

# Workforce Development & Overview





# Student Access

Partially supporting >6 postdocs/RS, >30PhDs, 6MS students





# Collaborative Interactions

## Current AFRL Engagement

- Joint publications
- SMART Fellowship student at RW (Zach Bell) – advertising to current students
- AFRL Scholar (Christian Harris) – advertising to other students for upcoming round
- AFRL Summer Faculty Fellows program
  - Riccardo Bevilacqua (2019 AFRL/RW)

## Shortcourses & Summer School & etc.

- Website listing of short courses, summer school opportunities (hybrid systems, formal methods, imaging, learning, introduction to nonlinear systems, reinforcement learning/ADP, etc)

- **M. Pajic** ACM SIGBED Early-Career Researcher Award -- Awarded by the ACM Special Interest Group on Embedded Systems (SIGBED) to recognize outstanding contributions by early career investigators in the area of embedded, real-time, and cyber-physical systems (2019)
- **M. Pajic** IEEE TCCPS Early-Career Award -- Awarded by the IEEE Technical Committee on Cyber-Physical Systems (TCCPS) for outstanding contributions to design and analysis methodologies for high-assurance cyber-physical systems (2019)
- **W. Dixon (et al.)** IEEE Control Systems Society, Control Systems Technology Award (2019)
- **M. Pajic** 19th ACM SIGBED International Conference on Embedded Software (EMSOFT), Best Paper Award Finalist (2019)
- **R. Sanfelice** Best Paper Award Finalist, International Conference on Automation Science and Engineering (CASE) (2019)
- **J. Shea** Darpa Spectrum Challenge Finalist (2019)



- **47 Papers Published for AACE**
- **9 Collaborative Publications**

## Topics/Problems Covered

- Multi Agent Herding
- Uncertain Nonlinear Dynamics
- Synchronization of systems
- Intermittent Feedback
- Asynchronous Communication
- Cyber Physical Systems
- Network-Based Attacks
- Safety
- Obstacle Avoidance
- Markov Decision Processes
- Stochastic Problems
- Jamming Attacks
- Dynamic Regret
- Human-Robot Interactions
- Stochastic Multiplayer Games
- Privacy

## Tools/Methods Used

- Neural Networks
- Switched/Hybrid Systems
- Barrier Functions
- Model Predictive Control
- Poncaré Maps
- Convex Optimization
- Temporal Logic
- Polynomial-Time Algorithms
- Spectral Partitioning
- Greedy Methods
- Harmony Search Methods
- Differential Privacy
- Heavy Ball Algorithm
- Quadratic Programming

