

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 17-09-2021	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 30-Apr-2020 - 29-Apr-2021
---	--------------------------------	---

4. TITLE AND SUBTITLE Final Report: High-Performance CPU-GPU Compute Cluster for Research on Computational Game Theory and Biological Steering	5a. CONTRACT NUMBER W911NF-20-1-0081
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611103

6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Carnegie Mellon University Associate Director, Sponsored Programs Carnegie Mellon University Pittsburgh, PA 15213 -3890	8. PERFORMING ORGANIZATION REPORT NUMBER
--	--

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 75778-CS-RIP.28

12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.
--

13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Tuomas Sandholm
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 412-268-8216

RPPR Final Report
as of 22-Sep-2021

Agency Code: 21XD

Proposal Number: 75778CSRIP

Agreement Number: W911NF-20-1-0081

INVESTIGATOR(S):

Name: Tuomas Sandholm
Email: sandholm@cs.cmu.edu
Phone Number: 4122688216
Principal: Y

Organization: **Carnegie Mellon University**

Address: Associate Director, Sponsored Programs, Pittsburgh, PA 152133890

Country: USA

DUNS Number: 052184116

EIN: 250969449

Report Date: 29-Jul-2021

Date Received: 17-Sep-2021

Final Report for Period Beginning 30-Apr-2020 and Ending 29-Apr-2021

Title: High-Performance CPU-GPU Compute Cluster for Research on Computational Game Theory and Biological Steering

Begin Performance Period: 30-Apr-2020

End Performance Period: 29-Apr-2021

Report Term: 0-Other

Submitted By: Tuomas Sandholm

Email: sandholm@cs.cmu.edu

Phone: (412) 268-8216

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees:

STEM Participants:

Major Goals: The goal was to build a significant hybrid CPU-GPU compute cluster.

Accomplishments: We built the significant hybrid CPU-GPU compute cluster as planned.

The cluster has been in very active use by my research group ever since.

Training Opportunities: Most of my PhD student Research Assistants have been using the cluster, including Ellen Vitercik, Siddharth Prasad, Gabriele Farina, Brian Zhang, and Carlos Martin. They have all gotten training in how to use the cluster, how to do high-performance computing, and how to develop high-performing algorithms using a combination of theory and large-scale computational experiments.

Ellen Vitercik has accepted a tenure-track position at Stanford. She will first do one year in the prestigious Miller Postdoctoral Fellowship at UC Berkeley. The other students have not yet graduated.

Results Dissemination: We have published a number of papers (see list of publications in this report) that used the cluster for computational experiments.

RPPR Final Report as of 22-Sep-2021

Honors and Awards: Prof. Sandholm received the following awards during the reporting period.

- IJCAI John McCarthy Award, 2021. "For his significant research contributions to multiagent systems, computational economics, optimization and game playing, and their application in real-world settings". The IJCAI John McCarthy Award is intended to recognize established mid-career researchers, typically between fifteen to twenty-five years after obtaining their PhD, that have built up a major track record of research excellence in artificial intelligence. Nominees of the award will have made significant contributions to the research agenda in their area and will have a first-rate profile of influential research results. One award per year is given.
- AAAI Robert S. Englemore Award, 2021. "For outstanding research contributions in Artificial Intelligence, its application to electronic market places, the highly original use of AI in strategic multi-player games, and the application of AI to optimize organ exchanges". "The award is given to people who have demonstrated excellence in scholarship in AI, outstanding applications of AI, as well as extraordinary service to AAI and the AI community."
- University Professor, 5/2020. The title of University Professor is the highest designation a faculty member can receive at Carnegie Mellon. The number of University Professors should be no more than about 10 percent of number of faculty at Carnegie Mellon University holding the rank of Professor.
- 100 Most Intriguing Entrepreneurs, award from Goldman Sachs, 2020.

