Research Statement 2020

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Background and Goal

The goal of my research is "to evolve humanity's collective intelligence through the ideas and technologies of multi-agent systems, and thereby to realize new social systems." The explosive spread of social networks and smartphones has brought an essential change to the quality of everyday human interaction. The classical social systems we use in daily life are mechanisms built on interactions from an era without social networks or smartphones. Collective intelligences such as swarms of insects or schools of fish are said to be the result of an advantageous evolution as a whole system that includes their methods of interaction. To promote human collective intelligence, the human "swarm" also needs new methods of interaction enabled by new social systems. Multi-agent systems provide the methodologies and concepts for realizing new social systems and for promoting human collective intelligence through information technology. Multi-agent systems explore the essence of social intelligence and the possibilities of new social systems through interdisciplinary research centered on distributed artificial intelligence, including simulation, robotics, and game theory. Meanwhile, in recent years, "crowd computing" projects such as Wikipedia and Linux—individual, voluntary, and open activities—have been producing results of very high quality as a whole. New social and collective human activity through the Internet has indeed become a part of daily life. Furthermore, these changes have made it possible to operate, in the real world, mechanisms that were once only discussed mathematically. A concrete example is the auction mechanism adopted in Google AdWords. Drawing on the insights of mechanism design, it has become a system used by virtually everyone in the world. In other words, the methods and technologies for properly controlling and coordinating rational agents—long discussed at the core of multi-agent systems—have become actually realizable with the people of the entire world as participants. This is precisely a technology for promoting human collective intelligence.

Against this background, I conduct research on the theory, models, simulation, and social implementation of multi-agent systems. In particular, I carry out cutting-edge research on consensus-building support, computational mechanism design, automated negotiating agents, and social simulation.

My research to date can be broadly divided into the following four items.

> [Research Item 1: Theory] Pursuit of computational mechanism design and auction theory.
>
> [Research Item 2: Models] Automated negotiating agent models and the international competition ANAC.
>
> [Research Item 3: Simulation] Large-scale multi-agent social simulation.
>
> [Research Item 4: Social Implementation] Social implementation and commercialization of large-scale consensus-building support systems using agent technology.

Although the items are classified from the perspectives of theory, models, simulation, and social implementation, they are all deeply related. I have been internationally recognized as a leading researcher who drives the international community of computational mechanism design and automated negotiation in multi-agent systems, and I have received the JSPS Prize, the Commendation for Science and Technology by the Minister of MEXT (Science and Technology Award), the Commendation for Science and Technology by the Minister of MEXT (Young Scientists' Award), the JSAI (Japanese Society for Artificial Intelligence) Achievement Award, and the IPSJ Makoto Nagao Memorial Special Prize. I have also received the JSSST (Japan Society for Software Science and Technology) Paper Award, and the IPSJ National Convention Encouragement Award and Excellence Award, among others. Each research item is described in detail below.

[Research Item 1: Theory] Pursuit of computational mechanism design and auction theory

The field of computational mechanism design theoretically studies the fundamental mechanisms of information-based social systems. It is a new field that aims to study economics—particularly microeconomics, game theory, and mechanism design—from the perspective of informatics. Traditional economics has many solution

concepts and equilibrium concepts, but it lacked analysis based on computational algorithms. In addition, recent commerce based on the Internet and information goods requires new economic analysis. Computational mechanism design is a research field that realizes entirely new social systems and mechanisms by combining two perspectives: the analysis of desirable interactions among multiple agents that hold private information and preferences (the perspective of mathematical economics and game theory), and the analysis of computational efficiency and algorithms in distributed information systems (the perspective of information science and multi-agent systems). The main challenge here is to design mechanisms in which truthful reporting is the best strategy for each agent. That is, by designing mechanisms in which cheating is impossible (or difficult), the goal is robust and stable operation over wide-area networks. Applications include the Google electronic advertising mechanism based on the second-price auction and the airport takeoff-and-landing planning mechanism of the U.S. Federal Aviation Administration. In particular, the following two topics are described in detail: auction mechanisms based on interdependent values, and auction mechanisms in the presence of both experts and amateurs.

