Implementation and Evaluation of Natural Synchronization Scheme using Environmental Noise

Ryuzo Kuwahara†, Hiroyuki Yasuda† and Mikio Hasegawa†

†Department of Electrical Engineering, Tokyo University of Science
6-3-1 Niijuku, Katsushika-ku, Tokyo, 125-8585 Japan

Abstract– We investigate performance of a novel synchronization scheme, which does not require any signal exchange between the devices. This synchronization scheme is based on noise-induced synchronization phenomenon, that the phase difference of nonlinear limit cycle oscillators are synchronized by adding common noise to each of them. Our natural synchronization scheme uses natural environmental noise as the input noise to each oscillator, which is mounted in the devices. Those oscillators can be synchronized in some cases while the noise fluctuations measured at the neighboring devices are similar. In this paper, we investigate the feasibility of the proposed synchronization scheme using environmental electromagnetic waves. Our experiments result show that the nonlinear limit cycle oscillators can be synchronized by the environmental electromagnetic waves. We also investigate the feasibility of the proposed scheme implemented on the wireless sensor network devices. Our experiments show that the independent devices can be synchronized by the natural environmental fluctuations.

1. Introduction

We have proposed a novel synchronization scheme based on noise-induced synchronization theory [1]. In conventional scheme, signal exchange was necessary to synchronize devices, such as the radio clock, the GPS and so on. Those systems require a built-in module to receive synchronization signal, which becomes an overhead on energy consumption, and exchange of such signal is necessary to synchronize on the conventional systems. On the other hand, in the proposed scheme, no signal exchange between the devices is required to synchronize. It enables synchronization only by the natural environmental fluctuations or noises, such as temperature, humidity, environmental sounds and electromagnetic wave, around the devices.

The noise-induced synchronization is a phenomenon that the phase difference of limit cycle nonlinear oscillators is synchronized with each other by adding a common noise to each of them [5]. The limit cycle oscillators can be synchronized by common noise, such as the Gaussian white noise [2,3], Poisson noise [4,5], Colored noise [6] and so on.

The proposed scheme has been realized based on such phenomena, by introducing natural environmental noise as the input noise. Independent oscillators can be synchronized by such natural noise because the fluctuations of environmental noise measured at the neighboring devices are similar, Ref. [1] showed feasibility of this proposed scheme using real natural noise collected by the experiments, such as temperature and humidity.

In this paper, we investigate the feasibility of noise-induced synchronization that uses environmental electromagnetic waves. We show that the uncoupled nonlinear oscillators can be synchronized by the noise. We also investigate feasibility of the proposed scheme using the wireless sensor network devices. We implement the proposed scheme on real wireless sensor devices, and observe synchronization of those independent devices.

2. Noise-induced Synchronization

Noise-induced synchronization is a phenomenon that the phase difference of limit cycle nonlinear oscillators is synchronized with each other by adding a common noise to each of them [5]. The dynamics of two limit oscillators $\mathbf{X}_1$ and $\mathbf{X}_2$ with common noise $\xi(t)$ can be defined by the following equations,

$$\dot{\mathbf{X}}_1(t) = \mathbf{F}(\mathbf{X}_1) + \alpha\xi(t), \tag{1}$$

$$\dot{\mathbf{X}}_2(t) = \mathbf{F}(\mathbf{X}_2) + \alpha\xi(t), \tag{2}$$

where α is a parameter of noise amplitude, $\xi(t)$ is the Gaussian white noise which find $\langle\xi(t)\rangle = 0, \langle\xi(t)\xi(s)\rangle = 2\delta(t-s)$. When the strength of the noise is weak, the dynamics of the phase of limit cycle oscillators can be expressed as follows,

$$\dot{\theta}_1(t) = \omega + \alpha Z(\theta_1)\xi(t), \tag{3}$$

$$\dot{\theta}_2(t) = \omega + \alpha Z(\theta_2)\xi(t), \tag{4}$$

where $\mathbf{Z}(\theta) = grad_{\mathbf{X}}\theta(\mathbf{X})|_{\mathbf{X}=\mathbf{X}_0(\theta)}$ is called the phase sensitivity function.

