

Negative Halotropism Expressed by 3-input-3-output Tomato Root Arithmetic-Logic Gate

Ronnie Concepcion II^{1,*}, Jonah Jahara Baun², Mike Louie Enriquez¹, Adrian Genevie Janairo², Joshua Emmanuel Gomez³, Maria Gemel Palconit², Argel Bandala², Luigi Gennaro Izzo⁴, Elmer Dadios¹, Alvin Culaba⁵

¹Department of Manufacturing Engineering and Management, De La Salle University, Manila, Philippines

²Department of Electronics and Computer Engineering, De La Salle University, Manila, Philippines

³Department of Computing Science, University of Alberta, Edmonton, Canada

⁴Department of Agricultural Sciences, University of Naples Federico II, Portici, Italy

⁵Department of Mechanical Engineering, De La Salle University, Manila, Philippines

{ronnie.concepcion*, jonah_baun, mike_enriquez, adrian_janairo, maria_gemel_palconit, argel.bandala, elmer.dadios, alvin.culaba}@dlsu.edu.ph, jbgomez@ualberta.ca, luigigennaro.izzo@unina.it

Abstract—Root foraging is affected by environmental stimuli that dictates its propagation vector. Multiple-root interaction has the potential to provide relevant information about asynchronous systems like the natural soil system. In this study, tomato root was used as the information producing element in three fabricated three-input-three-output negative chemotropism root logic gates: synchronized (rNHG1), and desynchronized (rNHG2 and rNHG3). Specific output channels in rNHG2 and rNHG3 were fertigated with highly acidic sodium chloride solutions (30 mM and 75 mM) and only one channel was enriched with control solution providing additional desynchronization in the system computing the logic functions of $(x, y, z) = (y + z + xz)$ for rNHG1, $(x, y, z) = (xy + xz, y + z + xz)$ for rNHG2, and $(x, y, z) = (x\bar{y}z + x\bar{y}\bar{z}, y + z + xz)$ for rNHG3 where $x, y,$ and z represent the presence of root in the output channel, whereas negated variables indicate the absence of root. Overall, root channels fertigated with control nutrients for all root logic gates resulted in the same Boolean function and negative halotropism not only repelled the growth direction of root, but it also reduced the radicle, xylem, and phloem diameters. As the root channels become more desynchronized, root fresh and dry weights decreased due to energy utilization in bending response. Here, it was proven that plant roots manifest computation and signaling based on repellent chemical. Hence, the developed root logic provides valuable information that can be extended in developing plant root-based robotic applications.

Keywords—*biocomputing, chemotropism, halotropism organic circuit, root logic gate, root bending, root tropism, unconventional computing*

I. INTRODUCTION

Approaches in solving universal natural problems using conventional computing, processing 1s and 0s individually, face limitations since solutions require performing enormous number of iterations with voluminous amount of data that includes irrational numbers which traditional computers cannot handle or at least would take unreasonable amount of time in getting a result [1]. In the observance of universal theories and phenomenon with interdisciplinary science, unconventional computing's objective is to utilize natural transformation principles of science, mathematics, and engineering in developing algorithms providing efficient solutions and make it a part of future computing devices [1-3]. An example of this is the use of behavioral equations of memristors producing a variable resistance based on boundary shifting of the doped and undoped regions when electrical field is applied to its terminals. It was used as a latch to save and a switch for computing data in digital gates. Memristor

principles with material implication and crossbar array was used to develop logic gates which had significant attributes compared to complementary metal-oxide semiconductor (CMOS)-based logic gates like combined computing and storing in a single non-volatile compact unit [3]. Hence, conventional computing pertains to solving desynchronized system involving nature-derived values.

Tropistic responses enables plants to adapt to the environment thanks to directional growth of organs. Charles and Francis Darwin first referred to the 'power of movement' in plants investigating hydrotropism, gravitropism, and phototropism in late 1800 [4]. Recent studies have used a genetic approach to investigate the impact of environmental stimuli on growth of tomato lateral roots, which exhibit tropistic response to gravity, light, touch, and moisture gradients that contribute to guide plant growth direction such as increasing absorption of nutrients from the soil [5]. Tropism behaviors are categorized as positive or negative based on the biological development towards or away from the stimulus, respectively. Recent advances in tropism research have facilitated investigation of roots ability to recognize a variety of environmental stimuli, synchronize cellular stress responses, and alter their growth direction [6]. Plant tropisms have been essentially utilized for enhancing plant-based life support systems in space since it will help direct root development under altered gravity conditions and increase crop production [5,7].

