Research Statement

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I am a computer science researcher who is eager to 1) devise new algorithmic and mathematical techniques and 2) design novel AI and robotic systems with interesting properties, with the hope that these techniques and properties are enablers of novel applications that could make a great impact on society. Therefore, one way to look at my work is from a **system perspective** and focus on the properties of the AI and robotic systems my students and I developed:

1. **High Throughput:**

   (a) A set of mobile conveyors can form a **dynamic robot chain** that can achieve a much higher throughput when transferring many objects simultaneously. We studied how to deploy dynamic robot chain networks in foraging tasks in which robots search for resources and bring them back to a collection zone [28, 43, 45]

   (b) We designed a new robotic system called **mobile workstation robots** in which a mobile robot can perform some operations on the objects it carries on the move. The key to unlocking the power of these robots is a better scheduling algorithm for overlapping production time and delivery time [29, 37].

   (c) Autonomous intersection management (AIM) is an intersection control protocol for autonomous vehicles that can achieve a near-zero traffic delay at intersections. I extended AIM to **autonomous traffic management** for more than one intersection and studied how to maximize its throughput [17, 18, 20, 23, 24, 25, 27].

2. **High Responsiveness:**

   (a) There are many practical planning situations in which planners acquire information from external sources during the planning process, but the information may change or expire during the planning process. We presented a reactive planning framework for handling **volatile external information** [3, 7, 12].

   (b) In drone light shows, a group of drones displays a sequence of light patterns in the sky. We consider using drone light shows for **drone-swarm-based games** and devise planning algorithms that provide a real-time guarantee for displaying pixels in animations and a fast response to user inputs [47, 49].

3. **High Safety Guarantee:**

   (a) Autonomous intersection management cannot tolerate mechanical failures that cause vehicles to deviate from their trajectories. We proposed a preemptive approach that pre-computes **evasion plans** for several common mechanical failures before vehicles enter an intersection [15, 21].

   (b) A robotic system is fail-safe if the robot can steer the system to a safe state when an error occurs. We proposed a neural network model that can be used to speed up the generation of **backup paths** for robots in emergency situations in

cooperative transportation tasks [35].

4. **High Degree of Cooperation:**

In multiagent systems, self-interested agents need to resolve conflicts before they can cooperate with each other. Existing strategies, such as Tit-For-Tat for Iterated Prisoner's Dilemma, perform poorly in the presence of noise. We proposed a **noise detection technique** that is very effective in many non-zero-sum games [6, 8, 10, 11].

5. **High Density:**

High-density parking increases the capacity of parking lots by allowing vehicles to block each other but making way for departing vehicles by driving autonomously upon request. We proposed **autonomous parking lots**, which employ different parking strategies to increase the car density of parking lots [41, 46].

6. **High Accuracy:**

A fast algorithm for checking whether a vehicle can arrive at a position at a given **arrival time and velocity** is the key to autonomous intersection management. We presented a complete set of closed-form equations that fully describe the set of all reachable arrival configurations in **longitudinal motion planning** [22, 34, 39].

7. **High Agility:**

(a) In autonomous parking lots, a group of vehicles can be asked to move to another location when they block other vehicles. I described a dynamic programming algorithm for **formation planning** that minimizes the makespan of moving multiple vehicles from one location to another [46].

(b) We built and programed fully autonomous drones for **autonomous drone racing**. These drones can fly in cluttered environments as fast as possible while delivering an object to a target location [38].

8. **High Availability:**

Drones have a fairly short range due to their limited battery life. We propose an adaptive exploration technique to **extend the range of delivery drones** by taking advantage of physical structures such as tall buildings and trees in urban environments [33, 40].

9. **High Security:**

Goal recognition design (GRD) is the task of modifying environments to aid observers in recognizing the objectives of agents during online observations. We presented a new GRD framework called **extended goal recognition design** for goal recognition that involves multiple goals [44, 48].

Most of my work fits very well into multiagent systems, specifically multirobot systems [32]. My work spans across many application domains: intelligent transportation systems [17, 19, 42], logistics systems [45], security systems [44], drone-swarm-based entertainment systems [47], drone delivery systems [40], disaster management systems [36], smart warehouses [31], smart factories [30], mixed re-

ality systems [16], and web applications [4]. I am most interested in studying the mathematical properties of these systems (e.g., [17] and [39]) and devising new algorithms to provide these properties (e.g., [11] and [46]). The techniques that I often use are planning techniques such as motion planning [26] and domain-independent planning [2, 5, 14]. I particularly like to use search algorithms [44] and dynamic programming [9, 46] for combinatorial optimization. I like to put multiagent systems in game theoretical settings [8] and study the best strategies for the agents [13]. Sometimes, I use logic [9, 44] and case-based reasoning [1] to specify the properties of a system. I have already added deep learning and reinforecement learning to my arsenal of machine-learning tools for investigating the systems I studied previously.

