Robust synchronization of a uncertain complex dynamical network with Markovian jumping topology via pinning sampled-data control

J.H. Park¹, T.H. Lee¹, H.Y. Jung¹, S.M. Lee²

¹Department of EE/ICE, Yeungnam University, Kyongsan 712-749, Republic of Korea.
²Department of Electronic Engineering, Daegu University, Kyongsan 712-714, Republic of Korea.

Corresponding author: moony@daegu.ac.kr (S.M. Lee)

Abstract—In this paper, the robust synchronization problem of a uncertain complex dynamical network with Markovian jumping topology via pinning sampled-data control is investigated. In order to make full use of the sawtooth structure characteristic of the sampling input delay, a discontinuous Lyapunov functional is used based on the Extended Wirtinger Inequality. By utilizing Finsler’s lemma, a new stability condition is obtained in terms of linear matrix inequalities (LMIs) for the synchronization.

Keywords: Complex network, Synchronization, Markovian jumping, Robust control, Sampled-data control, Pinning method.

1. Introduction

During the last decade, complex dynamical networks, which are a set of interconnected nodes with specific dynamics, have attracted increasing attention in various fields such as physics, biology, chemistry and computer science [1]-[2]. As science and society develop, our everyday lives have been closed to complex networks, for instance, transportation networks, World Wide Web, coupled biological and chemical engineering systems, neural networks, social networks, electrical power grids and global economic markets. Recently, one of the significant and interesting phenomena in complex dynamical network is the synchronization. Therefore, some attention of the problem, how to achieve the synchronization of asynchronous complex dynamical networks, has been increasing rapidly. Until now, in order to treat the synchronization problem for complex dynamical networks, several control schemes are applied. For example, the impulsive control scheme has been applied to achieve the projective synchronization of a complex dynamical network in [3]. In [4], a state observer-based control scheme has been proposed. In [5], an adaptive control scheme has been adopted to carry through the synchronization of a complex dynamical network, whereas in [6], the adaptive control for the synchronization between two complex dynamical networks has been investigated. Recently, the pinning-controllability and the method of choosing pinning nodes for the synchronization of a complex dynamical network are suggested in [7]. In addition, the synchronization of the complex dynamical network with linearly and nonlinearly coupling terms via pinning control has been studied in [8].

Recently, systems with Marvokian jumps have been attracting increasing research attention. This class of systems are the hybrid systems with two components in the state. The first one refers to the mode, which is described by a continuous-time finite-state Markovian process, and the second one refers to the state which is represented by a system of differential equations. The Markovian jump systems have the advantage of modeling the complex dynamical networks subject to abrupt variation in their communication topologies, such as component failures or repairs, sudden environmental disturbance, changing subsystem interconnections, and operating in different points of a nonlinear plant. However, just a few papers consider the complex network with Markovian jumping topology [9].

In many practical situations, the complex dynamical networks are usually subjected to parameter uncertainties, which are considered as one of the main source leading to undesirable behaviors [10]. Dynamic systems often have uncertainties due to parameter aging, saturation, modeling error and so on. Also, a real network system is usually influenced by external perturbations in communication between nodes. Therefore, the necessity of further investigation of robust synchronization schemes for an uncertain complex dynamical network is strongly raised.

On the other hand, because of the rapid growth of the digital hardware technologies, the sampled-data control method, whose control signals are kept constant during the sampling period and are allowed to change only at the sampling instant, has been more important than other control approaches. These discontinuous control signals which have stepwise form cause big trouble to control or analyze the system. In order to effectively deal with sampled-data control, Mikheev, Sobolev, and Fridman [11] and Astrom and Wittenmark [12] introduced a concept that discontinuous sampled control inputs treat time-varying delayed continuous signals, although applied actual control signals are discontinuous. Since the works of [11], [12], many types of the sampled-data control scheme by using the concept in [11]-[12] have been proposed. For instance, in [13], the robust $\mathcal{H}_\infty$ sampled-data control has been proposed. In [14], the sampled-data fuzzy controller has been proposed as well. Moreover, many researchers have adopted the sampled-data control scheme to solve control problems in various
systems such as chaotic system [15], fuzzy system [16], neural networks [17] and so on. However, there are only a few papers for complex dynamical networks using the sampled-data control approach [18]. Besides, to the best of our knowledge, the pinning sampled-data control method has never been tackled. Therefore, it is very worth to consider the pinning sampled-data control method for complex dynamical networks.