Chemotropism refers to the directional growth of plant organs in response to a chemical stimulus. The two forms of chemotropism are positive chemotropism and negative chemotropism. In positive chemotropism, the chemical stimulus causes the root growth to turn towards its origin, inversely, negative chemotropism happens when a chemical stimulus causes the root growth to turn away from its origin [8,9]. A particular type of chemotropism is the one in response to the presence of salts (NaCl) which is called halotropism [7]. The concentration of chemicals plays a fundamental role in chemotropic responses and the rhizosphere's microbial composition is also influenced by the chemical environment produced by plant roots as they secrete several low molecular-weight chemicals that can function as chemical signals through inhibiting or promoting the growth of specific microorganisms [10]. Previous studies have reported chemotropism assays exploiting elementary toxins or nutrients, self-generated signaling compounds, or exogenously derived chemical substances to test chemotropic

activity [10]. Reported chemo-attractants are glucose (preferred C-source), ammonium chloride, NH_4Cl , N-source glutamine, peroxidases, and oxylipins which are found to enhance overall chemotropic behavior optimizing the morphological appearance of plants and activating systematic responses to various stresses while the potent chemorepellents are copper with the highest negative Chemotropic Index (CI), zinc, and manganese [8,11]. Positive chemotropism has been observed in roots of *Daucus carota* grown under microgravity conditions of the International Space Station [12], using disodium phosphate as chemo-attractant which had already been proven in the early 1900s [13].

Dynamic biochemical and growth rates of plant roots could be an open solution for biocomputing, especially in an asynchronous system. However, one of its limitations is the lengthy duration to perform certain computations. More significantly, chemotropism is not yet explored in relation to plant root logic gate development.

In this study, a 3-input-3-output artificial root channel was manufactured to hold tomato roots during seedling growth and express the impact of negative halotropism through root interactions resulting in the formulation of Boolean Algebra-based root logic functions and logic circuits. Tomato Diamante genotype was used as it has fibrous root architecture making it more ideal for characterization in contrast to the taproot onion root architecture in Phytigel growth medium which has been previously studied [14]. The chemical stimulus in the form of solvent used to affect root propagation is sodium chloride solution of two different concentrations. It was hypothesized that all tomato roots will propagate towards the channel with no NaCl concentration. This study contributes to the: (1) elucidation of halotropism characterized by tomato root propagation in an artificial soil channel; (2) development of root logic function that could be an inspiration of future works like plant root-based robot end-effector movement; and (3) formulation of evidence of an application of unconventional computing in the field of plant root biology and tropism.

II. MATERIALS AND METHODS

This study involves three major steps in expressing negative halotropism on a 3-input-3-output tomato root logic gate (Fig. 1). It starts with the prototyping of artificial root channel, then, series of tests on the fabricated negative chemotropism root gate, and lastly, translation of root propagations and interactions into logic functions and circuits using classical logic gates. The output of this study is the formulation of these root activities in a controlled channel.

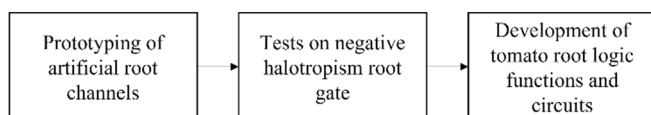


Fig. 1. Step-by-step procedure in expressing negative halotropism on a 3-input-3-output tomato root logic gate.

A. Plant Material

Tomato (*Solanum lycopersicum* L.) Diamante Max F1 genotype is the selected crop for this experiment as it has fibrous roots that easily propagates even on a limited channel unlike other genotypes [15]. Seeds were supplied by East-West Seed Company, Inc. (Manila, Philippines) and directly stored at 4°C until actual testing.

B. Prototyping of Artificial Root Channels

Three patterns of artificial root propagation channel were designed in Google Sketchup 2019 (Fig. 2). Each plate has base dimension of approximately 10 cm × 10 cm with thickness of 3 mm to firmly support the above soil component. The embossed patterns were intendedly desynchronized to adhere with the conditions of unconventional computing [1-3]. These patterns have a constant height of 1 cm and corresponding root propagation space of 0.5 cm. The round areas in the input section are allocated for seed placement. Polylactic acid (PLA, $(\text{C}_3\text{H}_4\text{O}_2)_n$) filament and 3D printer (Ender-3 Pro 3D Printer, Creality, China) were used in fabricating the three root logic gates. Here, artificial root channel patterns were named as rNHG1 (Fig. 2a), rNHG2 (Fig. 2b), and rNHG3 (Fig. 2c) where rNHG stands for root negative halotropism gate. The upper and lower section of rNHGs were connected through a section called “deciding joint” where most of the root interactions take place (Fig. 2d).