# Nonsmooth Systems

1. Forward Invariance of Sets for Hybrid Dynamical Systems: Part I, R. G. Sanfelice, *IEEE Transactions on Automatic Control*
2. L2 State Estimation with Guaranteed Convergence Speed in the Presence of Sporadic Measurements, R. G. Sanfelice, S. Tarbouriech, *IEEE Transactions on Automatic Control*
3. Single Agent Indirect Herding of Multiple Targets with Unknown Dynamics, W. E. Dixon, *IEEE Trans. Robotics*
4. Robust distributed synchronization of networked linear systems with intermittent information, S. Phillips, R. G. Sanfelice, *Automatica*
5. A Moving Target Defense to Reveal Cyber- Attacks in CPS And Minimize Their Impact, R. G. Sanfelice, *American Control Conference*
6. On Model Predictive Control for Hybrid Dynamical Systems, R. G. Sanfelice, *American Control Conference*
7. Adaptive Backstepping of Synergistic Hybrid Feedbacks with Application to Obstacle Avoidance, R. G. Sanfelice, *American Control Conference*
8. Set-Based Predictive Control for Collision Detection and Evasion, R.G. Sanfelice, *IEEE 15th International Conference on Automation Science and Engineering*
9. A Hybrid Control Strategy for Autonomous Navigation While Avoiding Multiple Obstacles at Unknown Locations, R.G. Sanfelice, *IEEE 15th International Conference on Automation Science and Engineering*
10. Inter-Event Times Analysis for Planar Linear Event-Triggered Controlled Systems (I), R.G. Sanfelice, *IEEE Conference on Decision and Control*
11. Observer-Based Synchronization of Multi-Agent Systems Using Intermittent Measurements, S. Phillips, R.G. Sanfelice, *IEEE Conference on Decision and Control*
12. On a Stabilizing Model Predictive Control Framework for Discretized Hybrid Dynamical Systems, R.G. Sanfelice, *IEEE Conference on Decision and Control*
13. Multiple Barrier Function Certificates for Weak Forward Invariance in Hybrid Inclusions, R.G. Sanfelice, *IEEE Conference on Decision and Control*
14. Monotonicity of Functions Along Flows of Hybrid Inclusions, R.G. Sanfelice, *IEEE Conference on Decision and Control*
15. Attack-Resilient Supervisory Control with Intermittently Secure Communication, M. Pajic, *IEEE Conference on Decision and Control*
16. Supervisory Control of Discrete Event Systems in the Presence of Sensor and Actuator Attacks, M. Pajic, *IEEE Conference on Decision and Control*
17. Controller Synthesis For Multi-Agent Systems with Intermittent Communication: A Metric Temporal Logic Approach, W. E. Dixon, U. Topcu
18. Reinforcement Learning with Sparse Bellman Error Extrapolation for Infinite-Horizon Approximate Optimal Regulation, S. Nivison, W. E. Dixon, *Proc. IEEE Conf. Decis. Control*
19. Structure and Velocity Estimation of a Moving Object via Synthetic Persistence by a Network of Stationary Cameras, W. E. Dixon, *Proc. IEEE Conf. Decis. Control*
20. A Switched Systems Approach to Consensus of a Distributed Multi-agent System with Intermittent Communication, W. E. Dixon, *Proc. Am. Control Conf*
21. Event/Self-Triggered Approximate Leader-Follower Consensus with Resilience to Byzantine Adversaries, J. M. Shae, W. E. Dixon, *Proc. IEEE Conf. Decis. Control*
22. Tools for Asymptotic Stability of Limit Cycles in Switched Systems, R. G. Sanfelice, In *Proc. Am. Control Conf.*
23. An Algorithm to Generate Solutions to Hybrid Dynamical Systems with Inputs and Applications to Series Interconnections, R. G. Sanfelice, In *Proc. Am. Control Conf*
24. Multiple barrier function certificates for forward invariance in hybrid inclusions, R. G. Sanfelice, In *Proc. Am. Control Conf*
25. Characterizations of safety in hybrid inclusions via barrier functions, R. G. Sanfelice, In *Proceedings of the 22nd ACM International Conference on Hybrid Systems: Computation and Control*
26. Analyzing Action Games: A Hybrid Systems Approach, R.G. Sanfelice. In *Foundation of Digital Games Conference*



