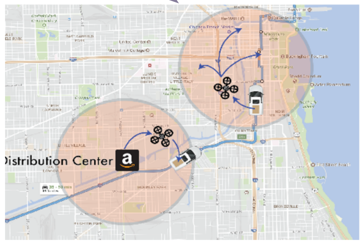
SYNDROME: SYNergetic DROne Delivery Network in MEtropolis

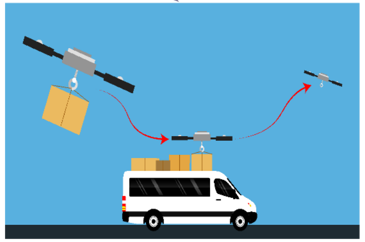
Naira Hovakimyan[†] , Lavanya Marla[†] , Marco Pavone[‡] , Srinivasa Salapaka[†] , Ranxiao Wang[†] , and Xiaofeng Wang[§]
[†]University of Illinois at Urbana-Champaign, [‡]Stanford University, [§]University of South Carolina

The rapid growth of e-commerce demands has resulted in increased traffic of delivery trucks while **slowing down the pace** of delivery operations

Dispatch a package over the delivery network



Use space on a ground vehicle's roof



Fly last-mile to the target position

The proposed delivery network is comprised of **autonomous flying robots** and **existing transport networks** (public and private ground vehicles).

Naira Hovakimyan

Lavanya Marla

Marco Pavone

Srinivasa Salapaka

Ranxiao Wang

Xiaofeng Wang

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❑ Industrial players:

- ✓ Prime Time Air of Amazon
- ✓ FedEx
- ✓ UPS Flight Forward
- ✓ DHL Parcelcopter
- ✓ Wing
- ✓ Matternet
- ✓ Zipline
- ✓ Flytrex

MATTERNET

FLYTREX

DHL DISCOVER

Wing™

zipline

❑ Economic benefits (cost-benefit analysis per ARK Invest, 2015):

- ✓ Amazon’s cost per package for delivery would be roughly 88 cents per parcel
- ✓ Market size: USD 860 million in 2021 (projected to reach USD 4,964 million by 2030)
- ✓ More than 2,000 drone deliveries are occurring each day worldwide

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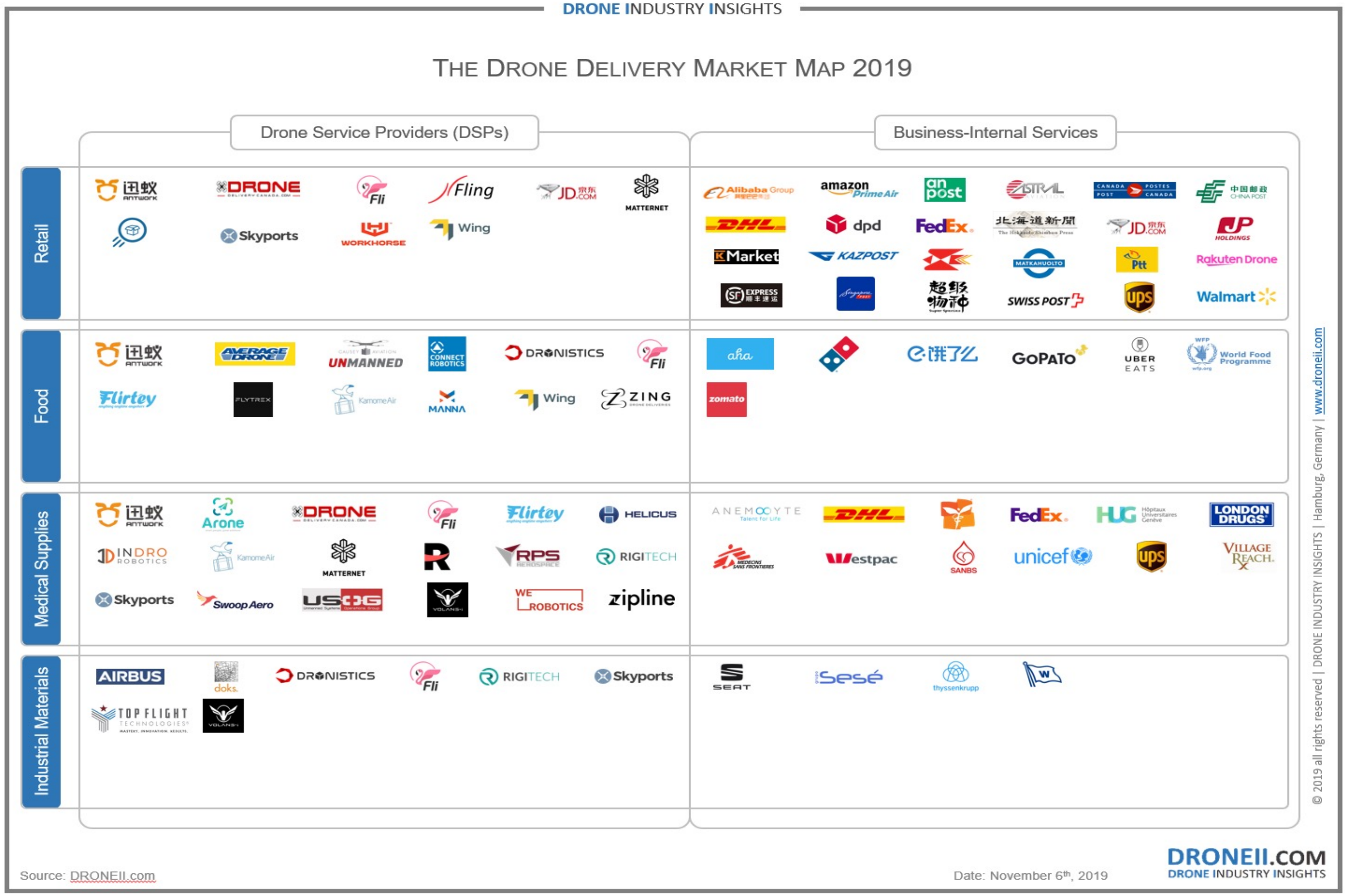
- ❑ A glimpse into the market map:
  - ✓ Drone-service providers
  - ✓ Business internal services
- ❑ Industry sectors:
  - ✓ Retail
  - ✓ Food
  - ✓ Mechanical Supplies
  - ✓ Industrial Materials



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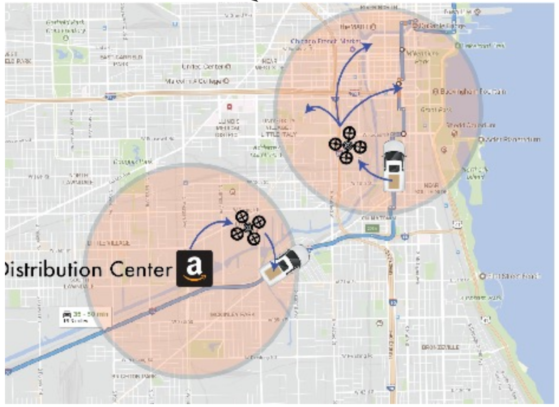
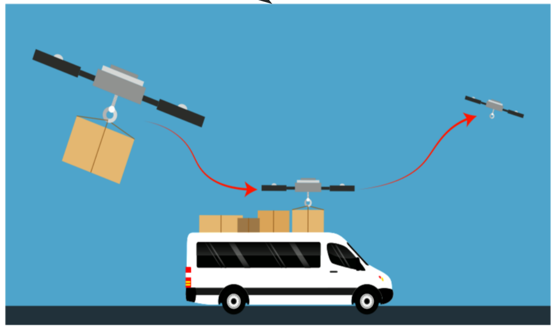


Use space on a ground vehicle's roof



Short flight distance is **overcome** by incorporating ground vehicles.

Fly last-mile to the target position

Cost in **last-mile** delivery is **improved** by autonomous flying robots.