[Auction mechanisms based on interdependent values]

I focus on auction mechanisms in cases where agents have interdependent values. Under the assumption of interdependent values, the value of a good to one agent depends on the private values (signals) of other agents. For example, consider an auction for fine wine. A bidder may have tasted a similar wine before, or may have heard others' evaluations. Under such conditions, I have concretely constructed efficient auctions and proposed schemes that maximize revenue. In this research, I use a linear model as the agents' value model, apply the model of Dasgupta and Maskin, and propose a price-maximization algorithm based on reserve prices. This theme is joint research with Harvard University in the United States, and it was accepted at AAMAS 2006—one of the highest-quality international conferences on autonomous agents and multi-agent systems—where it received the Best Paper Award [1], and was published in journals [3,4], receiving high acclaim. Generalized versions have been accepted at AAMAS 2007 and IJCAI 2013 [2,5].

1. Takayuki Ito, David Parkes, "Instantiating the Contingent Bids Model of Truthful Interdependent Value Auctions", In the Proc. of the Fifth International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS2006), 2006. (Best Paper Award)

2. Florin Constantin, David Parkes, Takayuki Ito, "Online auctions for bidders with interdependent values", In the Proceedings of the Sixth International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS2007), 2007.

3. Takayuki Ito, David C. Parkes, "Realizing Truthful Combinatorial Auctions with Contingent Bids Based on the Interdependent Value Model", IEICE Transactions D-I, IEICE, 2007 (in Japanese).

4. Takayuki Ito, David C. Parkes, "Truthful Interdependent Value Auctions Based on Contingent Bids", IEICE Transactions D-I, IEICE, 2007 (in Japanese).

5. Valentin Robu, David Parkes, Takayuki Ito, Nick Jennings, "Efficient Interdependent Value Combinatorial Auctions with Single-Minded Bidders", In the Proc. of IJCAI 2013, Beijing, China, on August 3-9, 2013.

[Auction mechanisms in the presence of experts and amateurs]

In Internet auctions, an unspecified large number of people sell goods, and it is difficult to accurately judge the quality of a good. For example, even if an antique is for sale, it is hard to tell whether it is genuine or fake. If a buyer purchases a fake antique at a high price, the buyer suffers a loss from the auction. On the other hand, if buyers bid conservatively to avoid loss, there is a risk that they fail to win antiques they could otherwise have obtained. This means that the auction protocol fails at the efficient allocation of goods. We therefore first succeeded in designing (1) a single-good auction and (2) a multi-good combinatorial auction in the presence of experts interested in a single good, in which a Pareto-efficient allocation is achieved and rational participants suffer no loss, by having experts truthfully report information about nature's selection. The contents of (1) and (2) were accepted at the highly competitive international conferences AAMAS 2002 [10] and AAMAS 2003 [8], among the highest-quality conferences in the world. The content of (1) received the Paper Award of the Japan Society for Software Science and Technology [9]. Generalized versions of this work were accepted at AAMAS 2004 [7] and AAAI 2005 [6].

6. Takayuki Ito, Makoto Yokoo, Shigeo Matsubara, and Atsushi Iwasaki "A New Strategyproof Greedy-Allocation Combinatorial Auction Protocol and its Extension to Open Ascending

Auction Protocol" In the Proc. of the Twentieth National Conference on Artificial Intelligence (AAAI2005), pp.261-266, 2005.

7. Takayuki Ito, Makoto Yokoo, and Shigeo Matsubara, "A Combinatorial Auction among Versatile Experts and Amateurs" In the Proceedings of the Third International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS2004), 2004.

8. Takayuki Ito, Makoto Yokoo, and Shigeo Matsubara, "Towards a Combinatorial Auction Protocol among Experts and Amateurs: The Case of Single-Skilled Experts," In the Proceedings of the Second International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS2003), pp.481-488, 2003.

