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Implementation of Boolean Control Network Based Intelligent System in Smart Home

M. Humayun Kabir, M. Robiul Hoque and Sung-Hyun Yang*

Department of Electronic Engineering, Kwangwoon University
Seoul, Republic of Korea
shyang@kw.ac.kr

Abstract

Smart home is a nondeterministic complex environment. Sensors and actuators network are involved in smart home to collect environmental information and to control the devices used by the user for comfort of life. Generally smart home system is implemented by logical rules which described the relation between each element (sensors and actuators). Controlling using logical rules is difficult. In this paper, we have represented an intelligent system for smart home by using Boolean Control Network. For easy control, we have used matrix expression of logic. The system is controlled in several states and in each state different device is operated through actuator network. Matlab based simulation work is done to show the state changes of the system. The result shows that using matrix expression it is easy to control the state of this system.

Keywords: *Boolean control network, intelligent system, smart home, semi-tensor matrix product*

1. Introduction

Smart home is an application of ubiquitous computing. Smart home provides automated or assistive services in the form of ambient intelligence, remote home control, or home automation [1]. Intelligent system in smart home automatically collect environmental information and provide services that maximize the user's comfort and safety while minimizing the user's explicit interaction with the devices as well as the cost of the service. Intelligent systems can be implemented using logic rules, artificial neural networks, fuzzy neural network, support vector machines, Bayesian networks, *etc.*, [2-6] for smart home. Controlling using this method is difficult due to using lack of sufficient model of environment. A Boolean network is a set of Boolean variables whose state is changed by other variables in the network. Boolean network is used for modelling complex system like neural networks, social and economic networks. In this paper, we have presented intelligent system using Boolean control network and for easy controlling we used matrix expression of logic. This intelligent system will provide automated service to user's in smart home. An intelligent system can be considered as a Boolean control networks, where different combination of devices as state variables and environmental elements are treated as control inputs. We describe the relation between state and environmental elements by logic rules. Using semi-tensor matrix product logic relation between different variables can be expressed by matrix equation that explains the system and represents the effects of different components. These environmental elements and states are considered as Boolean logical variables with value either true or false. Matrix expression is a convenient approach for logic inference. We have used semi-tensor product of matrix to make logic function into

* Corresponding Author

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algebraic equation. We have used Matlab for calculation of state change of this system. Using matrix calculation we can easily control the state of this system.

The organization of this paper is as follows. In Section 2 we define and review of related topics for Boolean control network. Section 3 presents the implementation of this system followed by conclusion in Section 4.

2. Boolean Control Network

A Boolean control network (BCN) is a discrete-time logical control system. The state variable at time *t+1* can be derived by the state of its neighbours at time *t*. It can be expressed as:

$$\begin{cases} s_1(t+1) = f_1(s_1(t), \dots, s_n(t), u_1(t), \dots, u_m(t)) \\ \vdots \\ s_n(t+1) = f_n(s_1(t), \dots, s_n(t), u_1(t), \dots, u_m(t)) \end{cases} \quad (1)$$

Where, $f_i : D^{n+m} \rightarrow D=\{1,0\}, i=1,\dots,n$, are logical functions, $s_j \in D, j=1,2,\dots n$, are states, $u_l \in D, l=1,2,\dots m$ are control inputs.

Boolean control network can be represented using directed graph with n nodes and m inputs. An edge from node i to node j represents that node j is effected by node i. The graphical representation of a Boolean control network is shown in Figure 1.

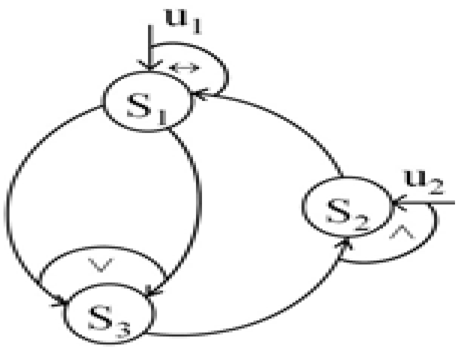

Figure 1. Graphical Representation of a Boolean Control Network

The concept of semi-tensor product is proposed by authors in [7] and it is used to represent BCNs in a linear algebraic state-space form. The topics related to Boolean control network are briefly presented in this section, which are useful for studying BCNs in a control-theoretic framework. Logical variable can be represented by $D=\{T,F\}$,or$\{1,0\}$. For matrix expression we identify truth "*T*" and false "*F*", with the following vectors

$$T := 1 \sim \begin{bmatrix} 1 \\ 0 \end{bmatrix} \ or \ \delta_2^1, F := 0 \sim \begin{bmatrix} 0 \\ 1 \end{bmatrix} \ or \ \delta_2^2$$

where, δ_k^i is the i^{th} column of the identity matrix I_k and $\Delta_k := \{\delta_k^i | i = 1,2,\dots,k\}$