There are still plenty of fundamental problems in multirobot systems that have not been widely studied. For example, 1) I used the term *high-throughput robotic systems* to refer to robotic systems that optimize for the number of tasks robots can handle instead of the speed of handling one task [17, 28, 45]. 2) *Contingency formation planning* for a team of mobile robots aims to provide certain performance guarantees in response to environmental changes [21, 35, 46] or user inputs [47, 49]. 3) *Environment design* focuses on modifying environments for optimizing the performance of robots or agents in the environments [41, 44]. Environment design offers a new way to achieve high throughput in the aforementioned robotic systems. These topics are relevant to some real world applications and they are fertile grounds for many interesting results.

The discovery of the incredible learning capabilities of artificial neural networks triggered a renaissance in artificial intelligence a decade ago. An artificial neural network is a complex system that exhibits an *emergent property* of learning by having many neurons interacting with each other. Similarly, other multiagent systems could possess emergent properties with highly desirable effects as well. For example, in my PhD work on cooperative games, I discovered that agents in cooperative environments often exhibit clarity in behaviors, and we can exploit this property to fend off noise in noisy environments such that agents can maintain cooperation in the Noisy Iterated Prisoner's Dilemma. Since then, one of my long-term goals has been to discover all kinds of interesting properties in multiagent systems and unleash the full potential of these properties. I have kept this goal in mind when I chose my research topics in the past, and I will keep working toward this goal in the future.

References

[1] Tsz-Chiu Au, Héctor Muñoz-Avila, and Dana S. Nau. On the complexity of plan adaption by derivational analogy in a universal classical planning framework. In *Proceedings of the European Conference on Case-Based Reasoning (ECCBR)*, pages 13–27, 2002.

[2] Dana Nau, Tsz-Chiu Au, Okhtay Ilghami, Ugur Kuter, William Murdock, Dan Wu, and Fusun Yaman. SHOP2: An HTN planning system. *Journal of Artificial Intelligence Research (JAIR)*, 20:379–404, 2003. http://www.jair.org/abstracts/nau03a.html.

[3] Tsz-Chiu Au, Dana Nau, and V.S. Subrahmanian. Utilizing volatile external information during planning. In *Proceedings of the European Conference on Artificial Intelligence (ECAI)*, pages 647–651, 2004.

[4] Tsz-Chiu Au, Ugur Kuter, and Dana Nau. Web service composition with volatile information. In *International Semantic Web Conference (ISWC)*, pages 52–66, 2005.

[5] Dana Nau, Tsz-Chiu Au, Okhtay Ilghami, Ugur Kuter, Héctor Muñoz-Avila, William Murdock, Dan Wu, and Fusun Yaman. Applications of shop and shop2. *IEEE Intelligent Systems*, 20(2):34–41, 2005.

[6] Tsz-Chiu Au and Dana Nau. Accident or intention: That is the question (in the noisy iterated prisoner's dilemma). In *Proceedings of the International Joint Conferenceon Autonomous Agents and Multi Agent Systems (AAMAS)*, pages 561–568, 2006.

[7] Tsz-Chiu Au and Dana Nau. The incompleteness of planning with volatile external information. In *Proceedings of the European Conference on Artificial Intelligence*, pages 839–840, 2006.

[8] Tsz-Chiu Au and Dana Nau. Maintaining cooperation in noisy environments. In *Proceedings of the AAAI Conference on Artificial Intelligence (AAAI)*, pages 1561–1564, 2006.

[9] Tsz-Chiu Au. Dynamic programming with stochastic opponent models in social games. In *Proceeding of the First International Conference on Computational Cultural Dynamics (ICCCD-2007)*, pages 9–15, 2007.

[10] Tsz-Chiu Au, Sarit Kraus, and Dana Nau. Symbolic noise detection in the noisy iterated chicken game and the noisy iterated battle of the sexes. In *Proceeding of the First International Conference on Computational Cultural Dynamics (ICCCD-2007)*, pages 16–25, 2007.

