TUTORIAL
TOWARDS NETWORKED AIRBORNE COMPUTING: APPLICATIONS, CHALLENGES, AND ENABLING TECHNOLOGIES

Chair: Yan Wan

Professor

University of Texas at Arlington

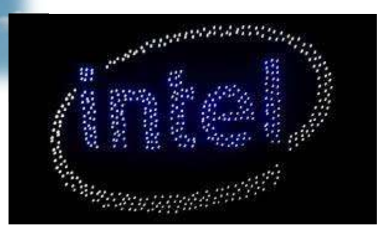
ICUAS'20
September 2020

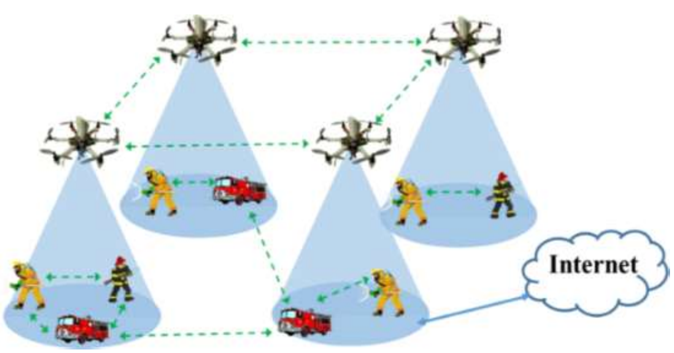
OUTLINE

- Background
- Applications of multiple UAVs
- Networked airborne computing
- Speakers
- Schedule

BACKGROUND

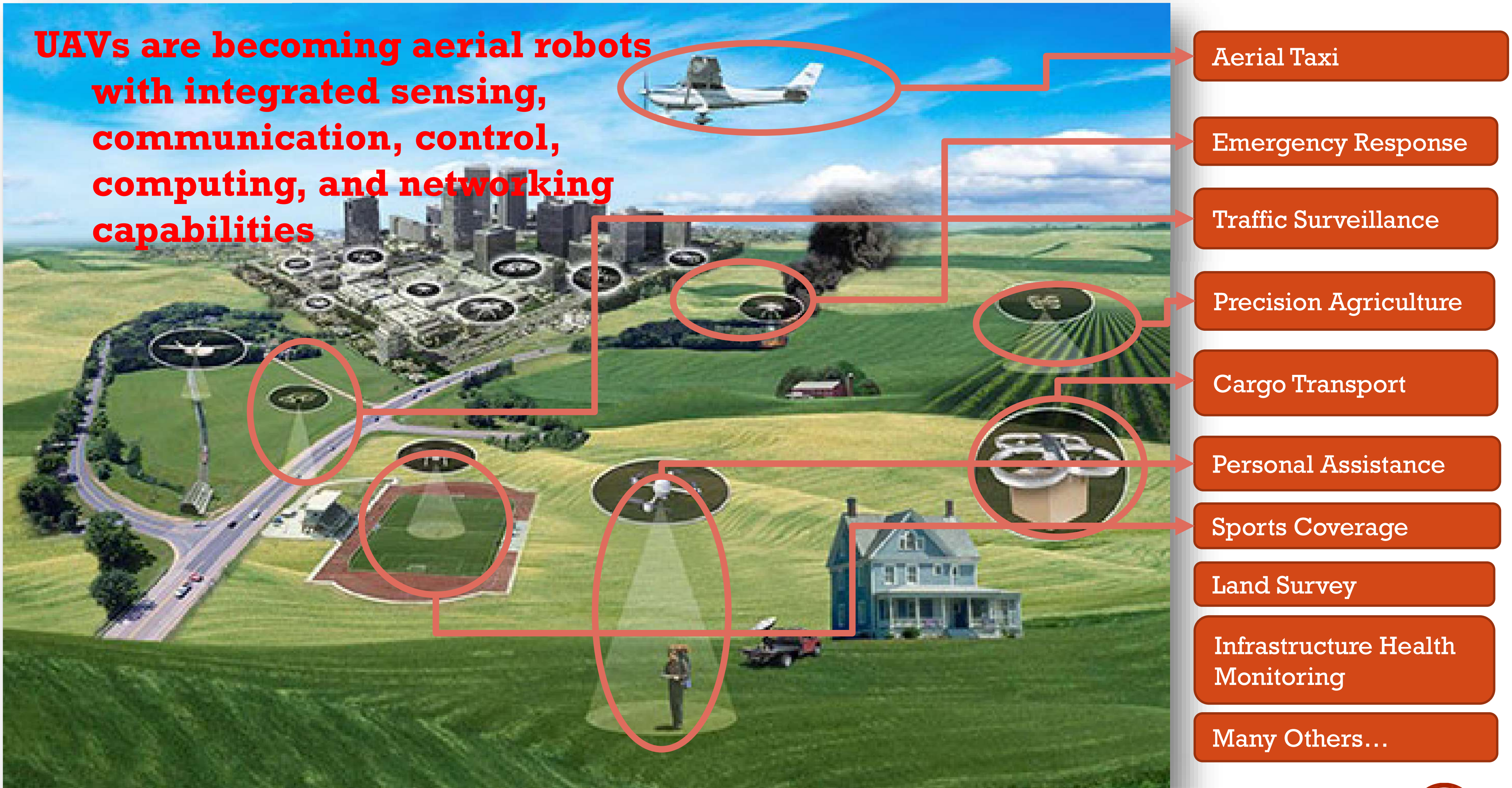
Global Drones Market Outlook and Projections: The global commercial drone market size is expected to reach USD 88.57 billion by 2027.





- Most UAV applications involve a single UAV
- Multiple UAVs are controlled through a central ground station
- UAV networking refers to networking in the aerial layer through direct UAV-to-UAV communication for information exchange, safe maneuvering, and coordination for time-critical missions.
- Broad Applications
  - IoT mobility applications
  - On-demand communication infrastructure for emergency response
  - Next-generation UAV traffic control