9. Takayuki Ito, Makoto Yokoo, Shigeo Matsubara "Designing an Auction Protocol under Asymmetric Information on Nature's Selection", Computer Software, Japan Society for Software Science and Technology, Vol.20, No.1, pp.16-26, 2003. (Paper Award)

10. Takayuki Ito, Makoto Yokoo, and Shigeo Matsubara, "Designing an Auction Protocol under Asymmetric Information on Nature's Selection," In the Proceedings of the International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS2002), Bologna, Italy, July 15-19, pp.61-68, 2002.

[Research Item 2: Models] Automated negotiating agent models and their international competition

To reach an agreement in real-world negotiation, it is necessary to reach agreement on multiple interdependent issues. Much of the existing research on negotiation mechanisms deals with a single issue. In this research, I consider a more general model that reaches agreement on multiple interdependent issues, as above. An agent's utility over multiple interdependent issues can be expressed as a multi-attribute utility, where each attribute is the utility for each issue. Research on negotiation mechanisms based on multi-attribute utility generally maps the multi-attribute utility to a linear or near-linear expression, thus handling, in practice, very simple utility functions. However, in the real world it is hard to think that the multi-attribute utility over multiple interdependent issues can be expressed as a simple linear function. We give the multi-attribute utility as a nonlinear function and propose negotiation methods among agents for reaching more desirable agreements [11,12,14,15,19,20]. In recent years, we have also attempted extensions to logical argumentation theory [18]. This work was accepted at high-quality international joint

conferences such as AAMAS 2006, AAAI 2006, IJCAI 2007 [11], and IJCAI 2009 [12], receiving high acclaim. To build an international research community, we have held the international workshop ACAN for twelve consecutive years, and we organize the international Automated Negotiating Agents Competition (ANAC) [13,16,17], an international programming competition. Together with Delft University of Technology in the Netherlands and Bar-Ilan University in Israel, we created a common simulator that has become a world standard, and we run the competition based on that simulator. In the first competition, my team won the championship.

11. Takayuki Ito, Mark Klein, Hiromitsu Hattori, "Multi-issue Negotiation Protocol for Agents: Exploring Nonlinear Utility Spaces", In the Twentieth International Joint Conference on Artificial Intelligence (IJCAI2007), Hyderabad, India, January 6-12, 2007.

12. Ivan Marsa-Maestre, Takayuki Ito, Katsuhide Fujita, Miguel A. Lopez-Carmona, Juan R. Velasco, Mark Klein, "Balancing Utility and Deal Probability for Negotiations in Highly Nonlinear Utility Spaces", In the Proceedings of the Twenty-First International Joint Conference on Artificial Intelligence (IJCAI2009), July 11-17 in Pasadena, California, pp.214-219, 2009.

13. Tim Baarslag, Katsuhide Fujita, Enrico Gerding, Koen Hindriks, Takayuki Ito, Nick R. Jennings, Catholijn Jonker, Sarit Kraus, Raz Lin, Valentin Robu, Colin Williams, "Evaluating Practical Negotiating Agents: Results and Analysis of the 2011 International Competition", Artificial Intelligence Journal (AIJ), Elsevier Science, Vol. 198, May 2013, pp. 73-103, 2013. (IF=2.511)

14. Ivan Marsá-Maestre, Miguel A. López-Carmona, Mark Klein, Takayuki Ito, Katsuhide Fujita: "Addressing Utility Space Complexity in Negotiations involving Highly Uncorrelated, Constraint-Based Utility Spaces". Computational Intelligence 30(1): 1-29 (2014).

15. Rafik Hadfi and Takayuki Ito. "Low-Complexity Exploration in Utility Hypergraphs". Journal of Information Processing. Vol. 23, No. 2 pp. 176-184, 2015.

16. Catholijn M. Jonker, Reyhan Aydogan, Tim Baarslag, Katsuhide Fujita, Takayuki Ito and Koen Hindriks, "Automated Negotiating Agents Competition (ANAC)", Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence (AAAI-17), pp. 5070-5072, AAAI Press, 2017.

17. Shun Okuhara, Otsuki Hamada, Takayuki Ito, Ahmed Moustafa, "A Prototype of an Automated Negotiating Agent Using the k-Nearest Neighbor Method Based on Past Negotiation Information", IPSJ Journal, pp.1662-1671, Vol.60, No.10, 2019 (in Japanese).