Challenge Content

- **Efficiency and Effectiveness**: co-existing with traditional ground delivery system
- **Coordination and collaboration**: synergistic drone and ground networks in the last-mile delivery in populated urban areas
- **Human-machine interaction**: people's safety and comfort with drones flying around

Scientific Impact

- Efficient package flow and network design
- Safe and robust robot motion execution
- Socially accommodative robot motion planning

Award ID#: 1830639
September 7, 2018

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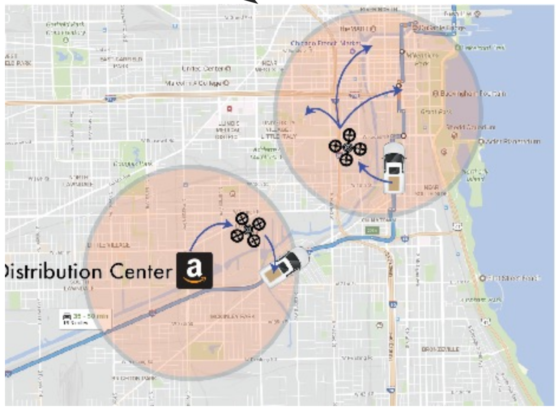

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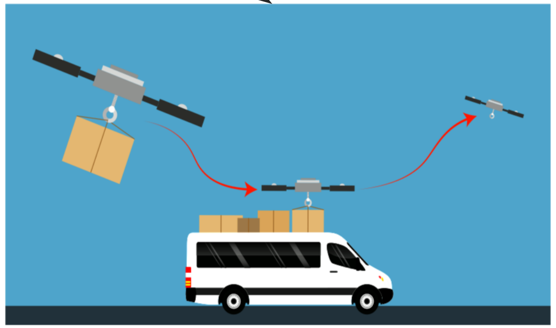

Short flight distance is **overcome** by incorporating ground vehicles.

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Broader Impact

- New discoveries on drone networks interfacing with people
- New solutions to the supply chain
- Improvement to transportation networks
- New applications of wireless sensor networks

Impact on society

- A step forward for incorporating drones into daily life.
- More efficient logistics for better e-commerce experience.
- Less congested traffic in urban transportation

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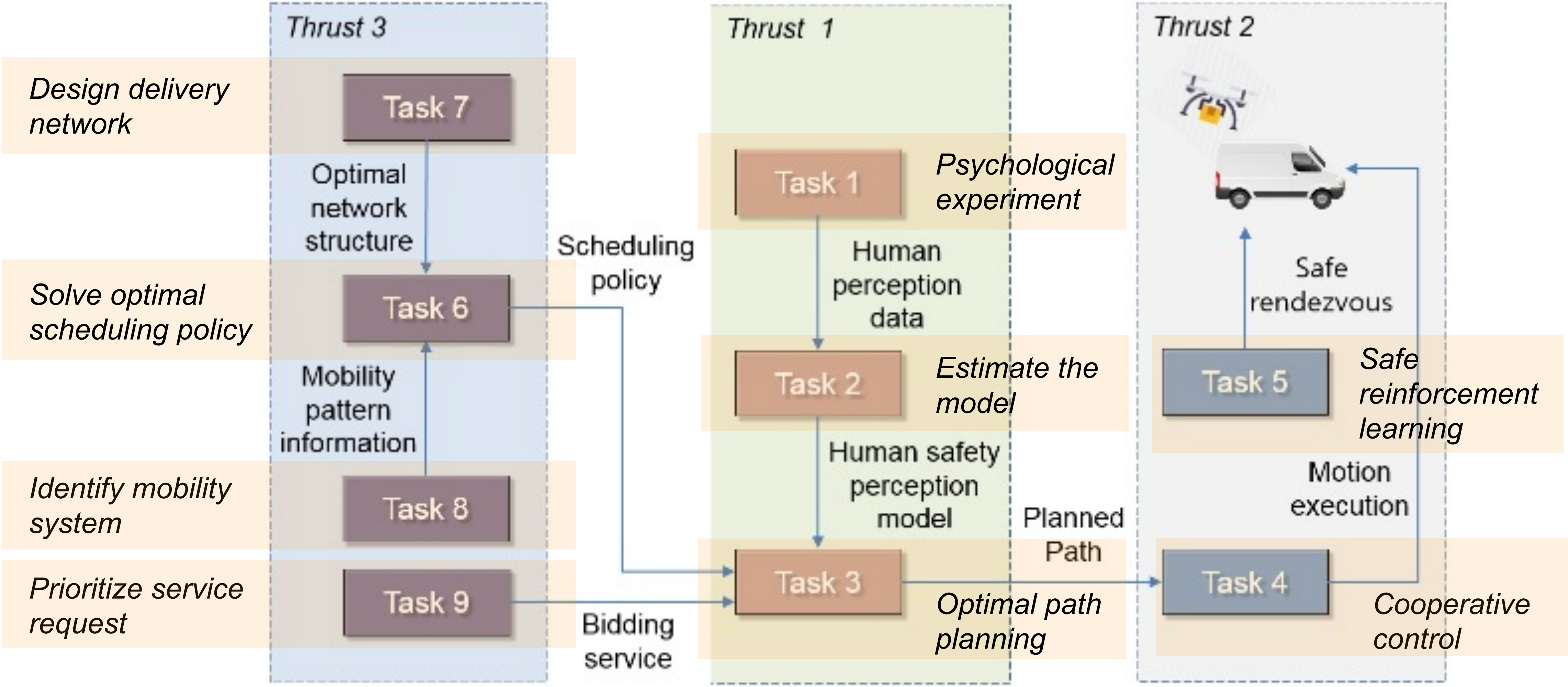

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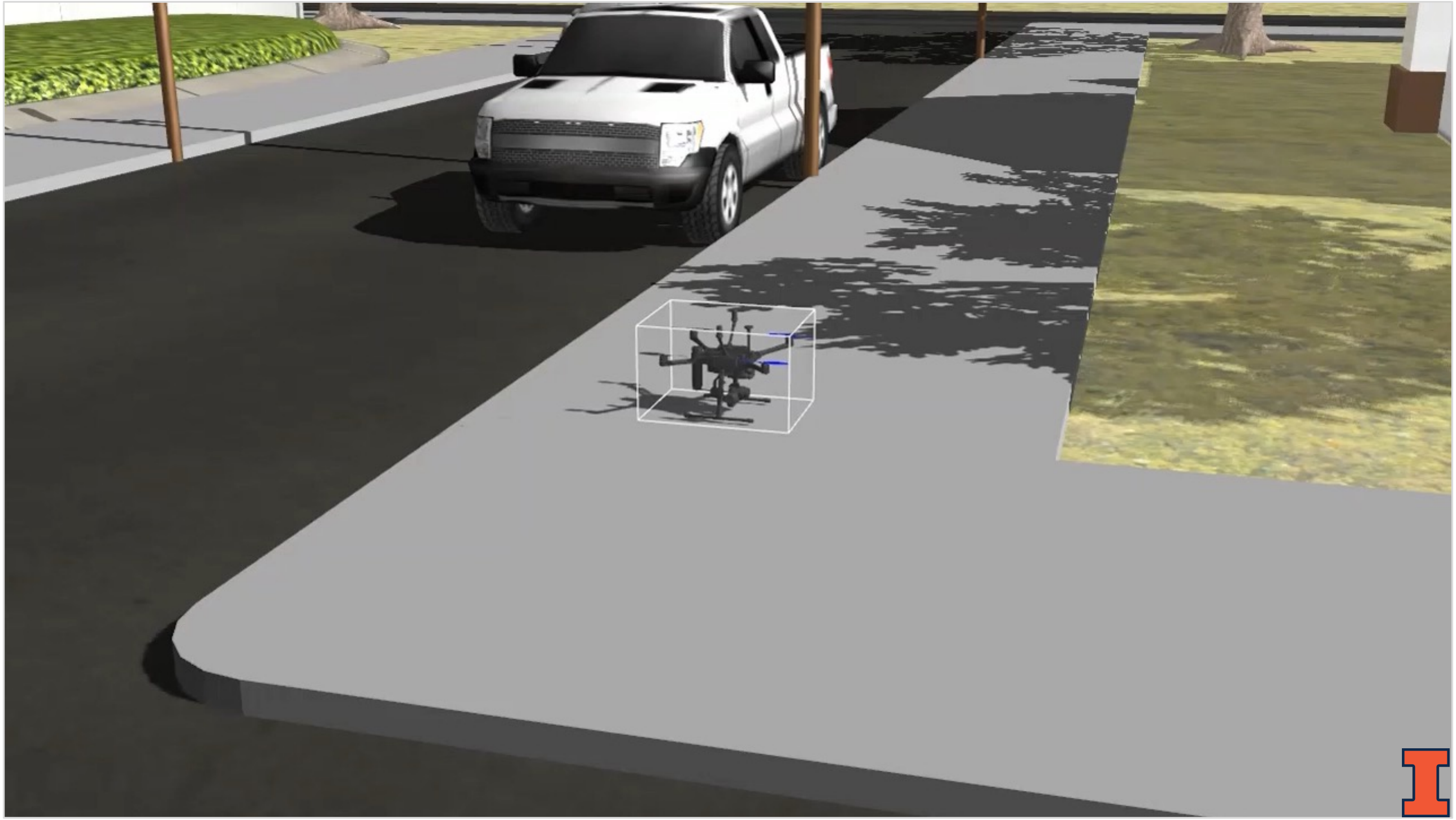
A Simulator for Integration of Drone Delivery Technologies (Hovakimyan group)

