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6. AUTHORS

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14. ABSTRACT

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Ashutosh Nayyar
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RPPR Final Report
as of 19-Oct-2021

Agency Code: 21XD

Proposal Number: 69047CS **Agreement Number: W911NF-17-1-0232**
INVESTIGATOR(S):

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DUNS Number: 072933393 EIN: 951642394
Report Date: 08-Jul-2021 Date Received: 10-Sep-2021
Final Report for Period Beginning 09-May-2017 and Ending 08-Apr-2021
Title: Stochastic Dynamic Games of Asymmetric Information: A Common Information Approach
Begin Performance Period: 09-May-2017 **End Performance Period:** 08-Apr-2021
Report Term: 0-Other
Submitted By: Ashutosh Nayyar Email: ashutosn@usc.edu
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STEM Degrees: **STEM Participants:**

Major Goals: The objective of this project is to study and analyze stochastic dynamic games where the participating strategic agents have asymmetric information, that is, they have different information about the game's status at each time instant. These games model strategic interactions among autonomous agents operating in uncertain dynamic environments and making decisions based on locally acquired incomplete information. Such scenarios arise in a range of military and security related applications including operations involving autonomous systems in the presence of adversarial agents, communication of sensitive information in the presence of jamming or eavesdropping agents, security of computer and communication networks, strategic arms' negotiations, transportation networks, energy markets etc. Our main focus is on finding the structure of equilibrium decision strategies in games of asymmetric information and enabling efficient computation of equilibrium strategies and performance in such games.

Accomplishments: (1) We investigated zero-sum stochastic dynamic games of asymmetric information where the common beliefs depend on the choice of players' strategies. For such a game, we showed that the equilibrium value can be computed via a sequential decomposition of the game. A preliminary version of this result was presented at the second Symposium on the Control of Network Systems (SCONES) held at Boston university in October 2017. A complete version was published in Dynamic Games and Applications journal.
(2) We discovered a dynamic mechanism, for situations where the agents' states (described by controlled Markov processes) are correlated and their utilities are interdependent, that possesses the following properties: incentive compatibility, social welfare optimality, budget balance, and ex-post individual rationality. Our results appear in the paper "An Efficient Dynamic Allocation Mechanism for Security in Networks of Interdependent Agents" that has been submitted for publication in the journal on Dynamic Games and Applications, special issue on cyber security; the paper is under review. A preliminary version of our results appeared in the proceedings of the Game Nets conference.
(3). We discovered an optimal information disclosure mechanism for two-agent games. Our results appear in the paper "Static and Dynamic Informational Incentive Mechanisms for Security Enhancement" that has been accepted for publication in the proceedings of the 2018 IEEE Mediterranean Control Conference.
(4). We refined our existing results on the common information approach to dynamic games with asymmetric information where strategic agents possess private and common information. Specifically, we discovered conditions that enable us to determine sufficient private information for each agent; using the sufficient private information of each agent we determine common information based beliefs on the dynamic system's state and the agents' sufficient private information, the corresponding common information based strategy prediction, and Sufficient Information Based Perfect Bayesian Equilibria (SIS-PBE). Using SIS-PBE as the solution concept for the dynamic game, we determine a sequential decomposition of the game. This sequential decomposition leads to an