18. Ryuta Arisaka and Takayuki Ito, "Semantics of Opinion Transitions in Multi-Agent Forum Argumentation", 2019 The 16th Pacific Rim International Conference on Artificial Intelligence (PRICAI 2019), August 26-30, 2019, Yanuca Island, Fiji. (Best Paper Award)

19. Shun Okuhara and Takayuki Ito, "Compromising Strategies for Agents in Multiple Interdependent Issues Negotiation", IEICE Transactions on Information and Systems, 2020.

20. Shun Okuhara, Takayuki Ito, "A Negotiation Strategy based on Compromising Degree", 20th IEEE/ACIS International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD 2019), July 8-10, 2019. (Best Paper Award)

[Research Item 3: Social Simulation] Large-scale multi-agent social simulation

Unlike classical physical simulation, multi-agent simulation can describe the behavioral rules of individual agents separately, and can therefore simulate a society in which humans with various behavioral characteristics coexist. With multi-agent social simulation, it is possible to realize, on a simulator, social systems and institutions that cannot be realized in reality, and to verify them. As multi-agent social simulation, I have worked on (3-1) the implementation of a rescue agent team in RoboCup Rescue; (3-2) under the Cabinet Office's FIRST (Funding Program for World-Leading Innovative R&D) program, the development of a simulator and simulation methodology that newly incorporates the environment as an axis of evaluation, with particular focus on traffic simulation and power-grid simulation; and (3-3) under the NICT R&D program "Social Big Data Utilization and Platform Technology," the realization of a multi-layer social simulator using large-scale multi-agent systems, with particular focus on traffic simulation.

(3-1) Under the guidance of Dr. Milind Tambe of the University of Southern California (now a professor at Harvard University), as a young visiting researcher, I implemented RoboCup Rescue agents for the first time in the world. In cooperation with the group implementing the RoboCup Rescue simulator, I carried out the implementation in Dr. Tambe's group. Here, to rescue victims on the simulator, I developed a method using auction mechanisms to efficiently and distributedly allocate the tasks that arise

moment by moment among fire engines, police, and ambulances, and won third place at the RoboCup WorldCup and second place at RoboFesta [21,22].

(3-2) Under the Cabinet Office's FIRST program, I conducted R&D on traffic simulation and power-grid simulation based on the environment as an axis of evaluation. As a result, I proposed a new method that gives a concrete branching model to the statistical cell-transmission model—one of the traffic-flow prediction models that had previously been difficult—and realized higher-accuracy simulation [26,27]. Furthermore, as a model for power-amount simulation, I proposed schemes incorporating mechanism design theory [23,24,25].

(3-3) Under the NICT R&D program "Social Big Data Utilization and Platform Technology," I focused on large-scale traffic simulation within large-scale social simulation systems, and realized a system that runs simulations while simultaneously processing a large number of agents (cars and people) that have behavioral rules. Moreover, as a method for simultaneously realizing such social simulation and weather simulation, I prototyped a multi-layer (holonic) social simulator [28].

21. Ranjit Nair, Takayuki Ito, Milind Tambe, and Stacy Marsella, "Rescue-ISI-JAIST", Rescue Simulation League, RoboCup WorldCup 2001 Seattle, 2001 (3rd place)

22. Takayuki Ito, Ranjit Nair, Milind Tambe, and Stacy Marsella, "Rescue-JAIST-ISI", RoboCup Rescue Simulation League, RoboFesta 2001 International Robotic Games Festival, 2001 (Silver Medal / Runner-up)

23. Shantanu Chakraborty, Takayuki Ito, Tomonobu Senjyu, AY Saber, "Intelligent Economic Operation of Smart-grid Facilitating Fuzzy Advanced Quantum Evolutionary Method". IEEE Transactions on Sustainable Energy (IF=7.65), Volume 4, issue 4, p. 905-916, October 2013.

24. Shantanu Chakraborty, Takayuki Ito, Tomonobu Senjyu, "Fuzzy Logic Based Thermal Generation Scheduling Strategy with Solar-Battery System Using Advanced Quantum Evolutionary Method," IET-Generation, Transmission and Distribution, Volume 8, No.3, pages 410-420, March 2014 (IF=1.41).