ROS/Gazebo based simulator for drone delivery

- Popular simulation environment with rich programming package support
- Ample resources for multi-modal vehicles and sensors
- Rich interfaces to incorporate new technologies and future development

ROS GAZEBO



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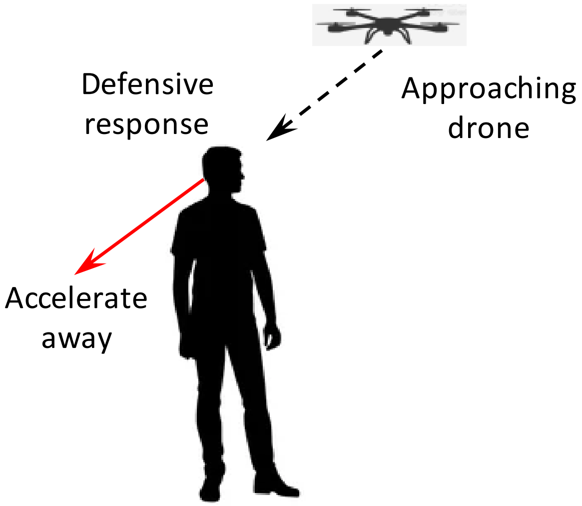
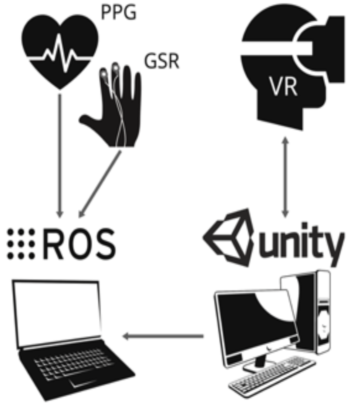
A Novel Index of Human Safety Perception (Collaboration: Hovakimyan and R. Wang)

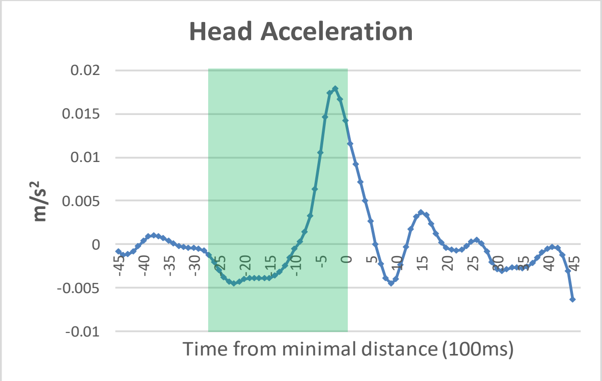


Unconscious, spontaneous defensive response: movement away from approach object



Advantages over traditional measurements

- Specific to perceived safety/danger
- Continuous
- Objective
- Non-invasive, non-contact



Quantify defensive response **as *peak head acceleration***: within a time window before time-of-contact

H. J. Yoon, P. Zhao, C. Tao, C. Widdowson, R. F. Wang, N. Hovakimyan, and E. Theodorou, "Socially Aware Motion Planning for a Flying Robot with Model Predictive Path Integral Control," ICRA 2019 Workshop.

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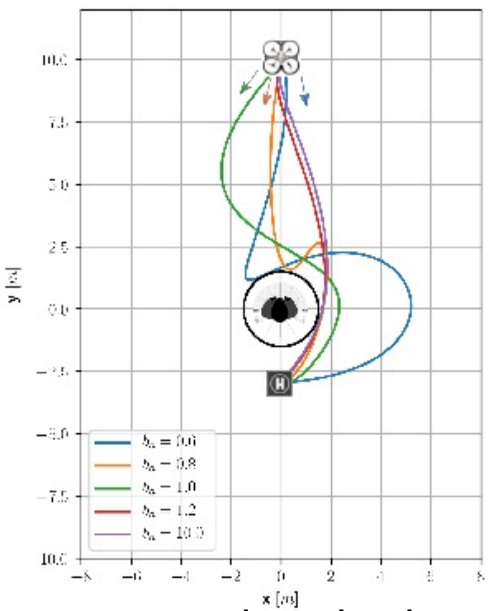
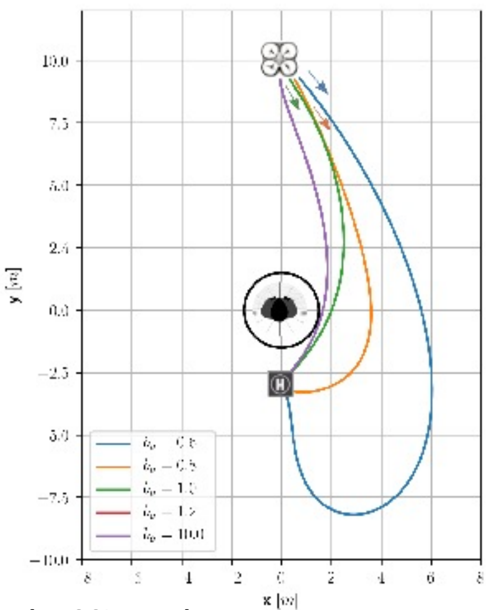
Motion planning with human safety perception (Collaboration: Hovakimyan and R. Wang)

Least square



HMM



Optimal path planning (**offline**) considering **safety perception models:**

Observation:
- Camera image
- Physiological sensor
- IMU

Hidden state:
- **User's guess on the path**
- User intention
- Emotional state

Reinforcement Learning (**online**) under **incomplete state observation**

H. Yoon, C. Widdowson, T. Marinho, R. F. Wang and N. Hovakimyan, "A Path Planning Framework for a Flying Robot in Close Proximity of Humans," 2019 American Control Conference (ACC), 2019, pp. 5254-5259.

