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14. ABSTRACT
This project opens up a brand new area of research that fuses two separate subareas of game theory: algorithmic game theory and behavioral game theory. More specifically, game-theoretic algorithms have been deployed by several security agencies, allowing them to generate optimal randomized schedules against adversaries who may exploit predictability. However, one key challenge in applying game theory to solving real-world security problems is the “perfect rationality” assumption of the players, which may not hold when dealing with human adversaries. Therefore, it is critical that we develop a new set of game-theoretic algorithms taking into account adversaries'

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UU	UU	UU	UU		Milind Tambe
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					213-740-6447

Report Title

Final Report: Towards Algorithmic Advances for Solving Stackelberg games: Addressing Model Uncertainties and Massive Game Scale-up

ABSTRACT

This project opens up a brand new area of research that fuses two separate subareas of game theory: algorithmic game theory and behavioral game theory. More specifically, game-theoretic algorithms have been deployed by several security agencies, allowing them to generate optimal randomized schedules against adversaries who may exploit predictability. However, one key challenge in applying game theory to solving real-world security problems is the “perfect rationality” assumption of the players, which may not hold when dealing with human adversaries. Therefore, it is critical that we develop a new set of game-theoretic algorithms taking into account adversaries' bounded rationality. To that end, our accomplishments include: i)integrating mathematical models of human decision making based on Prospect Theory and Quantal Response into game-theoretic algorithms; ii)comprehensive experiments with human subjects which evaluates the effectiveness of these new algorithm showing improvement over the previous leading contender; iii) enhancing the efficiency of these game-theoretic algorithms, thus the use of these algorithms for computing security schedules in real-world settings.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
01/22/2015 12.00	Albert Xin Jiang, Rong Yang, Milind Tambe, Fernando Ordo ?n ?ez. Scaling-up Security Games with Boundedly Rational Adversaries: A Cutting-plane Approach, 23rd International Joint Conference on Artificial Intelligence (IJCAI 2013). 03-AUG-13, . : ,
01/22/2015 18.00	Rong Yang, Fei Fang, Albert Xin Jiang, Karthik Rajagopal, Milind Tambe, Rajiv Maheswaran. Modeling Human Bounded Rationality to Improve Defender Strategies in Network Security Games, Workshop on Human-Agent Interaction Design and Models held at AAMAS 2012, Valencia, Spain. 04-JUN-12, . : ,
01/22/2015 19.00	Rong Yang, Christopher Kiekintveld, Fernando Ordonez, Milind Tambe, Richard John. Including Human Behavior in Security Games, Workshop on Optimization in Multi-Agent Systems (OPTMAS), AAMAS 2011. 02-MAY-11, . : ,

TOTAL: **3**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/26/2011	1.00	Rong Yang, Christopher Kiekintveld └, Fernando Ordonez, Milind Tambe, Richard John. Improving Resource Allocation Strategy AgainstHuman Adversaries in Security Games, International Joint Conference on Artificial Intelligence. 18-JUL-11, . : ,
08/26/2011	2.00	Rong Yang, Christopher Kiekintveld └, Fernando Ordonez, Milind Tambe, Richard John. Improved Computational Models of Human Behavior inSecurity Games, International Conference on Autonomous Agents and Multiagent Systems (Extended Abstract). 05-MAY-11, . : ,
08/28/2012	4.00	Rong Yang, Fernando Ordonez, Milind Tambe. Computing Optimal Strategy against Quantal Response inSecurity Games, the 11th International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2012). 04-JUN-12, . : ,
08/28/2012	7.00	Rong Yang, Fei Fang, Albert Xin Jiang, Karthik Rajagopal, Milind Tambe, Rajiv Maheswaran. Designing Better Strategies against Human Adversaries in Graph-Based Security Games (Extended Abstract), the 11th International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2012). 04-JUN-12, . : ,
08/28/2012	8.00	Richard John, James Pita , Rajiv Maheswaran , Milind Tambe, Rong Yang, Sarit Kraus. A Robust Approach to Addressing Human Adversaries inSecurity Games(Extended Abstract), the 11th International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2012). 04-JUN-12, . : ,

TOTAL: **5**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
01/22/2015	10.00	Rong Yang, Christopher Kiekintveldb, Fernando Ordonez, Milind Tambea, Richard Johna. Improving Resource Allocation Strategy Against Human Adversaries in Security Games: An Extended Study, Artifficial Intelligence Journal (02 2013)
08/30/2012	9.00	Rong Yang, Christopher Kiekintveld, Fernando Ordonez, Milind Tambe, Richard John. Improving Resource Allocation Strategies Against Human Adversaries in Security Games: An Extended Study (accepted with revision), Artificial Intelligence Journal (12 2011)