From motivation mentioned above, this paper proposes a discontinuous Lyapunov functional approach to achieve robust synchronization of an uncertain complex dynamical network with Markovian jumping topology via pinning sampled-data control. The discontinuous Lyapunov functional makes full use of the sawtooth structure characteristic of sampling input delays. A convex representation of the network with Markovian jumping topology via pinning sampled-data control method for complex dynamical networks.

Our objective of the paper is to achieve synchronization between all nodes of a complex dynamical network and a target node via controllers $u_i(t)$ which is denoted by the following definition.

**Definition 1.** A complex dynamical network is said to achieve the asymptotical inner synchronization, if

$$x_1(t) = x_2(t) = \cdots = x_N(t) = s(t) \quad \text{as} \quad t \to \infty,$$

where $s(t) \in \mathbb{R}^n$ is a solution of a target node, satisfying

$$\dot{s}(t) = Ax(t) + Bf(s(t)).$$

For our synchronization scheme, let us define the error vectors as follows:

$$e_i(t) = x_i(t) - s(t).$$
From Eq. (5), the error dynamics is given to
\[
\dot{e}_i(t) = Ae_i(t) + B(f(x_i(t)) - f(s(t))) + \sum_{j=1}^{N} c_{ij}(\rho(t))e_j(t) + u_i(t)
\]
\[
= Ae_i(t) + B\bar{f}_i(t) + \sum_{j=1}^{N} c_{ij}(\rho(t))e_j(t) + u_i(t), \quad i = 1, \ldots, N
\]
(6)
where \(\bar{f}_i(t) = f(x_i(t)) - f(s(t))\).

By the well-known mean value theorem, there exists a constant \(\nu \in (x_{ik}(t), s_{ik}(t))\) such that
\[
f_k(x_{ik}(t)) - f_k(s_k(t)) = df_k(\nu)(x_{ik}(t) - s_k(t)).
\]
(7)
From the slope bounds given in Assumption 1, we have
\[
\beta_k \leq \frac{df_k(\nu)}{d\nu} \leq \alpha_k.
\]
(8)
By Eqs. (7), (8) and \(e_i(t) = x_i(t) - s(t)\), we have
\[
\beta_k e_{ik}(t) \leq \bar{f}_i(\bar{e}_{ik}(t)) \leq \alpha_k e_{ik}(t).
\]
(9)
Therefore, Eq. (9) can be represented the following equality condition by properties of the convex hull:
\[
\bar{f}_i(e_i(t)) = \Delta_i e_i(t),
\]
(10)
where \(\Delta_i\) is an element of a convex hull \(Co(\alpha, \beta)\).

**Remark 1.** The slope bound of nonlinear function, \(f(\cdot)\), becomes new sector bound of the nonlinear function \(f(e_i(t)) = f(s(t)) - f(x_i(t))\). And this condition can be represented by a convex combination of the sector bounds \(\alpha_k\) and \(\beta_k\). This method was proposed in [19]. In general, most of nonlinear functions which consist of nonlinear system such as Chua’s circuit [20] and so on, satisfy this condition. Also, this condition includes Lipschitz condition as a special case.

On the other hand, in order to design the pinning controller using the sampled-data signal, the concept of the time-varying delay control input which is proposed in [11]-[12], is adopted in this paper. For this, the following pinning state feedback controller is considered
\[
u_i(t) = K_i e_i(t_k), \quad t_k \leq t < t_{k+1}, \quad i = 1, \ldots, h
\]
\[
u_i(t) = 0, \quad i = h + 1, \ldots, N
\]
(11)
where \(K_i\) is the gain matrix of feedback controller to be determined and \(h\) is the number of pinning nodes.

Denote by \(t_k\) the updating instant time of the Zero-Order-Hold (ZOH), we assume that the sampling intervals satisfy
\[
t_{k+1} - t_k = d_k \leq d,
\]
(12)
for any integer \(k \geq 0\), where \(d\) is a positive scalar and represents the largest sampling interval.