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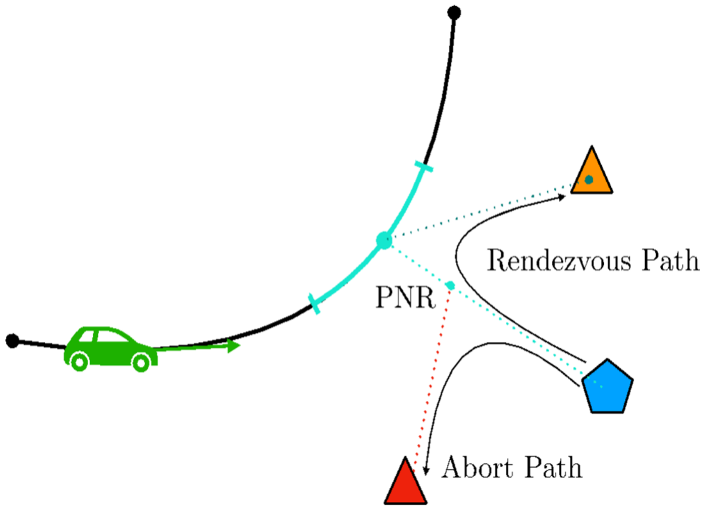
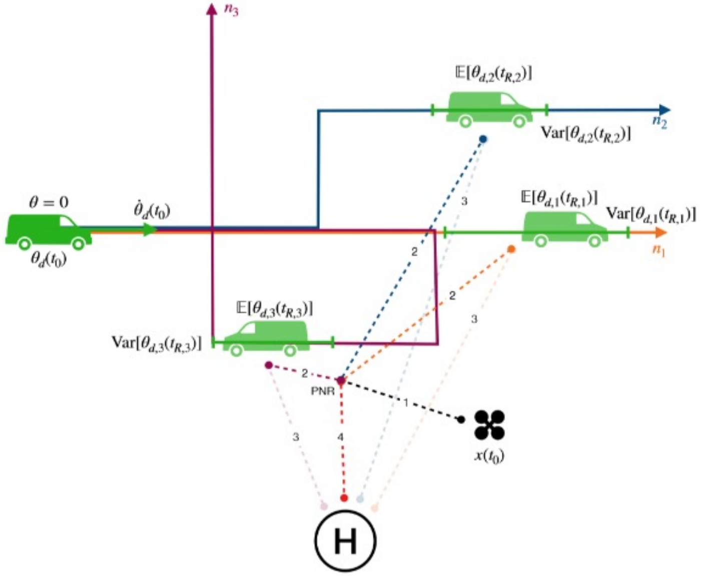
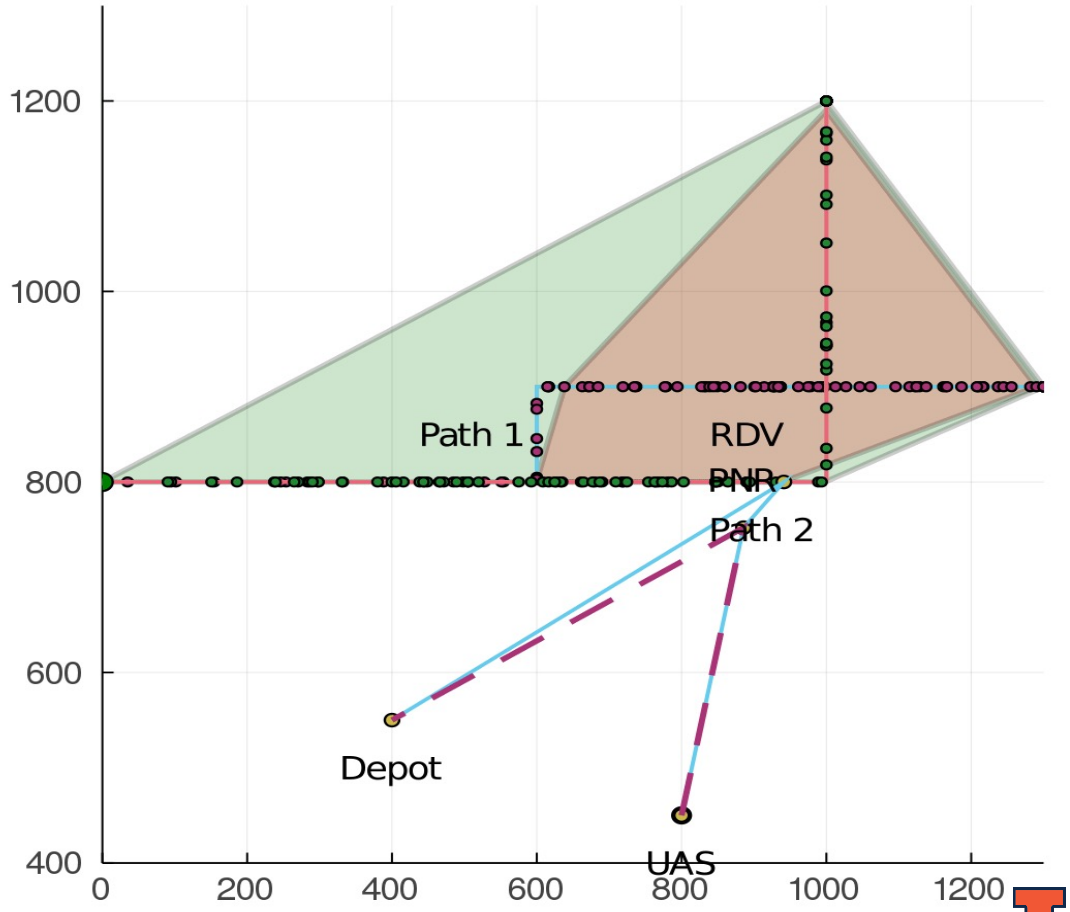
Risk-sensitive Rendezvous (Hovakimyan group)







A computationally tractable algorithm for **risk-aware rendezvous planning**

- Planning over multiple possible paths;
- Sampling based method relying on cross-entropy information updates.

G. Haberfeld, A. Gahlawat, and N. Hovakimyan, "Risk-Sensitive Rendezvous Algorithm for Heterogeneous Agents in Urban Environments." 2021 American Control Conference (ACC). 2021

Award ID#: 1830639
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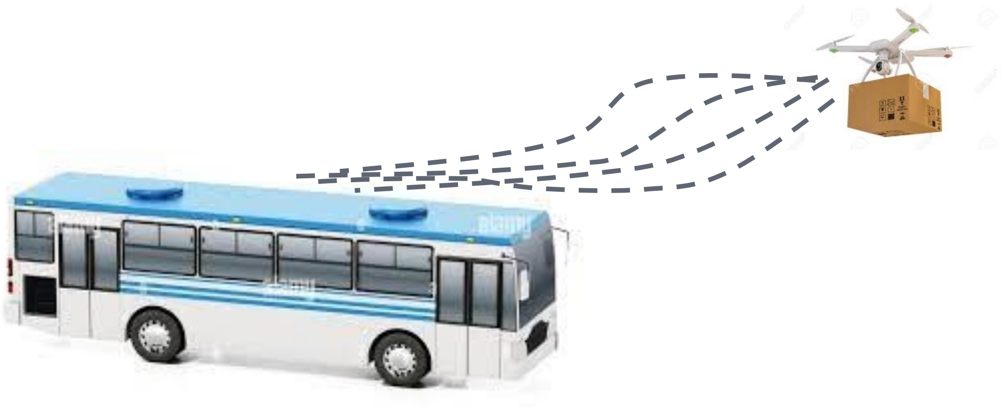
Uncertainty Quantification for Trajectory Optimization (Marla group)



- Drones in urban areas are subject to high degree of **wind uncertainty**
- Winds are **dynamic** and **non-stationary**
- Use drones as **sensors** to collect wind/weather information along their paths

Offline and online policies for exploring the airspace:

- **Offline**: design a set of times and trajectories using a nested partition structure with minimum regret;
- **Online**: design trajectories based on package deliveries with lowest expected cost

Use data from Bureau of Transportation Statistics and airline schedules in the National Airspace System

- Flight times and fuel burn can be **reduced** by 5% on average using our policies

J. Gao, A. Mani, L. Marla, “Sensing in Airspace for Sequential O-D Aircraft Routing”, under review at Operations Research.

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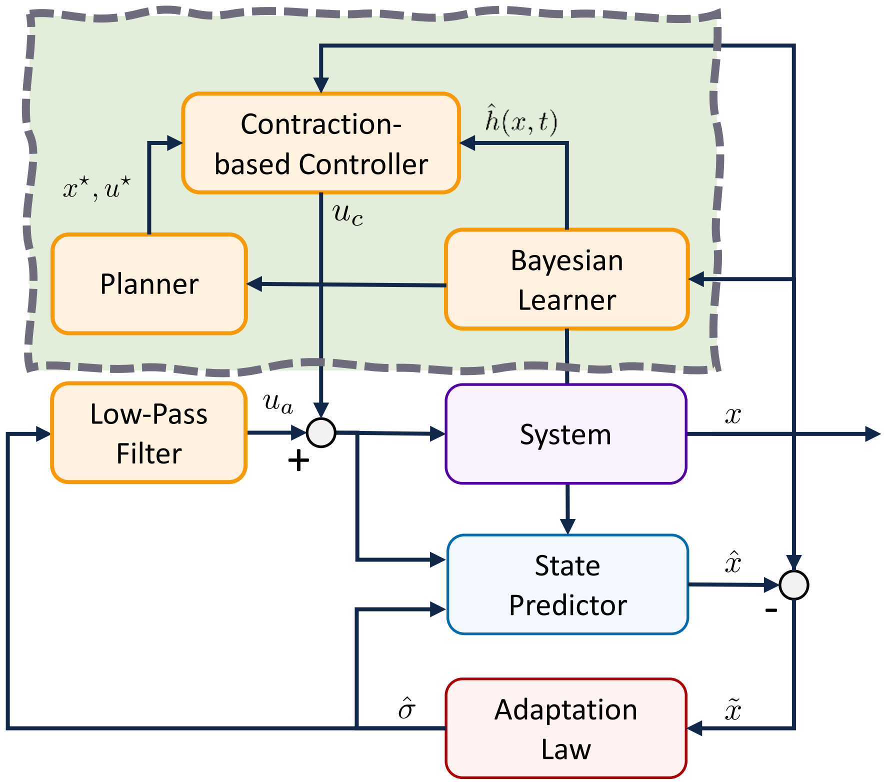
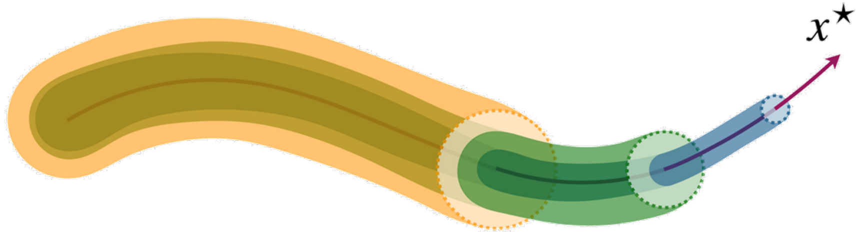
$\mathcal{CL}_1$-$\mathcal{GP}$: Contraction $\mathcal{L}_1$ with Bayesian Learning (Hovakimyan group)

