Researcher Profile

Hisa-Aki Tanaka
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Education, work experience, and views

Hisa-Aki Tanaka is a graduate of the Department of Informatics at Waseda University, Japan, where he received the Doctor of Engineering Degree, under the supervision of Prof. Shin'ichi Oishi in 1995. The title of his dissertation was Analysis of Nonlinear Dynamics in Phase-Locked Loops and Oscillatory Neural Networks.

He subsequently received a JSPS Research Fellowship for Young Scientists (PD). During this period, Tanaka was a visiting researcher at the Faculty of EECS at the University of California, Berkeley from 1996 to 1997.

He joined Sony Computer Science Laboratories, Inc. in 1997, where he worked as an associate researcher until 2001. During his time at Sony Computer Science Laboratories, Inc., he engaged mainly in advanced circuit designs. In 2001, he resigned from Sony Computer Science Laboratories, Inc. and joined the Faculty of Informatics and Engineering at the University of Electro-Communications (UEC). At UEC, he pioneered the theory and demonstration of injection locking and mutual synchronization, and research on decentralized autonomous networks; he invented several distributed algorithms for wireless sensor networks (WSN), all of which were patented, and successfully completed research collaborations with three companies, including Oki Electric Industry Co., Ltd. Simultaneously, he has been supervising many students and postdoctoral researchers, including, Kenta Shinohara (a recipient of IEICE Technical Committee on Ad-hoc Networks Young Researcher Encouragement Awards 2009), Youji Yabe (a recipient of IEICE Best Paper Award 2019), Masaki Nakagawa (currently, Osaka University), and Fumito Mori (currently, Kyushu University).

He loves mountaineering, and his favorite words are "無為自然" by Lao Tzu.

Research activities

Tanaka has made seminal contributions in the following subjects: (a) theory and demonstration of injection locking and mutual synchronization in nonlinear oscillators, (b) basic research on decentralized autonomous networks, and (c) applied mathematics, including optimization theory. These are detailed as follows:

[The theory and demonstration of injection locking and mutual synchronization]

Injection locking and mutual synchronization are among the most fundamental technologies used in electronic information communications. For example, without injection locking, the low phase noise of extremely high–frequency (millimeter waves) oscillators is difficult to achieve. Moreover, it is well known, for example, that in synchronous power generators, mutual synchronization occurs when injection locking is mutually carried out between multiple oscillators. However, the analytical treatment of injection locking and mutual synchronization is complicated due to their nonlinearity. The design theory of these synchronous systems, therefore, has remained limited to the level of classical Adler's equation. However, as shown in what follows, the situation has started to change.

(1) In 2010, Tanaka developed a theory of synchronizability maximization [1, 2, 3, 4] and invented design algorithms including two patents [5, 6]. István Kiss and Hiroo Sekiya independently carried out experimental tests of this theory [1, 2, 7, 8, 9] and verified its validity in practical problems.

(2) Tanaka's theory has contributed to elucidating and solving practical problems. For example, Sekiya et al. verified the theory of synchronizability maximization in practical electronic circuits [8, 9]. Meanwhile, Kiss et al. conducted verification tests using chemical oscillators and demonstrated the validity of not only the theory of synchronizability maximization [1, 7] but also the theory of achieving injection locking in minimal time [2].

(3) Moreover, the concepts in Tanaka's recent theory [3, 4] have been applied to various associated fields, such as the maximization problem of generalized entropy related to information theory, providing one of the most elegant solutions to the problem with impact beyond any single research area [10]. The most insightful point in

Tanaka's theory is the discovery that these maximization problems can be attributed to Hölder's inequality. It is widely known that the Cauchy-Schwarz inequality, a special case of Hölder's inequality, corresponds to the uncertainty principle of quantum mechanics. For more general Hölder's inequality, however, the physical (practical) correspondence regarding the manner in which this inequality reflects phenomena in the "real" world has remained unknown since its discovery about 100 years ago. Notably, Tanaka's theory and experimental demonstration described above have identified the physical correspondence for the first time in synchronizability maximization and Tsallis entropy maximization [7, 11, 12] (Figure 1).