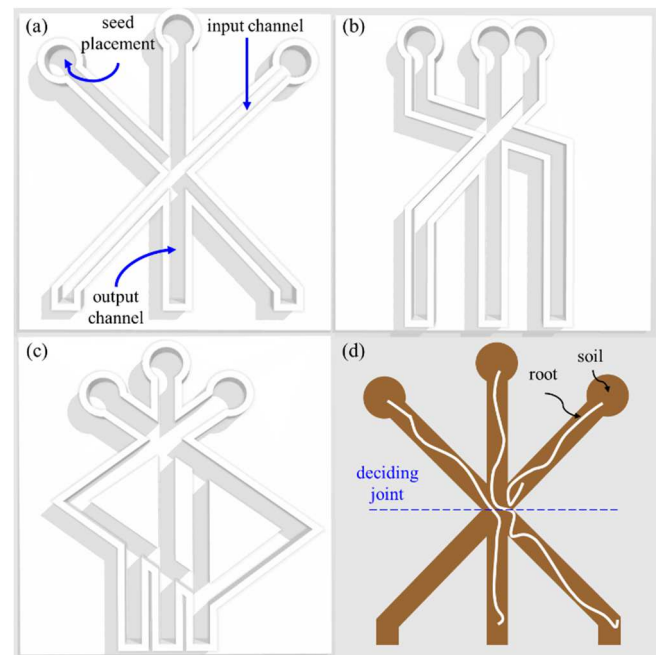


Fig. 2. CAD of 3-input-3-output logic gates: (a) rNHG1, (b) rNHG2, and (c) rNHG3. Designs are adapted from the theories discussed in [12]. (d) Schematic of soil placement and root propagation between channel allowances.

C. Tests on Negative Chemotropism Root Gate

Negative halotropism gate is a repulsion gate characterized by root bending toward the soil regions with lower or no concentration of repellent chemical introduced into the system. This type of root tropism gate manifests the principle that plant roots can sense chemicals belowground and decide to grow towards or avoid that region [15,16]. Here, the negative halotropism experiment utilized the three rNHG prototypes (Fig. 2) with three chemical treatments applied to each output channel, namely: control (C), low NaCl concentration of 30 mM (NaCl^+), and toxic NaCl of 75 mM (NaCl^{++}). It is known that NaCl is one of the harmful acidic salts and chemicals that typically makes roots to grow in the opposite direction and dries out water from root cells [4,6]. For all treatments, the full strength of inorganic nutrients used are 16 mM KNO_3 , 6 mM $\text{Ca}(\text{NO}_3)_2 \cdot 10\text{H}_2\text{O}$, 2 mM $\text{NH}_3\text{H}_2\text{PO}_4$, 1 mM $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 50 μM KCl, 25 μM H_3BO_3 , 2 μM $\text{MnSO}_4 \cdot \text{H}_2\text{O}$, 1 μM $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 0.5 μM $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 0.5 μM $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$, 50 μM Fe-EDTA. Soil composition is

50% loam, 40% sand, and 10% pulverized vermiculite. Before the actual test, seed floatation was performed by placing tomato seeds in a container of deionized water in a 23°C for 24 hours. The uniformly germinated seeds were transferred to the logic gate prototypes and sown individually on seed sockets. To vary the root interactions aside from the geometry of the artificial channel, three fertigation treatments (5 mL of formulated nutrients) were also developed (Table 1). Note that applying nutrient solution is limited from output channel end up to 1 cm before the deciding joint to make sure that roots can still decide in which channel to grow. Sixteen replicates were performed for each artificial channel under an 18-h photoperiod and 6-h dark period in an open environment with an average air temperature of $28 \pm 3.8^\circ\text{C}$ and humidity from 68 to 85%. After two weeks of root propagation, soil layer was dismantled using weak water pressure so not to disturb the apparent root network arrangement.

TABLE I. NEGATIVE HALOTROPISM FERTIGATION TREATMENTS WHERE THE POINT OF NUTRIENT INJECTIONS ARE THE OUTPUT CHANNELS

Artificial Root Propagation Channel	Output Channels		
	p	q	r
rNHG1	C	NaCl+	NaCl++
rNHG2	NaCl+	C	NaCl++
rNHG3	NaCl++	NaCl+	C

D. Development of Tomato Root Logic Functions and Circuits

Unconventional computing was employed by formulating truth table for each negative halotropism gate showing the actual logic operations exhibited by root propagation and interactions. In the truth tables, Boolean values of 0 and 1 represent no root presence and root presence in the output channels, respectively. Karnaugh mapping was performed on each root logic gate with grouping of minterms resulting in negative halotropism gate Boolean function following a sum-of-products (SOP) mathematical topology: $\{p, q, r\} = f(x, y, z)$, where x, y , and z are the input channel states and p, q , and r represent the output channel states, and logic circuit composed of 2- and 3-input AND and OR, and NOT gates.

E. Biological Measurements of Root Phenex

For each rNHG, the radix root that completely diverged onto the output channel was dissected and a thin transverse root tissue was stained using 1% toluidine blue (TBO, Sigma-Aldrich) to measure the average diameter of xylem (d_{xy} , μm) and phloem (d_{ph} , μm) under a light microscope (Howell Medical Supply, Philippines). Root diameter (ϕ_{avg} , μm) was also measured using ImageJ software. Fresh (w_f , g) and dry weight (w_d , g) of root systems from x, y , and z channels were also measured using digital balance with 1 mg resolution.