Dr. Sandholm's -- with his students -- best paper awards & other recognition of specific papers

- My PhD student Noam Brown's dissertation won the International Foundation for Autonomous Agents and Multiagent Systems (IFAAMAS) Victor Lesser Distinguished Dissertation award, 2021.
- My PhD student Noam Brown's dissertation won the CMU School of Computer Science Distinguished Dissertation Award, 2020. It also won CMU School of Computer Science's nomination for the ACM Doctoral Dissertation Award and CMU's nomination for the AAI/SIGAI AI Dissertation award.
- Our paper "Superhuman AI for Multiplayer Poker" was selected to be presented in the special plenary session on Highlights Beyond EC, at the ACM Conference on Economics and Computation (EC), 2020.

Protocol Activity Status:

Technology Transfer: The cluster has not led to additional new collaborations with other DoD organizations directly yet, but as you know, I have a lot of ongoing and new work with the DoD through my startup Strategy Robot.

ARTICLES:

RPPR Final Report

as of 22-Sep-2021

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 5-Submitted
Journal: arXiv
Publication Identifier Type: Other **Publication Identifier:** arXiv:2106.06068
Volume: **Issue:** **First Page #:**
Date Submitted: 8/18/21 12:00AM **Date Published:**
Publication Location:

Article Title: Subgame solving without common knowledge

Authors: Brian Hu Zhang, Tuomas Sandholm

Keywords: Game theory

Abstract: In imperfect-information games, subgame solving is significantly more challenging than in perfect-information games, but in the last few years, such techniques have been developed. They were the key ingredient to the milestone of superhuman play in no-limit Texas hold'em poker. Current subgame-solving techniques analyze the entire common-knowledge closure of the player's current information set, that is, the smallest set of nodes within which it is common knowledge that the current node lies. However, this set is too large to handle in many games. We introduce an approach that overcomes this obstacle, by instead working with only low-order knowledge. Our approach allows an agent, upon arriving at an info set, to basically prune any node that is no longer reachable, thereby massively reducing the game tree size relative to the common-knowledge subgame. We prove that, as is, our approach can increase exploitability compared to the blueprint strategy.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 **Conference Date:** 03-Feb-2021 **Date Published:** 03-Feb-2021
Conference Location: Virtual conference
Paper Title: Bandit Linear Optimization for Sequential Decision Making and Extensive-Form Games
Authors: Gabriele Farina, Robin Schmucker, Tuomas Sandholm
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 **Conference Date:** 02-Feb-2021 **Date Published:** 02-Feb-2021
Conference Location: Virtual conference
Paper Title: Bayesian Multiagent Inverse Reinforcement Learning for Policy Recommendation
Authors: Carlos Martin, Tuomas Sandholm
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: EC 2021
Date Received: 18-Aug-2021 **Conference Date:** 19-Jul-2021 **Date Published:** 19-Jul-2021
Conference Location: Virtual conference
Paper Title: Better Regularization for Sequential Decision Spaces: Fast Convergence Rates for Nash, Correlated, and Team Equilibria
Authors: Gabriele Farina, Christian Kroer, Tuomas Sandholm
Acknowledged Federal Support: Y

RPPR Final Report
as of 22-Sep-2021

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Proceedings of the 38th International Conference on Machine Learning, PMLR
Date Received: 18-Aug-2021 Conference Date: 18-Jul-2021 Date Published: 18-Jul-2021
Conference Location: Virtual conference
Paper Title: Connecting Optimal Ex-Ante Collusion in Teams to Extensive-Form Correlation: Faster Algorithms and Positive Complexity Results
Authors: Gabriele Farina, Andrea Celli, Nicola Gatti, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 Conference Date: 02-Feb-2021 Date Published: 02-Feb-2021
Conference Location: Virtual conference
Paper Title: Faster Game Solving via Predictive Blackwell Approachability Connecting Regret Matching and Mirror Descent
Authors: Gabriele Farina, Christian Kroer, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 Conference Date: 02-Feb-2021 Date Published: 02-Feb-2021
Conference Location: Virtual conference
Paper Title: Finding and Certifying (Near-)Optimal Strategies in Black-Box Extensive-Form Games
Authors: Brian Hu Zhang, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 Conference Date: 02-Feb-2021 Date Published: 02-Feb-2021
Conference Location: Virtual conference
Paper Title: Generalization in portfolio-based algorithm selection
Authors: Maria-Florina Balcan, Tuomas Sandholm, Ellen Vitercik
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: STOC 2021
Date Received: 18-Aug-2021 Conference Date: 21-Jun-2021 Date Published: 21-Jun-2021
Conference Location: Virtual conference
Paper Title: How much data is sufficient to learn high-performing algorithms generalization guarantees for data-driven algorithm design
Authors: Maria-Florina Balcan, Dan DeBlasio, Travis Dick, Carl Kingsford, Tuomas Sandholm, Ellen Vitercik
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IJCAI 2021
Date Received: 18-Aug-2021 Conference Date: 18-Aug-2021 Date Published: 18-Aug-2021
Conference Location: Montreal & Virtual conference
Paper Title: Learning Within an Instance for Designing High-Revenue Combinatorial Auctions
Authors: Maria-Florina Balcan, Siddharth Prasad, Tuomas Sandholm
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 22-Sep-2021