- **Safety certificates** in the form of tubes from the $\mathcal{CL}_1$- $\mathcal{GP}$ framework which **enables safety during learning**
- Natural framework for learning using $\mathcal{GP}$:
  - **guaranteed performance** during the learning transients
  - improved performance of the $\mathcal{L}_1$ adaptive controller, i.e., **smaller tubes**
  - **improved quality** of the planned trajectory





A. Gahlawat, A. Lakshmanan, L. Song, A. Patterson, Z. Wu, N. Hovakimyan, E. Theodorou, "Contraction L1-Adaptive Control using Gaussian Processes," In Proceedings of 3rd Learning for Dynamics and Control Conference, 2021

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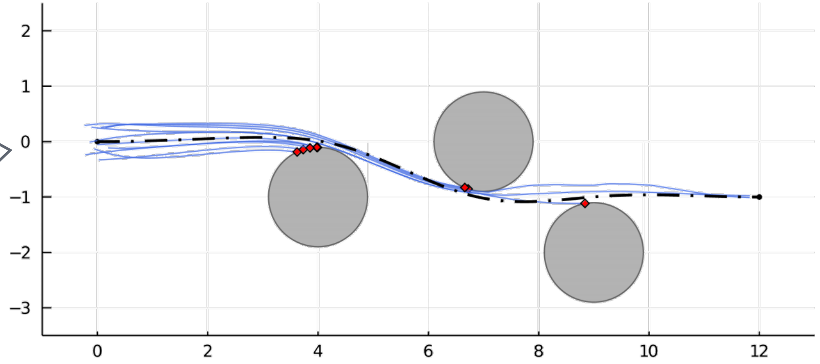
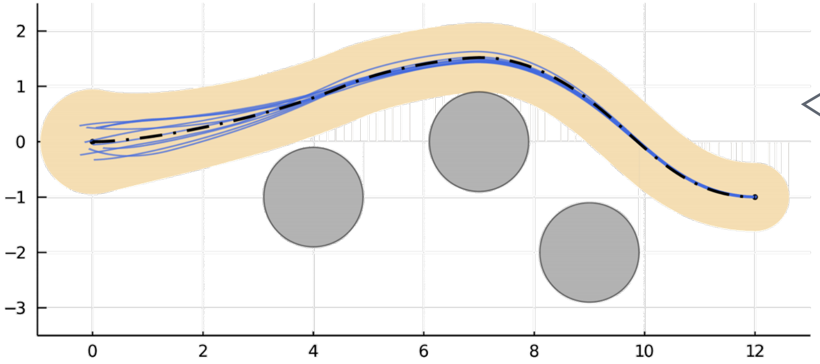
Performance improvement with safety guarantees (Hovakimyan group)

No safety guarantees!

Out of ten random initial conditions, 8 trajectories collide with obstacles.



(a) Contraction-based feedback

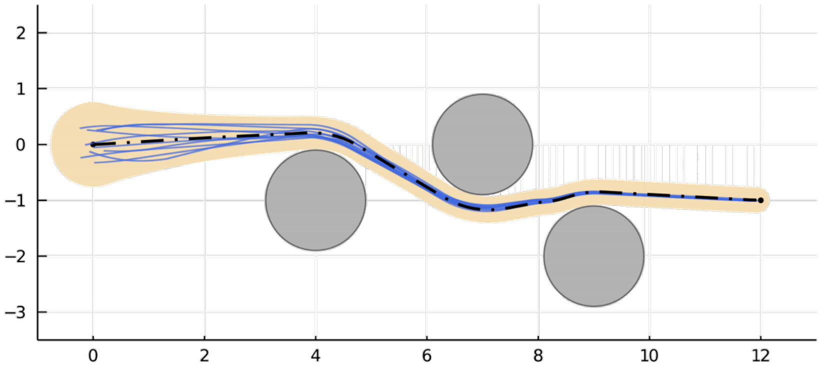


(b) $\mathcal{CL}_1$

Uses a conservative knowledge of the uncertainty.

Safety is guaranteed!

As the uncertainty is learned, performance is improved without sacrificing robustness.



Planner-agnostic: Previous example uses MPPI, and this one uses BIT*

A. Gahlawat, A. Lakshmanan, L. Song, A. Patterson, Z. Wu, N. Hovakimyan, E. Theodorou, "Contraction L1-Adaptive Control using Gaussian Processes," In Proceedings of 3rd Learning for Dynamics and Control Conference, 2021

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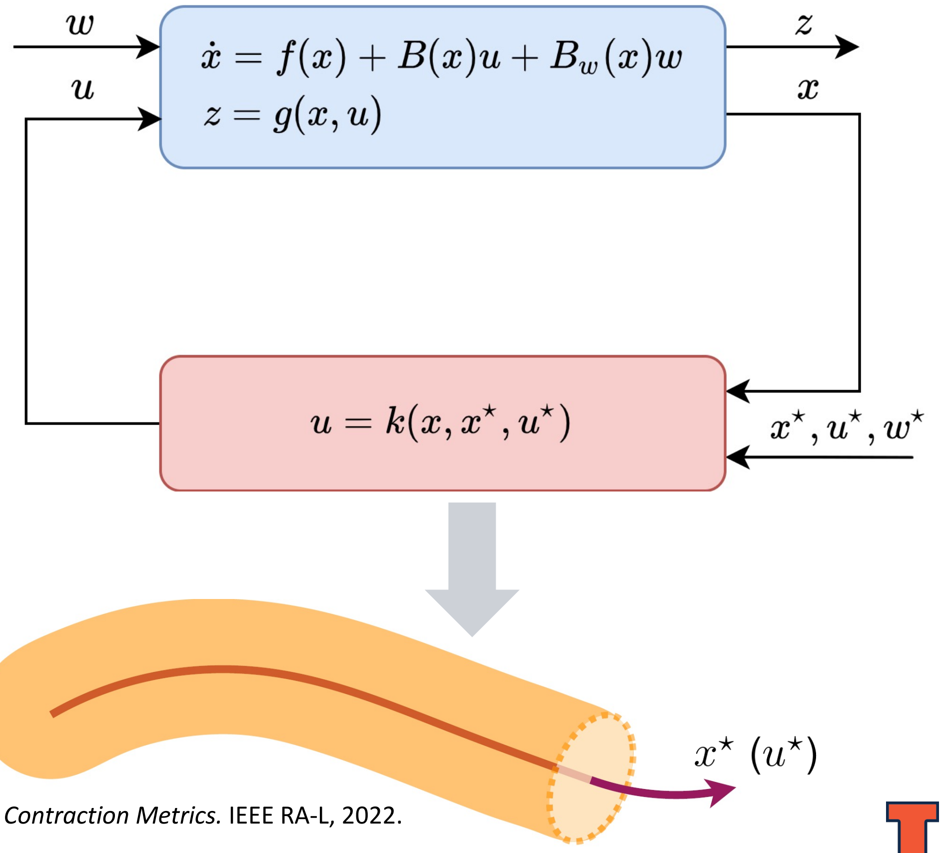
Robust CCM: Tube-Certified Trajectory Tracking (Collaboration: Hovakimyan and Pavone)

- The controller and state tubes **are jointly optimized** through solving convex optimization problems involving state-dependent linear matrix inequalities (LMIs)[1]
- The resulting controller has **explicit disturbance rejection** property
- It provides **certificate tubes for both states and control inputs** in a unified way
- Under certain assumptions, it proves to **yield tighter state tubes** than the CCM-based approach[2], which
  - first designs a controller for the **nominal** system, and
  - then derives the tube for the **disturbed** system using input-to-state stability analysis



1 Zhao, Lakshmanan, Ackerman, Gahlawat, Pavone, Hovakimyan. *Tube-Certified Trajectory Tracking for Nonlinear Systems with Robust Control Contraction Metrics.* IEEE RA-L, 2022.
2 Singh, Landry, Majumdar, Slotine, Pavone. *Robust Feedback Motion Planning via Contraction Theory*, IJRR, 2019.