III. RESULTS AND DISCUSSION

A. Tomato Root Behavior in Chemotropism Gate

In this study, three experimental prototypes (rNHG1, rNHG2, rNHG3) of negative halotropism gates were 3D manufactured where control (C) and NaCl-excess fertilizers (NaCl+ and NaCl++) were supplemented in the exit channels of p, q , and r based on the three fertigation treatments (Table 1).

These halotropism gates allow the propagation and interaction of roots from input channel x, y , and z (Fig. 3). In rNHG1, when root x propagated solo ($x = 1$), it passed through decision joint j and exited towards channel p where C nutrient

treatment (NaCl = 0 mM) was injected (Fig. 3a). When root y propagated solo ($y = 1$), it passed through joint j and exits via channel p , and the same when root z emerged solo. When two roots emerged at the same time across joint j ($y = 1$ and $z = 1$), root z propagates with a faster rate towards channel p , impeding root y to grow at the same direction. rNHG1 exhibited same root propagation when roots x and z emerged at the same instance at joint j (Fig. 3a). Interestingly, when all roots emerged at same instance at joint j ($x = 1, y = 1$, and $z = 1$), root z still blocked the entry of roots x and y towards exit channel p (Fig. 3a). These findings imply that when plant roots are subjected to soil with gradients of NaCl concentration, they tend to exhibit negative halotropism by moving on the opposite direction where the repellent is located. Based on rNHG1 experiments, the side of root y exposed to the gradient of NaCl at joint j due to osmotic distribution becomes more transparent during root excavation, that is primarily because of the acidic component of the introduced salt solution. The actual logic operations of roots in rNHG1 (Table 2) were transformed into its corresponding logic circuit with two OR, an AND, and NOT gates (Fig. 3d). Also, root interactions in these pre-defined three-input-three-output artificial root logic gate compute the following SOP Boolean function: $p = y + z + xz$. There is no computational output for q and r as roots observed to exhibit biological communications with other roots allowing others to consume the nutrients available in a specific soil region [14-16].

TABLE II. ACTUAL LOGIC OPERATIONS EXHIBITED BY THREE-INPUTS-THREE-OUTPUTS NEGATIVE HALOTROPISM GATE (rNHG1). BOOLEAN VALUES OF 0 AND 1 REPRESENT NO ROOT PRESENCE AND ROOT PRESENCE IN THE CHANNEL RESPECTIVELY.

Input Channels			Output Channels			Root Propagation and Interaction
x	y	z	p	q	r	
0	0	0	0	0	0	There is no root emergence from x, y , and z input channels
0	0	1	1	0	0	Root in channel z exits via channel p
0	1	0	1	0	0	Root in channel y exits via channel p
0	1	1	1	0	0	Roots in y and z meet at junction j where z exits via channel p blocking y
1	0	0	1	0	0	Root in channel x exits via channel p
1	0	1	1	0	0	Roots in x and z meet at junction j where z exits via channel p blocking x
1	1	0	1	0	0	Roots in x and y meet at junction j where x exits via channel p stopping y to propagate
1	1	1	1	0	0	Root in x exits via p , deviating y to q and blocking z

Note: $p = y + z + xz$

Similar to rNHG1, rCNG2 is a three-input-three-output artificial root channel that allows three roots to propagate at the same time (Table 3), but this was intendedly manufactured to have desynchronized channel length and angles to exhibit unconventional computing. In rNHG2 trials, when root z propagated solo ($z = 1$), it passed through joint j and exited via channel q (Fig. 3b). When root y propagated solo ($y = 1$), it passed through joint j and exited down to channel q (Fig. 3b). When root x propagated solo ($x = 1$), it bent toward joint j and exited down to channel q (Fig. 3b). When two roots emerged at the same time across joint j ($y = 1$ and $z = 1$), root y propagates with a faster rate towards channel q , impeding root

z to grow at the same direction. Another important finding is that when two roots propagated at the same time at joint j ($x = 1$ and $z = 1$, or $x = 1$ and $y = 1$), the root that requires lesser energy wastage to bend towards the direction of channel with control nutrients propagates successfully on that end (Fig. 3b). It is because roots tend to move with minimal energy usage for forage. They benefit the osmotic distribution of nutrients in soil making them to expand their system [14-16]. However, it was also observed that those primary roots that were blocked by emerging root only grows at the entrance of NaCl+ (NaCl = 30 mM) channel, proving that this concentration is not growth-inducive for plant roots (Fig. 3b). When all roots emerged at same instance at joint j ($x = 1$, $y = 1$, and $z = 1$), only root y exits channel q , blocking root z and deviating root x to grow shortly in channel p (Fig. 3b). For this trial, it was observed that radicle and seminal roots of tomato seedling that grows in NaCl+-concentrated channel is a lot thinner compared to the root system in channel q . This implies that 30 mM of NaCl could destroy root cells and tissues. One of the limitations of this trial is the uncontrolled flow of different nutrient concentrations in soil channels as all these channels intersect at joint j . There is a high probability that control nutrients even spread partly at the mouth of channels p and r for rNHG2 trials leading to excitation of root meristematic cells to grow on that direction. Hence, the effect of negative halotropism for rNHG2 is profound with no root grown in channel r (NaCl++ channel). The actual logic operations of roots in rNHG2 (Table 3) were transformed into its corresponding logic circuit with three OR, three AND, and one NOT gates (Fig. 3d). Also, root interactions in these pre-defined three-input-three-output artificial root logic gate compute the following SOP Boolean functions: $p = xy + xz$ and $q = y + z + xz$. There is no computational output for r due to no single root had grown on that highly acidic channel.