# Adaptation, Optimality, and Synthesis

1. Forward Invariance of Sets for Hybrid Dynamical Systems: Part I, R. G. Sanfelice, IEEE Transactions on Automatic Control
2. **Approximate Optimal Orbit Transfer of Non-cooperative Debris, R. Bevilacqua, N. Fitz-Coy, W. E. Dixon, AIAA SciTech Forum**
3. Entropy Maximization for Markov Decision Processes Under Temporal Logic Constraints, U. Topcu, IEEE Transactions on Automatic Control
4. Single Agent Indirect Herding of Multiple Targets with Unknown Dynamics, W. E. Dixon, IEEE Trans. Robotics
5. A Robust Hybrid Heavy Ball Algorithm, for Optimization with High Performance, R. G. Sanfelice, American Control Conference
6. On Model Predictive Control for Hybrid Dynamical Systems, R. G. Sanfelice, American Control Conference
7. Adaptive Backstepping of Synergistic Hybrid Feedbacks with Application to Obstacle Avoidance, R. G. Sanfelice, American Control Conference
8. Set-Based Predictive Control for Collision Detection and Evasion, R.G. Sanfelice, IEEE 15th International Conference on Automation Science and Engineering
9. A Hybrid Control Strategy for Autonomous Navigation While Avoiding Multiple Obstacles at Unknown Locations, R.G. Sanfelice, IEEE 15th International Conference on Automation Science and Engineering
10. On a Stabilizing Model Predictive Control Framework for Discretized Hybrid Dynamical Systems, R.G. Sanfelice, IEEE Conference on Decision and Control
11. Switched Linear Systems Meet Markov Decision Processes: Stability Guaranteed Policy Synthesis, U. Topcu, IEEE Conference on Decision and Control
12. Entropy-Regularized Stochastic Games, U. Topcu, IEEE Conference on Decision and Control
13. Strategy Synthesis for Surveillance-Evasion Games with Learning-Enabled Visibility Optimization, U. Topcu, IEEE Conference and Decision and Control
14. Constrained Online Learning in Networks with Sublinear Regret and Fit, M. Zavlanos, IEEE Conference on Decision and Control
15. Distributed Off-Policy Actor-Critic Reinforcement Learning with Policy Consensus, M. Zavlanos, IEEE Conference on Decision and Control
16. Transfer Planning for Temporal Logic Tasks, M. Zavlanos, IEEE Conference on Decision and Control
17. **Spacecraft Attitude Regulation in Low Earth Orbit Using Natural Torques, R. Bevilacqua, W. E. Dixon, IEEE Colombian Conference on Automatic Control**
18. Security-Aware Synthesis Using Delayed-Action Games, M. Pajic, Computer Aided Verification
19. **Reinforcement Learning with Sparse Bellman Error Extrapolation for Infinite-Horizon Approximate Optimal Regulation, S. Nivison, W. E. Dixon, Proc. IEEE Conf. Decis. Control**
20. Tools for Asymptotic Stability of Limit Cycles in Switched Systems, R. G. Sanfelice, In Proc. Am. Control Conf.
21. An Algorithm to Generate Solutions to Hybrid Dynamical Systems with Inputs and Applications to Series Interconnections, R. G. Sanfelice, In Proc. Am. Control Conf
22. Multiple barrier function certificates for forward invariance in hybrid inclusions, R. G. Sanfelice, In Proc. Am. Control Conf
23. Characterizations of safety and conditional invariance in dynamical systems, R. G. Sanfelice, Proc. Am. Control Conf
24. Analyzing Action Games: A Hybrid Systems Approach, R.G. Sanfelice, In Foundation of Digital Games Conference
25. **Relative Maneuvering for Multiple Spacecraft via Differential Drag using LQR and Constrained Least Squares, R. Bevilacqua, W. E. Dixon, AAS/AIAA Space Flight Mechanics Meeting**

1. L2 State Estimation with Guaranteed Convergence Speed in the Presence of Sporadic Measurements, R. G. Sanfelice, IEEE Transactions on Automatic Control
2. Entropy Maximization for Markov Decision Processes Under Temporal Logic Constraints, U. Topcu, IEEE Transactions on Automatic Control
3. Single Agent Indirect Herding of Multiple Targets with Unknown Dynamics, W. E. Dixon, IEEE Trans. Robotics
4. **Robust distributed synchronization of networked linear systems with intermittent information, S. Phillips, R. G. Sanfelice, Automatica**
5. Entropy-Regularized Stochastic Games, U. Topcu, IEEE Conference on Decision and Control
6. Strategy Synthesis for Surveillance-Evasion Games with Learning-Enabled Visibility Optimization, U. Topcu, IEEE Conference and Decision and Control
7. Constrained Online Learning in Networks with Sublinear Regret and Fit, M. Zavlanos, IEEE Conference on Decision and Control
8. A Distributed Online Convex Optimization Algorithm with Improved Dynamic Regret, M. Zavlanos, IEEE Conference on Decision and Control
9. Distributed Off-Policy Actor-Critic Reinforcement Learning with Policy Consensus, M. Zavlanos, IEEE Conference on Decision and Control
10. Attack-Resilient Supervisory Control with Intermittently Secure Communication, M. Pajic, IEEE Conference on Decision and Control
11. Supervisory Control of Discrete Event Systems in the Presence of Sensor and Actuator Attacks, M. Pajic, IEEE Conference on Decision and Control
12. **Controller Synthesis For Multi-Agent Systems with Intermittent Communication: A Metric Temporal Logic Approach, W. E. Dixon, U. Topcu**
13. Structure and Velocity Estimation of a Moving Object via Synthetic Persistence by a Network of Stationary Cameras, W. E. Dixon, Proc. IEEE Conf. Decis. Control
14. A Switched Systems Approach to Consensus of a Distributed Multi-agent System with Intermittent Communication, W. E. Dixon, n Proc. Am. Control Conf
15. **Event/Self-Triggered Approximate Leader-Follower Consensus with Resilience to Byzantine Adversaries, J. M. Shae, W. E. Dixon, Proc. IEEE Conf. Decis. Control**
16. **Optimal Jammer Placement in the Real Plane to Partition a Wireless Network, W. E. Dixon, T. Wong, J. Shea, IEEE Wirel. Commun. and Netw. Conf**
17. An Algorithm to Generate Solutions to Hybrid Dynamical Systems with Inputs and Applications to Series Interconnections, R. G. Sanfelice, In Proc. Am. Control Conf
18. **Relative Maneuvering for Multiple Spacecraft via Differential Drag using LQR and Constrained Least Squares, R. Bevilacqua, W. E. Dixon, AAS/AIAA Space Flight Mechanics Meeting**