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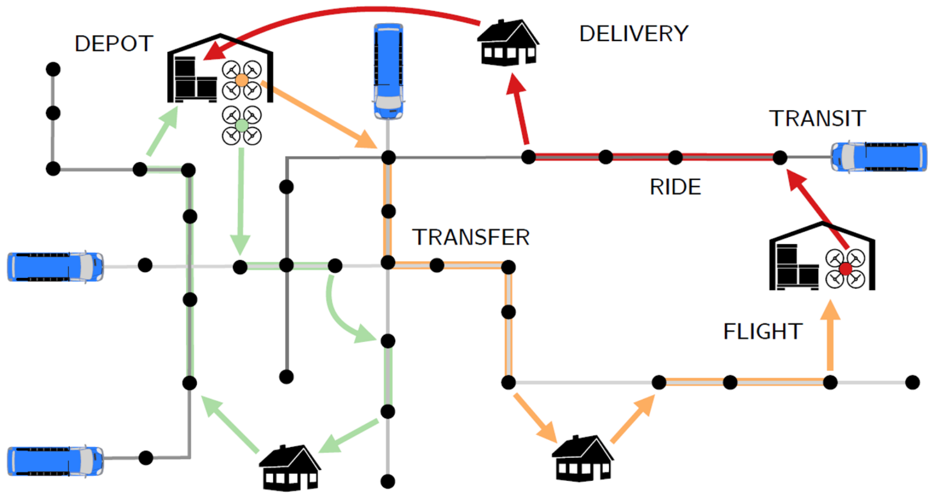
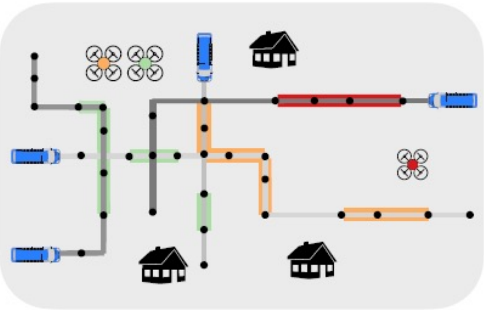
An efficient and scalable framework for multi-drone delivery (Pavone group)



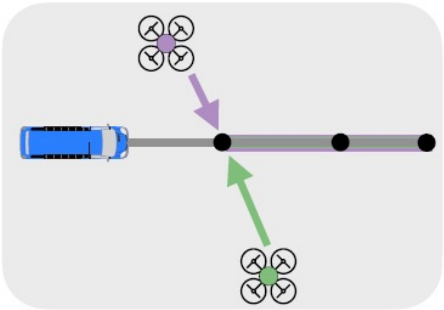
- Assigning drone routes to deliver packages while **avoiding conflicts between drones**;
- Striving to **minimize the overall delivery time** of all the packages in the system;
- Utilizing **public transit network** over large urban areas.

Computational challenges

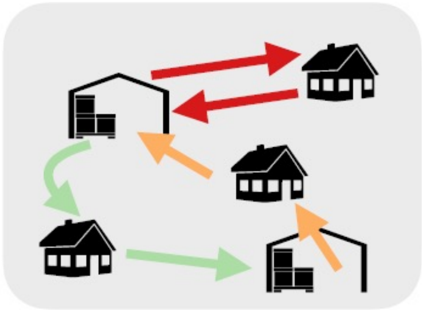
Large Networks



Constraints



Allocation



S. Choudhury, K. Solovey, M. Kochenderfer and M. Pavone, "Efficient Large-Scale Multi-Drone Delivery Using Transit Networks," ICRA 2020: 4543-4550.

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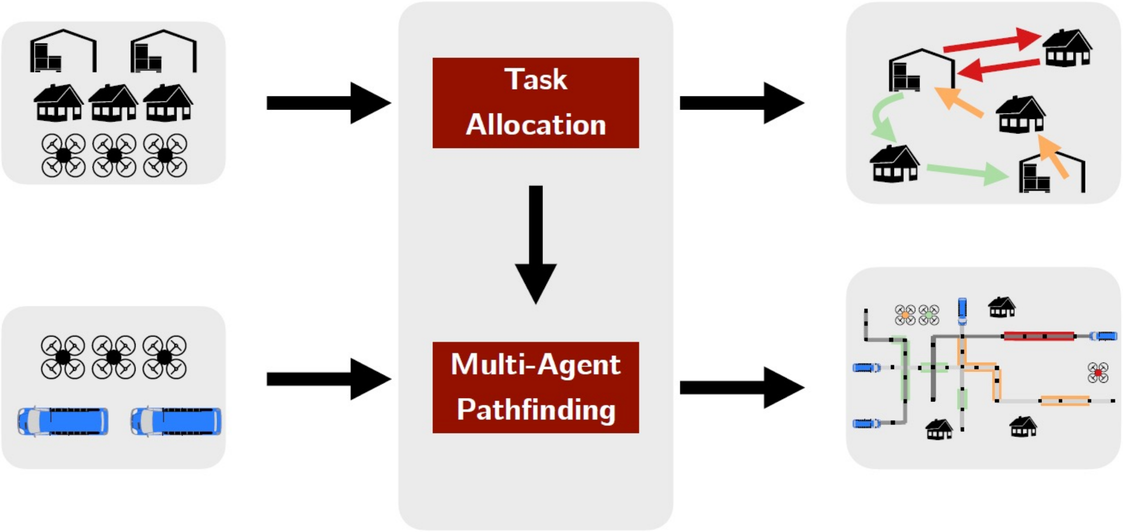
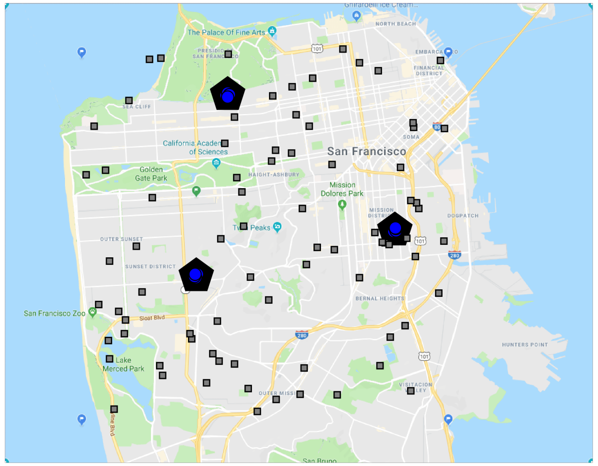
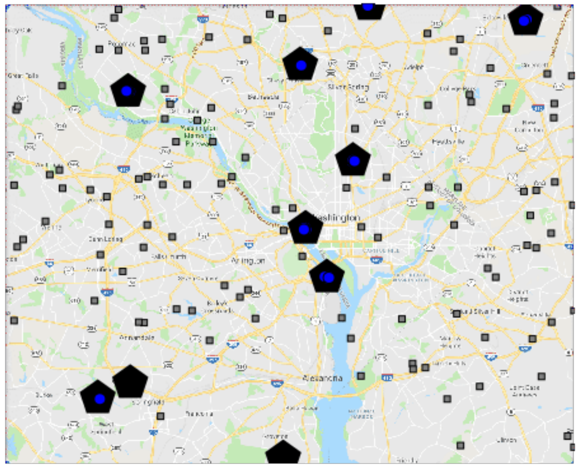
Solution: two-stage algorithmic approach with theoretical guarantees (Pavone group)



We decompose the problem into **task allocation** and **routing for multiple drones** to deliver multiple packages to minimize make span.





S. Choudhury, K. Solovey, M. Kochenderfer and M. Pavone, "Efficient Large-Scale Multi-Drone Delivery Using Transit Networks," ICRA 2020: 4543-4550.