TABLE III. ACTUAL LOGIC OPERATIONS EXHIBITED BY THREE-INPUTS-THREE-OUTPUTS NEGATIVE HALOTROPISM GATE (rNHG2). BOOLEAN VALUES OF 0 AND 1 REPRESENT NO ROOT PRESENCE AND ROOT PRESENCE IN THE CHANNEL RESPECTIVELY.

Input Channels			Output Channels			Root Propagation and Interaction
x	y	z	p	q	r	
0	0	0	0	0	0	There is no root emergence from x , y , and z input channels
0	0	1	0	1	0	Root in channel z exits via channel q
0	1	0	0	1	0	Root in channel y exits via channel q
0	1	1	0	1	0	Roots in y and z meet at junction j where y exits via channel q blocking z
1	0	0	0	1	0	Root in channel x exits via channel q
1	0	1	1	1	0	Roots in x and z meet at junction j where z exits via channel q , deviating x to p
1	1	0	1	1	0	Roots in y and z meet at junction j where z exits via channel p blocking y
1	1	1	1	1	0	Root in x exits via p , deviating y to q and blocking z

Note: $p = xy + xz$, $q = y + z + xz$

A more desynchronized three-input-three-output root logic gate than rNHG2 is rNHG3. Based on construction, there is another possible rout that directly links to exit channel r (Fig. 3c). In rNHG3 trials (Table 4), when root z propagated solo ($z = 1$), it passed through joint j following the path of

channel b , then, crossing joint j_5 and exited via channel r (Fig. 3c). This is a longer route, but the roots preferred it. The possible reason behind this is the fact that there might be some volume of NaCl+ nutrients that flows downward joint j_5 and spreads through channel d . In fact, the other solo root emergence, ($x = 1$) and ($y = 1$), resulted in the same manner (Fig. 3c). When two roots have emerged at the same time at joint j_1 ($y = 1$ and $z = 1$) and ($x = 1$ and $z = 1$), root z exited via channel r through channel b (Fig. 3c). Root z blocked the other emerging root (roots x and y), deviating them to express growth in channel q (Fig. 3c). Same root interaction is exhibited here as with the two-root emergence of rNHG2. When $x = 1$ and $y = 1$, root x passed through joint j_1 and channel b , and exited via channel r (Fig. 3c). A significant finding in rNHG3 trials is when there are three root emergences at the same time at joint j_1 , root x blocked roots y and z , exiting via channel r where control nutrient treatment has been injected (Fig. 3c). The actual logic operations of roots in rNHG3 (Table 4) were transformed into its corresponding logic circuit with three OR, three AND, and three NOT gates (Fig. 3d). Also, root interactions in these pre-defined three-input-three-output artificial root logic gate compute the following SOP Boolean functions: $q = \bar{x}yz + x\bar{y}z$ and $r = y + z + xz$. Even desynchronized artificial channel representing system entropy are being deduced correctly by roots. It is a proof that root functions, just like in negative chemotropism and halotropism expression, can be used in higher form computing.

TABLE IV. ACTUAL LOGIC OPERATIONS EXHIBITED BY THREE-INPUTS-THREE-OUTPUTS NEGATIVE HALOTROPISM GATE (rNHG3). BOOLEAN VALUES OF 0 AND 1 REPRESENT NO ROOT PRESENCE AND ROOT PRESENCE IN THE CHANNEL RESPECTIVELY.

Input Channels			Output Channels			Root Propagation and Interaction
x	y	z	p	q	r	
0	0	0	0	0	0	There is no root emergence from x , y , and z input channels
0	0	1	0	0	1	Root in channel z exits via channel r
0	1	0	0	0	1	Root in channel y exits via channel r
0	1	1	0	1	1	Roots in y and z meet at junction j where y exits via channel q and z to r
1	0	0	0	0	1	Root in channel x exits via channel r
1	0	1	0	1	1	Roots in x and z meet at junction j where x exits via channel q and z to r
1	1	0	0	0	1	Roots in x and y meet at junction j where x exits via channel r , blocking y
1	1	1	0	0	1	Root in z exits via r , deviating x to q and blocking y