# Asynchronous Information

1. L2 State Estimation with Guaranteed Convergence Speed in the Presence of Sporadic Measurements, R. G. Sanfelice, IEEE Transactions on Automatic Control
2. Robust distributed synchronization of networked linear systems with intermittent information, S. Phillips, R. G. Sanfelice, Automatica
3. On Model Predictive Control for Hybrid Dynamical Systems, R. G. Sanfelice, American Control Conference
4. A Hybrid Control Strategy for Autonomous Navigation While Avoiding Multiple Obstacles at Unknown Locations, R.G. Sanfelice, IEEE 15th International Conference on Automation Science and Engineering
5. Totally Asynchronous Distributed Quadratic Programming with Independent Stepsizes and Regularizations, M.T. Hale, IEEE Conference on Decision and Control
6. Tools for Asymptotic Stability of Limit Cycles in Switched Systems, R. G. Sanfelice, In Proc. Am. Control Conf.
7. An Algorithm to Generate Solutions to Hybrid Dynamical Systems with Inputs and Applications to Series Interconnections, R. G. Sanfelice, In Proc. Am. Control Conf
8. Multiple barrier function certificates for forward invariance in hybrid inclusions, R. G. Sanfelice, In Proc. Am. Control Conf



# Attack Resilient Designs

1. Statistical Verification of Hyper-properties for Cyber-Physical Systems, M. Pajic, ACM Transactions on Embedded Computing Systems
2. A Moving Target Defense to Reveal Cyber- Attacks in CPS And Minimize Their Impact, R. G. Sanfelice, American Control Conference
3. Security-Aware Synthesis Using Delayed-Action Games, M. Pajic, Computer Aided Verification
4. Attack-Resilient Supervisory Control with Intermittently Secure Communication, M. Pajic, IEEE Conference on Decision and Control
5. Supervisory Control of Discrete Event Systems in the Presence of Sensor and Actuator Attacks, M. Pajic, IEEE Conference on Decision and Control
6. Event/Self-Triggered Approximate Leader-Follower Consensus with Resilience to Byzantine Adversaries, J. M. Shae, W. E. Dixon, Proc. IEEE Conf. Decis. Control



# Protecting Information

1. Entropy Maximization for Markov Decision Processes Under Temporal Logic Constraints, U. Topcu, IEEE Transactions on Automatic Control
2. A Moving Target Defense to Reveal Cyber- Attacks in CPS And Minimize Their Impact, R. G. Sanfelice, American Control Conference
3. Towards Differential Privacy for Symbolic Systems, M.T. Hale, Proceedings of the 2019 American Control Conference
4. Trust-Driven Privacy in Human-Robot Interactions, M. Hale, Proceedings of the 2019 American Control Conference
5. A Hybrid Approach to Secure Function Evaluation Using SGX, K. Butler, Proceedings of the 14th ACM ASIA Conference on Computer and Communications Security
6. Incentive Design for Temporal Logic Objectives, U. Topcu, IEEE Conference on Decision and Control
7. Entropy-Regularized Stochastic Games, U. Topcu, IEEE Conference on Decision and Control
8. Strategy Synthesis for Surveillance-Evasion Games with Learning-Enabled Visibility Optimization, U. Topcu, IEEE Conference and Decision and Control
9. Characterizations of safety in hybrid inclusions via barrier functions, R. G. Sanfelice, In Proceedings of the 22nd ACM International Conference on Hybrid Systems: Computation and Control



A rapid and shallow overview of a subset of recently published results to provide a backdrop to the classes of problems under investigation and training/expertise of students

Deep dives into some specific problems are provided in subsequent presentations



## Towards Differential Privacy for Symbolic Systems M.T. Hale



In this paper, we develop a privacy implementation for symbolic control systems.