algorithm that determines, via backward induction, the SIS-PBE of the game. Such equilibria are easier to compute than Common Information Based Perfect Bayesian Equilibria (CIB-PBE), as the domain of SIS-PBE is smaller than the domain of CIB-PBE. These results appear in Hamidreza Tavafoghi's Ph.D. thesis that was supported in part by this grant. A summary of these results has been submitted to the 2018 IEEE Conference on Decision and Control (CDC); the paper has been accepted for presentation at CDC and will appear in the CDC's proceedings.
(5) We started investigating multi-agent control and coordination problems in unknown environments. In particular, we investigated decentralized problems where agents have to learn the underlying system dynamics and cooperate to minimize a shared cost function. We use a Thompson sampling approach to bound the regret in this decentralized learning and control problem. A preliminary version of this work has been accepted for presentation at the 2018 IEEE conference on decision and control.
(6) We investigated the problem of designing public and private information disclosure mechanisms by a principal (transportation authority) in a transportation network so as to improve the overall congestion. We showed that perfect disclosure of information about the routes' congestion is not optimal. The principal can improve /decrease congestion by providing coordinated routing recommendation to drivers based on the routes' conditions. When the uncertainty about the routes' conditions is high relative to the ex ante difference in the routes' conditions (i.e. the value of information is high), we showed that the socially efficient routing outcome is achievable using a private information disclosure mechanism. Furthermore, we studied the problem of optimal dynamic private information disclosure mechanism design in a dynamic two-step setting. We considered different pieces of information that drivers may observe and learn from time t=1 and investigated qualitative properties of optimal dynamic information disclosure mechanisms using numerical simulations. The results of this work were documented in a paper that was presented at the 2017 Allerton Conference and was published in the conference's proceedings.
(7) Sequential decision-making in teams: A key goal of our project is to investigate optimal decision-making under asymmetric information among agents. As a first step, we looked at this problem in the context of cooperative teams. We showed how the concept of common knowledge can be used to find dynamic program type decompositions of the strategy optimization problem in teams. This work has been published in the IEEE Transactions on Automatic Control.

Training Opportunities: The project trained several graduate and undergraduate students to integrate knowledge and tools from diverse fields like stochastic and minimax control and game theory to address problems related to the project. In particular, Seyed Mohammad Asghari, Mukul Gagrani, Dhruva Kartik, Sagar Sudhakara and Shiva Navabi (graduate students at USC), were partially supported by this grant.
In addition, six students, three undergraduate and three graduate, were trained at the University of Michigan during the reporting period.

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Results Dissemination: The results related to this project were presented/published at the following conferences and journals:

1. M. Gagrani and A. Nayyar, “Thompson Sampling for some decentralized control problems,” 2018 IEEE Conference on Decision and Control (CDC), FL, USA, 2018, pp. 1053-1058, doi: 10.1109/CDC.2018.8619423.

2. A. Nayyar and D. Teneketzis, “Common knowledge and sequential team problems,” IEEE Transactions on Automatic Control, vol. 64, no. 12, pp. 5108-5115, Dec. 2019.

3. F. Farhadi, D. Teneketzis and S. J. Golestani, "Static and Dynamic Informational Incentive Mechanisms for Security Enhancement," 2018 European Control Conference (ECC), Limassol, 2018, pp. 1048-1055.

4.F. Farhadi, H. Tavafoghi, D.Teneketzis, and J.S. Golestani. “An Efficient Dynamic Allocation Mechanism for Security in Networks of Interdependent Strategic Agents,” Dynamic Games & Applications, 9, 914–941 (2019).

5. H. Tavafoghi, Y. Ouyang and D. Teneketzis, "A Sufficient Information Approach to Decentralized Decision Making," 2018 IEEE Conference on Decision and Control (CDC), Miami Beach, FL, 2018, pp. 5069-5076.

6. M. Rasouli and D. Teneketzis, “An Efficient Market Design for Electricity Networks with Strategic Users Possessing Local Information”, to appear in IEEE Transactions on Control of Network Systems, Special Issue on Analysis, Control and Optimization of Energy System Networks.

7. D. Kartik and A. Nayyar, “Upper and Lower Values in Zero-sum Stochastic Games with Asymmetric Information, ” Dynamic Games and Applications, July 2020, https://doi.org/10.1007/s13235-020-00364-x.

8. D. Tang, H. Tavafoghi, V. G. Subramanian, A. Nayyar, D. Teneketzis, “Private Information Compression in Dynamic Games among Teams,” 2021 IEEE Conference on Decision and Control (CDC), accepted.

9. D. Kartik and A. Nayyar, “Zero-sum Stochastic Games with Asymmetric Information,” 2019 IEEE 58th Conference on Decision and Control (CDC), Nice, France, 2019, pp. 4061-4066, doi: 10.1109/CDC40024. 2019.9030177.