Thus, by defining \(d(t) = t - t_k\), \(t_k \leq t < t_{k+1}\), the controller (11) can be represented as following:
\[
u_i(t) = K_i e_i(t_k), \quad t_k \leq t < t_{k+1}
\]
\[
u_i(t) = K_i e_i(t - d(t)), \quad i = 1, \ldots, h
\]
(13)
From (12), we can find that \(d(t) < t_{k+1} - t_k \leq d\) and \(d(t) = 1\) for \(t \neq t_k\). Now, substituting (13) into (6) and considering system uncertainties gives
\[
\dot{e}_i(t) = Ae_i(t) + B\bar{f}_i(e_i(t)) + \sum_{j=1}^{N} c_{ij}(\rho(t))e_j(t) + K_i e_i(t - d(t)),
\]
(14)
\(t_k \leq t < t_{k+1}, \quad i = 1, \ldots, N\).

where \(K_i = 0(i = h + 1, \ldots, N)\). Then Eq. (14) can be rewritten as a vector-matrix form
\[
\dot{e}(t) = A_N e(t) + B_N F(e(t)) + C_N(\rho(t))e(t) + K e(t - d(t)),
\]
(15)
where \(e(t) = [e_1(t), \ldots, e_N(t)]^T, \ F(t) = [\bar{f}^T(e_1(t)), \ldots, \bar{f}^T(e_N(t))]^T, \ A_N = I_N \otimes A, \ B_N = I_N \otimes B\) and \(C_N = C \otimes I_h, \ K = diag\{K_1, \ldots, K_h, 0, \ldots, 0\}\).

In this paper, we consider system uncertainties as follows:
\[
\dot{e}(t) = (A_N + \Delta A(t))e(t) + (B_N + \Delta B(t))F(e(t)) + (C_N(\rho(t)) + \Delta C(\rho(t)))e(t) + K e(t - d(t)),
\]
(16)
where \(\Delta A(t), \Delta B(t)\) and \(\Delta C(\rho(t))\) are the uncertainties of system matrices of the form
\[
[\Delta A(t) \quad \Delta B(t) \quad \Delta C(\rho(t))] = DF(t) \begin{bmatrix}
E_a & E_b & E_c(\rho(t))
\end{bmatrix}\]
(17)
in which \(D, E_a, E_b\) are known constant matrices, \(E_c(\rho(t))\) is known function of random jumping process \(\rho(t)\) and the time-varying nonlinear function \(F(t)\) satisfies
\[
F^T(t)F(t) \leq I, \forall t \geq 0.
\]
(18)
So, Eq. (16) can be rewritten as
\[
\dot{e}(t) = (A_N + C_N(\rho(t))e(t) + B_N F(e(t)) + K e(t - d(t)) + Dp(t),
\]
(19)
p(t) = F(t)q(t),
\[
q(t) = (E_a + E_c(\rho(t)))e(t) + E_b f(e(t))
\]
For simplicity of notations, in this paper, we denote the matrices associated with the \(l\)th mode \((\rho(t) = l)\) by \(C_N^l = C_N(\rho(t)), \ E_a^l = E_a(\rho(t)), \\) where \(C_N^l\) and \(E_a^l\) are known constant matrices of appropriate dimensions.

In order to investigate the stochastic stability analysis for Markovian jumping complex dynamical network (19), we
introduce the following definition and lemmas.

**Definition 2.** [21] The system (19) is said to be stochastically stable, if for any finite \( \phi(s) \in C_{n,d} \), and the initial condition of the mode \( \rho_0 \in S \) the following condition if satisfied

\[
\lim_{t \to \infty} \mathbb{E} \left\{ \int_0^t e^T(s) e(s) ds | \phi, \rho_0 \right\} < \infty. \quad (20)
\]

**Remark 2.** Many systems such as the continuous-time systems with the digital control, the networked control systems and so on, can be modelled by sampled-data systems. Now days, most of controllers are the digital controller or networked to the system, so the sampled-data control approach is eligible to receive much attention.