Definition 1: A matrix $L \in M_{n\times m}$ is called a logical matrix if $Col(L) \subset \Delta_n$. The set of $n\times m$ logical matrices is denoted by $\mathcal{L}_{n\times m}$. If $L \in \mathcal{L}_{n\times m}$, then it has the form $L = [\delta_n^{i_1} \ \delta_n^{i_{21}} \ \cdots \ \delta_n^{i_m}]$ or in compact form $L = \delta_n [i_1 \, i_2 \dots i_m]$

Definition 2: The semi-tensor product ($\ltimes$) is a generalization of the conventional matrix product that allows multiplying two matrices of arbitrary dimensions. The semi-tensor product of two matrices $A \in M_{m\times n}$ and $B \in M_{p\times q}$ is

$$A \ltimes B = (A \otimes I_{\alpha/n})(B \otimes I_{\alpha/p}) \tag{2}$$

where α is equal to least common multiple of n and p (lcm(n,p)).

A Boolean function can be converted into an algebraic form using the semi-tensor matrix product. Any Boolean function of n variables f: $\{F,T\}^n \rightarrow \{F,T\}$ can be equivalently represented as a mapping $f = \{\delta_2^1, \delta_2^2\}^n \rightarrow \{\delta_2^1, \delta_2^2\}$

Definition 3: A 2×2^r matrix R_σ is said to be the structure matrix of the *r-ary* logical operator σ if

$$\sigma(p_1, \ldots, p_r) = M_\sigma \ltimes p_1 \ltimes \ldots \ltimes p_r := M_\sigma \ltimes_{i=1}^{r} p_i \tag{3}$$

The structure matrix of the function $\sigma(q_1, q_2, \ldots, q_r)$ can be calculated in the following three steps:

Step 1. Using the fact that $qR = (I_2 \otimes R)q$, all factors of structure matrices R_j or $I_2 \otimes R_j$ can be move to the front and move all the variables, q_i, to the rear of the product.

$$\sigma(q_1, q_2, \ldots, q_r) = \ltimes_i \xi_i = \ltimes_j M_j \ltimes_k q_{ik} \tag{4}$$

where $M_j \in \{I_{2^s} \otimes MN, I_{2^s} \otimes MD, I_{2^s} \otimes MC \mid s = 0,1,2,\ldots\}, i_k \in \{1, 2, \ldots, r\}$

Step 2. Using a swap matrix the order of two logical variables can be changed $W_{[2]} q_i q_j = q_j q_i$

$$\ltimes_k p_{i_k} = M \ltimes p_1^{k_1} \ltimes p_2^{k_2} \ltimes \ldots \ltimes p_r^{k_r} \tag{5}$$

Step 3. Using a power-reducing matrix, the power of the q_i's can all be reduced to 1. The coefficient matrices, generated by reducing orders, can be moved to the front part.

Some of the structure matrices used in BCN are tabulated in Table1.

Table 1. Listed some of the Structure Matrices used in BCN

Logical Operator	Structure Matrix	Logical Operator	Structure Matrix
Negation($\neg$)	$MN = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \delta_2[2 \ \ 1]$	Disjunction($\vee$)	$MD = \begin{bmatrix} 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \delta_2[1 \ \ 1 \ \ 1 \ \ 2]$
Conjunction($\wedge$)	$MC = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix} = \delta_2[1 \ \ 2 \ \ 2 \ \ 2]$	Conditional($\rightarrow$)	$MI = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \delta_2[1 \ \ 2 \ \ 1 \ \ 1]$
Biconditional($\leftrightarrow$)	$ME = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} = \delta_2[1 \ \ 2 \ \ 2 \ \ 1]$	Exclusive Or	$MP = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} = \delta_2[2 \ \ 1 \ \ 1 \ \ 2]$
Dummy(σ_d)	$ED = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} = \delta_2[1 \ \ 2 \ \ 1 \ \ 2]$	Power reduced	$MR = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} = \delta_2[1 \ \ 4]$