Here, we consider the phase difference between two limit cycle oscillators

$$\phi = \theta_1 - \theta_2. \tag{5}$$

When the difference ϕ is sufficiently small, analyzing the Lyapunov exponent of the phase Λ

$$\Lambda = \left\langle \frac{d}{dt}\ln|\phi(t)| \right\rangle. \tag{6}$$

When the phase difference is sufficiently small, the phase difference is approximately linearized,

$$\phi(t) \sim e^{\Lambda t} . \tag{7}$$

When $\Lambda < 0$, the phase difference is reduced. Here,

$$\frac{d}{dt}\ln|\phi(t)| = \frac{\dot{\phi}(t)}{\phi(t)},$$

$$= \frac{\alpha Z'(\theta(t))\phi(t)\xi(t)}{\phi(t)},$$

$$= \alpha Z'(\theta(t))\xi(t) . \tag{8}$$

From eq.(8), eq.(6) can be represented as follows,

$$\Lambda = \langle \alpha Z'(\theta(t))\xi(t) \rangle,$$

$$= \alpha^2 \langle Z''(\theta(t))Z(\theta(t)) \rangle,$$

$$\cong \frac{\alpha^2}{2\pi}\int_0^{2\pi} Z''(\theta)Z(\theta)d\theta,$$

$$= -\frac{\alpha^2}{2\pi}\int_0^{2\pi} \{Z'(\theta)\}^2 d\theta \le 0 . \tag{9}$$

Since the Lyapunov exponent of the phase difference is smaller than 0, the phase difference of the oscillators is reduced. That means the limit cycle oscillators can be synchronized by adding common noise.

3. Noise-induced Synchronization using Natural Environmental Noise

The above theory of noise-induced synchronization has been proved on the case that two input noise are common. Numerical experiments in Ref. [1] has showed that such synchronization can be achieved also by the noise collected from the environment by using wireless sensor network devices, which are similar if they are location close. Ref. [1] proposed natural synchronization scheme based on noise-induced synchronization using natural environmental noise. As shown in Fig. 1, limit cycle oscillators running on each device can be synchronized by inputting environmental fluctuations measured by the sensors on each. By using this scheme, no signal exchange is required to synchronize. It means that self-directive synchronization can be achieved by our scheme.

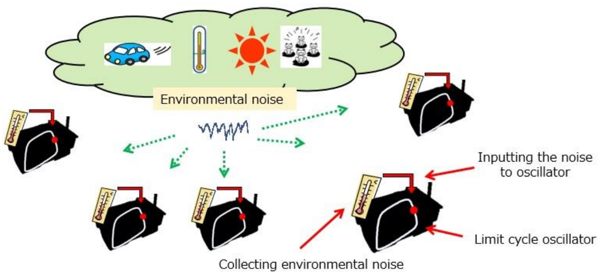


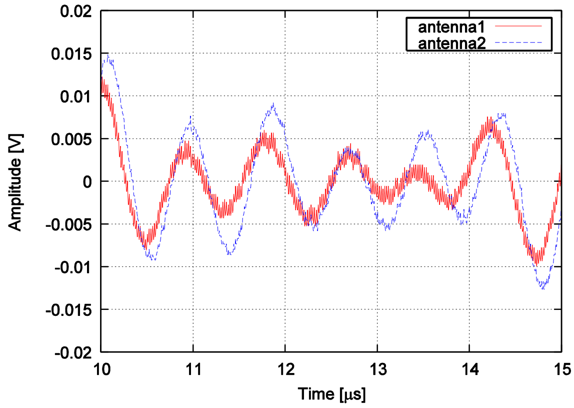
Figure 1: Natural synchronization scheme using environmental fluctuations.

4. Experiments of Noise-induced Synchronization using Environmental Noise

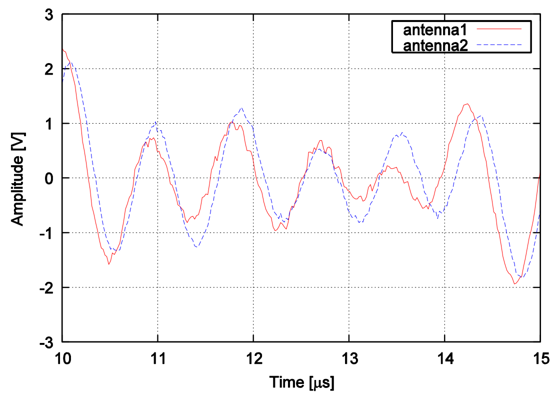
We investigate the feasibility of the proposed scheme using various environmental noise, such as temperature, humidity [1] and environmental sounds [7]. In this paper, we use the environmental electromagnetic waves for the natural synchronization scheme. We also investigate the feasibility of proposed scheme using wireless sensor network devices by implementing the proposed scheme on them.