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AAAI 2021
Date Received: 18-Aug-2021 Conference Date: 02-Feb-2021 Date Published: 02-Feb-2021
Conference Location: Virtual conference
Paper Title: Model-Free Online Learning in Unknown Sequential Decision Making Problems and Games
Authors: Gabriele Farina, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ICML 2020
Date Received: 18-Aug-2021 Conference Date: 13-Jul-2021 Date Published: 13-Jul-2021
Conference Location: Virtual conference
Paper Title: Refined bounds for algorithm configuration: The knife-edge of dual class approximability
Authors: Maria-Florina Balcan, Tuomas Sandholm, Ellen Vitercik
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: NeurIPS 2020
Date Received: 18-Aug-2021 Conference Date: 06-Dec-2020 Date Published: 06-Dec-2020
Conference Location: Virtual conference
Paper Title: Small Nash Equilibrium Certificates in Very Large Games
Authors: Brian Hu Zhang, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ICML 2020
Date Received: 18-Aug-2021 Conference Date: 12-Jul-2020 Date Published: 12-Jul-2020
Conference Location: Virtual conference
Paper Title: Sparsified linear programming for zero-sum equilibrium finding
Authors: Brian Zhang, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ICML 2020
Date Received: 18-Aug-2021 Conference Date: 18-Jul-2020 Date Published: 18-Jul-2020
Conference Location: Virtual conference
Paper Title: Stochastic regret minimization in extensive-form games
Authors: Gabriele Farina, Christian Kroer, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: NeurIPS Workshop on Cooperative AI
Date Received: 08-Sep-2021 Conference Date: 13-Dec-2020 Date Published: 13-Dec-2020
Conference Location: Virtual conference
Paper Title: Faster Algorithms for Optimal Ex-Ante Coordinated Collusive Strategies in Extensive-Form Zero-Sum Games
Authors: Gabriele Farina, Andrea Celli, Nicola Gatti, Tuomas Sandholm
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 22-Sep-2021

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: NeurIPS Workshop on Cooperative AI
Date Received: 08-Sep-2021 Conference Date: 12-Dec-2020 Date Published: 12-Dec-2020
Conference Location: Virtual
Paper Title: No-Regret Learning Dynamics for Extensive-Form Correlated Equilibrium
Authors: Andrea Celli, Alberto Marchesi, Gabriele Farina, Nicola Gatti
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: NeurIPS Workshop on Cooperative AI
Date Received: 08-Sep-2021 Conference Date: 12-Dec-2020 Date Published: 12-Dec-2020
Conference Location: Virtual conference
Paper Title: Polynomial-Time Computation of Optimal Correlated Equilibria in Two-Player Extensive-Form Games with Public Chance Moves and Beyond
Authors: Gabriele Farina, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: NeurIPS 2020
Date Received: 08-Sep-2021 Conference Date: 06-Dec-2020 Date Published: 06-Dec-2020
Conference Location: Virtual conference
Paper Title: Polynomial-Time Computation of Optimal Correlated Equilibria in Two-Player Extensive-Form Games with Public Chance Moves and Beyond
Authors: Gabriele Farina, Tuomas Sandholm
Acknowledged Federal Support: **Y**

Partners

I certify that the information in the report is complete and accurate:

Signature: Tuomas Sandholm

Signature Date: 9/17/21 10:38PM

Here are pictures of the cluster being built:





No person months were charged, so no personnel are listed on this Final Report.