Figure 1

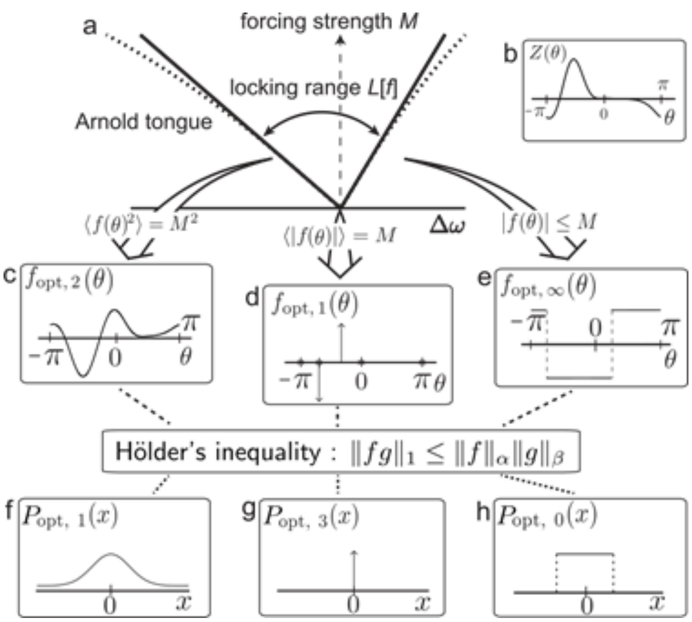

Figure 1 illustrates the unified solution of synchronizability maximization and Tsallis entropy maximization (reproduced from [7]).

These achievements are indirectly supported by two subtle but important innovations shown below.

・ Innovation of methodology

Tanaka combined (i) the analysis method focusing on the oscillation phase of oscillators [13, 14] and (ii) the phase-reduction method [11], and applied the combined method to several practical problems for the first time. For example, in study [13], in the case of a mutually synchronized system of two phase-locked loops (PLL) [17], the generation of strong noise under certain conditions was experimentally observed [18]. Tanaka elucidated that this noise can be attributed to chaotic oscillations [13], and provided the proof using the latest knowledge in mathematics [13].

In another study [14], Tanaka developed a theory that extends Kuramoto's theory, applied it to the swing equation of synchronous power generators, which has been difficult to analyze beyond conventional linear approximation, and elucidated its global dynamics for the first time (Figure 2).

Figure 2

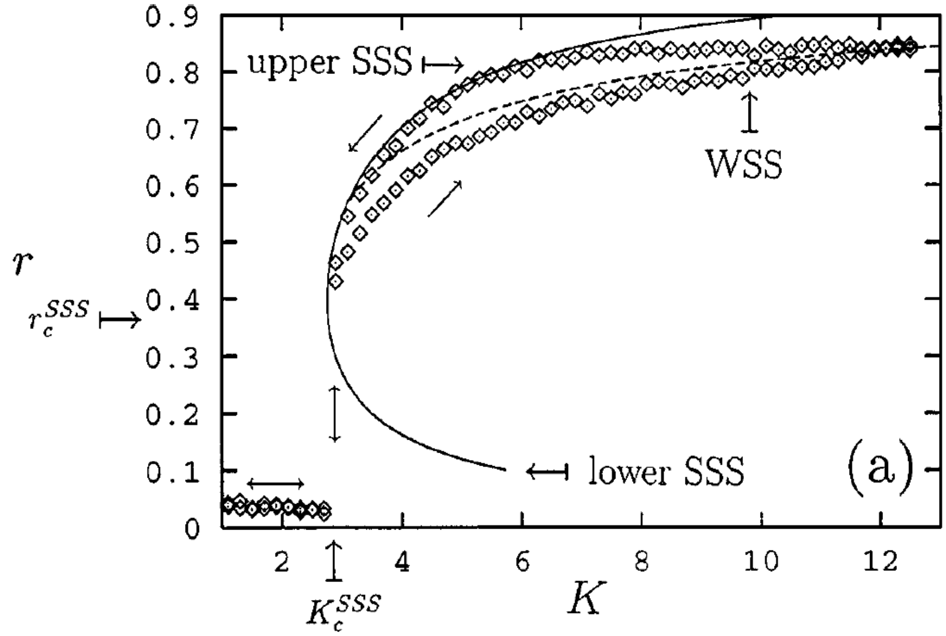

Figure 2 illustrates the theoretically expected collective hysteresis effect in the swing equation that describes synchronous power generators (500 units). The horizontal axis shows the coupling strength between the generators, and the vertical axis shows the overall degree of synchronization. This result is consistent with the empirical finding that overall synchronization is relatively easy to maintain once achieved, and conversely, it is difficult to recover once impaired. It should be noted that the example in Figure 2 assumes the case of all-to-all coupling, wherein the generator network is the densest. Real power generator networks are sparser, and theoretical elucidation in such cases is yet to be provided (reproduced from [14]).