Note: $q = \bar{x}yz + x\bar{y}z$, $r = y + z + xz$

Shown in Fig. 3e are the sample actual root placement deflecting the channels injected with NaCl+ and NaCl++, clearly expressing negative halotropism. For rNHG1, the pre-defined three-input-three-output root logic gate resulted in three-input-one-output, while for rNHG2 and rNHG3, the three-input-three-output root logic gate turned out to operate in three-input-two-output functions (Fig. 3d). It is also apparent that the channel injected with control nutrients is always characterized with $\{y + z + xz\}$ for all developed rNHGs. In all trials, most primary root avoided the channels with excess NaCl (NaCl = 30 mM) and there is no single root

that propagated towards the channel enriched with toxic NaCl concentration ($\text{NaCl} = 75 \text{ mM}$). It can also be observed that the number of logic gates used to transform the formulated root logic functions increased by almost two-fold from synchronized (rNHG1) and desynchronized channels (Fig.

3d). Unlike the use of onion plant which has tap root system [14], this study expressed root logic and unconventional computing using fibrous root which is more complicated as it has seminal and lateral roots that has a high tendency to be affected by nearby gradient of NaCl as tropistic stimulus.

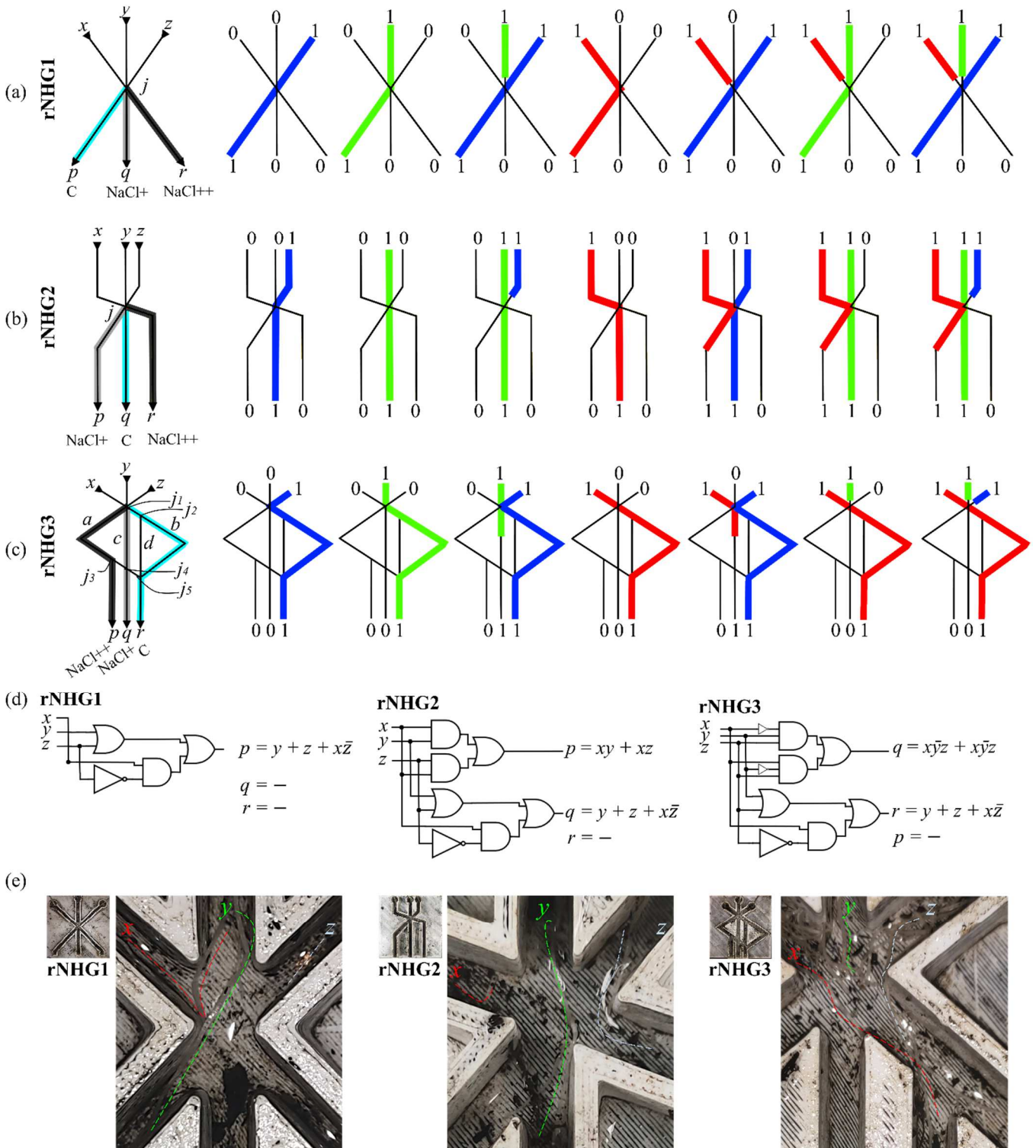


Fig. 3. Root schemes of three-input-three-output root logic channel: (a) synchronized rNHG1; and desynchronized (b) rNHG2 and (c) rNHG3 expressing negative halotropism through the application of control and NaCl-excess nutrients on varied exit channels where x, y, z are input channels, p, q, r are output channels, and 1 and 0 are Boolean representations of presence and absence of root emergence. (d) Equivalent logic circuit of actual root propagation and interaction. (e) Primary root subsoil placement as impacted by NaCl as negative tropistic element.