... we develop an exponential mechanism that **approximates a sensitive word using a randomly chosen word** that is likely to be near it. The notion of “near” is given by the **Levenshtein distance**, which counts the number of operations required to change one string into another

## Trust-Driven Privacy in Human-Robot Interactions M. Hale



In this paper we present a trust-driven differential privacy implementation for private trajectory sharing in human-robot interactions.



To enable collaboration in scenarios with unfamiliar robots, we **dynamically adapt a human user's privacy level** when sending information to a robot by using a quantitative measure of trust. We develop a **trust model that reflects a robot's level of cooperation over time** and captures key features of trust from both the psychological and human-robot interaction communities.



# Protecting Information

## A Hybrid Approach to Secure Function Evaluation Using SGX

K. Butler



Intel's Software Guard Extensions (SGX) provides hardware-protected execution environments as trusted computation oracles. SGX provides native CPU speed for secure computation, but vulnerable to side-channel and micro-architecture attacks



...construct a protocol for evaluating functions relative to a partitioning...alleviates the burden of trust on the enclave by allowing the protocol designer to choose which components should be evaluated within the enclave, and which via standard cryptographic techniques. We implement the protocol and apply it to two practical problems: privacy-preserving queries to a database, and a version of Dijkstra's algorithm for privacy-preserving navigation.



## Attack-Resilient Supervisory Control with Intermittently Secure Communication M. Pajic



...we study supervisory control of discrete event systems in the presence of network-based attacks on information delivered to and from the supervisors.



...we solve the problem of computing the maximal controllable sub-language (MCSL) of a desired language and propose the design algorithm for an attack-resilient supervisor, in scenarios where no security guarantees exists for communication between the plant and the supervisor.... propose the notion of accessibility as a measure of distance between a language and its sub-language, and show that a desired language is controllable with intermittently secure communication





## Security-Aware Synthesis Using Delayed-Action Games M. Pajic



Stochastic multiplayer games (SMGs) have gained attention in the field of strategy synthesis for multi-agent reactive systems. However, standard SMGs are limited to modeling systems where all agents have full knowledge of the state of the game.



In this paper, we introduce delayed-action games (DAGs) formalism that simulates hidden-information games (HIGs) as SMGs, where hidden information is captured by delaying a player's actions.

## Statistical Verification of Hyper-properties for Cyber-Physical Systems, M. Pajic



Focus on verifying probabilistic hyperproperties for cyber physical systems.



To formally specify hyperproperties, we propose a new temporal logic, hyper probabilistic signal temporal logic (HyperPSTL) that serves as a hyper and probabilistic version of the conventional signal temporal logic (STL).



## Strategy Synthesis for Surveillance-Evasion Games with Learning-Enabled Visibility Optimization, U. Topcu



Studies a two-player game with a quantitative surveillance requirement on an adversarial target moving in a discrete state space and a secondary objective to maximize short-term visibility of the environment.



We impose the surveillance requirement as a temporal logic constraint. We then use a greedy approach to determine vantage points that optimize a notion of information gain. By using a convolutional neural network trained on a class of environments, we can efficiently approximate the information gain at each potential vantage point.

## Controller Synthesis For Multi-Agent Systems with Intermittent Communication: A Metric Temporal Logic Approach

W. E. Dixon, U. Topcu



This paper develops a controller synthesis approach for a multi-agent system (MAS) with intermittent communication



**Dwell-time conditions** are developed to guarantee the stability of the switched system and the consensus of the followers, in a relay explorer problem. Furthermore, the leader needs to satisfy **practical constraints such as charging its battery and staying in specific regions of interest**. Both the maximum and minimum dwell-time conditions and these practical constraints can be expressed by **metric temporal logic (MTL) specifications**.





## Incentive Design for Temporal Logic Objectives U. Topcu



We study the problem of designing an optimal sequence of incentives so that the agent's optimal behavior realizes the principal's objective expressed as a temporal logic formula



...we present a polynomial-time algorithm to synthesize an incentive sequence that minimizes the cost to the principal  
...if the underlying MDP has only deterministic transitions, the principal can hide its objective from the agent and still realize the desired behavior through incentives.  
....an MDP with stochastic transitions may require the principal to share its objective with the agent.