Furthermore, the theory described in the study [15] was used for the first time to elucidate the novel experimental result of the interconnected system of CMOS ring oscillators, presented in 1998 at ISSCC by Hitachi Central Research Laboratory [16] (Figure 3).

・ Development of computational algorithms

Two algorithms described below and related research [15] enabled the application of the phase-reduction method to injection locking and mutual synchronization in real complex oscillator circuits for the first time. The first algorithm developed in the study [15] can provide accurate results most effectively among all known reduction algorithms. In fact, since the publication of the study [15], much relevant research using this algorithm has been reported in IEEE Trans., CAS, and others.

Figure 3

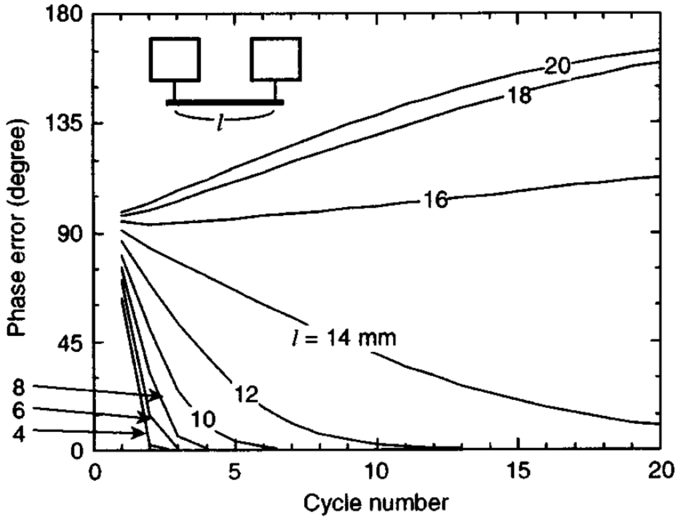

Figure 3 illustrates an example of the theoretical elucidation of the experimental result of mutually synchronized CMOS ring oscillators [16]. The theory in the study clarifies the phenomenon of sudden change in the synchronization state (phase difference) depending on the wiring length (l [mm]) between oscillators, and consequently providing the upper limit of the wiring length that can achieve perfect synchronization [15].

On the other hand, the second algorithm [6] directly contracts the data of injection locking into the governing phase equation using several sinusoidal wave inputs with multiple harmonics. This algorithm was presented at the international conference DDAP5 in 2008 [19]. The development of these basic algorithms [6, 15] enabled the application of the synchronizability maximization algorithm [5] to real complex oscillators, thus building the optimal design theory of synchronous systems for the first time.

[Basic research on decentralized autonomous network; from ad hoc network to giant amoeba]

Current information networks have become as large and complex as the Internet; consequently, they are beginning to exhibit autonomous decentralized characteristics similar to neural networks in living organisms and communication networks among cells. Tanaka is one of the first to recognize this trend and has pioneered many achievements in information networks since 2001, particularly in timing (time) synchronization. Some examples are indicated below.

(1) In 2001, Tanaka devised a (circuit-level) system for flexible timing synchronization and confirmed its effectiveness through experiments. For example, [20] demon-

strated that a reconfigurable injectionlocked ring oscillator can be constructed by connecting an odd number of field-programmable gate array (FPGA) EXOR-gates in series (Figure 4), and that the mutual synchronization of such oscillators is achievable (Figure 5). These results are among the first in the multitude of research regarding FPGAs that effectively utilizes the "analog nature" inherent to logic gates.

Figure 4

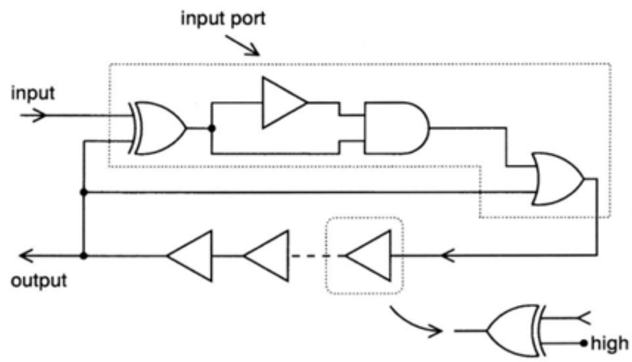

Figure 4 illustrates an example of reconfigurable, injection-locked ring oscillators implemented on a FPGA (reproduced from [20]).