4.1. Noise-induced Synchronization using Environmental Electromagnetic Waves

In this experiment, environmental electromagnetic waves collected by two independent antennas are used as input noise for the nonlinear oscillators. Ref. [1] has showed that synchronization probability is high when inputting noise to the oscillators is similar. We use normalized fluctuations of environmental noise. Electromagnetic wave fluctuations are shown in Fig.2 (a) and normalized data are shown in Fig.2 (b).



(a) Raw data.



(b) Normalized data.

Figure 2: Examples of the time series of environmental electromagnetic waves used for the natural synchronization. Fig. (a) is raw data and Fig. (b) is normalized data.

These environmental electromagnetic waves are inputted to each oscillator independently. FitzHugh-Nagumo oscillators are used as nonlinear oscillators of noise-induced synchronization which is calculated by PC using Runge-Kutta method. The FitzHugh-Nagumo oscillators can be defined by the following equation,

$$\frac{du}{dt} = \varepsilon(v + c - d \cdot u), \tag{10}$$

$$\frac{dv}{dt} = v - \frac{v^3}{3} - u + I. \tag{11}$$

where ε, c, d, I are parameters. In this experiment, we fix the parameters at $\varepsilon = 0.08$, $c = 0.7$, $d = 0.8$ and $I = 0.8$.

We observe the time series of the phase difference between two oscillators, which have different initial phases. We evaluate the time difference between two oscillators. Time difference is defined as difference of the time crossing phase 0. Fig. 3 shows the time series of the phase difference of oscillators. From Fig. 3, we confirm that the phase difference is gradually reduced. The oscillators can be approximately synchronized by our proposed natural synchronization scheme.

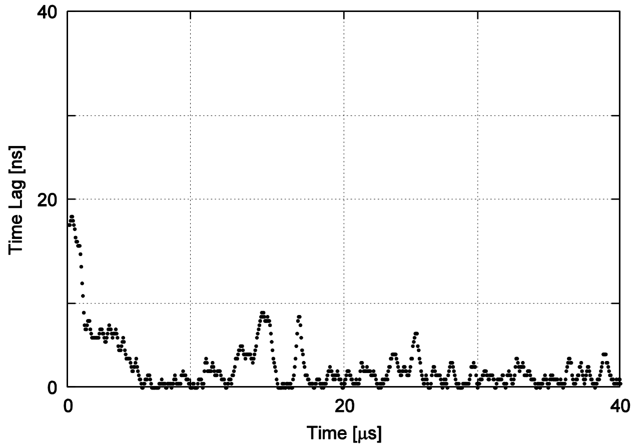


Figure 3: Phase difference between two oscillators.

4.2. Experiments of Noise-induced Synchronization using Two Independent Wireless Sensor Devices

4.2.1. Implementation of the proposed scheme on Wireless Sensor Network Devices

In previous study, synchronization of the oscillators based on noise-induced synchronization using environmental noise is shown by computer simulations [1, 7]. It is need that we evaluate the proposed system by two independent wireless devices. In this experiment, we use wireless sensor network devices, MICAz produced by Crossbow Inc. for our experiment. We implement the natural synchronization scheme on MICAz. In more detail, we have implemented a limit cycle nonlinear oscillator, the data collection part using a built-in sensor, the normalization part applied to the raw sensor data, and display part using LED, on each sensor device. Each sensor device runs the nonlinear oscillator on each with inputting the normalized data of collect noise by the built-in sensor. The phase of the oscillators is displayed by the LED of MICAz. While they are synchronized, the timing of LED lighting is simultaneous. Our implementation on the MICAz is shown in Fig. 4.

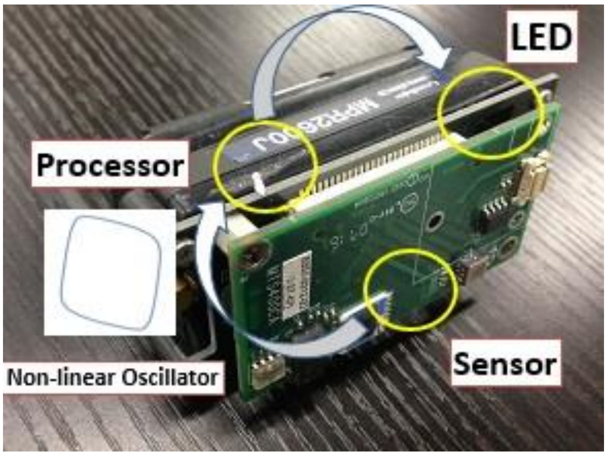


Figure 4: Implementation of the natural synchronization scheme on MICAz.