[11] Tsz-Chiu Au and Dana Nau. Is it accidental or intentional? a symbolic approach to the noisy iterated prisoner's dilemma. In *The Iterated Prisoners' Dilemma: 20 Years on*, pages 231–262. World Scientific, 2007.

[12] Tsz-Chiu Au and Dana Nau. Reactive query policies: A formalism for planning with volatile external information. In *Proceedings of the 2007 IEEE Symposium on Computational Intelligence and Data Mining (CIDM)*, pages 243–250, 2007.

[13] Tsz-Chiu Au, Sarit Kraus, and Dana Nau. Synthesis of strategies from interaction traces. In *Proceedings of the International Joint Conferenceon Autonomous Agents and Multi Agent Systems (AAMAS)*, pages 855–862, 2008.

[14] Tsz-Chiu Au, Ugur Kuter, and Dana Nau. Planning for interactions among autonomous agents. In *Proceedings of International Workshop on Programming Multi-Agent Systems (ProMAS'08)*, 2009.

[15] Tsz-Chiu Au and Peter Stone. Motion planning algorithms for autonomous intersection management. In *AAAI 2010 Workshop on Bridging The Gap Between Task And Motion Planning (BTAMP)*, 2010.

[16] Michael Quinlan, Tsz-Chiu Au, Jesse Zhu, Nicolae Stiurca, and Peter Stone. Bringing simulation to life: A mixed reality autonomous intersection. In *IEEE/RSJ International conference on Intelligent Robots and Systems (IROS)*, 2010.

[17] Tsz-Chiu Au, Neda Shahidi, and Peter Stone. Enforcing liveness in autonomous traffic management. In *Proceedings of the AAAI Conference on Artificial Intelligence (AAAI)*, pages 1317–1322, 2011.

[18] Matthew Hausknecht, Tsz-Chiu Au, and Peter Stone. Autonomous intersection management: Multi-intersection optimization. In *Proceedings of IROS 2011-IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2011.

[19] Matthew Hausknecht, Tsz-Chiu Au, Peter Stone, David Fajardo, and Travis Waller. Dynamic lane reversal in traffic management. In *IEEE Intelligent Transportation Systems Conference*, 2011.

[20] Neda Shahidi, Tsz-Chiu Au, and Peter Stone. Batch reservations in autonomous intersection management. In *Proceedings of the International Joint Conferenceon Autonomous Agents and Multi Agent Systems (AAMAS)*, 2011.

[21] Tsz-Chiu Au, Chien-Liang Fok, Sriram Vishwanath, Christine Julien, and Peter Stone. Evasion planning for autonomous vehicles at intersections. In *IEEE/RSJ International conference on Intelligent Robots and Systems (IROS)*, pages 1541–1546, 2012.

[22] Tsz-Chiu Au, Michael Quinlan, and Peter Stone. Setpoint scheduling for autonomous vehicle controllers. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 2055–2060, 2012.

[23] David Fajardo, Tsz-Chiu Au, S. Travis Waller, Peter Stone, and C. Y. David Yang. Automated intersection control: Performance of a future innovation versus current traffic signal control. *Transportation Research Record : Journal of the Transportation Research Board*, (2259):223–232, 2012.

[24] Chien-Liang Fok, Maykel Hanna, Seth Gee, Tsz-Chiu Au, Peter Stone, Christine Julien, and Sriram Vishwanath. A platform for evaluating autonomous intersection management policies. In *ACM/IEEE Third International Conference on Cyber-Physical Systems (ICCPS)*, pages 87–96, 2012.

[25] Tsz-Chiu Au, Shun Zhang, and Peter Stone. Semi-autonomous intersection management. In *Proceedings of the International Joint Conferenceon Autonomous Agents and Multi Agent Systems (AAMAS)*, pages 1451–1452, 2014.

[26] Tsz-Chiu Au and Ty V. Nguyen. Augmented motion plans for planning in uncertain terrains. In *Proceedings of the 9th International Workshop on Planning and Scheduling for Space (IWPSS)*, pages 2–7, 2015.

[27] Tsz-Chiu Au, Shun Zhang, and Peter Stone. Autonomous intersection management for semi-autonomous vehicles. In Dušan Teodorović, editor, *Handbook of Transportation*, pages 88–104. Routledge, 2015.

[28] Dohee Lee and Tsz-Chiu Au. Automatic configuration of mobile conveyor lines. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 3841–3846, 2016.

[29] Dohee Lee and Tsz-Chiu Au. Graph-based scheduling algorithms for mobile workstations. In *Proceedings of IJCAI Workshop on Autonomous Mobile Service Robots*, 2016.