10. S. Navabi and A. Nayyar, “A Dynamic Mechanism for Security Management in Multi-Agent Networked Systems,” IEEE INFOCOM 2020, accepted.

11. H. Tavafoghi, Y. Ouyang and D. Teneketzis, “A Unified Approach to Dynamic Decision Problems with Asymmetric Information-Part I: Non-strategic Agents”, conditionally accepted by IEEE Transactions on Automatic Control, July 2020.

12. H. Tavafoghi, Y. Ouyang and D. Teneketzis, “ A Unified Approach to Dynamic Decision Problems with Asymmetric Information-Part II: Strategic Agents”, submitted to IEEE Transactions on Automatic Control.

13. M. Rasouli and D. Teneketzis, "An Efficient Market Design for Electricity Networks with Strategic Users Possessing Local Information," in IEEE Transactions on Control of Network Systems, vol. 6, no. 3, pp. 1038-1049, Sept. 2019.

14. S. M. Asghari, Y. Ouyang and A. Nayyar, “Regret bounds for decentralized learning in cooperative multi agent dynamical systems,” Conference on Uncertainty in Artificial Intelligence (UAI) 2020, accepted.

15. M. Rayati and D. Teneketzis,” Electricity market design and implementation in the presence of asymmetrically informed strategic producers and consumers: A surrogate optimization-based mechanism”, submitted to Energy Economics

16. M. Rasouli and D. Teneketzis, “Economizing the uneconomic: Markets for reliable, sustainable and price efficient electricity”, to be submitted to Energy Economics.

17. F. Farhadi and D. Teneketzis, “ Dynamic information design: A simple problem on optimal sequential information disclosure “, submitted to Dynamic Games and Applications, (under revision).

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Honors and Awards: PI Ashutosh Nayyar received the Okawa Foundation Research Grant in 2020.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Ashutosh Nayyar
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
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Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Seyed Mohammad Asghari
Person Months Worked: 7.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Seyed Mohammad Asghari
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Mukul Gagrani
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Shiva Navabi
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Dhruva Kartik

Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Dengwang Tang
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Farzaneh Farhadi
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
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Participant Type: Graduate Student (research assistant)
Participant: Hamidreza Tavafoghi
Person Months Worked: 1.00 **Funding Support:**
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ARTICLES:

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Journal: IEEE Transactions on Automatic Control
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Volume: 64 Issue: 12 First Page #: 5108
Date Submitted: 8/22/20 12:00AM Date Published: 4/22/20 7:00AM
Publication Location:
Article Title: Common knowledge and sequential team problems
Authors: Ashutosh Nayyar, Demosthenis Teneketzis
Keywords: Sequential Teams, Information structure, commom knowledge
Abstract: We consider a general sequential team problem based on Witsenhausen's intrinsic model. Our formulation encompasses all teams in which the uncontrolled inputs can be viewed as random variables on a finite probability space, the number of control inputs/decisions is finite and the decisions take values in finite spaces. We define the concept of common knowledge in such teams and use it to construct a sequential decomposition of the problem of optimizing the team strategy profile. If the information structure is classical, our common knowledge based decomposition is identical to classical dynamic program. If the information structure is such that the common knowledge is trivial, our decomposition is similar in spirit to Witsenhausen's standard form based decomposition [17]. In this case, the sequential decomposition is essentially a sequential reformulation of the strategy optimization problem and appears to have limited value.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Dynamic Games and Applications
Publication Identifier Type: DOI Publication Identifier: 10.1007/s13235-018-0284-4
Volume: Issue: First Page #:
Date Submitted: 4/24/19 12:00AM Date Published: 9/19/18 7:00AM
Publication Location:
Article Title: An Efficient Dynamic Allocation Mechanism for Security in Networks of Interdependent Strategic Agents
Authors: Farzaneh Farhadi, Hamidreza Tavafoghi, Demosthenis Teneketzis, S. Jamaloddin Golestani
Keywords: Security games, dynamic mechanism design, Epidemics over networks, Strategic agents
Abstract: Motivated by security issues in networks, we study the problem of incentive mechanism design for dynamic resource allocation in a multi-agent networked system. Each strategic agent has a private security state which can be safe or unsafe and is only known to him. At every time, each agent faces security threats from outside as well as from his unsafe neighbors. Therefore, the agents' states are correlated and have interdependent stochastic dynamics. Agents have interdependent valuations, as each agent's instantaneous utility depends on his own security state as well as his neighbors' security states. There is a network manager that can allocate a security resource to one agent at each time so as to protect the network against attacks and maximize the overall social welfare. We propose a dynamic incentive mechanism that implements the efficient allocation and is ex-ante (in expectation) individually rational and budget balanced.
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Volume: Issue: First Page #:
Date Submitted: 4/24/19 12:00AM Date Published:
Publication Location:
Article Title: A Unified Approach to Dynamic Decision Problems with Asymmetric Information-Part I: Non-strategic Agents
Authors: Hamid Tavafoghi, Yi Ouyang and Demosthenis Teneketzis
Keywords: Dynamic decision problems, asymmetric information, non-strategic agents
Abstract: We study a general class of dynamic multi-agent de- cision problems with asymmetric information and non-strategic agents, which includes dynamic teams as a special case. When agents are non-strategic, an agent's strategy is known to the other agents. Nevertheless, the agents' strategy choices and beliefs are interdependent over times, a phenomenon known as signaling. We introduce the notions of private information that effectively compresses the agents' information in a mutually consistent manner. Based on the notions of sufficient information, we propose an information state for each agent that is sufficient for decision making purposes. We present instances of dynamic multi-agent decision problems where we can determine an information state with a time-invariant domain for each agent. Furthermore, we present a generalization of the policy- independence property of belief in Partially Observed Markov Decision Processes (POMDP) to dynamic multi-agent decision problems.
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Journal: IEEE Transactions on Automatic Control
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Date Submitted: 4/24/19 12:00AM Date Published:
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Article Title: A Unified Approach to Dynamic Decision Problems with Asymmetric Information-Part II: Strategic Agents
Authors: Hamid Tavafoghi, Yi Ouyang and Demos Teneketzis
Keywords: Dynamic decision problems, strategic agents, asymmetric information
Abstract: We study a general class of dynamic games with asymmetric information where agents' beliefs are strategy dependent, i.e. signaling occurs. We show that the notion of sufficient information, introduced in the companion paper [2], can be used to effectively compress the agents' information in a mutually consistent manner that is sufficient for decision- making purposes. We present instances of dynamic games with asymmetric information where we can characterize a time- invariant information state for each agent. Based on the notion of sufficient information, we define a class of equilibria for dynamic games called Sufficient Information Based Perfect Bayesian Equi- librium (SIB-PBE). Utilizing the notion of SIB-PBE, we provide a sequential decomposition of dynamic games with asymmetric information over time; this decomposition leads to a dynamic program that determines SIB-PBE of dynamic games. We provide conditions under which we can guarantee the existence of SIB- PBE.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
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Volume: Issue: First Page #:
Date Submitted: 4/24/19 12:00AM Date Published:
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Article Title: An Efficient Market Design for Electricity Networks with Strategic Users Possessing Local Information
Authors: Mohammad Rasouli, Demos Teneketzis
Keywords: Efficient Market Design, Strategic users
Abstract: We consider electricity wholesale markets with multiple strategic users that possess localized information about the electricity network and can be either producers or consumers. The objective is to design a mechanism that maximizes the social welfare (the sum of the users' utilities) and has the following additional features. It satisfies the users' informational constraints along with the constraints imposed by the lines' thermal capacity limit and the network's physical laws (Kirchhoff's laws); furthermore it is budget balanced, individually rational, and price efficient. Using ideas from the theory of local public goods and auctions, we construct a social welfare maximizing mechanism that possesses all of the above features at equilibrium. We present an intuitive interpretation of the mechanism and discuss possible extensions of the model considered in the paper.
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: IEEE Conference on Decision and Control
Date Received: 27-Jan-2019 Conference Date: 18-Dec-2018 Date Published: 25-Dec-2018
Conference Location: Miami Beach, FL, USA
Paper Title: Thompson Sampling for some decentralized control problems
Authors: Mukul Gagrani and Ashutosh Nayyar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE Conference on Decision and Control
Date Received: 27-Jan-2019 Conference Date: 17-Dec-2018 Date Published: 24-Dec-2018
Conference Location: Miami Beach, FL, USA
Paper Title: A Sufficient Information Approach to Decentralized Decision Making
Authors: H. Tavafoghi, Y. Ouyang and D. Teneketzis
Acknowledged Federal Support: **Y**