26. Rafik Hadfi, Sho Tokuda, and Takayuki Ito. "Traffic Simulation in Urban Networks using Stochastic Cell Transmission Model". Computational Intelligence. (IF=0.776) 12 December 2016.

27. Sho Tokuda, Ryo Kanamori, Takayuki Ito, "Improvement of the Stochastic Cell Transmission Model for Application to General Road Networks", ITS Symposium 2014. (ITS

Symposium 2014 Best Paper Award) (in Japanese)

28. Takayuki Ito, Takanobu Otsuka, Teruyoshi Imaeda, and Rafik Hadfi, "An Implementation of Large-scale Holonic Multi-agent Society Simulator and Agent Behavior Model", The 15th Pacific Rim International Conference on Artificial Intelligence (PRICAI2018), August 27-31, 2018, Nanjing, China.

[Research Item 4: Social Implementation] Social implementation and commercialization of large-scale consensus-building support systems using agent technology

In this research, I realize systems that build crowd consensus over the Internet. Through SNS such as Twitter and Facebook, it has become possible to collect the opinions of tens of thousands or millions of people over the Internet. There is a possibility of skillfully consolidating these opinions and forming the consensus of millions of people. If large-scale consensus can be formed, decision-making by a large number of people—previously impossible—becomes possible. However, because the scale is very large, it is difficult to do this by hand. Therefore, in this research, using artificial-intelligence programs called agents, I realize a system that efficiently collects the opinions of a large number of people and supports consensus building, verify it in social experiments, and carry it through to commercialization.

At the international conference IJCAI 1997, I presented a group decision support system based on multi-agent negotiation [29]. It is a prototype and evaluation of a system in which agents negotiate on behalf of humans to support the selection of group alternatives. Here, I expressed human preferences using AHP (the Analytic Hierarchy Process) and proposed an algorithm that attempts persuasion by computing the possibility of preference change, exploiting the ambiguity of judgment.

29. Takayuki Ito and Toramatsu Shintani, "Persuasion among Agents: An Approach to Implementing a Group Decision Support System Based on Multi-Agent Negotiation", In the Proc. of the 15th International Joint Conference on Artificial Intelligence (IJCAI-97), pp.592-597, 1997.

Around 2009, under the JST PRESTO program, I applied negotiation mechanisms to consensus building, proposed ideas for methods of supporting human consensus

building, and prototyped a system. Here, I first proposed a scheme premised on a human utility model, limited the problem domain, and designed the consensus-building topic itself to fit the utility model, thereby enabling automatic consensus building. The problem, however, was that the consensus-building topic became tailor-made for each domain, making real-world social application impossible. From 2010, I began practical joint research with researchers specializing in urban planning and architectural design who shared the goal of consensus-building support. There, we actually built a consensus-building support system, Collagree, that can be used in the real field of local government, and real users employed the system to aggregate opinions [30,31,32,33,34,35]. In particular, the aggregation of citizens' opinions concerning Nagoya City's next-term comprehensive plan was well received, and opinion aggregation using this system has since been carried out in the same city and elsewhere.

30. Takayuki Ito, Yuma Imi, Takanori Ito, and Eizo Hideshima, "COLLAGREE: A Facilitator-mediated Large-scale Consensus Support System", ACM Collective Intelligence 2014. MIT Cambridge, USA. (poster)

31. Takayuki Ito, Mei Okumura, Takanori Ito, Eizo Hideshima, "Prototype and Evaluation Experiment of an Opinion-Aggregation Support System Collagree for Large-Group Workshops—Opinion-Aggregation Support through Weak Structuring of the Discussion Process—", Journal of Japan Industrial Management Association, Vol.66, No.2, 2015 (in Japanese).

32. Yuma Imi, Takayuki Ito, Takanori Ito, Eizo Hideshima, "COLLAGREE: A Large-scale Opinion-Aggregation System Based on an Online Facilitation Support Mechanism—Social Implementation toward Citizen Discussion for Nagoya City's Next-term Comprehensive Plan", IPSJ Journal, 2015 (in Japanese).