B. Dependency of Root Phenotypes on Negative Halotropic Stimulus and Channel Synchronization

Roots from sixteen replicates exposed to halotropism were imaged and analyzed confirming the negative tropistic property of NaCl to plant roots. Radicles exhibiting negative halotropism (moved away from the area of NaCl-enriched soil) showed a decreasing average diameter by a factor of 0.345 from synchronized to desynchronized channels (Fig. 4a). Xylem and phloem diameters also decreased in rNHG2 and rNHG3 by a factor of 0.172 and 0.534 (Fig. 4a). This indicates that as root utilizes energy in bending towards the suitable soil region without additional suitable nutrients, its cells morphology varies by reducing its diameter. When the cell diameter gets smaller, it means it supplies out water [6,16]. In terms of fresh and dry weights of root systems, desynchronized rNHG1 is heavier than the other two desynchronized root logic gates by a factor of 1.55 (Fig. 4b). Overall, the actual findings and the developed root Boolean root logic function is not a misnomer because rNHG1 computed only the channel p , and rNHG2 and rNHG3 computed only channels p and q , and q and r , respectively. The three-input-three-output pertains to the actual root channel, and it can be enhanced by exposing the roots to different tropistic stimuli in order to design a suitable robot [17-23].

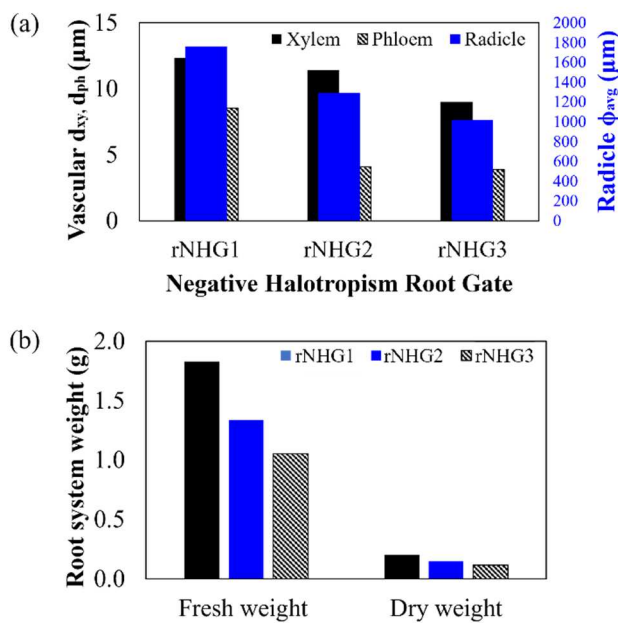


Fig. 4. Dynamic impacts of synchronized and desynchronized negative chemotropism root gate to (a) radicle and vascular bundle (xylem and phloem tissues) average diameters and (b) root system fresh and dry weight. For diameter measurement, only the radicle that reached the control nutrient-enriched channel was considered. For weigh measurement, the whole root network per rNHG was considered.

IV. CONCLUSION AND RECOMMENDATION

This study is an initial exploration of developing Boolean functions and logic circuits based on the propagation and interaction of roots from three tomato plants as affected by different concentrations of excess NaCl, thus, expressing unconventional computing due to negative halotropism. Three artificial root logics were fabricated and categorized as synchronized (rNHG1) and desynchronized (rNHG2 and rNHG3). Three logic circuits were constructed using AND, OR, and NOT gates based on root interactions. Major findings confirmed that channels fertigated with control nutrients for

all root logic gates resulted in the same Boolean function and negative halotropism not determine the growth direction of roots, but it also reduces the radicle, xylem, and phloem diameters. As the root channels become more desynchronized, root fresh and dry weights decrease due to energy utilization in bending. Hence, the developed root logic provides valuable information that can be extended in developing plant root-based robotic applications. In this framework, it is recommended to explore other tropistic stimuli that could easily impact root interaction and propagation.

ACKNOWLEDGMENT

The authors would like to thank the Department of Science and Technology-Engineering Research and Development for Technology (DOST-ERDT) Program and the Intelligent Systems Laboratory and Office of the Vice President for Research and Innovation of De La Salle University, Manila, for all granted supports.