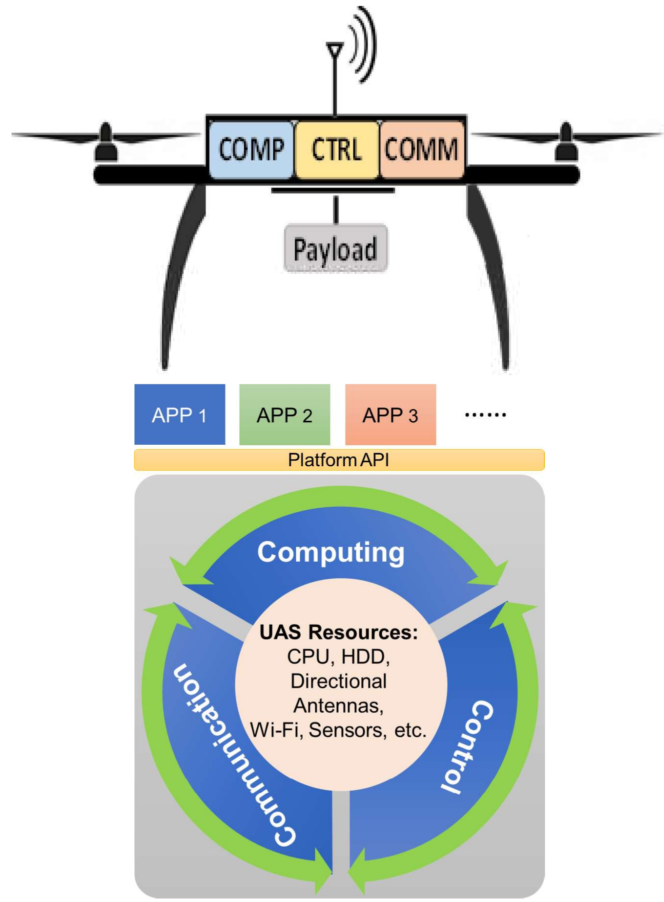
APPLICATIONS OF NETWORKED UAVS



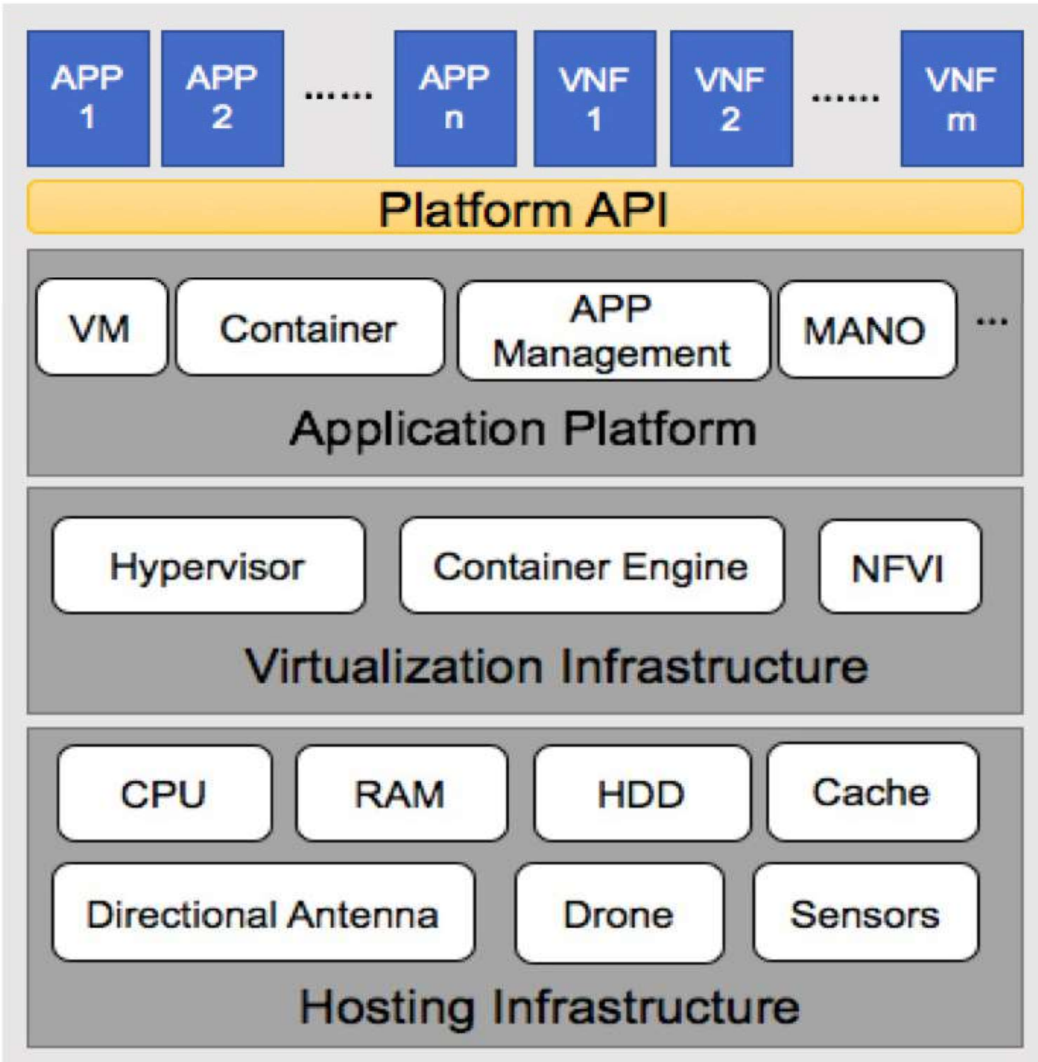
https://www.nasa.gov/ames/utm/

OUR EFFORTS

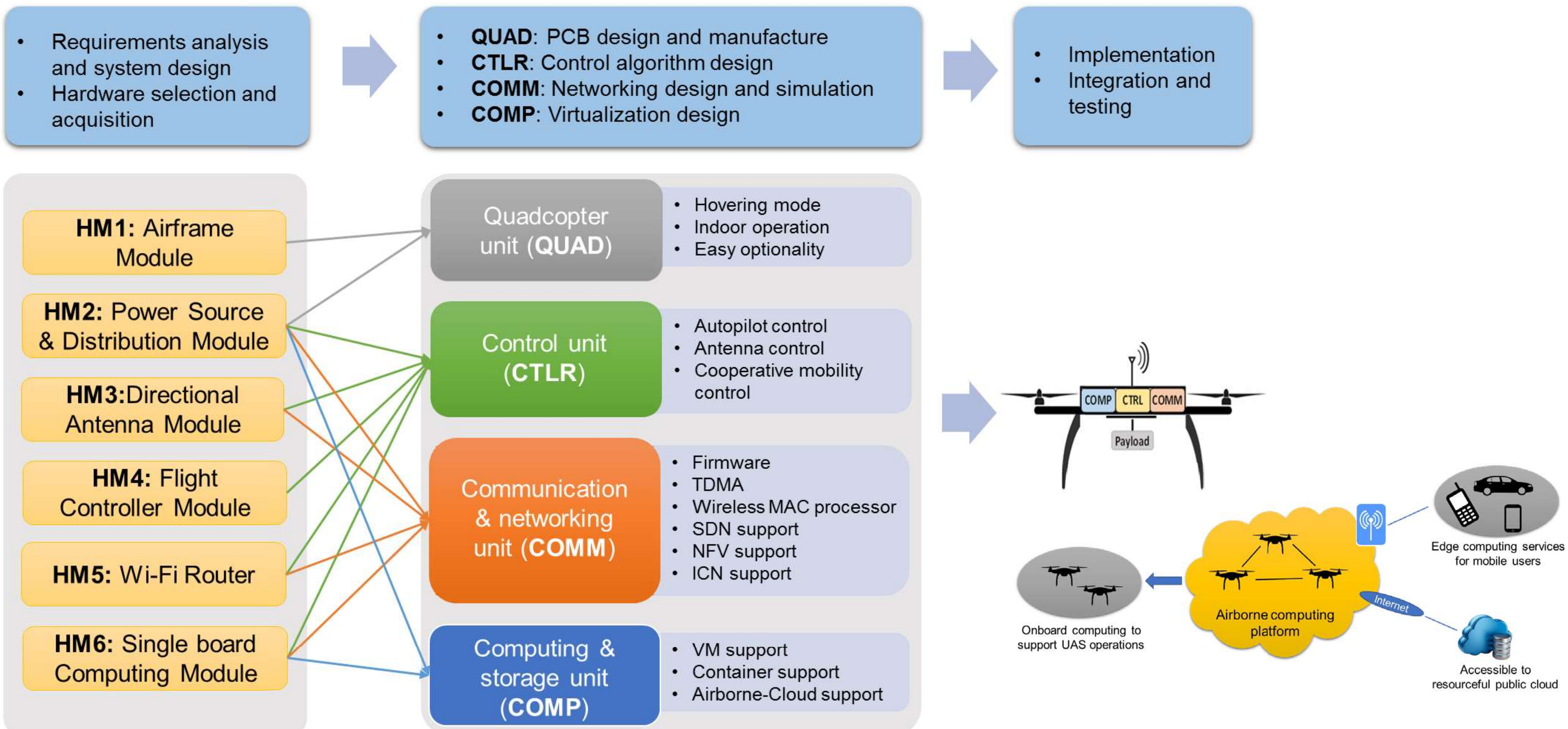
- We put forth effort to develop a new community infrastructure to enable advanced research on networked airborne computing systems.
- The proposed community infrastructure will
  - Provide hardware/software designs and development tools
  - Provide workshop and training opportunities and field-test support.
  - Facilitate various research and development activities for the fundamental research on networked airborne computing, and their applications and services.
  - Benefit many important civilian applications, including intelligent transportation, emergency response, infrastructure monitoring, precision agriculture, etc.



NETWORKED UAV COMPUTING PLATFORM

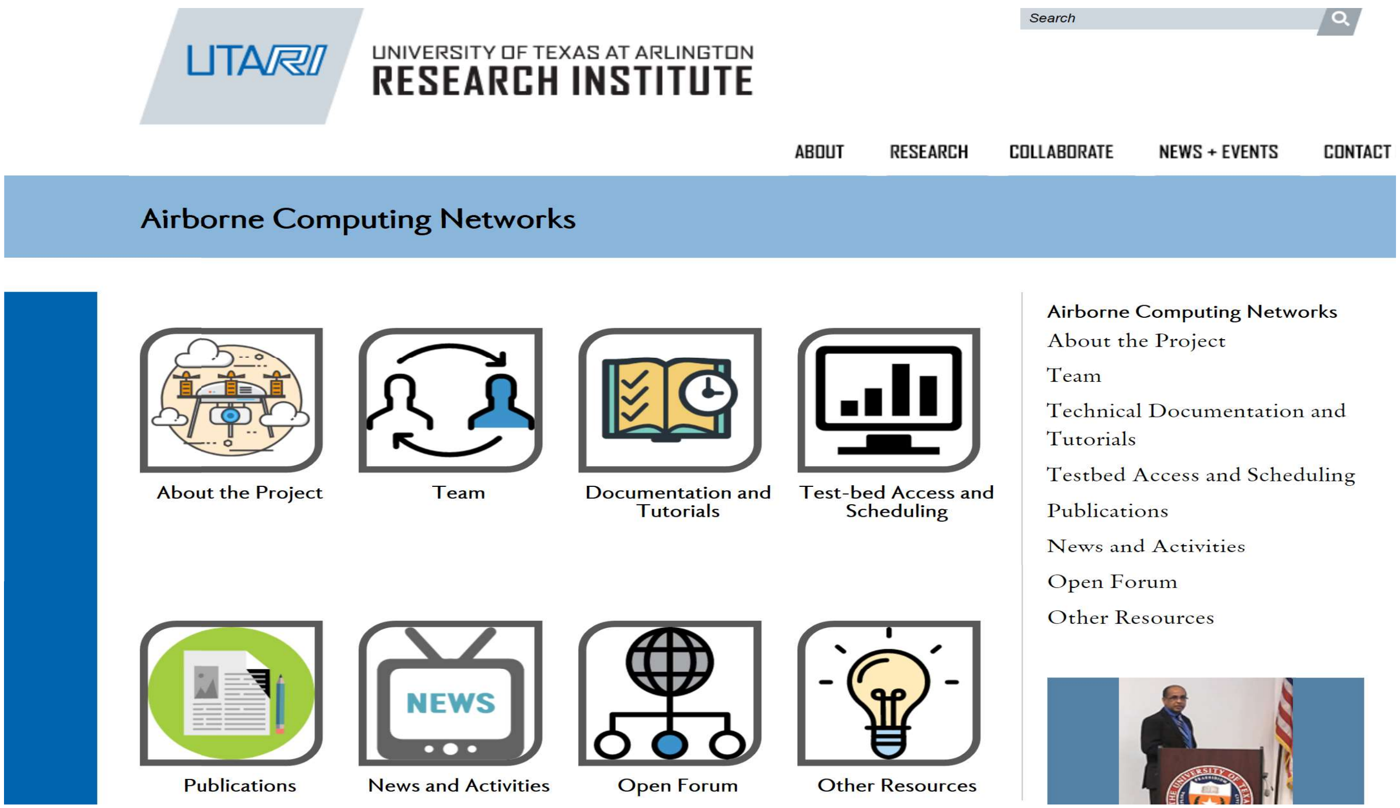


NETWORKED UAV COMPUTING PLATFORM



RESOURCES

http://www.uta.edu/utari/research/robotics/airborne/index.php



SCHEDULE AND ORGANIZERS

Activity	Speaker
Welcome	Yan Wan
1. Hardware	Shengli Fu
2. Computing	Junfei Xie
3. Networking	Kejie Lu
4. Control	Yan Wan
Demos, Summary, and Discussions	All

Towards Networked Airborne Computing: Applications, Challenges, and Enabling Technologies

Part 1: Hardware

Dr. Shengli Fu

Professor
Dept. of Electrical Engineering
University of North Texas

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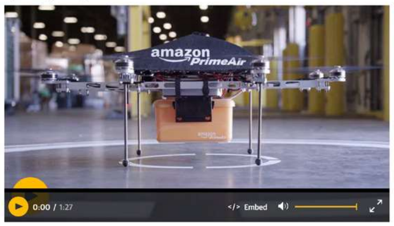
Brief History

Amazon trialling the use of drones for parcel delivery

CEO Jeff Bezos hopes online retailer's drone scheme will be operating in major US cities in 2015



2013 The Guardian

As I mentioned a couple weeks back, my single favorite tech purchase of 2014 was the DJI Phantom quad-copter. And suddenly here we are with a great deal on one!

Today only, and while supplies last, B&H Photo has the DJI Phantom 1 for $379 shipped. You also get a Watson 4-hour rapid charger and four NiMH rechargeable batteries -- but they're not what you think.

GoPro not included, but at least the mount is.

DJI

2014 cnet

CADE METZ BUSINESS 07.21.16 12:00 PM

FACEBOOK'S GIANT INTERNET-BEAMING DRONE FINALLY TAKES FLIGHT

2016 WIRED

HOME \ NEWS

UNT researchers develop drone with Wi-Fi signal

3 Share | 0 Facebook | 3 Twitter | 0 +1 | Email

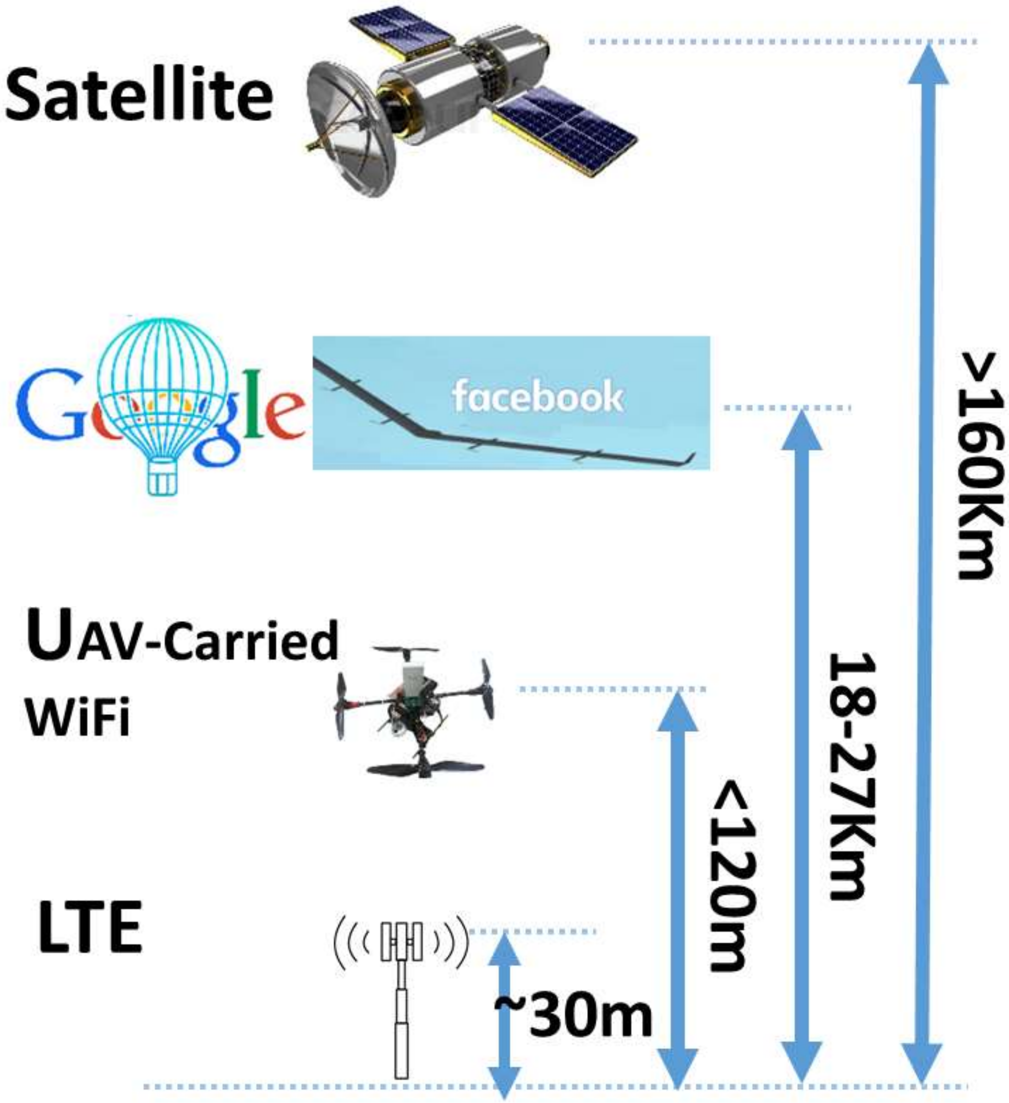
0 Comment(s) Print

By JENNA DUNCAN - *Associated Press* - *Tuesday, May 13, 2014*

DENTON, Texas (AP) - A small drone built at the University of North Texas could eventually be the key to improved communications at a major disaster.

2014 The Washington Times

Related Technologies



Multirotor VS Fixed Wing

- Vertical takeoff
- Hover
- Easy DIY
- Short flight time
- Low speed
- Low payload

- Fast
- Energy efficient
  - Payload
  - Flight time
- Large take-off and landing area
- Need moving

How it works?