33. Takayuki Ito, Katsuhide Fujita, Tokuro Matsuo, Naoki Fukuta, "Creation of a Large-scale Consensus-Building Support System Based on Agent Technology—Toward the Realization of Automated Facilitation Agents—", Journal of the Japanese Society for Artificial Intelligence, Vol. 32, No. 5, 2017 (in Japanese).

34. Takayuki Ito, et al., "Experimental Results on Large-scale Cyber-Physical Hybrid Discussion Support", International Journal of Crowd Science, Emerald Publishing, ISSN2398-7294, Vol.1, Issue:1, pp.26-38, 2017.

35. Satoshi Kawase, Takayuki Ito, et al., "Cyber-physical hybrid environment using a large-scale discussion system enhances audiences' participation and satisfaction in the panel discussion", IEICE Trans. on Information and Systems, Vol. E101.D Issue 4, pp. 847-855, 2018.

Since 2015, as a JST CREST project, I continue to conduct research on large-scale discussion support on social media, particularly through facilitator agents. A facilitator agent, using a problem-solving structuring method inspired by IBIS—one of the facilitation techniques—extracts the problem-solving structure within a discussion and facilitates it; that is, by extracting the problem-solving structure on a large scale and at high speed, it leads to creative consensus. To grasp the structure within a text-based discussion, the facilitator agent program extracts the problem-solving structure using highly optimized deep-learning methods. In 2018, this system was actually applied to the collection of citizens' opinions on the interim draft of Nagoya City's next-term comprehensive plan, becoming the world's first attempt to facilitate, with agent technology, an actual citizens' discussion [36,37,38]. The work has also developed into joint research with the city of Kabul, Afghanistan.

36. Takayuki Ito, et al., "D-Agree: An Agent-facilitated Crowd-scale Discussion Support System", IJCAI 2019. (Best Video Award) https://www.youtube.com/watch?v=F1lECXasOhw

37. Takayuki Ito, Daichi Shibata, Shota Suzuki, Naoko Yamaguchi, Tomohiro Nishida, Kentaro Hiraishi, and Kai Yoshino, "Agent that Facilitates Crowd Discussion", The 7th ACM Collective Intelligence 2019, Carnegie Mellon University, Pittsburgh, USA, June 13-14, 2019.

38. Takayuki Ito, Shota Suzuki, Naoko Yamaguchi, Tomohiro Nishida, Kentaro Hiraishi, Kai Yoshino, "Large-scale Consensus-Building Support System—Scaling Up Discussion through ICT—", Journal of the Institute of Systems, Control and Information Engineers "Systems/Control/Information", Vol. 63, No.10, p.440-446, 2019 (in Japanese).

[Commercialization]

While papers are important as venues for presenting research results, I believe it is also important to receive direct evaluation from society and the world at large. I am therefore actively pursuing entrepreneurship and commercialization. In particular, I have established AgreeBit, Inc., developing the results of the JST CREST project, and I am carrying out activities to apply the system in real-world settings.

[Future Directions]

As a future development, I would like to propose a "social reasoning system," which can also be called a "distributed expert system." I noted that, in online discussion support, sharing and managing the structure of discussion is important. Going forward, beyond the structure of the discussion, one can also envision sharing simulations of the content being discussed. For example, in the case of traffic problems, experts on cars, on traffic congestion, on roads, on pedestrian flow, and on urban planning would jointly create a simulator. The "simulator" here is not a mere simulation but one that has an integrated structure of a system simulator and reasoning-based discussion. Each expert provides scenarios based on several hypotheses. The content discussed can include international issues, environmental issues, budget issues, traffic issues, and so on, with players at the national level, the city level, the university-professor level, the household level, and various other levels, and various problems can be considered. The simulation is assumed to be a dynamic simulation based on modeling such as system dynamics or qualitative modeling/qualitative reasoning. Ordinary citizens can further add discussion to the simulations and scenarios created by experts, or modify the simulation models. In this way, by simulating and hypothetically reasoning about the very systems that are solutions to social problems, experts and citizens can, as one, discuss and build the next-generation society.