Figure 5

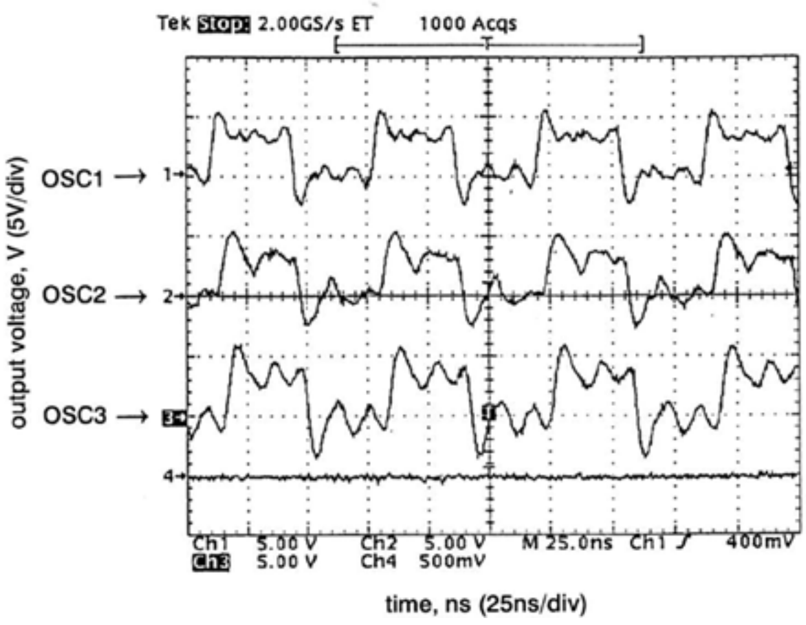

Figure 5 shows output waveforms from three mutually synchronized reconfigurable ring oscillators with 31-stage EXOR-gate arrays (reproduced from [20]).

Mutual synchronization in networks of oscillators such as ring oscillators is known to result in the "mode-lock" phenomenon, in which the phase difference between oscillators becomes a nonzero steady-state value, a phenomenon that must be avoided or eliminated. In this context, [21] discovered in 2002 that this phenomenon can be avoided almost completely by introducing a stochastic switch in the coupling between oscillators, establishing the first practical solution to this problem in the field. This method has since been developed further, and [22] was the first to eliminate the mode-lock phenomenon that occurs in timing synchronization in wireless networks.

Subsequently, [23] clarified the nature of skew in the crystal oscillator of each wireless terminal (MICA motes) of wireless sensor networks (WSNs) (Figure 6) against the flooding timing synchronization protocol (FTSP) [24], which is known for its high synchronization accuracy at the time (Figure 7). Additionally, it was demonstrated that the synchronization accuracy can be further improved by several folds by incorporating it into the FTSP.

Figure 6

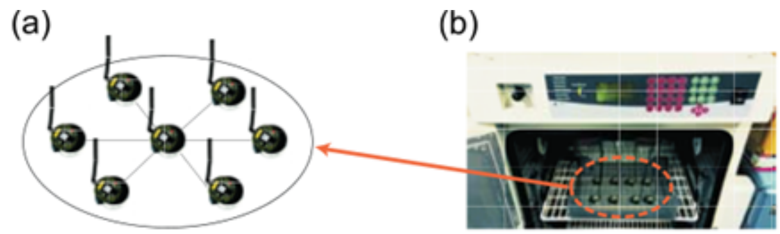

Figure 6 illustrates an experimental setup for FTSP. (a) A single-hop WSN in a Mica2Dot testbed. (b) All experiments were performed at a constant temperature and humidity in the incubator (reproduced from [23]).