### 3. Main results

In this section, a design problem of the pinning sampled-data feedback controller for the synchronization of a complex dynamical network with Markovian jumping topology will be investigated via a discontinuous Lyapunov functional approach. Before proceeding further, the following notations of several matrices are given.

\[
\zeta(t) = \begin{bmatrix} e^T(t) e^T(t-d(t)) e^T(t-d) F^T(t) \\ e^T(t) p(t) \end{bmatrix}^T,
\]

\[
\Delta = \text{diag}\{\Delta_1, \ldots, \Delta_N\}
\]

\[
\gamma = \frac{\pi^2}{4}
\]

\[
\Phi^l = \begin{bmatrix} E_a + E_c^l & 0 & 0 & E_b \\ 0 & 0 & 0 \end{bmatrix}
\]

\[
\Psi^l = \begin{bmatrix} A_N + C_N \Gamma & 0 & B_N & -I & D \end{bmatrix}
\]

\[
\Gamma_{11} = \sum_{g=1}^L \pi_{lg} P^g + Q - R - \gamma Z + \Delta N_1^T + N_1 \Delta,
\]

\[
\Gamma_{12} = R - S + \gamma Z, \quad \Gamma_{14} = -N_1 + \Delta N_2^T,
\]

\[
\Gamma_{22} = -2R + S + S^T - \gamma Z,
\]

\[
\Gamma_{23} = R - S, \quad \Gamma_{33} = -Q - R,
\]

\[
\Gamma_{44} = -N_2 - N_2^T, \quad \Gamma_{55} = d^2 (R + Z),
\]

\[
\Gamma_{66} = -\epsilon I.
\]

\[
\Gamma^l = \begin{bmatrix} \Gamma^l_{11} & \Gamma^l_{12} & S & \Gamma^l_{14} & P^l & 0 \\ * & \Gamma^l_{22} & \Gamma^l_{23} & 0 & 0 & 0 \\ * & * & \Gamma^l_{33} & 0 & 0 & 0 \\ * & * & * & \Gamma^l_{44} & 0 & 0 \\ * & * & * & * & \Gamma^l_{55} & 0 \\ * & * & * & * & * & \Gamma^l_{66} \end{bmatrix},
\]

\[
\Upsilon^l = \Gamma^l + \epsilon \Phi^T \Phi^l.
\]

Now, the main result is given by the following theorem.

**Theorem 1.** For given matrix \( K \) and a positive scalar \( d \), system (19) is stochastically stable for the conditions, if there exist positive definite matrices \( P^l (l = 1, \ldots, L) \), \( R, Z \in \mathbb{R}^{nN \times nN} \), matrices \( N_1, N_2, S \in \mathbb{R}^{nN \times nN} \) and a positive scalar \( \epsilon \) satisfying the following LMIs:

\[
(\Psi^l)^T \Upsilon^l (\Psi^l)^T < 0, \quad (22)
\]

\[
\begin{bmatrix} R & S \\ \ast & R \end{bmatrix} \geq 0, \quad (23)
\]

where \( \Psi^l \) is the right orthogonal complement of \( \Psi^l \).

**Proof.** Consider the following discontinuous Lyapunov functional for error system (14)

\[
V(t) = V_1(t) + V_2(t) + V_3(t), \quad t \in [t_k, t_{k+1}) \quad (24)
\]

where

\[
V_1(t) = e^T(t) P^l e(t),
\]

\[
V_2(t) = \int_{t-d}^t e^T(s) Q e(s) ds + d \int_{t-d}^t \int_{t+\theta}^t e^T(s) R e(s) ds d\theta,
\]

\[
V_3(t) = \int_{t-k}^t e^T(s) Z e(s) ds + \frac{\pi^2}{4} \int_{t-k}^t (e(s) - e(t_k))^T Z (e(s) - e(t_k)) ds.
\]

It is noted that \( V_3(t) \) which is first proposed by Fridman [23], can be rewritten as

\[
\tilde{V}_3(t) = d^2 \int_{t-d}^t e^T(s) Z e(s) ds + \tilde{V}_4(t) \quad (25)
\]

where

\[
\tilde{V}_4(t) = \frac{\pi^2}{4} \int_{t-k}^t (e(s) - e(t_k))^T Z (e(s) - e(t_k)) ds.
\]

According to Extended Wirtinger Inequality [22], it is easy to find that \( \tilde{V}_3(t) \geq 0 \). In addition, it is correct that \( \lim_{t \to t_k} V(t) \geq V(t_k) \), because \( \tilde{V}_3(t) \) will disappear at \( t = t_k \).

In [24], it is known that the random process \( \{e(t), \rho(t), t \geq 0\} \) is a \( C_{n,d} \times S \)-valued Markovian jump process with initial state \( (\phi(\cdot), \rho(\cdot)) \).