- Our approach quickly solves scenarios with up to **hundreds of drones** delivering **thousands of packages** over large urban areas.
- By allowing drones to utilize existing public transit infrastructure, drones can increase their effective delivery range by **at least x2.5**

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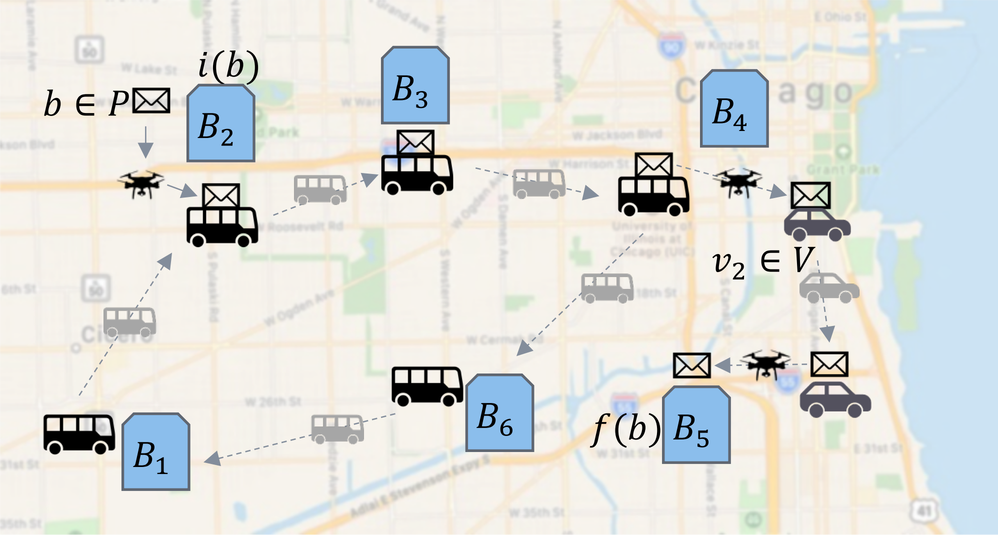
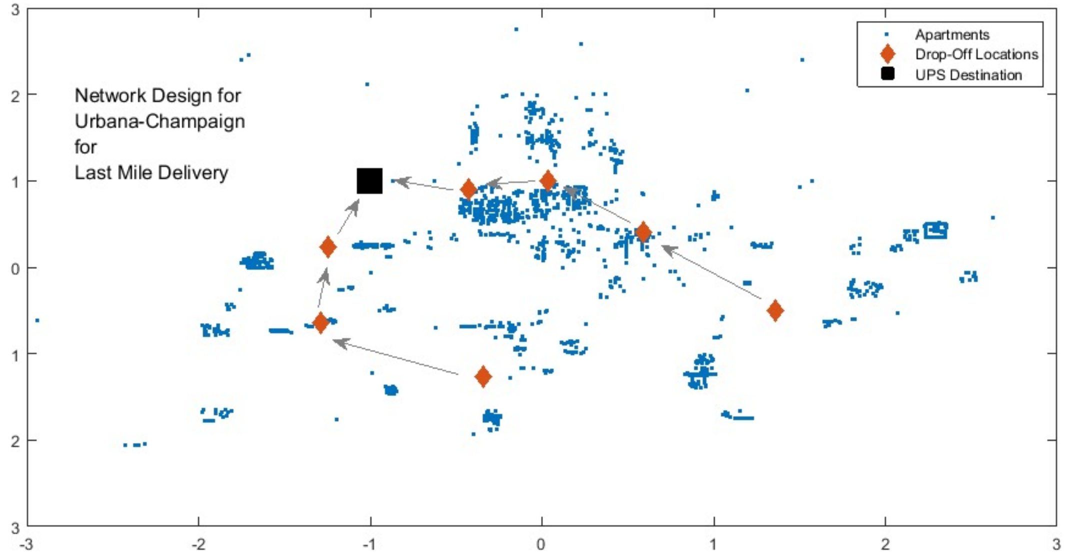
Simultaneous Facility and Path Optimization (Salapaka group)





A framework for **simultaneously** solving facility location and path optimization

- Considering **both static and dynamic** spatial networks;
- A novel **stage-wise viewpoint** of the paths to design the decision variable space;
- Optimization via **maximum entropy principle**.

Pick-Up/Drop-Off Depot LMDP Network Design for the City of Urbana-Champaign

- Apartment street address from **CU city website**.
- **Google API** to obtain latitude-longitude co-ordinates of the apartment.
- Solving **Parameterized Markov Decision Problem**

Srivastava, Amber, and Srinivasa M. Salapaka. "Simultaneous Facility Location and Path Optimization in Static and Dynamic Networks." IEEE Transactions on Control of Network Systems7.4 (2020): 1700-1711.

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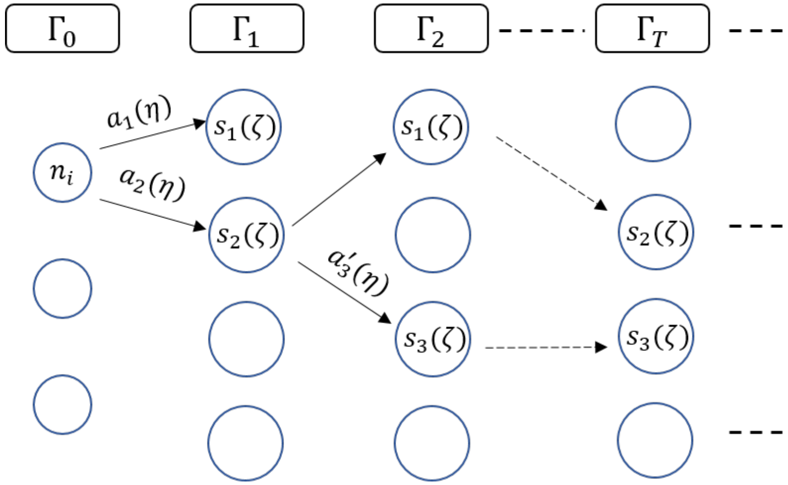
Parameterized Sequential Decision-Making problems (Salapaka group)



$$\min_{\mu,\zeta,\eta} J^{\mu}_{\zeta\eta}(s) = \mathbb{E}_{p_\mu}\left[\sum_{t=0}^{\infty} \alpha^t c(x_t(\zeta), u_t(\eta), x_{t+1}(\zeta)) \,|x_0 = s\right] = \sum_{\omega\in\Omega} p_\mu(\omega|s)\ \bar{c}(s,\omega)$$

- $p_\mu : \omega \to [0,1]$ and $\omega = (a_0, x_1, a_1, x_2, \dots)$
  - $p_\mu(\omega|s) = \mu(a_0|s)p(x_1|a_0,s)\mu(a_1|x_1)p(x_2|x_1,a_1)\cdots$
- state, action parameters: $\zeta = \{\zeta_s\}, \eta = \{\eta_a\}$
- cost and dynamics: $c(s,a,s'), p(s'|s,a)$

Generalized the approach to **Parameterized Sequential Decision-Making problems**

- Maximum entropy principled based framework
- Routing + Resource allocation on a common platform
- Models many combinatorial optimization problems (e.g., network design, planning, supply chain, scheduling, Markov decision processes, reinforcement learning, model predictive control)

Srivastava, Amber, and Srinivasa M. Salapaka. "Parameterized MDPs and Reinforcement Learning Problems--A Maximum Entropy Principle Based Framework." *arXiv preprint, arXiv:2006.09646* (2020).