Figure 7

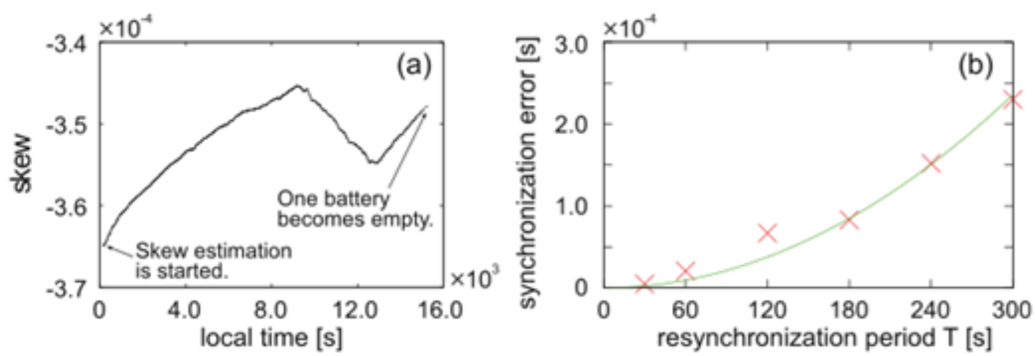

Figure 7 shows short-term skew variations observed in the experiment illustrated in Fig. 6. (a) Temporal variation in an estimated skew in one node. (b) Averaged synchronization errors in one node for several different resynchronization periods T [s]. The curve represents the quadratic function of T fitting data points × (reproduced from [23]).

(2) In addition to the circuit-level research described above, Tanaka has pioneered several achievements in system-level timing synchronization since 2002. For example, he clarified the reason for the significant amount of time required to complete

synchronization for the IEEE 802.11 TSP (timing synchronization protocol) [25], which is the most widely used protocol in wireless ad hoc networks. Consequently, this problem has been solved by rendering IEEE 802.11 TSP self-adaptive with only a few modifications, enabling fast synchronization.

Another fundamental research regarding system-level timing synchronization is summarized as follows. When sending data packets in wireless ad-hoc networks as well as in WSNs, it is essential to avoid data packet collisions in advance. Two major approaches have been developed for collision avoidance in WSNs, i.e., carrier sense multiple access with collision avoidance (CSMA/CA) and (distributed versions of) time division multiple access (TDMA). However, neither of these methods is ideal for the following reasons. First, CSMA/CA requires the density of sensor nodes to be relatively low and the traffic to be light. Furthermore, TDMA requires the global timing synchronization of all sensor nodes, as well as computation and communication overheads in each sensor node (SN) to allocate the communication timings in advance.

Motivated by the aforementioned situation, an alternative collision avoiding method has been proposed [26, 27] that is expected to satisfy the necessity for more flexible techniques with less communication overheads. The original idea of this method originates from a certain self-organizing mechanism of the timing allocation process, which is analyzed in a collaborative study with Hiroya Nakao [28]. Improvements of this method have been continued [29] and experimental verifications have been conducted in real environments [30]. However, the reason that this method generates the correct timing allocations for SNs has not yet been elucidated. [28] revealed the hidden mechanism behind this method and explained the reason that this method functioned as intended for the first time; the essential questions, as listed below, have been answered.
(i) How does the allocation process (Eq. (1) presented in [28]) result in reasonable patterns such asthose shown in Fig. 8 (b) or Fig. 8 (c)?
(ii) How can we select the interaction function Γ between SNs to obtain the specific pattern of Fig. 8 (b) or Fig. 8 (c)?
(iii) To what extent is the presented method robust to external noises?

This method has contributed to the construction and development of autonomous distributed communication timing control algorithms for sensor network. Its ap-

Figure 8

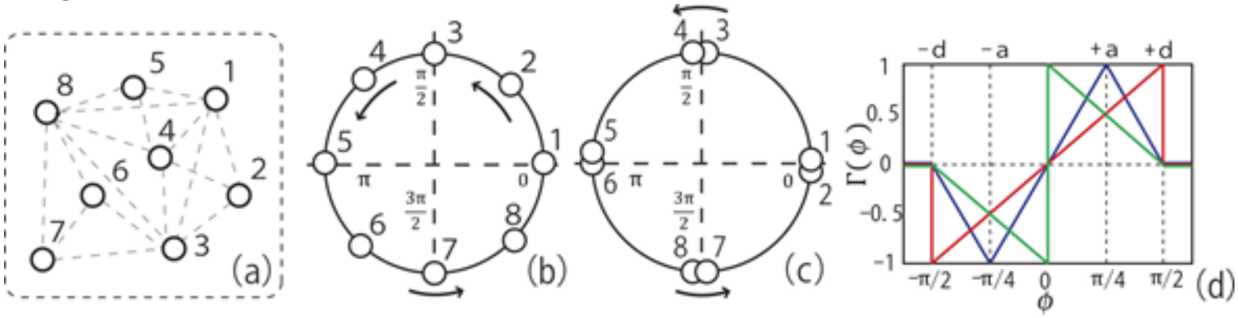

Figure 8 illustrates the concepts and some of the results from [27]; (a) Sensor networks of N nodes ($N = 8$, for instance). (b), (c) Resulting timing allocation for type 1 and type 2 functions, and (d) function Γ with a tuning parameter a (blue line); type 1 function (green line, $a = 0$), type 2 function (red line, $a = d$) (reproduced from [28]).

plication has been demonstrated in a joint study with Oki Electric Industry Co., Ltd., and an international patent network has been established in Japan [27], the United States [31], the EU [32], Germany [33] and China [34]. This achievement was awarded with the Telecom System Encouragement Award by the Telecommunications Advancement Foundation in 2010, as reported in newspapers and published in prominent technical books.