Definition 4: A swap matrix $W_{[m,n]}$ is an $mn \times mn$ matrix, defined as follows. Its rows and columns are labeled by double index (i, j), the columns are arranged by the ordered multi-index Id(i, j: m, n), and the rows are arranged by the ordered multi-index Id(j, i: m, n). The element at position [(I, J), (i, j)] is then

$$w_{(I,J),(i,j)} = \delta_{i,j}^{I,J} = \begin{cases} 1, & I = i \text{ and } J = j, \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

The Boolean control network can be represented by a set of Boolean functions.

Theorem 1: A BCN with state variables $s_1,\ldots\ldots,s_n$ and inputs $u_1,\ldots\ldots,u_m$ with s_i, $u_i \in \{\partial_2^1, \partial_2^2\}$ then the logic function of equation (1) can be expressed as:

$$s(t+1)=H \ltimes u(t) \ltimes s(t) \tag{7}$$

where, the matrix H is called the transition matrix of the BCN and $H \in \mathcal{L}_{2^m \times 2^{n+m}}$, $s(t+1)= \ltimes_{i=1}^{n} s_i(t+1)$, $u(t)= \ltimes_{j=1}^{m} u_j(t)$, $s(t)= \ltimes_{k=1}^{n} s_k(t)$

3. Implementation of the System

This system realizes by five states: wake up (s_1), standard (s_2), recreation (s_3), sleeping (s_4), and security (s_5). For input it uses seven environmental elements with Boolean logic values true and false. These environmental elements are categorized as person (u_1), time (morning(u_2), evening(u_6), night(u_4)), and location (bedroom(u_3), sofa(u_7), outside (u_5)). This system can be expressed by equation (1). Each state can be defined by logical relation between the environmental elements and state. Table 2 shows logic rules for state change.

Table 2. Logic Rules for State Change

	Logic rules for state change
i.	if State=(wake up ∨ sleeping) ∧ person ∧ Time=morning ∧ Location=Bedroom then State=wake up
ii.	if State=(wake up ∨ standard ∨ security) ∧ person ∧ Location= ¬outside then State= Standard
iii.	if State=(standard ∨ recreation ∧¬ sleeping) ∧ person ∧ Time=evening ∧ Location= sofa then State= recreation
iv.	if State=(standard ∨ recreation ∨ sleeping) ∧ person ∧ Time=night ∧ Location =Bedroom then State=sleeping
v.	if State=(standard∨security)∧ ¬person∧ Location=outside then State=security

Logic rules can be expressed by propositional logic as follows:

$wakeup(t+1) = (wakeup(t) \vee Sleeping(t)) \wedge Person(t) \wedge Time\_morning(t) \wedge Location\_bedroom(t)$

standard(t+1) = (wakeup(t)∨ standard(t)∨ security(t)) ∧ Person(t)∧ (¬Location_outside(t))

recreation(t+1) =(standard(t)∨ recreation(t))∧(¬ sleeping(t))∧Person(t)∧Time_evening(t)∧ Location_sofa(t)

sleeping(t+1) = (standard(t)∨ recreation(t)∨ sleeping(t))∧Person(t)∧Time_night(t)∧ Location_bedroom(t)

security(t+1) = (standard(t)∨ security(t)) ∧(¬Person(t))∧Location_outside(t) (8)

Using logic variables and structure matrix of the logical operator (Table 1) we can express above logical equation can be expressed algebraic function as follows:

$$s_1(t+1) = (s_1 \vee s_4) \wedge u_1 \wedge u_2 \wedge u_3 \\ = MC \ltimes MC \ltimes MC \ltimes MD \ltimes s_1 \ltimes s_4 \ltimes u_1 \ltimes u_2 \ltimes u_3$$

$$s_2(t+1) = (s_1 \vee s_2 \vee s_5) \wedge u_1 \wedge (\neg u_6) \\ = MC \ltimes MC \ltimes MD \ltimes MD \ltimes s_2 \ltimes s_5 \ltimes s_1 \ltimes u_1 \ltimes MN \ltimes u_6$$