Applying on \( V(e(t), l; C_{n,d} \times S \times \mathbb{R}^+ \to \mathbb{R} \), its weak infinitesimal operator \( L \) is defined by

\[
LV(e(t), l) = \lim_{\delta \to 0^+} \frac{1}{\delta} \mathbb{E} \{ V(e(t+\delta), \rho(t+\delta)) \mid e(t), \rho(t) = l \} - V(e(t), \rho(t) = l) \quad (26)
\]
Then, for each $i \in \mathcal{S}$, we obtain
\begin{align}
\mathbb{L}V_1(t) &= 2e^T(t)P^i\dot{e}(t) + e^T(t)\left(\sum_{l=1}^{N} \pi_{lg}P^l\right)e(t), \quad (27) \\
\mathbb{L}V_2(t) &= e^T(t)Qe(t) - e^T(t - d)Qe(t - d) \\
&+ 2\int_{t-d(t)}^{t} \dot{e}(s)\dot{R}\dot{e}(s)ds \\
&- d\int_{t-d}^{t-d(t)} e^T(s)\dot{R}\dot{e}(s)ds,
\end{align}
\begin{align}
\mathbb{L}V_3(t) &= d^2\dot{e}^T(t)Z\dot{e}(t) - \frac{\pi^2}{4} \left[ e(t) ight] \\
&\times \left[ \begin{array}{cc} Z & -Z \\ \ast & Z \end{array} \right] \left[ e(t - d(t)) \right].
\end{align}
By Jensen inequality and Theorem 1 in [25], the integral terms of the $\mathbb{L}V_2(t)$ can be bounded as
\begin{align}
&-d\int_{t-d}^{t-d(t)} e^T(s)\dot{R}\dot{e}(s)ds - d\int_{t-d}^{t-d(t)} e^T(s)\dot{R}\dot{e}(s)ds \\
&\leq - \left[ \begin{array}{c} \eta_1(t) \\ \eta_2(t) \end{array} \right]^T \left[ \begin{array}{cc} \frac{d}{dt}(R) & 0 \\ \ast & \frac{d}{dt}(R) \end{array} \right] \left[ \begin{array}{c} \eta_1(t) \\ \eta_2(t) \end{array} \right] \\
&\leq - \left[ \begin{array}{c} \eta_1(t) \\ \eta_2(t) \end{array} \right]^T \left[ \begin{array}{cc} R & S \\ \ast & R \end{array} \right] \left[ \begin{array}{c} \eta_1(t) \\ \eta_2(t) \end{array} \right]
\end{align}
where $\eta_1(t) = \int_{t-d}^{t-d(t)} \dot{e}(s)ds$, $\eta_2(t) = \int_{t-d}^{t-d(t)} \dot{e}(s)ds$.
From the convex representation (10), we can obtain the following equation:
\begin{equation}
F(t) = \Delta e(t).
\end{equation}
The constraint (31) is rewritten as
\begin{equation}
\left[ \begin{array}{cc} \Delta & -I \end{array} \right] \left[ \begin{array}{c} e(t) \\ F(t) \end{array} \right] = 0.
\end{equation}
For matrices $N_1$ and $N_2$, the following equality is always satisfied:
\begin{equation}
2 \left[ \begin{array}{c} e(t) \\ F(t) \end{array} \right]^T \left[ \begin{array}{cc} N_1 & N_2 \end{array} \right] \left[ \begin{array}{cc} \Delta & -I \end{array} \right] \left[ \begin{array}{c} e(t) \\ F(t) \end{array} \right] = 0.
\end{equation}
Eq. (17) and (18) give
\begin{equation}
p^T(t)p(t) \leq q^T(t)q(t).
\end{equation}
So, there exists a positive constant, $\epsilon$, satisfying the following equation
\begin{equation}
\epsilon [\dot{\zeta}^T(t)\Phi^T \Phi \zeta(t) - p^T(t)p(t)] \geq 0
\end{equation}
where $\zeta(t)$ and $\Phi^T$ are defined in (21).
From (27)-(30), (33) and (35), the $\mathbb{L}V$ has a new upper bound as
\begin{equation}
\mathbb{L}V(e(t), l) \leq \zeta^T(t)\Phi^l\zeta(t)
\end{equation}
Also, the system (19) with the augmented vector $\zeta(t)$ and each $l \in \mathcal{S}$ can be rewritten as
\begin{equation}
\Psi^l\zeta(t) = 0
\end{equation}
where $\Psi^l$ is defined in Theorem 1. Therefore, a delay-dependent stability condition for system (19) can be
\begin{equation}
\zeta^T(t)\Phi^l\zeta(t) < 0, \quad \text{subject to} \quad \Psi^l\zeta(t) = 0.
\end{equation}
From Finsler’s lemma, the inequality (38) is equivalent to
\begin{equation}
(\Psi^l)^T\Phi^l(\Psi^l)^T < 0,
\end{equation}
Therefore if the LMI(22) satisfies, then the condition (38) holds. This completes proof.