Fly forward: Pitch — Increase rotation rate of rotors 3 and 4, Decrease the rate of rotors 1 and 2

Move to right: Roll — Increase rotation rate of rotors 2 and 3, Decrease the rate of rotors 1 and 4

Rotate to right: Yaw — Increase rotation rate of rotors 2 and 4, Decrease the rate of rotors 1 and 3

Drone System

RC controller

Sensors

Frame

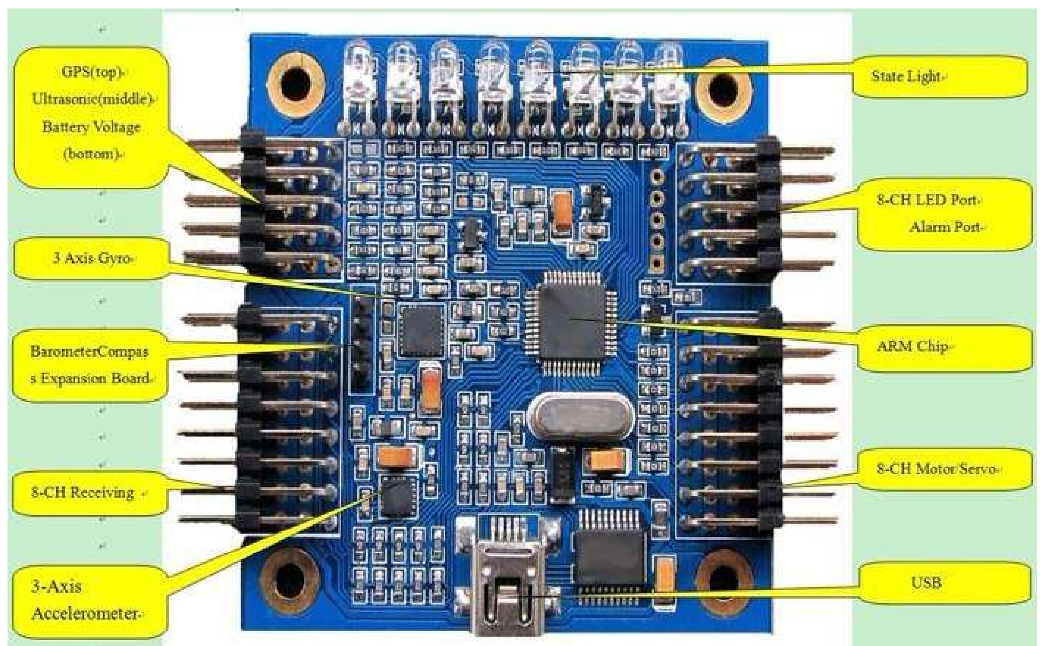
Flight controller

Propeller

Motor

Battery

ESC – Electronic Speed Controller



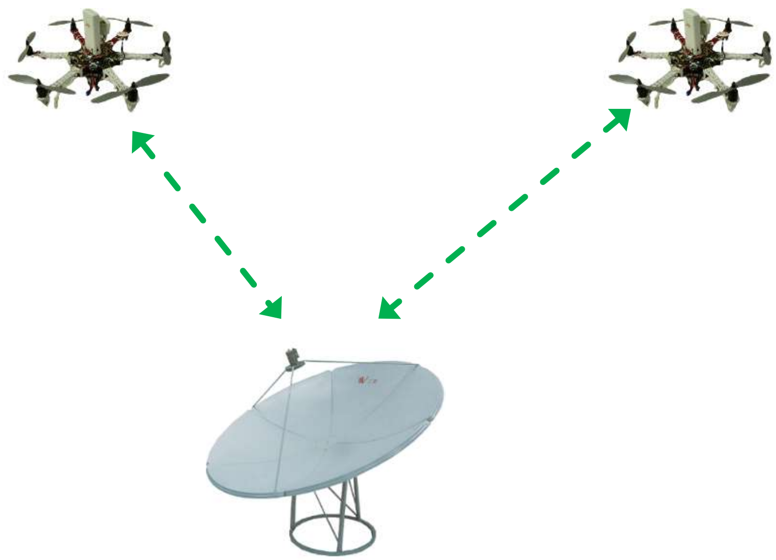
Flight controller

	KK2	ArduPilot Mega	Pixhawk 4	Naza N3
Manufacturer	Hobbyking	ArduPilot	3DR	DJI
Microcontrolle	8-bit	8-bit	32-bit	32-bit
IMU	Yes	Yes	Yes	Yes
GPS	No	Yes	Yes	Yes
Open API	N/A	ArduPilot	ArduPilot	SDK
Weight	21g	44g	38g	132g
Cost	$23	$75	$130	$319

Drone System

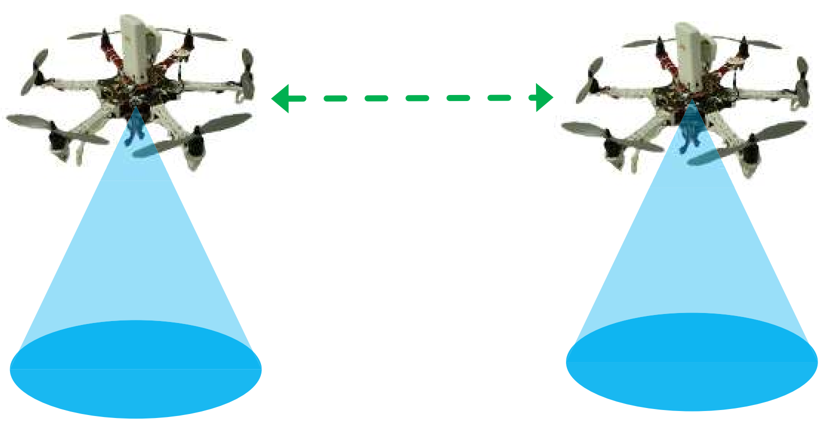
	Phantom 4 Pro	Inspire 2	Mavic Pro	Bebop 2 Power	Typhoon H Pro	H520	X-Star Premium
Manufacturer	DJI	DJI	DJI	Parrot	Yuneec	Yuneec	Autel
Price	$1,400	$4,900	$700	$600	$1,000	$3,000	$699
Meagpixels	20	20	12	14	12	20	12
Flight time (min)	30	27	27	30	22	28	25
Flight dist (miles)	4.3	4.3	4.3	1.2	1	1	1
Flight speed (mph)	45	58	40	40	30	38	35
Weight (grams)	1390	4000	730	525	1695	1633	1600
Obstacles avoidance	All directions	No backward	Forward and downwards	No	All directions	All directions	No

Communication: Drone - Ground



- Matured cellular system
- Good for large systems
- New infrastructure
- Transmission delay
- Limited capacity

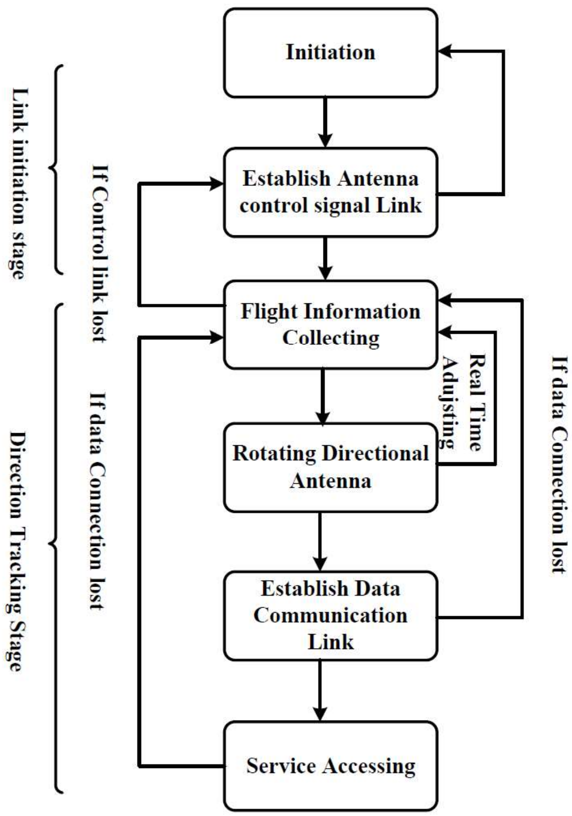
Communication: Drone - Drone

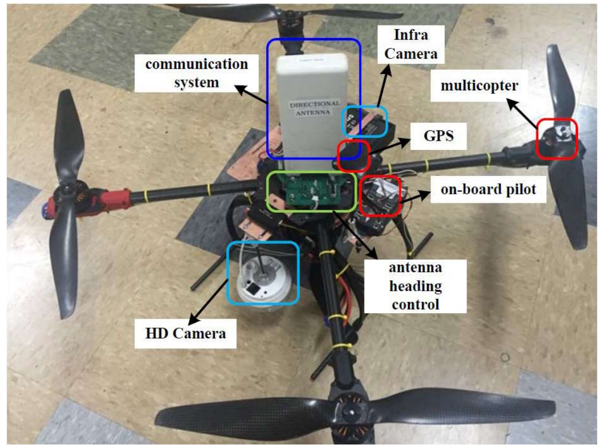


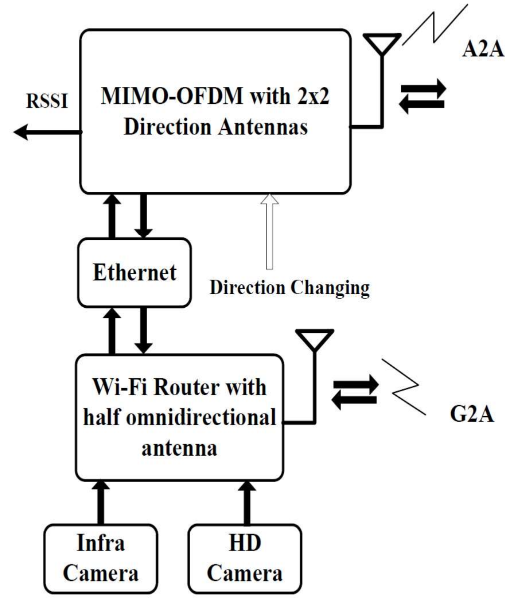
Directional supersedes Omni

- Distance
- Interference
- Power
- Bandwidth

Drone Communication – WiFi







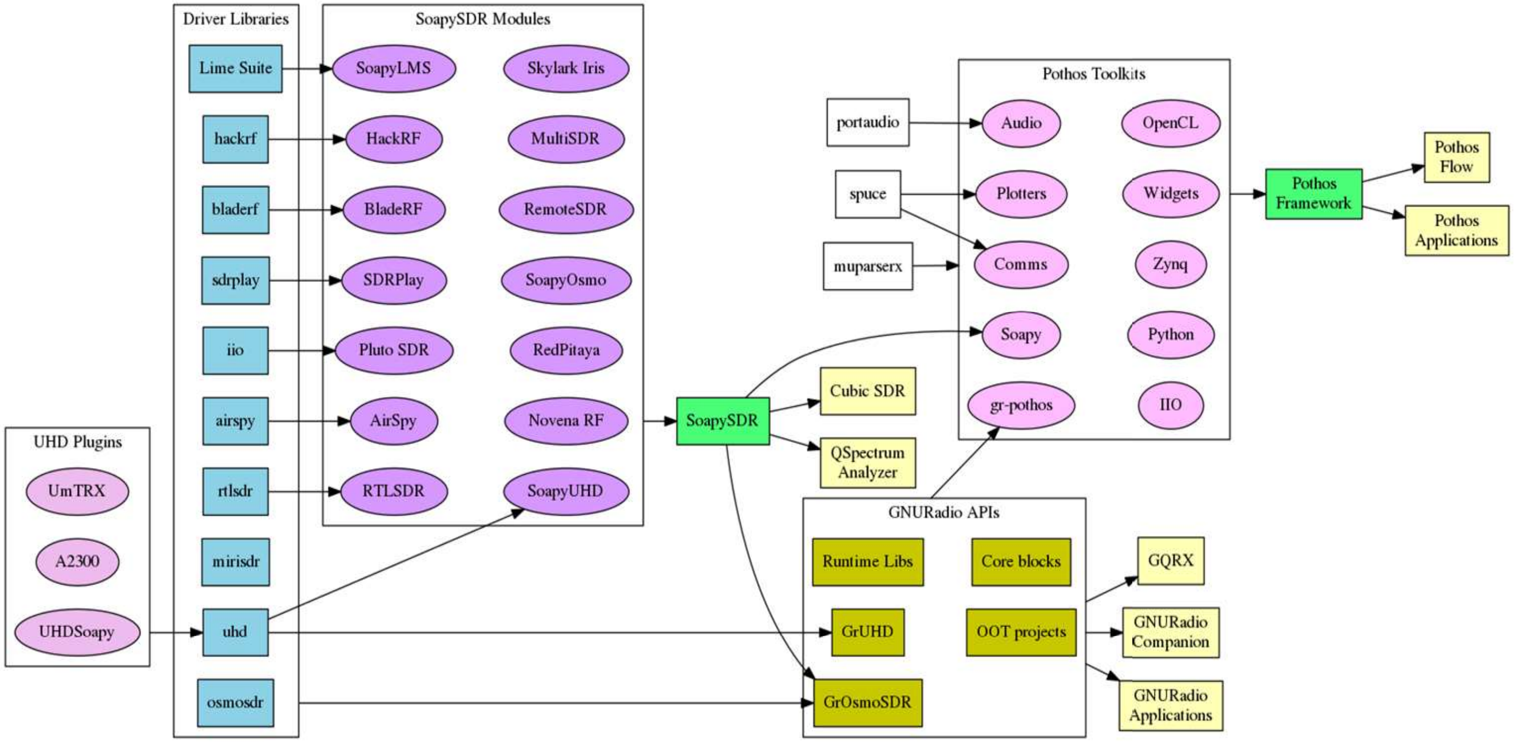
G2A-A2A-A2G Link					
Distance	Throughput		Delay		
Method	[13]	Proposed	[13]	proposed	
300 m	5 Mbps	36 Mbps	840ms	173 ms	
1000 m	N/A	12 Mbps	N/A	218 ms	
3000 m	N/A	2 Mbps	N/A	311 ms	
5000 m	N/A	800 kbps	N/A	419 ms	
A2A Link					
Method	[13]	Proposed	[13]	proposed	RSSI
300 m	19 Mbps	48 Mbps	230ms	41 ms	-57 dBm
1000 m	N/A	16 Mbps	N/A	67 ms	-63 dBm
3000 m	N/A	6 Mbps	N/A	87 ms	-76 dBm
5000 m	N/A	2 Mbps	N/A	101 ms	-81 dBm
Imperfect Antenna heading at 3000m G2A-A2A-A2G Link					
Degree	Throughput		Delay		RSSI
15	1.1 Mbps		71 ms		-79 dBm
30	N/A		N/A		-89 dBm