4.2.2. Experiments and Evaluation using Real Devices

In this experiment, we use the FitzHugh-Nagumo oscillators as the nonlinear oscillator. We use temperature sensor data of the MICAz. We set the period of the limit cycle oscillators to approximately 1 hour, and environmental data is added to the oscillator at each 150seconds. It is possible to change the period of the limit cycle oscillators to use the synchronized system. The phase of each oscillator displayed on the LED are recorded by a video camera. We quantify the phase state of each frame of the video. Fig. 5 shows that phase difference between two FitzHugh-Nagumo oscillators. Our results show that the two oscillators are gradually synchronized.

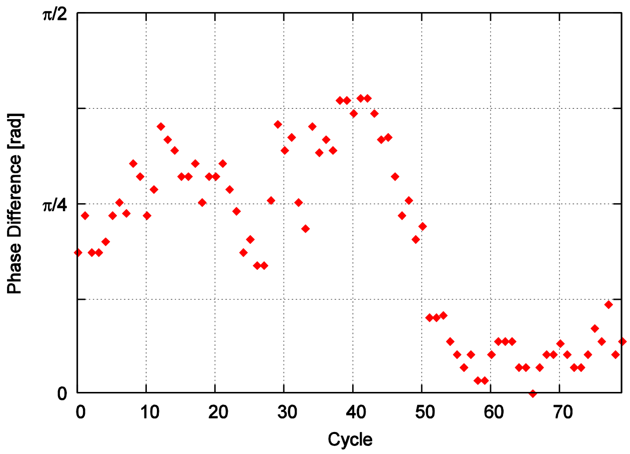


Figure 5: Phase difference between two oscillators by inputting noise.

5. Conclusion

In this paper, we investigate the feasibility of the proposed scheme, which synchronizes the devices by natural environmental noise without any communication. First, we verify the feasibility of the noise-induced synchronization using environmental electromagnetic waves. We collect environmental electromagnetic waves, and input those time series to each oscillator. Our experiment results shows that the phase difference of the oscillators could be gradually reduced, and synchronization could be approximately achieved. We also verify the feasibility of proposed system by implementing the limit cycle nonlinear oscillators on wireless sensor network devices. We use MICAz as the wireless sensor. Our results show that the phase difference of the oscillators could be gradually decreased. We confirm the feasibility of our proposal on such a real experiment using real devices.

References

[1] H. Yasuda and M. Hasegawa, "Natural Synchronization of Wireless Sensor Networks by Noise-Induced Phase Synchronization Phenomenon," *IEICE Trans. Commun*, Vol.E96-B, No.11, pp.2749-2755, 2013.

[2] H. Nakao, K. Arai, and Y. Kawamura, "Noise-Induced Synchronization and Clustering in Ensembles of Uncoupled Limit-Cycle Oscillators, " *Physical Review. Letter*, vol.98, 184101, 2007.

[3] H. Nakao, K. Arai and K. Nagai, "Synchrony of limit-cycle oscillators induced by random external impulses," *Physical Review E*, vol.72, 026220, 2005.

[4] Hata, K. Arai, R. F. Galan and H. Nakao, "Optimal phase response curves for stochastic synchronization of limit-cycle oscillators by common Poisson noise," *Physical Review E*, vol.84, 016229, 2011.

[5] Teramae and D. Tanaka, "Noise Induced Phase Synchronization of a General Class of Limit Cycle Oscillators," *Progress of Theoretical Physics Supplement*, No.161, pp.360-363, 2006.

[6] Kurebayashi, K. Fujiwara and T. Ikeguchi, "Colored noise induces synchronization of limit cycle oscillators," *Europhysics Letters*, vol.97, 50009, 2012.

[7] Y. Honda, H. Yasuda and M. Hasegawa, "Time Synchronization Scheme based on noise-Induced synchronization using Environmental Sound," *Proc. RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing*, pp.125-128. 2013.