4. Numerical examples

Fig. 1: The error signals of the uncontrolled system (19).

In this example, MATLAB YALMIP 3.0 and SeDuMi 1.1 are used to solve LMI problem. In order to show pinning controllability of a complex dynamical network with Markovian jumping topology using the sampled-data, we consider a set of five linearly coupled Chua’s chaotic circuit [20] which is typical benchmark three dimensional chaotic systems. The parameters of Chua’s circuit are given by

\begin{equation}
A = \begin{bmatrix} -am_1 & a & 0 \\ 1 & -1 & 1 \\ 0 & -b & 0 \end{bmatrix}
\end{equation}
\begin{equation}
B = \begin{bmatrix} -am_0 & -m_1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},
\end{equation}
\begin{equation}
f(x_{ik}(t)) = \frac{1}{2}(|x_{ik}(t) + c| - |x_{ik}(t) - c|), \quad k = 1, \ldots, n
\end{equation}
where the nonlinear function $f(\cdot)$ belongs to sector $[0, 1]$ and slope $[0, 1]$. Chua’s circuit is also chosen as a target
The parameters associated with system uncertainty are given
\[ D = 0.1 I_{nN}, \quad E_a = 0.4 I_{nN}, \quad E_b = 0.2 I_{nN}, \]
\[ E_c^1 = 0.1 * I_{nN}, \quad E_c^2 = 0.2 I_{nN}, \]
\[ F(t) = 0.5 \sin t \] (42)

Under the above parameter settings, we can obtain the

maximum sampling interval \(d = 0.16\) by Theorem 1.

In this example, initial conditions of each nodes are chosen:
\( x_1(0) = [-0.1 \quad -0.5 \quad -0.7] \),
\( x_2(0) = [-0.1 \quad 0.4 \quad 0.3] \),
\( x_3(0) = [0.6 \quad 1.5 \quad 0] \),
\( x_4(0) = [0.1 \quad 0.1 \quad 0.1] \),
\( x_5(0) = [0.5 \quad 0.4 \quad 0] \)
and \( s(0) = [0.1 \quad 0.5 \quad -0.7] \).

In order to show effectiveness of the controller, the error signals of the uncontrolled system (19) are depicted in Fig. 2. Under the given control gain, \( K \), and sampling interval \( d = 0.12 \), the simulation result of the controlled system (19) and the sampled control inputs are presented in Fig. 3 and Fig. 4, respectively. As seen in Fig. 3, the trajectories of error systems are indeed well stabilized. It means that all states are synchronized up to the states of the target node by control inputs which are seen in Fig. 4. In order to show the effectiveness of the different sampling intervals, Fig. 5 is presented. Fig. 5 (a) and (b) show the error signals of the system (19) with sampling interval \(d = 0.1\) and \(d = 0.16\), respectively. From this figure, it is clear that short sampling interval time is more effective to control the system.

5. Conclusions

In this paper, the pinning sampled-data control for the robust synchronization of a uncertain complex dynamical network with Markovian jumping topology has been discussed. Based on Extended Wirtinger Inequality, a discontinuous Lyapunov functional which gives full information of sawtooth structure characteristic of the sampling delay
has been used. Then the stability criterion of the controller has been derived in terms of LMIs which are based on Lyapunov stability theory, Finsler’s lemma and the sector-slope restricted nonlinearity conditions. A numerical example has shown the effectiveness and good performance of the proposed method.

Acknowledgements

This research of J.H. Park was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology. Also, this work of S.M. Lee was supported in part by MEST & DGIST (12-IT-04, Development of the Medical & IT Convergence System).

References