Drone Communication: Software Defined Radio

LimeSDR

- Small size for drone: 100mm x 60mm
- 4G cellular communication
- IoT gateway
- RADAR

GNU Radio



Operations - FAA

- Fly for hobby or recreation ONLY
- Register your model aircraft
- Fly during daylight. Maximum altitude is 400 feet. Maximum speed 100 mph.
- Fly a drone under 55 lbs. unless certified by a community-based organization
- Need a remote pilot certificate with a small UAS rating

Drone safety

Operator Safety

Space Safety

Part 2: Towards Networked Airborne Computing

Junfei Xie
Assistant Professor
Dept. of Electrical and Computer Engineering
San Diego State University

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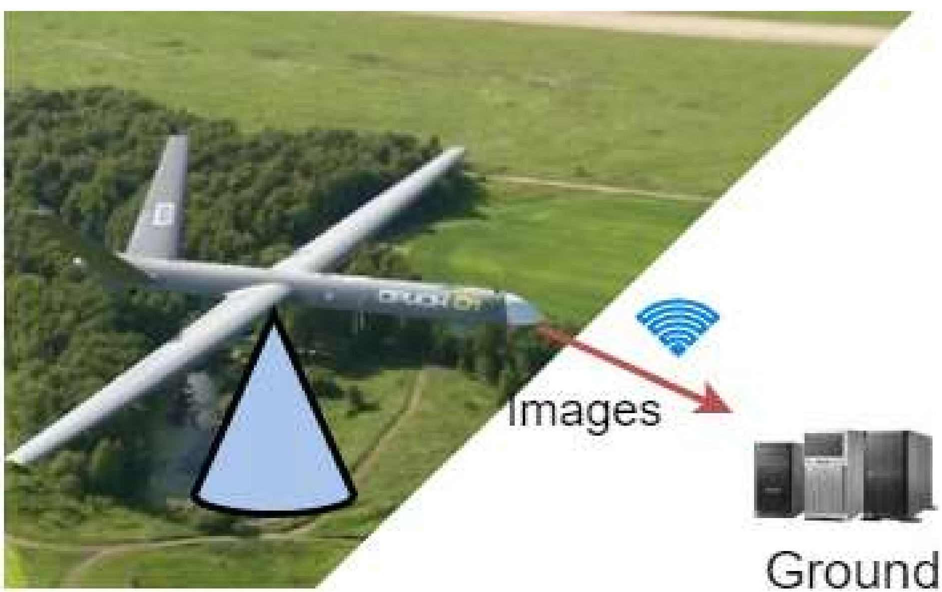
Introduction

- **The design of UAV platforms has largely ignored the computation aspect.**
  – Most existing studies on the design of UAV platforms focus on the control, communication and networking aspects.

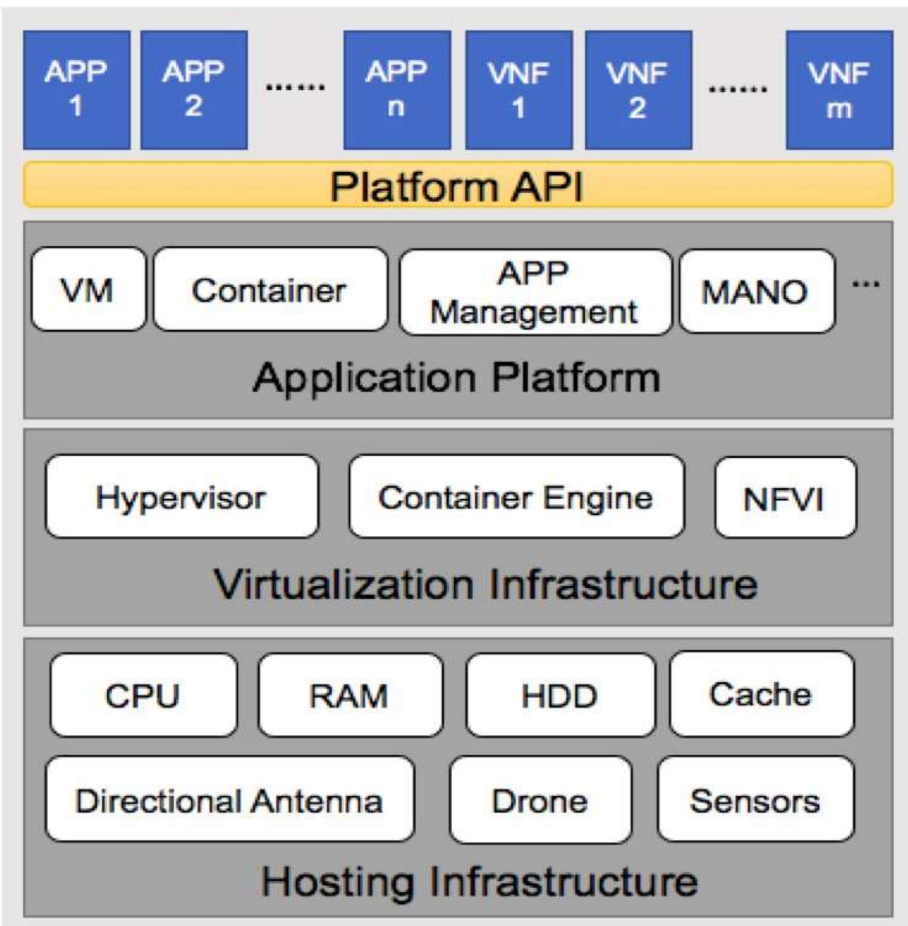
- **Many existing UAV platforms have limited computing capability.**
  – Computation-intensive tasks are offloaded to the ground.



Issues:
- May lead to significant transmission delays or failures
- For high-bandwidth applications, such a computing model requires large communication bandwidths.

Computing Unit of the Networked Airborne Computing Platform

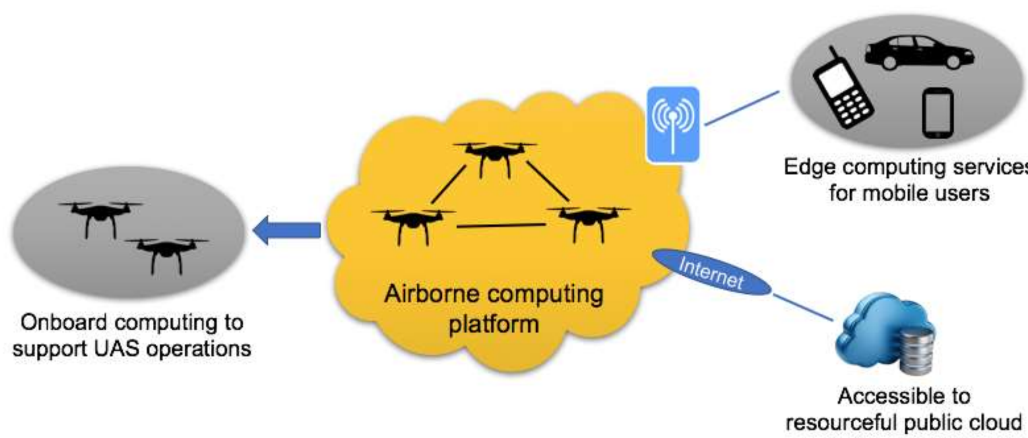
- **Allow computation-intensive tasks to be carried out onboard of UAV in real-time**



System Architecture

Three layers:

- **Hosting infrastructure layer** contains all hardware resources.
- **Virtualization infrastructure layer** provides support to virtualize physical resources.
- **Application platform layer** manages software and hardware resources, and facilitates the design of APPs and/or VNFs.