Figure 9

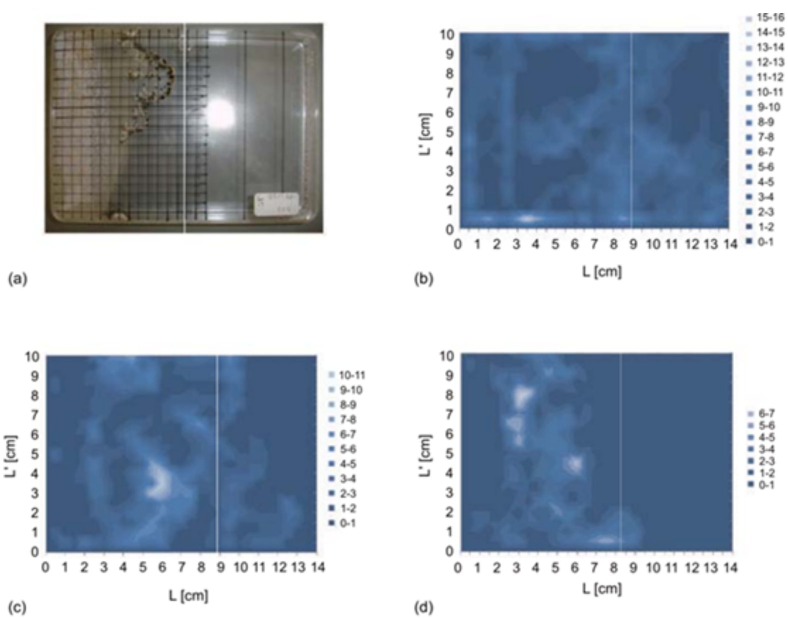

Figure 9 shows the spatial pattern of fruiting bodies formation for three different local humidity patterns. (a) Typical formation pattern of fruiting bodies. (b), (c), (d) Two-dimensional histograms of fruiting bodies distribution over multiple instances; (b) sum of 25 instances for case of 90% RH humidity in the incubator, (c) 24 instances for the case of 50% RH humidity in the incubator, and (d) 26 instances for the case of 30% RH humidity in the incubator (reproduced from [35]).

Motivated by these experiences in ad-hoc wireless sensor networks research, Tanaka conducted studies in biology to gain insights for designing more efficient, smart "reconfigurable" distributed communication networks; [35] investigated the efficient moving behavior of a living network, which was observed before a giant amoeba transformed into "fruiting bodies," i.e., before it sporulated. More specifically, [35] observed the behavior of Physarum polycephalum after a severe environmental change, i.e., exposure to strong light. Through systematic, controlled experiments (in a constant dark condition, 26°C), [35] obtained four pieces of evidence that suggested an efficient mechanism of the network reconfiguration by which Physarum polycephalum rendered sporulation more effective, i.e., a mechanism considered as important for its survival. Hence, the finding in [35] contributes to biological knowledge in network sciences, as well as provides insights for designing environment-aware mobile communication networks.

[Applied mathematics; for entertainment and profit]

As introduced in the first section above, Tanaka's recent theory [3, 4] are associated with various fields; [10] provided an example related to information theory. Recently, another mathematical thread to optimization theory has been discovered in a collaborative study with Hayato Waki, where conic optimization was discovered to be useful for addressing problems in physics.

Tanaka has contributed to the writing of textbooks for laypeople. [36] presented a Japanese translation of a famous textbook by Steven H. Strogatz, which has now become the standard nonlinear dynamics textbook in Japan.

Awards

Tanaka has co-received several awards, including, 2007 Telecom System Technology Award, 2008 IEICE Technical Committee on Ad Hoc Networks Young Researcher's Award, 2008 Telecom System Technology Award, 2009 IEICE Technical Committee on Ad Hoc Networks Young Researcher's Award, 2015 NOLTA Society Contribution Award, and 2019 IEICE Best Paper Award.

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