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Conference Name: IEEE European Control Conference
Date Received: 27-Jan-2019 Conference Date: 12-Jun-2018 Date Published: 31-Aug-2018
Conference Location: Limassol, Cyprus
Paper Title: Static and Dynamic Informational Incentive Mechanisms for Security Enhancement
Authors: F.Farhadi, D. Teneketzis, J.S Golestani
Acknowledged Federal Support: **Y**

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Conference Name: 7th International EAI Conference on Game Theory for Networks, GAMENETS
Date Received: 20-Jul-2018 Conference Date: 09-May-2017 Date Published: 01-Jul-2017
Conference Location: Knoxville Tennessee
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Authors: F. Farhadi, D. Teneketzis, J.S. Golestani
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Conference Name: 55th Allerton Conference on Control, Communication and Computation
Date Received: 20-Jul-2018 Conference Date: 03-Oct-2017 Date Published: 31-Oct-2017
Conference Location: Monticello, Illinois
Paper Title: Informational Incentives for Congestion Games
Authors: H. Tavafoghi, D. Teneketzis
Acknowledged Federal Support: **Y**

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Conference Name: 2017 American Control Conference (ACC)
Date Received: 24-Apr-2019 Conference Date: 24-May-2017 Date Published:
Conference Location: Seattle, WA, USA
Paper Title: Information structures and values in zero-sum stochastic games
Authors: Ashutosh Nayyar, Abhishek Gupta
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE conference on decision and control
Date Received: 21-Aug-2020 Conference Date: 12-Dec-2019 Date Published: 12-Mar-2020
Conference Location: Nice, France
Paper Title: Zero-sum Stochastic Games with Asymmetric Information
Authors: Dhruva Kartik, Ashutosh Nayyar
Acknowledged Federal Support: **Y**

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Conference Name: IEEE Conference on Decision and Control
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Conference Location: Nice, France
Paper Title: Regret Analysis for Learning in a Multi-Agent Linear-Quadratic Control Problem
Authors: Seyed Mohammad Asghari, Mukul Gagrani, Ashutosh Nayyar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 5-Submitted
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Paper Title: A Dynamic Mechanism for Security Management in Multi-Agent Networked Systems
Authors: Shiva Navabi, Ashutosh Nayyar
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Conference Name: IEEE INFOCOM 2020 - IEEE Conference on Computer Communications
Date Received: 25-Aug-2020 Conference Date: 06-Jul-2020 Date Published: 04-Aug-2020
Conference Location: Online conference
Paper Title: A Dynamic Mechanism for Security Management in Multi-Agent Networked Systems
Authors: Shiva Navabi, Ashutosh Nayyar
Acknowledged Federal Support: **Y**

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Conference Name: Uncertainty in Artificial Intelligence (UAI) 2020
Date Received: 25-Aug-2020 Conference Date: 03-Aug-2020 Date Published:
Conference Location: Online conference
Paper Title: Regret Bounds for Decentralized Learning in Cooperative Multi-Agent Dynamical Systems
Authors: Seyed Mohammad Asghari, Yi Ouyang, Ashutosh Nayyar
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Southern California
Date Received: 14-Jul-2019 Completion Date: 6/30/19 10:52PM
Title: Team Decision Theory and Decentralized Stochastic Control
Authors: Seyed Mohammad Asgharipari
Acknowledged Federal Support: **N**

Partners

,

Prof. Vijay Subramanian, University of Michigan.

I certify that the information in the report is complete and accurate:
Signature: Ashutosh Nayyar
Signature Date: 9/10/21 2:33PM

Nothing to report in the uploaded pdf (see accomplishments)