Hardware Design: Single-board Computer Selection

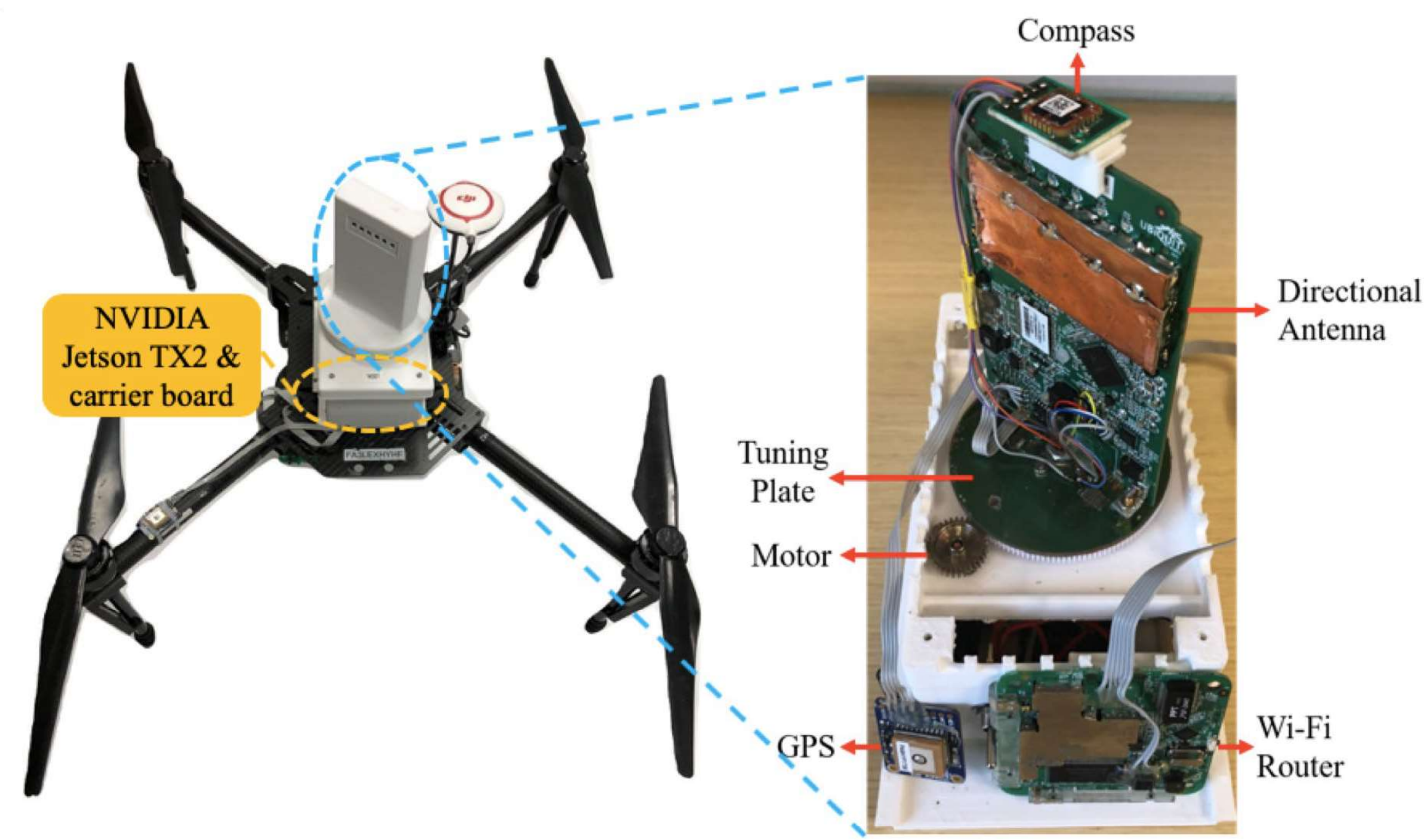
- Comparison of single-board computers

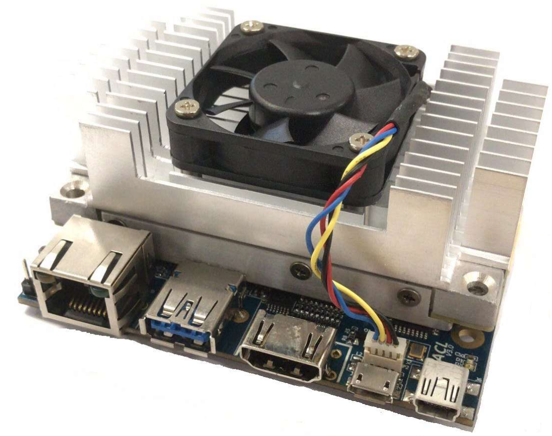
	CPU	GPU	Memory	Connectivity	Dimension (mm)	Power consumption	OS	Weight	Virtualization support	Storage	Price
Jetson TX2	Denver 2 (2 cores) 2MB Cache, 2GHz + ARM® A57 (4 cores) 2MB Cache, 2GHz	256-core NVIDIA Pascal GPU	8 GB	1 Gigabit Ethernet, 802.11ac WLAN, Bluetooth	50 × 87	7.5W	Linux	85g	Yes	32GB	$400
UDOO X86 ULTRA	Intel® Pentium N3710 (4 cores) 2MB Cache, 2.56GHz	Intel® HD Graphics 16 units, 405-700 MHz	8 GB	1 Gigabit Ethernet, M.2 Key … optional Wireless (WiFi…	120 × 85	6W	Windows, Linux, Android	117g	Yes	32GB	$267
Intel Aero Compute Board	Intel® Atom™ x7-Z8750 (4 cores) 2MB Cache, 2.56GHz	Intel® HD Graphics 16 units, 405-600 MHz	4 GB	Intel® Dual… Wireless…							$399
Lattepanda Alpha	Intel® 7th Gen M3-7Y30 (2 cores) 4 MB Cache, 2.60GHz	Intel® HD Graphics 615 300-900MHz	8 GB	1 Gig… 802.1… B…							$398
UP Squared	Intel® Apollo Lake (2-4 cores)	Intel® Gen 9 HD with 12 (Celeron) or 18 (Pentium) Execution Units	8 GB	1 Gig… 802.1… B…							$399
Jetson Xavier	ARM V8.2 (8 cores) 8MB L2+4MB L3, 2.26GHz	512-core Volta GPU with Tensor Cores	16 GB	1 Gig…							1299
DJI Manifold	ARM Cortex-A15 (4 cores)	192-core NVIDIA CUDA GPU	2 GB	10/100…							$499
HiKey 960	ARM Cortex-A73 (4 cores) +Cortex A53 (4 cores)	ARM Mali G71 MP8	4 GB	Blu…							$249
Rock 960	ARM Cortex-A72 (2 cores) Cortex A53 (4 cores)	ARM Mali T860 MP4	4 GB	WLAN 8… Blu…							$139
Jetson TX1	ARM Cortex-A57 (4 cores) 2MB L2	256-core NVIDIA Maxwell GPU	4 GB	1 Gig… 802.11… Blue…							$299

Jetson TX2
- Powerful **CPU**
  - ARM A57 (4 cores)
  - Denver 2 (2 cores)
- Powerful **GPU** (256-core NVIDIA Pascal GPU)
- Powerful **memory** (8GB)
- Out-of-the-box high-throughput WLAN interface
- Smallest in size (large carrier board)

Hardware Design: A Prototype

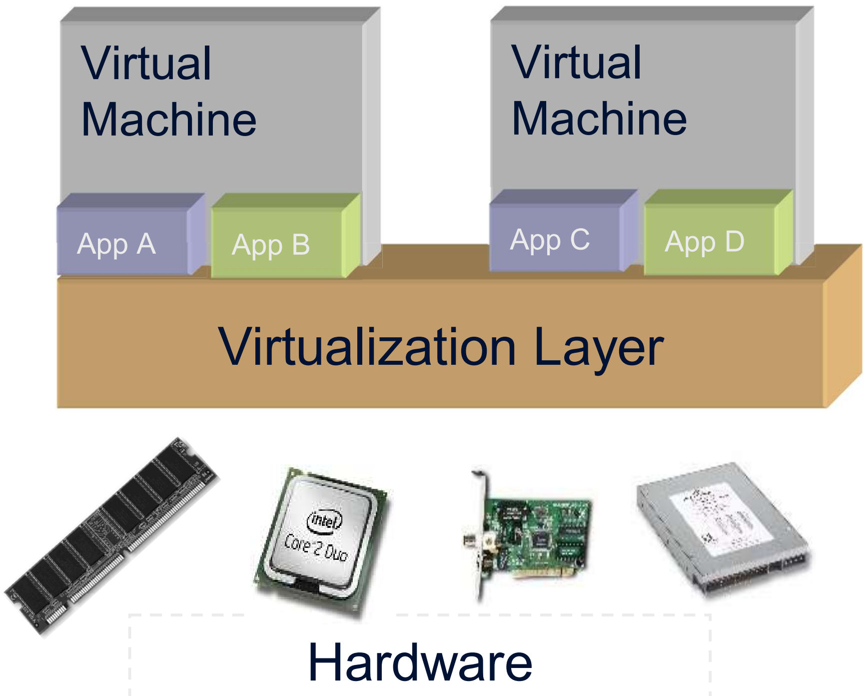
- Jetson TX2 as the computing hardware
- A new Jetson TX2 carrier board





Software Design: Virtualization

- **Virtualization is needed to improve the flexibility and programmability of the airborne computing platform.**

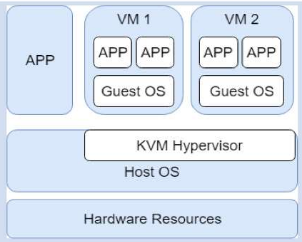
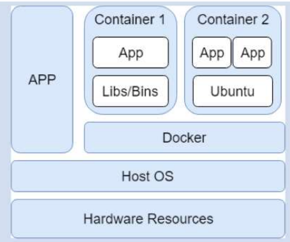


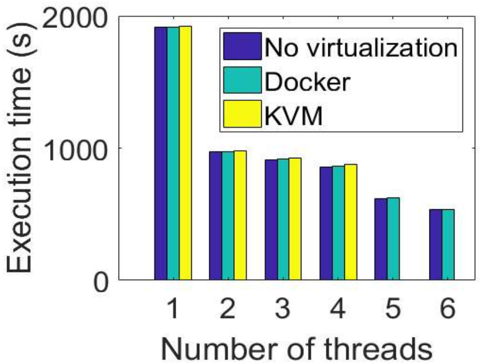
Virtualization refers to the process of creating virtual representations of physical hardware to allow multiple OSs to coexist.

Benefits of Virtualization:

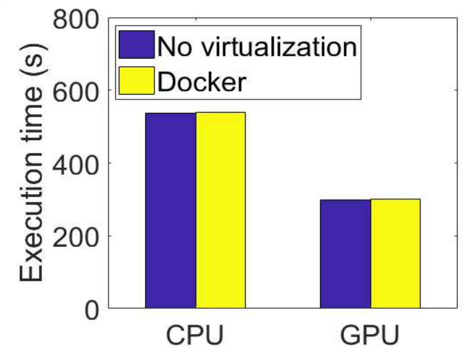
- Provide powerful resource management capability.
- Enhance security through isolating unreliable and untrustworthy functionalities.
- Support concurrent execution of applications with different OS requirements.
- Help to exploit the distributed computing capabilities on multiple connected UAVs.

Software Design: KVM vs Docker

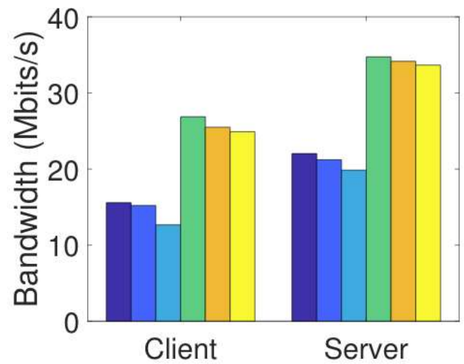
		KVM	Docker
Architecture			
Virtualization level		Hardware	Operating System (OS)
Key components		Hypervisor, QEMU	Namespaces, Cgroups, AuFS
Performance Comparison between KVM and Docker on Jetson TX2			
Computing	CPU	Docker outperforms KVM, and has a very minor impact on the computing performance.	
	GPU	• Docker successfully virtualizes the GPU in Jetson TX2, while KVM does not support CUDA-based GPU virtualization. • For Docker, the computing performance of GPU significantly outperforms CPU when dealing with large computation problems.	
Network		• Docker has better network performance than KVM. • The communication range and bandwidth between UASs can be increased by using directional antennas.	
Isolation		• Docker outperforms KVM in isolating most hardware resources including CPU, memory, disk I/O, and network. • Docker performs poorly in the fork bomb isolation test due to the shared kernel among containers.	
Power consumption		Docker consumes less power than KVM	
Resource usage		Docker is more lightweight than KVM and thus consumes fewer resources.	
Live migration		• KVM does not support live migration on ARM-based devices. • Docker live migration may be achieved by checkpoint and restore utility.	
Security		KVM is more secure than Docker and is more resilient to virus attacks.	



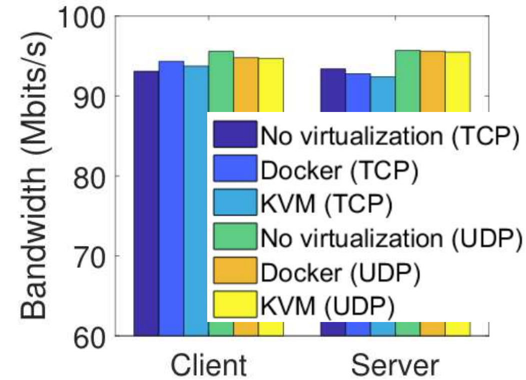
CPU



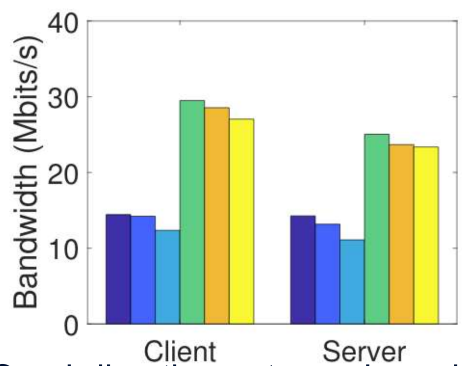
GPU



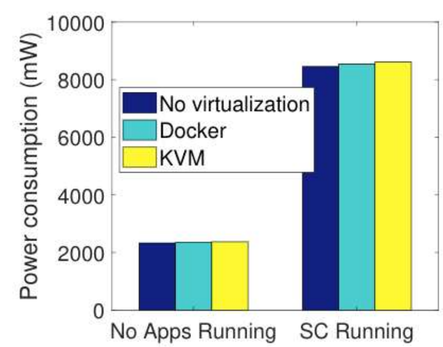
UAV-to-Ground communication



Directional antenna based UAV-to-UAV communication



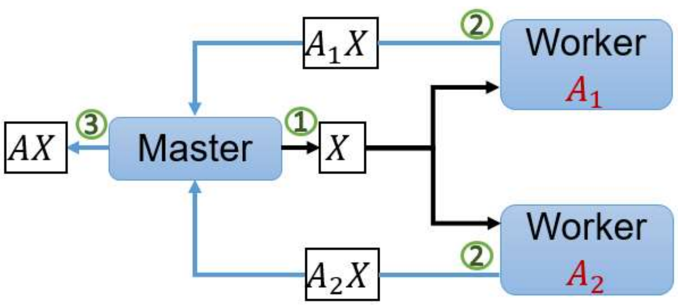
Omni-direction antenna based UAV-to-UAV communication



Power consumption

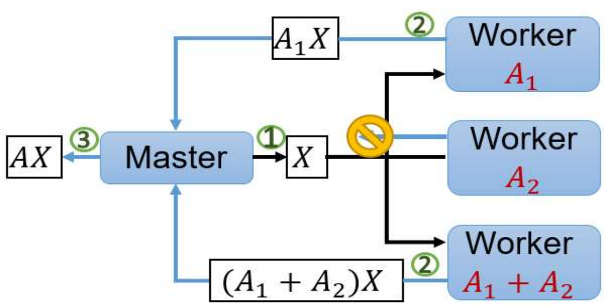
Software Design: Distributed Computing

- The computing capability of a UAV can be further enhanced by using distributed computing techniques to enable resource sharing among multiple UAVs.
- **Traditional distributed computing:**



- **Scheme:** allocate non-overlapping tasks to different computing nodes
- **Disadvantage:** sensitive to system noises, e.g., stragglers.