[30] Dohee Lee and Tsz-Chiu Au. Virtual safety cages for human-robot collaboration in factories. In *HCI Korea*, 2016.

[31] Dohee Lee and Tsz-Chiu Au. Wearable devices for human-robot collaboration in workplaces. In *The 11th Korean Robotics Society Annual Conference*, 2016.

[32] Tsz-Chiu Au, Bikramjit Banerjee, Prithviraj Dasgupta, and Peter Stone. Multirobot systems. *IEEE Intelligent Systems*, 2017.

[33] Ty Nguyen and Tsz-Chiu Au. Extending the range of delivery drones by exploratory learning of energy models. In *Proceedings of the International Joint Conferenceon Autonomous Agents and Multi Agent Systems (AAMAS)*, pages 1658–1660, 2017.

[34] Ty Nguyen, Dung Nguyen, and Tsz-Chiu Au. Learning of vehicular performance models for longitudinal motion planning to satisfy arrival requirements. In *IEEE/RSJ International conference on Intelligent Robots and Systems (IROS)*, pages 4731–4736, 2017.

[35] Dung Nguyen and Tsz-Chiu Au. Learning to generate backup paths in cooperative transportation of human-robot teams. In *Proceedings of the ICRA Workshop on Robot Teammates Operating in Dynamic, Unstructured Environments (RT-DUNE)*, 2018.

[36] Jungho Im, Cheolhee Yoo, Dongjin Cho, Kyoungmin Kim, Juhyun Lee, Dong-Hyun Cha, and Tsz-Chiu Au. Deep learning-based monitoring and forecast of the intensity of tropical cyclones. In *Proceedings of the IEEE Geoscience and Remote Sensing Society (IGARSS)*, 2019.

[37] Dohee Lee and Tsz-Chiu Au. Scheduling of mobile workstations for overlapping production time and delivery time. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 4147–4152, 2019.

[38] Hyungpil Moon, Jose Martinez-Carranza, Titus Cieslewski, Matthias Faessler, Davide Falanga, Alessandro Simovic, Davide Scaramuzza, Shuo Li, Michael Ozo, Christophe De Wagter, Guido de Croon, Sunyou Hwang, Sunggoo Jung, Hyunchul Shim, Haeryang Kim, Minhyuk Park, Tsz-Chiu Au, and Si Jung Kim. Challenges and implemented technologies used in autonomous drone racing. *Intelligent Service Robotics*, 12:137–148, 2019.

[39] Ty Nguyen and Tsz-Chiu Au. A constant-time algorithm for checking reachability of arrival times and arrival velocities of autonomous vehicles. In *IEEE Intelligent Vehicles Symposium*, 2019.

[40] Tsz-Chiu Au. Extending the range of drone-based delivery services by exploration. arXiv, 2020.

[41] Tsz-Chiu Au. Gridlock-free autonomous parking lots for autonomous vehicles. In *IEEE/RSJ International conference on Intelligent Robots and Systems (IROS)*, pages 4881–4887, 2021.

[42] Jaebak Hwang, Sungahn Ko, and Tsz-Chiu Au. Calibrating dynamic traffic assignment models by parallel search using Active-CMA-ES. In *IEEE International Conference on Intelligent Transportation Systems (ITSC)*, 2021.

[43] Dohee Lee, Qi Lu, and Tsz-Chiu Au. Multiple-place swarm foraging with dynamic robot chains. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2021.

[44] Tsz-Chiu Au. Extended goal recognition design with first-order computation tree logic. In *Proceedings of the AAAI Conference on Artificial Intelligence (AAAI)*, pages 9661–9668, 2022.

[45] Dohee Lee, Qi Lu, and Tsz-Chiu Au. Dynamic robot chain networks for swarm foraging. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2022.

[46] Tsz-Chiu Au. A dynamic programming algorithm for grid-based formation planning of multiple vehicles. In *IEEE/RSJ International conference on Intelligent Robots and Systems (IROS)*, 2023.

[47] Minhyuk Park and Tsz-Chiu Au. Challenges in using drone swarms as video game platforms. In *Proceedings of Human Multi-Robot Interaction Workshop (HMRI) at IROS*, 2023.

[48] Tsz-Chiu Au. Block-level goal recognition design. In *Proceedings of the AAAI Conference on Artificial Intelligence (AAAI)*, 2024.

[49] Tsz-Chiu Au. Real-time pixel formation planning in interactive drone light shows. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2024. Under review.