## Optimal Jammer Placement in the Real Plane to Partition a Wireless Network W. E. Dixon, J. Shea



Wireless communication systems are susceptible to jamming attacks, and the use of unmanned vehicles brings new opportunities for coordinated jamming attacks... autonomous vehicles that coordinate their movements may be particularly vulnerable to jamming attacks that disrupt the control information



... **formulate several optimization problems** for jammer placement. Since the optimal solution to these problems are computationally complex, we develop **suboptimal solutions** using **spectral partitioning** followed by **greedy jammer placement** and also a **harmony search**



# Barrier Functions

## Multiple barrier function certificates for forward invariance in hybrid inclusions R. G. Sanfelice



...using multiple barrier functions, this paper studies forward invariance in hybrid systems modeled by hybrid inclusions



After introducing the notion of a **multiple barrier function**, we propose sufficient conditions to guarantee different **forward invariance properties of a closed set for hybrid systems** with nonuniqueness of solutions, solutions terminating prematurely, and Zeno solutions.



Characterizations of safety in hybrid inclusions via barrier functions

R. G. Sanfelice

Characterizations of safety and conditional invariance in dynamical systems

R. G. Sanfelice



...investigates characterizations of safety in terms of barrier functions for hybrid systems modeled by hybrid inclusions.  
...sufficient and necessary conditions for safety in terms of barrier functions.



...nonautonomous barrier functions and conditions are developed that are shown to be both necessary as well as sufficient  
...time-varying barrier functions are proposed and infinitesimal conditions are shown to be both necessary as well as sufficient,





# Markov Decision Processes

## Entropy Maximization for Markov Decision Processes Under Temporal Logic Constraints

U. Topcu



We study the problem of synthesizing a policy that maximizes the entropy of a Markov decision process (MDP) subject to a temporal logic constraint.



...a convex optimization problem is used to synthesize a policy that maximizes the entropy of an MDP



# Markov Decision Processes

## Entropy-Regularized Stochastic Games

U. Topcu



Implementing a two-player zero-sum stochastic games, where two competing players make decisions under uncertainty, may make the players vulnerable to unforeseen changes in the environment.



...introduce entropy-regularized stochastic games where each player aims to maximize the causal entropy of its strategy in addition to its expected payoff...each player's rationality is balanced with its belief about the level of misinformation about the transition model....consider both entropy-regularized N-stage and discounted stochastic games... prove the sufficiency of Markovian and stationary mixed strategies to attain the value...convex optimization problems used to compute the optimal strategies.



# Reinforcement Learning

## Constrained Online Learning in Networks with Sublinear Regret and Fit M. Zavlanos



In this paper, we consider groups of agents in a network that select actions in order to satisfy a set of constraints that vary arbitrarily over time and minimize a time-varying function of which they have only local observations



To determine such a strategy, we propose a decentralized saddle point algorithm and show that the corresponding global fit and regret are bounded



# Reinforcement Learning

## Distributed Off-Policy Actor-Critic Reinforcement Learning with Policy Consensus M. Zavlanos



Method to solve multi-agent reinforcement learning problems



...propose a distributed off-policy actor critic method to solve multi-agent reinforcement learning problems. Specifically, we assume that all agents keep local estimates of the global optimal policy parameter and update their local value function estimates independently. Then, we introduce an additional consensus step to let all the agents asymptotically achieve agreement on the global optimal policy function



# Hybrid/Switched Systems

A Switched Systems Approach to Consensus of a Distributed Multi-agent System with Intermittent Communication

W. E. Dixon



To enable a distributed multi-agent system to reach consensus under intermittent communication.



A novel switched systems analysis **determines the maximum dwell-time the leader can allow each follower to drift from a predicted trajectory before state correction is necessary**, despite the fact that the neural network predictor only achieves asymptotic convergence



# Hybrid/Switched Systems

## On a Stabilizing Model Predictive Control Framework for Discretized Hybrid Dynamical Systems

R.G. Sanfelice



We present a model predictive control (MPC) algorithm for hybrid dynamical systems.



The proposed algorithm **relies on a terminal constraint and a cost function, as well as a set-based notion of prediction horizon**, reminiscent of free end-time optimal control problems. When the terminal cost is a control Lyapunov function (CLF) on the terminal constraint set, and the prediction horizon has a certain geometry, under standard assumptions from conventional MPC, **the closed-loop system governed by MPC is shown to have an asymptotically stable compact set using the value function.**