- **Coded distributed computing:**



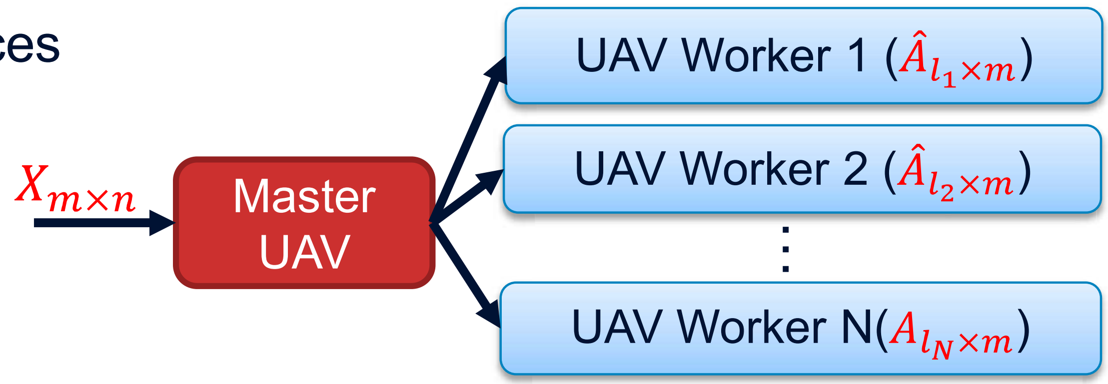
- **Scheme:** Introduce redundancy into computation through erasure codes
- **Advantage:** Resilient to failures & Higher efficiency

- **Limitation of existing (coded) distributed computing solutions**
  - Each worker node waits to send back the result until the whole task is completed, which may incur significant computation latency.
  - They may not be suitable UAV applications that require timely decisions.

Software Design: A New Coded Distributed Computing Scheme

- **Key idea to address the aforementioned limitation**
  - Allow partial results to be returned, which can be used to generate approximate solutions ➡ Batch processing based coded computation (BPCC)

- **Consider the matrix multiplication problem:** $\boldsymbol{A_{r\times m}X_{m\times n}}$
  - Encode the pre-stored matrix $A_{r\times m}$ to a larger matrix $\hat{A}_{p\times m}$ by $\hat{A}_{p\times m} = H_{p\times r}A_{r\times m}$
  - Decompose $\hat{A}_{p\times m}$ into N sub-matrices $\{\hat{A}_{l_1\times m}, \hat{A}_{l_2\times m}, \dots, \hat{A}_{l_N\times m}\}$
    - $p > r$
    - $H_{p\times r}$ is the encoding matrix with any r rows being full-rank.



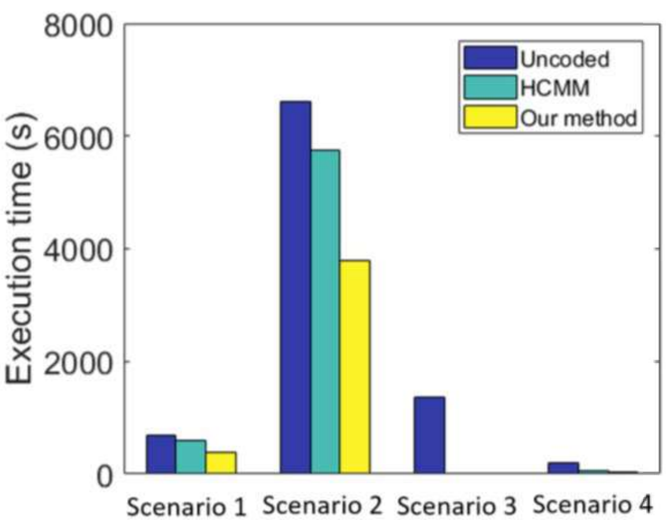
  - Each worker node i further decomposes $\hat{A}_{l_i\times m}$ into p_i sub-matrices of $\left\lceil \frac{l_i}{p_i} \right\rceil = b_i$ rows, called **batches.** p_i is the number of batches.
  - Upon receiving the input matrix $X_{m\times n}$, each worker multiplies each batch with $X_{m\times n}$, and returns the result back to the master node.
  - Once receiving at least r rows of results, denoted as $B_{r\times n} = \hat{A}_{r\times m} X_{m\times n}$, the master node can recover the final result by $A_{r\times m}X_{m\times n} = H_{r\times r}^{-1} B_{r\times n}$

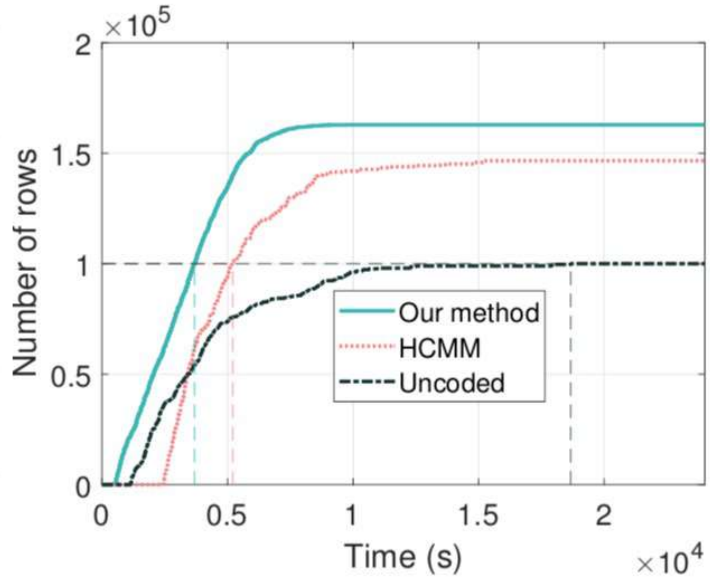
Software Design: BPCC

- **An Optimization Problem for BPCC**
  - Given p_i, $\forall i \in \{1,2,\dots,N\}$, determine the optimal load allocation $\ell = (l_1, l_2, \dots, l_N)\}$, such that the expected task completion time T is minimized, i.e.,

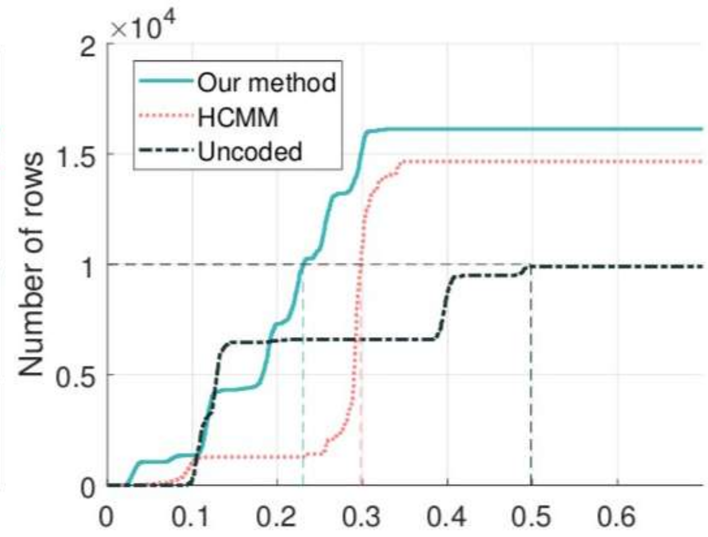
$$\mathcal{P}_{\text{main}} : \underset{l_i, \forall i \in \{1,2,\dots,N\}}{\text{minimize}} \quad E[T]$$
$$\text{subject to} \quad l_i \in \mathbb{Z}^+, i \in \{1,2,\dots,N\}$$

- **Example Simulation and Real Experimental Results**





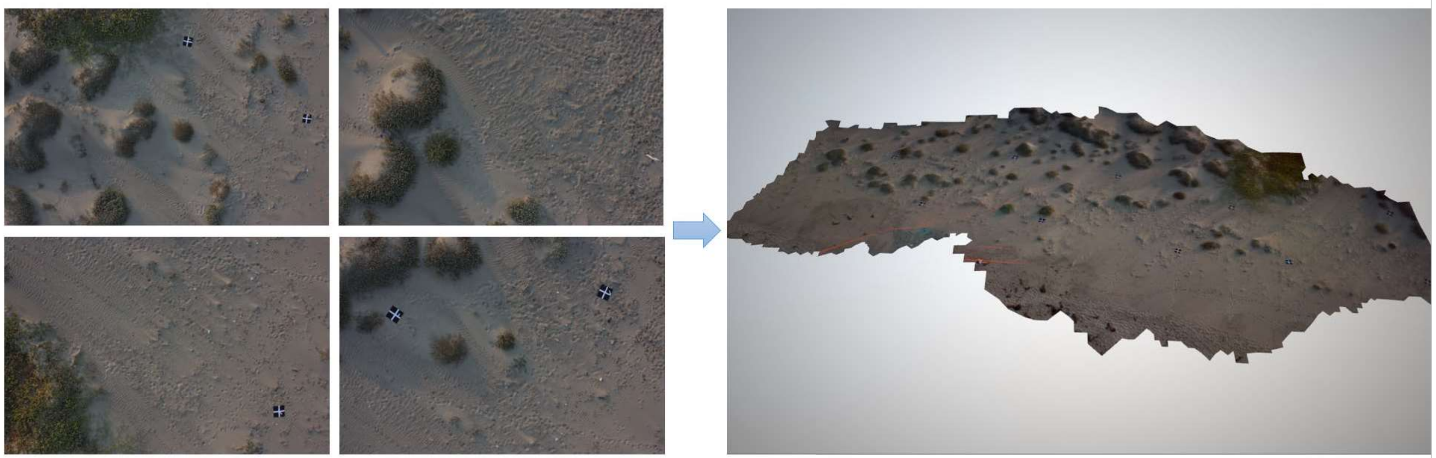
Simulation



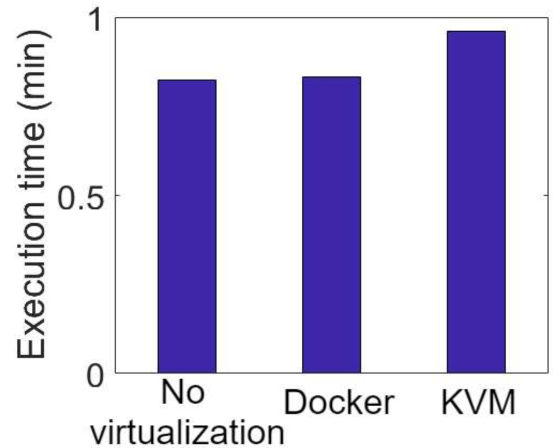
Computing over multiple UAVs

Applications

2-D UAS images **3-D geographical model**



3-D mapping



Execution time per image

Object detection

- Jetson TX2 without virtualization: 0.129s per image
- Docker container: 0.148s per image
- Size of image: 850 kB