REFERENCES

- [1] A. Adamatzky, "Handbook of unconventional computing," Handbook of Unconventional Computing, 2021. doi: <https://doi.org/10.1142/12232-vol1>
- [2] A. Adamatzky, "Unconventional computing," International Journal of General Systems, vol. 43, no. 7, pp. 671-672, 2014.
- [3] M. Shahsavari, M. Faisal Nadeem, S. Arash Ostadzadeh, P. Devienne, and P. Boulet, "Unconventional Digital Computing Approach: Memristive nanodevice platform," physica status solidi c, vol. 12, no. 1-2, pp. 222-228, 2014.
- [4] K. Yamazaki, Y. Ohmori, and T. Fujiwara, "A positive tropism of rice roots toward a nutrient source," Plant Cell Physiol., vol. 61, no. 3, pp. 546-553, 2020.
- [5] L. G. Izzo and G. Aronne, "Root tropisms: New insights leading the growth direction of the hidden half," Plants, vol. 10, no. 2, pp. 1-4, 2021.
- [6] Y. Zou, Y. Zhang, and C. Testerink, "Root dynamic growth strategies in response to salinity," Plant Cell Environ., vol. 45, no. 3, pp. 695-704, 2022.
- [7] L. W. F. Muthert, L. G. Izzo, M. van Zanten, and G. Aronne, "Root Tropisms: Investigations on Earth and in Space to Unravel Plant Growth Direction," Front. Plant Sci., vol. 10, no. February, pp. 1-22, 2020.
- [8] M. Beccaccioli, V. Scala, and M. Reverberi, "Communication with plants," In Encyclopedia of Mycology, vol. 1, no. 2, 2021.
- [9] A. Lichius and K. M. Lord, "Chemoattractive mechanisms in filamentous fungi," Open Mycol. J., vol. 8, pp. 28-57, 2014.
- [10] N. Lombardi, S. Vitale, D. Turrà, A. M. Reverberi, C. Fanelli, F. Vinale, R. Marra, M. Ruocco, A. Pascale, G. D'Errico, S. L. Woo, and M. Lorito, "Root exudates of stressed plants stimulate and attract trichoderma soil fungi," Molecular Plant-Microbe Interactions, vol. 31, no. 10, pp. 982-994, 2018.
- [11] D. Moreno-Ruiz, A. Lichius, D. Turrà, A. Di Pietro, and S. Zeilinger, "Chemotropism Assays for Plant Symbiosis and Mycoparasitism Related Compound Screening in Trichoderma atroviride," Frontiers in Microbiology, vol. 11, pp. 1-17, 2020.
- [12] L. G. Izzo, L. E. Romano, S. De Pascale, G. Mele, L. Gargiulo, L., and G. Aronne. Chemotropic vs hydrotropic stimuli for root growth orientation in microgravity. Frontiers in Plant Science, 1547, 2019.
- [13] F. C. Newcombe, and A. L. Rhodes. Chemotropism of roots. Botanical Gazette, vol. 37, no. 1, pp. 23-35, 1904.
- [14] A. Adamatzky et al., "On plant root logical gates," BioSystems, vol. 156-157, pp. 40-45, 2017.
- [15] R. Concepcion II et al., "Differential Effects of Potassium Chloride on Vascular Tissues, Morphological Traits and Germination of Tomato with Sperm Swarm-based Nutrient Optimization," Trends in Sciences, vol. 19, no. 14, 2022.
- [16] R. Concepcion II and E. Dadios, "Bioinspired optimization of germination nutrients based on Lactuca sativa seedling root traits as influenced by seed stratification, fortification and light spectrums," AGRIVITA Journal of Agricultural Science, vol. 43, no. 1, pp. 174-189, 2021.
- [17] K. Francisco et al., "Analytical Hierarchical Process-based Material Selection for Trailer Body Frame of an Underground Imaging System," 2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), 2021.
- [18] R. Concepcion II et al., "Aquaphotomics determination of total organic carbon and hydrogen biomarkers on aquaponic pond water and concentration prediction using genetic programming," 2020 IEEE 8th R10 Humanitarian Technology Conference (R10-HTC), 2020.
- [19] R. Concepcion II et al., "Trophic state assessment using hybrid classification tree-artificial neural network," International Journal of Advances in Intelligent Informatics, vol. 6, no. 1, pp. 46-59, 2020.
- [20] A. Bracino et al., "Biofiltration for Recirculating Aquaponic Systems: A Review," 2020 IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), 2020.
- [21] R. Concepcion II et al., "Adaptive fertigation system using hybrid vision-based lettuce phenotyping and fuzzy logic valve controller towards sustainable aquaponics," Journal of Advanced Computational Intelligence and Intelligent Informatics, vol. 25, no. 5, pp. 610-617, 2021.
- [22] R. A. Bedruz et al., "Design of a Robot Controller for Peloton Formation Using Fuzzy Logic," 2019 7th International Conference on Robot Intelligence Technology and Applications (RITA), 2020.
- [23] M. G. Palconit et al., "Diffusion of Robotics in the Philippines: Impact of Policies, Laws, R & D, and Word of Mouth," 2020 IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), 2020.