$$s_3(t+1) = (s_2 \vee s_3) \wedge (\neg x_4) \wedge u_1 \wedge u_7 \wedge u_8 \\ = MC \ltimes MC \ltimes MC \ltimes MC \ltimes MD \ltimes s_2 \ltimes s_3 \ltimes MN \ltimes s_4 \ltimes u_1 \ltimes u_7 \ltimes u_8$$

$$s_4(t+1)=(s_2 \vee s_3 \vee s_4) \wedge u_1 \wedge u_5 \wedge u_3 \\ = MC \ltimes MC \ltimes MC \ltimes MD \ltimes MD \ltimes s_2 \ltimes s_3 \ltimes s_4 \ltimes u_1 \ltimes u_5 \ltimes u_3$$

$$s_5(t+1) = (s_2 \vee s_5) \wedge (\neg u_1) \\ = MC \ltimes MD \ltimes s_2 \ltimes s_5 \ltimes MN \ltimes u_1 \qquad (9)$$

Following the procedure described in section 2 algebraic equation of (9) can be expressed as:

$$\mathbf{s}(t+1)=H \ltimes \mathbf{u}(t) \ltimes \mathbf{s}(t) \qquad (10)$$

where, $H \in \mathcal{L}_{2^5 \times 2^{5+7}}$, $s(t+1)= \ltimes_{i=1}^{5} s_i(t+1)$, $u(t)= \ltimes_{j=1}^{7} u_j(t)$, $s(t)= \ltimes_{k=1}^{5} s_k(t)$.

The first and last few columns of transition matrix H are δ_{32}[14 14 14 14 6 6 6 6 16 16 16 16 8 8 8 8 32 32 32 32 24 24 24 24 32 32 32 32 24 24 24 24 30 30 30 30 22 22 22 22 32 32 32 32 24 24 24 24 32 32 32 32 24 24 24 24 32 32 32 32 24 24 24 24 31 31 31 31 31 31 31 31 31
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32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32]

We have used Matlab for calculation of state change of this system. Using matrix calculation we can easily control the state of this system. The state space graph of equation (10) is shown in Figure 2. State value is shown in serially as (wake up, standard, recreation, sleeping, and security). The value 1 represents available and 0 for unavailable. For example if state value is (1,0,0,0,0) it means wake up state.

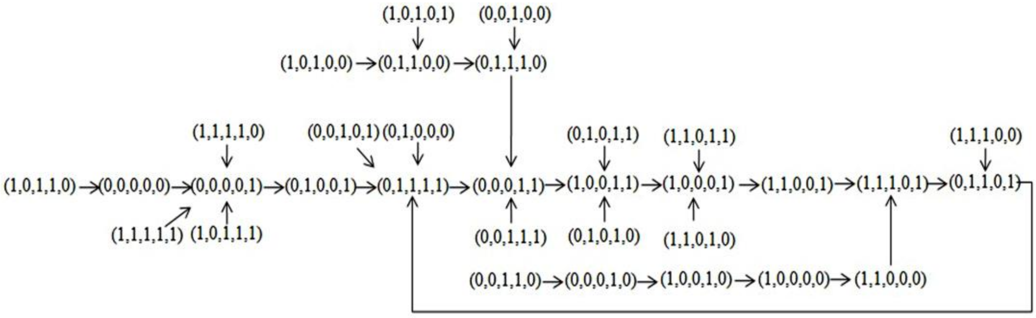

Figure 2. State Space Graph

If the control inputs of the corresponding states are true then a list of home appliances and devices will be operated. For simplification we use two operating state: turn on and turn off. Table 3. shows the service description. Service description equation and algorithm was presented in [8].

Table 3. Service Description

Service	Device on operation
Wake up	Alarm, Room light, Blind, Coffee maker, Water heater
Standard	Room light, Blind, Air conditioner
Recreation	TV, Room light, Air conditioner
Sleeping	Air conditioner
Security	No devices

4. Conclusion

Intelligent system in smart home can be realized by using Boolean control network. All the logical variables represented by Boolean true and false values in this system. There are five states in this system. The states are expandable due to the matrix representation of elements. These states are described using logic rule, then state transition matrix is formed. This state-transition matrix represents the logical mapping between context input and service output. In future, we will investigate the controllability and observability of this Boolean Control network used in this system. The problem of observability also will be verified by necessary and sufficient conditions.

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