Towards UAV-Based Airborne Computing: Applications, Design, and Prototype

Part 3: Wireless Networking for Airborne Computing

Dr. Kejie Lu

IEEE Senior Member
Professor
Department of Computer Science and Engineering
University of Puerto Rico at Mayaguez

uprm.edu

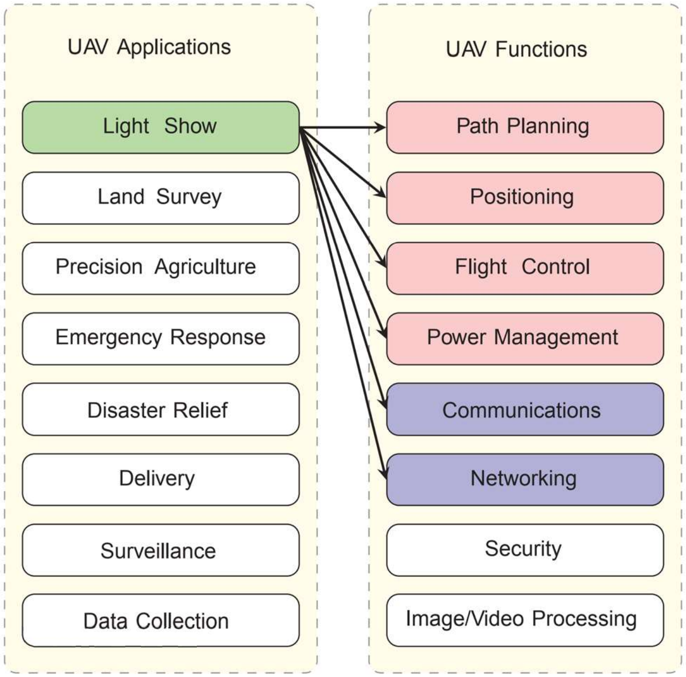
ICUAS 2020

Outline

- Background of UAV-based airborne computing
- Airborne wireless networks
- Design guidelines
- Enabling technologies

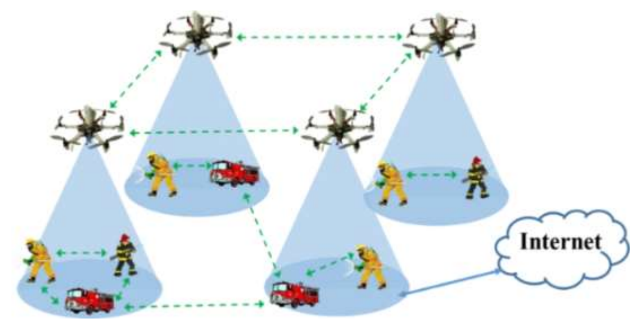
Background

- In recent years, there are many emerging civilian unmanned aerial vehicles (UAVs) applications
- In general, to facilitate a UAV application, multiple UAV functions shall be supported.
  - However, most existing UAV functions were designed separately and there is a lack of a general framework to exploit airborne computing for all on-board UAV functions.
- To address this issue, we proposed a unified UAV-based airborne computing framework.
  - Kejie Lu, Junfei Xie, Yan Wan, Shengli Fu, "Toward UAV-Based Airborne Computing,", IEEE Wireless Communications, Dec. 2019.



Airborne Wireless Networks

- An airborne wireless network consists of UAVs with wireless communications capabilities
  - Air-to-air, air-to-ground
- To support airborne computing in wireless network, there are many challenges and opportunities
  - Challenges
    - Complicated application requirements
      - Control, monitoring, data processing, etc.
    - Limited resources
      - Weight, energy, communication, computing, etc.
  - Opportunities
    - Reduced response time
    - Improving network performance
    - More design choices



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Design Guidelines

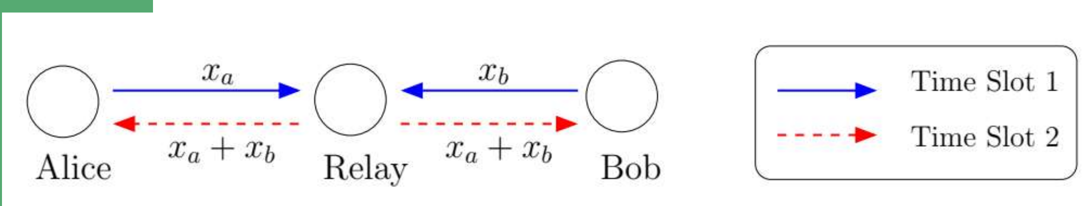
- Understand the computing model
  - Algorithms, implementation of algorithms, etc.
- Understand the network formation
  - The number of UAVs, trajectories of UAVs, etc.
- Understand the network operation
  - Topology control, topology update, mobility, etc.
- Understand the network performance
  - Throughput, delay, loss, energy, etc.
- Understand the constraints
  - Weight, energy, cost, etc.
- Understand the optimality and tradeoff
  - Optimality: maximal throughput, minimal response time, etc.
  - Tradeoffs: throughput-delay, computing-energy, etc.

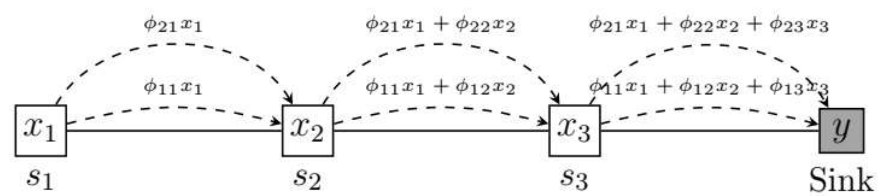
Enabling Technologies

- Desired features
  - Enhancing performance
  - Improving scalability
  - Providing flexibility
- Enabling Networking Technologies
  - Network coding
  - Compressed sensing
  - Coded computing
  - Information-centric networking (ICN)
  - Software-defined networking (SDN)
  - Network function virtualization (NFV)
  - Multiple-access edge computing (MEC)

Network Coding and Compressed Sensing

- Network coding
  - Main idea
    - Each node in the network sends or forwards coded packets
      - Existing solution: each node forwards the original packets
  - Why it is important?
    - Provide the optimal throughput capacity
    - Simplify the routing problem for multicast
- Compressed sensing
  - Main idea
    - Compress data while collecting data
  - Why it is important?
    - Improve the throughput capacity
    - Reduce the delay
    - Improve the lifetime

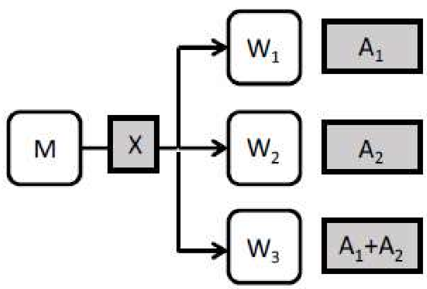


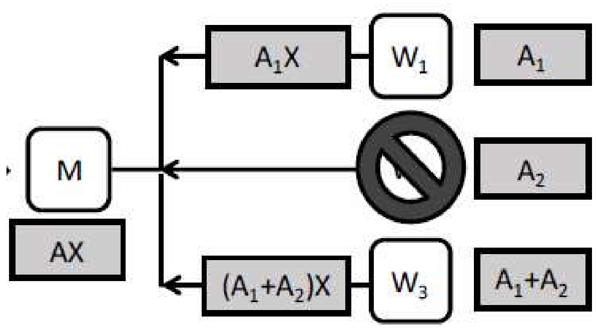


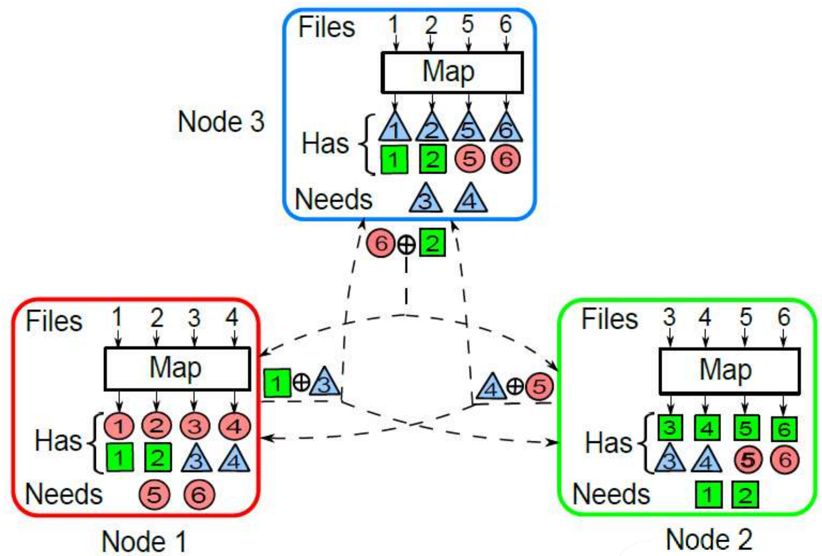
Coded Computing

- Distributed computing
  - Main ideas
    - Use more computing nodes to reduce the processing time
  - Why it is important?
    - Reduce the processing time of a computing task

- Data exchange
  - Main ideas
    - Use index coding to reduce the number of packets to be exchanged in nodes
  - Why it is important?
    - Minimize the traffic in the network







(b) Coded Distributed Computing Scheme.

ICN and SDN

- Information-centric networking
  - Main ideas
    - Use an ID to access information/service
      - In the current Internet, one needs to access a host (server) to obtain information/service
    - Use cache to store content inside a network
  - Why it is important?
    - Optimize the network performance in terms of throughput, delay, lifetime, etc.

- Software-Defined Networking
  - Main ideas
    - Physically separate the control plane and the data plane
      - One controller: Updating forwarding policy at each switch
      - Many switches
        - » Forwarding packets according to the policy
        - » Forwarding unknown packets to the controller
  - Why it is important?
    - Simplify the control
    - Improve scalability
    - Reduce the cost
    - Quickly deploy new services: flexibility

NFV and MEC

- Network function virtualization
  - Main ideas
    - Use common hardware platform
    - Network functions are virtualized
  - Why it is important? (Compared to proprietary system)
    - Reduce cost of hardware/maintenance/etc.
    - Enable/disable functionality flexibly
- Multiple-access edge computing
  - Main idea
    - Provide computing capability at the edge of cellular network
  - Why it is important? (Compared to traditional cloud computing)
    - Reduce the delay of computation tasks
    - Provide computation and storage capability for user devices
    - Reduce energy consumption of user devices

PART 4: CONTROL IN NETWORKED UAV COMPUTING SYSTEMS

Yan Wan

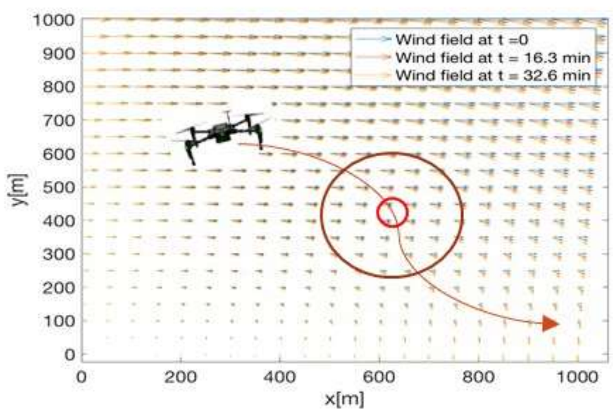
Professor

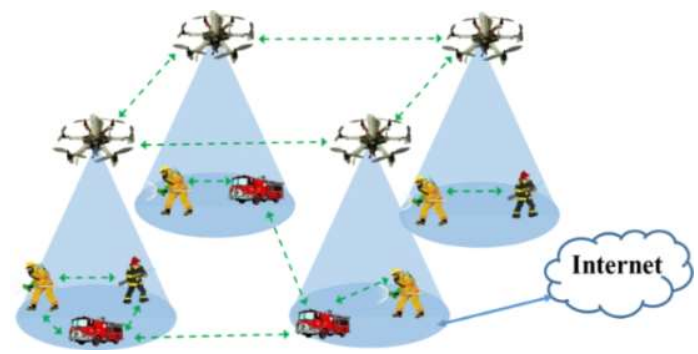
University of Texas at Arlington

ICUAS
September 2020

CONTROL COMPONENTS

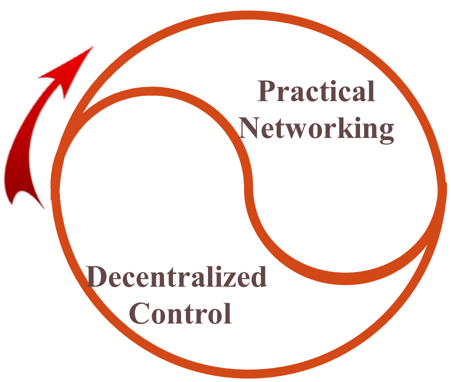
- Networked UAV computing systmes include
  - UAV mobility
  - UAV traffic control
  - Multi-UAV control
  - UAV path planning
  - Antenna control
- Here we emphasize on the antenna control component.