TOTAL: **2**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Rong Yang Runner up Best PhD thesis 2014

Rong Yang best research assistant computer science department USC 2013

Wanger Prize for Excellence in Operations Research Practice at INFORMS 2012

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Fei Fang	0.25	
Rong Yang	0.54	
Leandro Marcolino	0.14	
Zhengyu Yin	0.08	
Jun-Young Kwak	0.04	
FTE Equivalent:	**1.05**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Matthew Johnson	0.02
Albert Jiang	0.04
FTE Equivalent:	**0.06**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Milind Tambe	0.24	
Fernando Ordonez	0.08	
Rajiv Maheswaran	0.07	
FTE Equivalent:	**0.39**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Mohit Goenka	
Mayuresh Janorkark	
Rishika Agarwal	
Jie Zheng	
Total Number:	**4**

Names of personnel receiving PHDs

NAME	
Rong Yang	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This project opens up a brand new area of research that fuses two separate subareas of game theory: algorithmic game theory and behavioral game theory. More specifically, game-theoretic algorithms have been deployed by several security agencies, allowing them to generate optimal randomized schedules against adversaries who may exploit predictability. However, one key challenge in applying game theory to solving real-world security problems is the “perfect rationality” assumption of the players, which may not hold when dealing with human adversaries. Therefore, it is critical that we develop a new set of game-theoretic algorithms taking into account adversaries' bounded rationality. To that end, our accomplishments include: i)integrating mathematical models of human decision making based on Prospect Theory and Quantal Response into game-theoretic algorithms; ii)comprehensive experiments with human subjects which evaluates the effectiveness of these new algorithm showing improvement over the previous leading contender; iii) enhancing the efficiency of these game-theoretic algorithms, thus the use of these algorithms for computing security schedules in real-world settings.

We first investigated different theories in the behavioral literature to develop models of human decision-making for predicting adversary behavior. More specifically, we explored two fundamental theories, i.e. Prospect Theory [Kahneman and Tvesky, 1979] and Quantal Response (QR) Model [McKelvey and Palfrey, 1995], to model the decision-making process of human adversaries [Yang et al., 2011] via thorough experiments with human subjects using a simulated security game that we developed. Prospect Theory is a Nobel Prize winning theory which provides a descriptive model of human decision making. Quantal Response Model originates from the literature of discrete choice models [Train, 2003; McFadden, 1984], which models the player’s behavior as a stochastic choice making. In experiments with human subjects, the defender strategy computed using the quantal response model to predict the human adversary significantly outperformed its competitors, including the previous leading contender COBRA [Pita et al., 2010].

Unfortunately, while the quantal response model outperformed competitors, it presented a complex optimization challenge. Given the non-convexity of this optimization problem, computing defender optimal strategies is an NP-hard problem [Vavasis, 1995]. We provided two novel algorithms (GOSAQ and PASAQ) to solve the problem [Yang et al., 2012c]. These two novel algorithms are based on three key ideas: (i) use of a binary search method to solve the fractional optimization problem efficiently, (ii) construction of a convex optimization problem through a non-linear transformation,(iii) building a piecewise linear approximation of the non-linear terms in the problem. We also provided proofs of approximation bounds, detailed experimental results showing the advantages of GOSAQ and PASAQ in solution quality over the benchmark algorithm (BRQR) and the efficiency of PASAQ.

Given that many real-world security problems are massive, such as for Federal Air Marshals [Kiekintveld et al., 2009], further scaling-up for computing defender strategy incorporating models of adversary bounded rationality is needed. Unfortunately, previously proposed branch-and-price approaches fail to scale-up given the non-convexity of such models, as we show with a realization called COCOMO. Therefore, we presented a novel cutting-plane algorithm called BLADE to scale-up SSGs with complex adversary models,with three novelties: (i) an efficient scalable separation oracle to generate deep cuts; (ii) a heuristic that uses gradient to further improve the cuts; (iii) techniques for quality-efficiency tradeoffs.

Technology Transfer

The work initiated in this grant led to the use of the quantal response model in security games. This model was used in the original PROTECT application developed for the US Coast Guard for patrolling the port of Boston. The idea here is to patrol in a randomized fashion yet giving higher weights to more important targets. The application went into effect in 2011 and was used by the US Coast Guard in regular patrolling; later a newer version of PROTECT got implemented. The application won the prestigious Wagner prize of the INFORMS society.