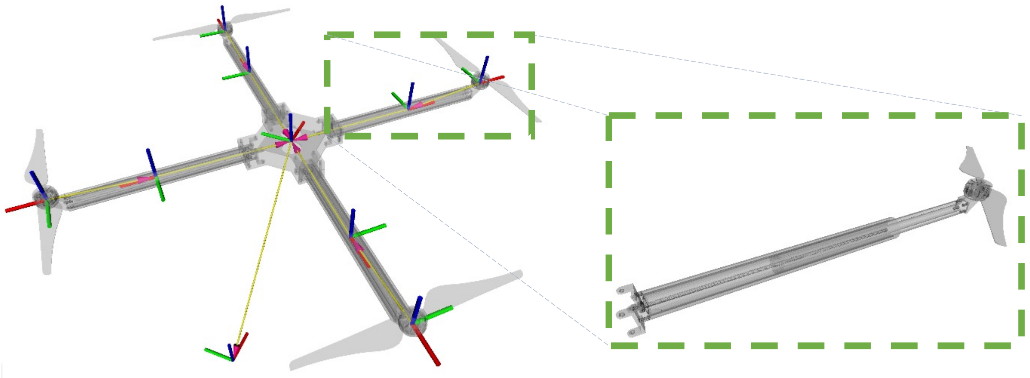
SYNDROME: SYNergetic DROne Delivery Network in MEtropolis

Naira Hovakimyan[†], Lavanya Marla[†], Marco Pavone[‡], Srinivasa Salapaka[†], Ranxiao Wang[†], and Xiaofeng Wang[§]
[†]University of Illinois at Urbana-Champaign, [‡]Stanford University, [§]University of South Carolina

Education and Outreach (Hovakimyan, X. Wang)

Senior undergraduate design projects

Autonomous drone landing on a non-cooperative ground vehicle



Morphing Multi-Rotor with Extendable Motors

Outreach

PI Hovakimyan's visit to Montessori school of C-U to showcase robotics to elementary-age students.

Students and postdocs funded

	Completed	Ongoing	Total
Postdoc	4	2	6
PhD	12	5	17
Master	3	4	7
Undergraduate	17	5	22

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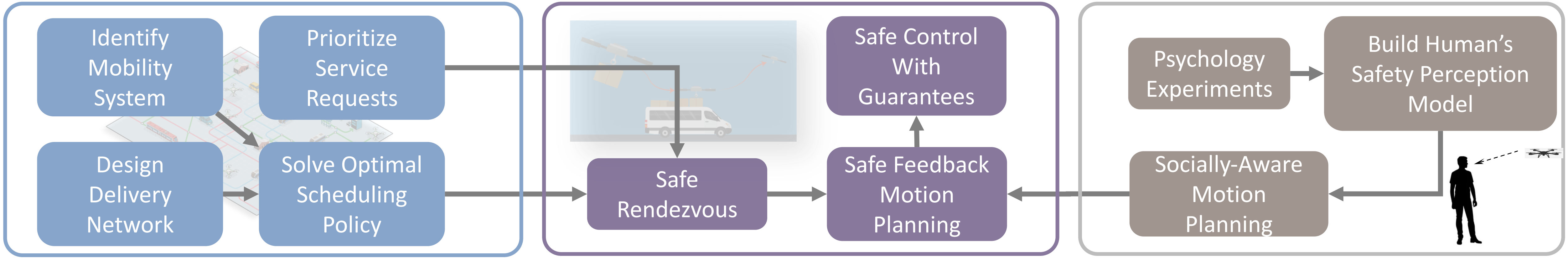
Conclusion and Future Work



Commodity (Package) Flow Problem and Network Design

- Algorithmic foundations:
  - Hardness proofs
  - Accounting for uncertainty
  - Faster solvers
- Information-sharing across operators and drones
- Extension to urban air mobility

Safe and Robust Motion Execution

- Lift abstractions of robustness to the sense of distributions
- Tube certificates in the space of distributions
- Deploy tube-based safety controllers to real vehicles

Socially-Accommodative Cooperative Motion Planning

- Studying effects of greeting voice on PSD
  - Female vs male voice
- Studying effects of social context
- Invoking the hidden Markov model-based RL

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
Stanford University
UNIVERSITY OF SOUTH CAROLINA

Award ID#: 1830639
September 7, 2018

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Incomplete list of publications

Conference Proceedings

1. H. J. Yoon, P. Zhao, C. Tao, C. Widdowson, R. F. Wang, N. Hovakimyan, and E. Theodorou, "Socially Aware Motion Planning for a Flying Robot with Model Predictive Path Integral Control," ICRA 2019 Workshop.
2. H. Yoon, C. Widdowson, T. Marinho, R. F. Wang and N. Hovakimyan, "A Path Planning Framework for a Flying Robot in Close Proximity of Humans," 2019 American Control Conference (ACC), 2019, pp. 5254-5259.
3. G. Haberfeld, A. Gahlawat, and N. Hovakimyan, "Risk-Sensitive Rendezvous Algorithm for Heterogeneous Agents in Urban Environments." 2021 American Control Conference (ACC), pp. 3455-3460, 2021.
4. G. Haberfeld, A. Gahlawat, and N. Hovakimyan, "Safe Sampling-Based Air-Ground Rendezvous Algorithm for Dense Street Maps." 2021 International Conference on Unmanned Aircraft Systems (ICUAS), pp. 413-422, 2021.
5. A. Gahlawat, A. Lakshmanan, L. Song, A. Patterson, Z. Wu, N. Hovakimyan, E. Theodorou, "Contraction L1-Adaptive Control using Gaussian Processes," In Proceedings of 3rd Learning for Dynamics and Control Conference, 2021
6. S. Choudhury, K. Solovey, M. Kochenderfer, M. Pavone, "Efficient Large-Scale Multi-Drone Delivery Using Transit Networks," In Proceedings of the International Conference on Robotics and Automation (ICRA), pp. 4543-4550, 2020.
7. R. Sinha, J. Harrison, S. Richards, M. Pavone, "Adaptive Robust Model Predictive Control with Matched and Unmatched Uncertainty," Accepted for presentation at American Control Conference, 2022.
8. P. Zhao, Y. Mao, C. Tao, N. Hovakimyan, X. Wang, "Robust Adaptive Quadratic Programs using Control Lyapunov and Barrier Functions." IEEE Conference on Decision and Control, 2020
9. R. Abdelfattah, X. Wang, S. Wang, "TTPLA: An Aerial-Image Dataset for Detection and Segmentation of Transmission Towers and Power Lines." Asian Conference on Computer Vision (ACCV), 2020.
10. L. Yang, S. Dauchert, X. Wang, "A Framework for Predictive Control of Sampled-Data Systems Using Sporadic Model Approximation," American Control Conference, 2021

Journal Publications

1. J. Gao, A. Mani, L. Marla, "Sensing in Airspace for Sequential O-D Aircraft Routing", under review at Operations Research.
2. P. Zhao, A. Lakshmanan, K. Ackerman, A. Gahlawat, M. Pavone, N. Hovakimyan. "Tube-Certified Trajectory Tracking for Nonlinear Systems with Robust Control Contraction Metrics". Accepted for publication by IEEE Robotics and Automation Letters (RA-L) , 2022.
3. S. Choudhury, K. Solovey, M. Kochenderfer, M. Pavone, "Efficient Large-Scale Multi-Drone Delivery Using Transit Networks," Journal of Artificial Intelligence Research, 2021.
4. S. Choudhury, K. Solovey, M. Kochenderfer, M. Pavone, "Coordinated Multi-Agent Pathfinding for Drones and Trucks over Road Networks", Autonomous Agents and Multiagent Systems, 2022
5. A. Srivastava, S. Salapaka. "Parameterized MDPs and Reinforcement Learning Problems--A Maximum Entropy Principle-Based Framework". IEEE Transactions on Cybernetics, 2021.
6. A. Srivastava, S. Salapaka. "Simultaneous Facility Location and Path Optimization in Static and Dynamic Networks." IEEE Transactions on Control of Network Systems, 2020.
7. J. Tao, L. Yang, Z. Wu, X. Wang, H. Su. "Lebesgue-Approximation Model Predictive Control of Nonlinear Sampled-Data Systems. IEEE Transactions on Automatic Control. 65 (10) pp. 4047-4060, 2020.
8. J. Tao, C. Wei, J. Wu, X. Wang, P. Shi, "Nonfragile Observer-Based Control for Markovian Jump Systems Subject to Asynchronous Modes." IEEE Transactions on Systems, Man, and Cybernetics: Systems. Pp. 1-8, 2019
9. W. Yan, B. Zhang, G. Zhao, S. Tang, G. Niu, X. Wang, "Battery Management System with Lebesgue Sampling-Based Extended Kalman Filter," IEEE Transactions on Industrial Electronics, vol. 66, no. 4, 3227-3236, 2019.
10. J. Tao, Z. Xiao, Z. Li, J. Wu, R. Lu, P. Shi, X. Wang, "Dynamic Event-Triggered State Estimation for Markov Jump Neural Networks With Partially Unknown Probabilities," IEEE Transactions on Neural Networks and Learning Systems, DOI: 10.1109/TNNLS.2021.3085001, 2021.