B) for 100 beds (183 m width) and 20 m length.

in warehouses with longer picking aisles, that is, a broader width benefit more from this type of design. This can be ascertained in this study as the Figure 8(A) and 9(A) had the most improvement in travel time efficiency compared to Figure 8(B) and 9(B) that had different designs.

V. CONCLUSION

A layout optimization system that enables rapid and safe robot navigation in a greenhouse was developed. Required bed specification for optimal plant growth and space for robot inter-bed and rotary movement considering the size of the robot can be changed in the proposed system. Additionally, the area of the greenhouse, and base point for robot starting and termination can also be altered to required specifications. Experimental simulation of different greenhouse sizes showed percentage improvements in travel time between the proposed layouts and conventional layout ranging from 0 to about 13% in the investigated cases. Also, the results showed that the position of the base point affects the percentage improvement in travel time. A system that could find optimal points on each bed to create an access path that would enable reduction in travel time from all points in the greenhouse to the base point was developed.

REFERENCES

[1] H.-J. Tantau, ''Optimal control for plant production in greenhouses,'' *IFAC Proc. Volumes*, vol. 24, no. 11, pp. 1–6, Sep./Oct. 1991.

[2] J. E. Van Lenteren and J. Woets, ''Biological and integrated pest control in greenhouses,'' *Annu. Rev. Entomology*, vol. 33, pp. 239–269, Jan. 1988.

[3] U. Gerson and P. G. Weintraub, ''Mites for the control of pests in protected cultivation,'' *Pest Manage. Sci.*, vol. 63, no. 7, pp. 658–676, Jul. 2007.

[4] S. T. Murphy and J. LaSalle, ''Balancing biological control strategies in the IPM of new world invasive liriomyza leafminers in field vegetable crops,'' *Biocontrol News Inf.*, vol. 20, no. 3, pp. 91N–104N, 1999.

[5] K. S. Nemali and M. W. van Iersel, ''An automated system for controlling drought stress and irrigation in potted plants,'' *Scientia Horticulturae*, vol. 110, no. 3, pp. 292–297, Nov. 2006.

[6] U. D. Dooyum, S. Asem-hiablie, T. Park, S. Woo, H. Lee, and J. Kim, ''Trends in automation and robotics in protected horticulture,'' in *Proc. KSAM Autumn Conf.*, Seoul, South Korea, vol. 23, 2018, p. 244.

[7] J. Hemming, C. Bac, B. van Tuijl, R. Barth, J. Bontsema, and E. Pekkeriet, ''A robot for harvesting sweet-pepper in greenhouses,'' presented at the Int. Conf. Agricult. Eng., 2014. [Online]. Available: http://www.geyseco.es/geystiona/adjs/comunicaciones/304/C01140001.pdf

[8] E. Capri, R. Alberici, C. Glass, G. Minuto, and M. Trevisan, ''Potential operator exposure to procymidone in greenhouses,'' *J. Agricult. Food Chem.*, vol. 47, no. 10, pp. 4443–4449, Oct. 1999.

[9] C. A. Damalas and I. G. Eleftherohorinos, ''Pesticide exposure, safety issues, and risk assessment indicators,'' *Int. J. Environ. Res. Public Health*, vol. 8, no. 5, pp. 1402–1419, May 2011.

[10] C. Damalas and S. Koutroubas, *Farmers, Exposure to Pesticides: Toxicity Types and Ways of Prevention*. Basel, Switzerland: MDPI, 2016.

[11] P. J. Sammons, T. Furukawa, and A. Bulgin, ''Autonomous pesticide spraying robot for use in a greenhouse,'' in *Proc. Austral. Conf. Robot. Automat.*, Dec. 2005, pp. 1–9.

[12] E. J. Van Henten, B. A. J. Van Tuijl, J. Hemming, J. G. Kornet, J. Bontsema, and E. Van Os, ''Field test of an autonomous cucumber picking robot,'' *Biosyst. Eng.*, vol. 86, no. 3, pp. 305–313, Nov. 2003.
[13] T. Hertz and S. Zahniser, ''Is there a farm labor shortage?'' *Amer. J. Agricult. Econ.*, vol. 95, no. 2, pp. 476–481, Jan. 2013.
[14] S. Asem-Hiablie, ''Estrogen occurrence, transport, and biological effects resulting from wastewater reuse in irrigation and aquaculture,'' Ph.D. dissertation, Dept. Agricult. Biol. Eng., Penn State Univ., Pennsylvania, PA, USA, 2013.
[15] D.-H. Park and J.-W. Park, ''Wireless sensor network-based greenhouse environment monitoring and automatic control system for dew condensation prevention,'' *Sensors*, vol. 11, no. 4, pp. 3640–3651, Mar. 2011.
[16] D. Stipanicev and J. Marasovic, ''Networked embedded greenhouse monitoring and control,'' in *Proc. IEEE Conf. Control Appl.*, Jun. 2003, pp. 1350–1355.
[17] R. Testezlaf, F. S. Zazueta, and T. H. Yeager, "A real-time irrigation control system for greenhouses," *Appl. Eng. Agricult.*, vol. 13, no. 3, pp. 329–332, 1997.
[18] M. H. Ko, B.-S. Ryuh, K. C. Kim, A. Suprem, and N. P. Mahalik, ''Autonomous greenhouse mobile robot driving strategies from system integration perspective: Review and application,'' *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 4, pp. 1705–1716, Aug. 2014.
[19] S. Bachche, ''Deliberation on design strategies of automatic harvesting systems: A survey,'' *Robotics*, vol. 4, no. 2, pp. 194–222, Apr. 2015.
[20] S. Sakai, M. Iida, K. Osuka, and M. Umeda, "Design and control of a heavy material handling manipulator for agricultural robots," *Auton. Robots*, vol. 25, no. 3, pp. 189–204, Oct. 2008.
[21] R. González, F. Rodríguez, J. Sánchez-Hermosilla, and J. Donaire, ''Navigation techniques for mobile robots in greenhouses,'' *Appl. Eng. Agricult.*, vol. 25, no. 2, pp. 153–165, 2009.
[22] J. Baur, J. Pfaff, H. Ulbrich, and T. Villgrattner, "Design and development of a redundant modular multipurpose agricultural manipulator," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2012, pp. 823–830.
[23] J. J. Roldán, J. del Cerro, D. Garzón-Ramos, P. Garcia-Aunon, M. Garzón, and J. de León, ''Robots in agriculture: State of art and practical experiences,'' in *Service Robots*. Rijeka, Croatia: InTech, 2017.
[24] S. S. Mehta, W. MacKunis, and T. F. Burks, ''Robust visual servo control in the presence of fruit motion for robotic citrus harvesting,'' *Comput. Electron. Agricult.*, vol. 123, pp. 362–375, Apr. 2016.
[25] I. A. Hameed, ''Intelligent coverage path planning for agricultural robots and autonomous machines on three-dimensional terrain,'' *J. Intell. Robotic Syst.*, vol. 74, nos. 3–4, pp. 965–983, 2014.
[26] C. Schuetz, J. Baur, J. Pfaff, T. Buschmann, and H. Ulbrich, ''Evaluation of a direct optimization method for trajectory planning of a 9-DOF redundant fruit-picking manipulator,'' in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2015, pp. 2660–2666.
[27] J. Karásek, ''An overview of warehouse optimization,'' *Int. J. Adv. Telecommun., Electrotechnics, Signals Syst.*, vol. 2, no. 3, pp. 111–117, Nov. 2013.
[28] S. ÖnütaUmut, R. Tuzkaya, and B. Dogaç, "A particle swarm optimization algorithm for the multiple-level warehouse layout design problem,'' *Comput. Ind. Eng.*, vol. 54, no. 4, pp. 783–799, May 2008.
[29] R. de Koster, T. Le-Duc, and K. J. Roodbergen, ''Design and control of warehouse order picking: A literature review,'' *Eur. J. Oper. Res.*, vol. 182, no. 2, pp. 481–501, 2006.
[30] F. Queirolo, F. Tonelli, M. Schenone, P. Nan, I. Zunino, and S. Savona, ''Warehouse layout design: Minimizing travel time with a genetic and simulative approach—Methodology and case study,'' in *Proc. 14th Eur. Simulation Symp.*, 2002, pp. 1–5.
[31] N. Gademann and S. Velde, ''Order batching to minimize total travel time in a parallel-aisle warehouse,'' *IIE Trans.*, vol. 37, no. 1, pp. 63–75, 2005.
[32] T. Le-Duc, and R. M. B. M. de Koster, ''Travel time estimation and order batching in a 2-block warehouse,'' *Eur. J. Oper. Res.*, vol. 176, no. 1, pp. 374–388. Jan. 2007.
[33] C.-Y. Tsai, J. J. H. Liou, and T.-M. Huang, ''Using a multiple-GA method to solve the batch picking problem: Considering travel distance and order due time,'' *Int. J. Prod. Res.*, vol. 46, no. 22, pp. 6533–6555, Oct. 2008.
[34] K. R. Gue and R. D. Meller, ''Aisle configurations for unit-load warehouses,'' *IIE Trans.*, vol. 41, no. 3, pp. 171–182, Jan. 2009.
[35] L. M. Pohl, R. D. Meller, and K. R. Gue, ''Optimizing fishbone aisles for dual-command operations in a warehouse,'' *Nav. Res. Logistics*, vol. 56, no. 5, pp. 389–403, Aug. 2009.
[36] R. Mallipeddi, P. N. Suganthan, Q. K. Pan, and M. F. Tasgetiren, ''Differential evolution algorithm with ensemble of parameters and mutation strategies,'' *Appl. Soft Comput.*, vol. 11, no. 2, pp. 1679–1696, 2011.
[37] X. Li and M. Yin, ''Modified differential evolution with self-adaptive parameters method,'' *J. Combinat. Optim.*, vol. 31, no. 2, pp. 546–576, Feb. 2016.
[38] X. Li, S. Ma, and Y. Wang, ''Multi-population based ensemble mutation method for single objective bilevel optimization problem,'' *IEEE Access*, vol. 4, pp. 7262–7274, 2016.
[39] J.-P. Quadrat, J. B. Lasserre, and J.-B. Hiriart-Urruty, ''Pythagoras' theorem for areas,'' *Amer. Math. Monthly*, vol. 108, no. 6, pp. 549–551, Jun./Jul. 2001.