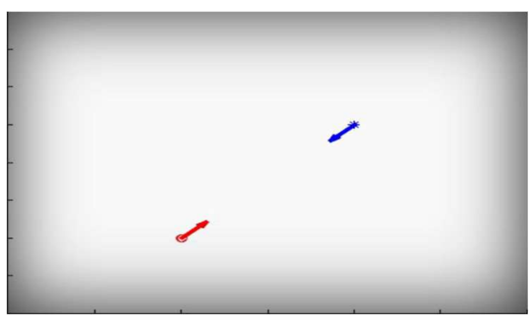


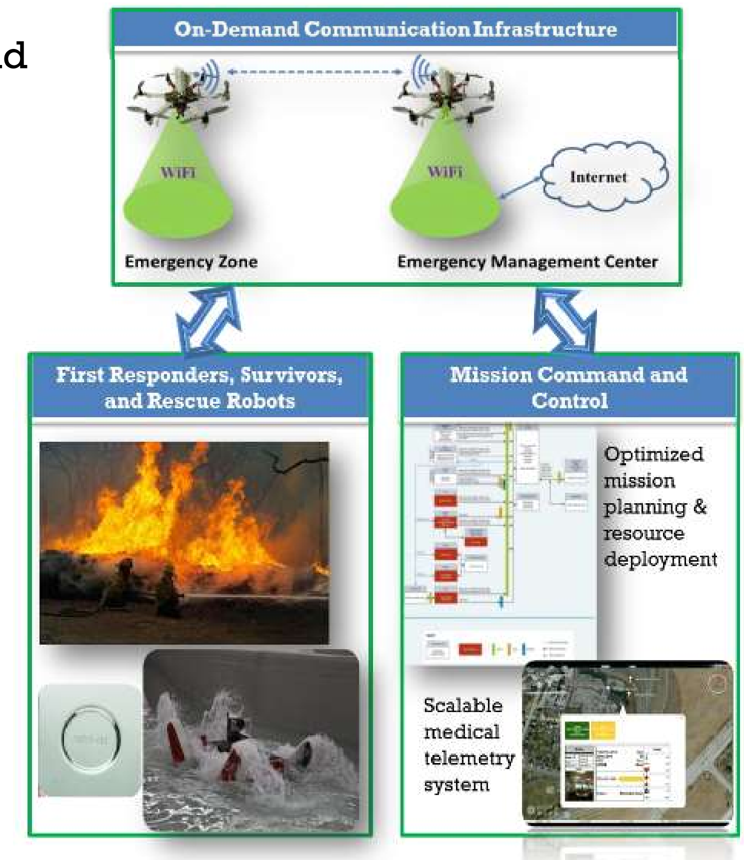


ANTENNA CONTROL: CO-DESIGN FOR LONG-DISTANCE AND BROAD-BAND UAV NETWORKING

- UAVs to provide long-distance broad-band on-demand emergency communication.
  - Independent of infrastructure/support
  - Quickly deployed
  - Flexibly configurable to emergency needs
  - Robust long-range broad-band communication
  - Simple to operate
  - Cost effective
- The control of directional antennas facilitates communication.

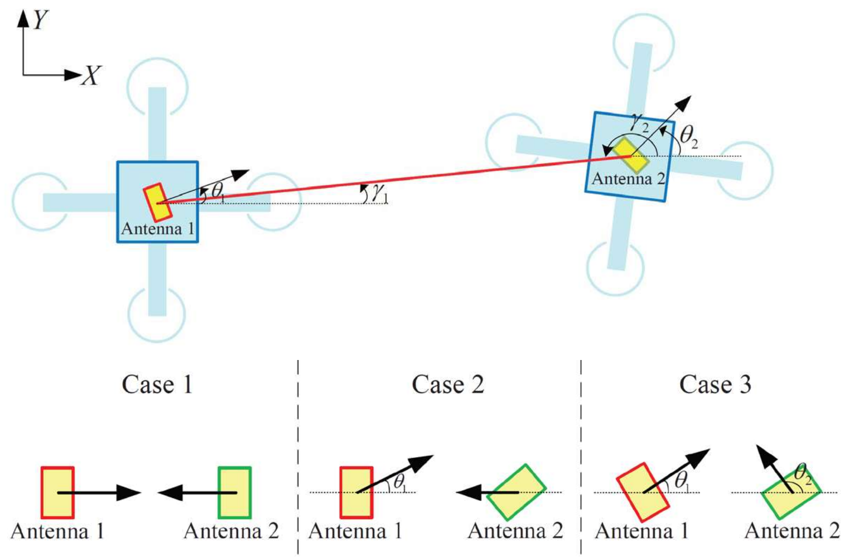


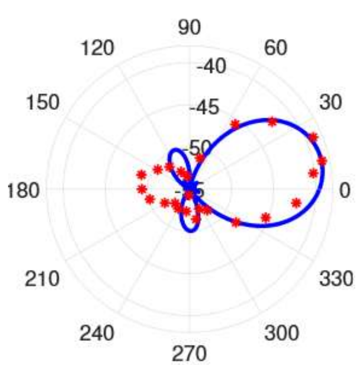




COMMUNICATION AND CONTROL CO-DESIGN FOR LONG-DISTANCE AND BROAD-BAND UAV NETWORKING

- UAVs to provide long-distance broad-band on-demand emergency communication.
- The control of directional antennas facilitates communication
- Received signal strength, the communication performance indicator, serves as measurement and goal function for control.
- Communication measurement data learns the environmental-specific communication model, and distributed reinforcement learning is used for adaptive optimal control.



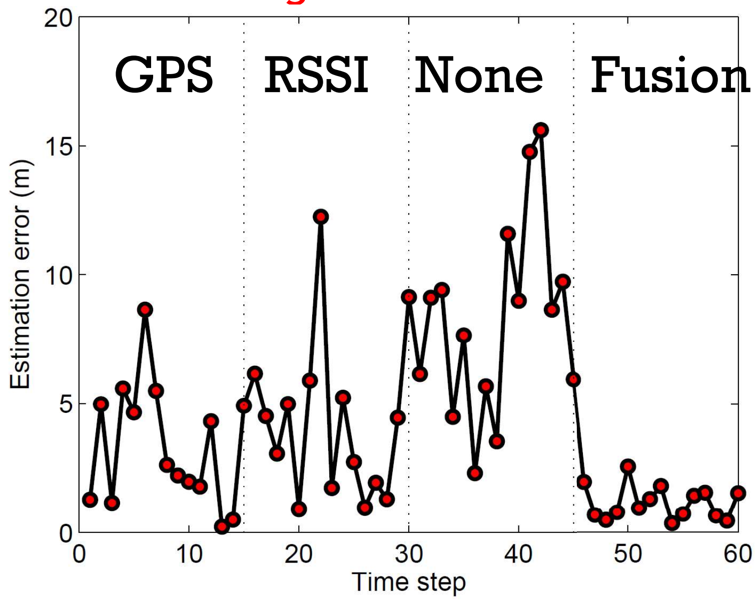


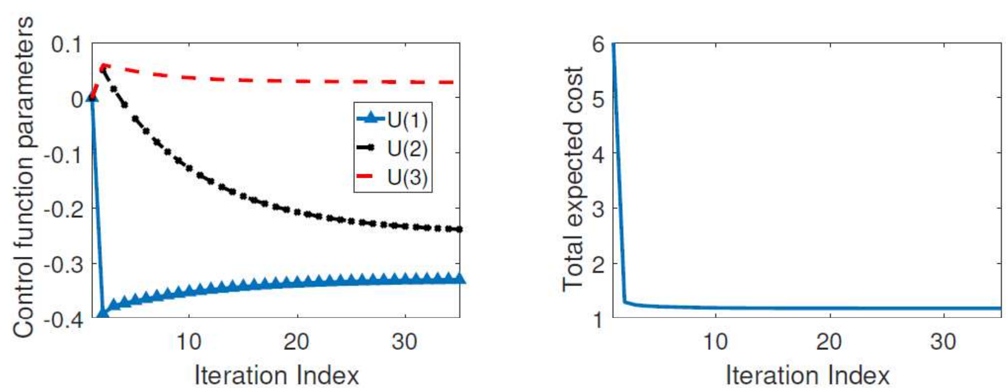
		Local antenna		Remote antenna	
Position	Control	RSSI	Heading	RSSI	Heading
1	RL	-37dBm	194.1°	-41dBm	16.4°
	GPS	-45dBm	170.6°	-45dBm	35.5°
2	RL	-37dBm	197.3°	-39dBm	15.1°
	GPS	-39dBm	176.2°	-42dBm	357.8°
3	RL	-39dBm	191.1°	-44dBm	13.2°
	GPS	-41dBm	182.6°	-44dBm	6.2°
4	RL	-35dBm	196°	-39dBm	15.2°
	GPS	-38dBm	195.8°	-39dBm	16.2°
5	RL	-35dBm	194.9°	-39dBm	15.4°
	GPS	-37dBm	186.1°	-39dBm	7.5°

$$
\begin{aligned}
G_{l|dBi}[k] =& (G^{max}_{t|dBi} - G^{min}_{t|dBi}) \\
& \times \sin \frac{\pi}{2n} \frac{\sin\left(\frac{n}{2}(k_a d_a(\cos(\gamma_t[k] - \theta_t[k])) - 1) - \frac{\pi}{n}\right)}{\sin\left(\frac{1}{2}(k_a d_a(\cos(\gamma_t[k] - \theta_t[k])) - 1) - \frac{\pi}{n}\right)} \\
& + (G^{max}_{r|dBi} - G^{min}_{r|dBi}) \\
& \times \sin \frac{\pi}{2n} \frac{\sin\left(\frac{n}{2}(k_a d_a(\cos(\gamma_r[k] - \theta_r[k])) - 1) - \frac{\pi}{n}\right)}{\sin\left(\frac{1}{2}(k_a d_a(\cos(\gamma_r[k] - \theta_r[k])) - 1) - \frac{\pi}{n}\right)} \\
& + G^{min}_{t|dBi} + G^{min}_{r|dBi},
\end{aligned}
$$

LEARNING AND TRACKING

- Antenna direction control is based on the fusion of GPS if exists, RSSI, and mobility tracking
  - We model random trajectory as stochastic systems, with random variables capturing random maneuvering operations
  - Learning random maneuvering operations through on-line estimation of these random variables
- Based on predicted random trajectory patterns, an effective uncertainty evaluation and control method is used to quickly choose a few samples to decide the best antenna heading.



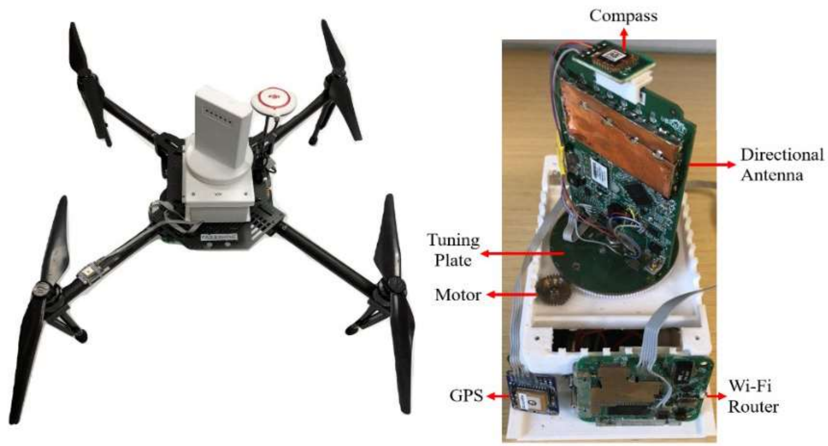


(a) U (b) $J(\mathbf{x}[0])$

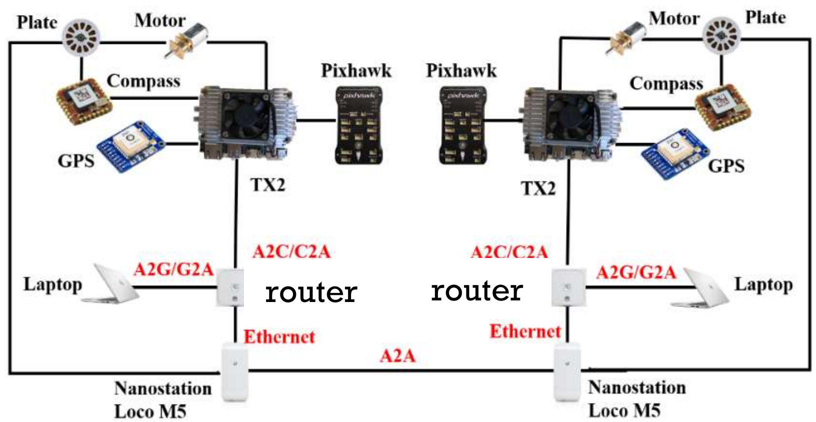
Convergence of Reinforcement learning-based control

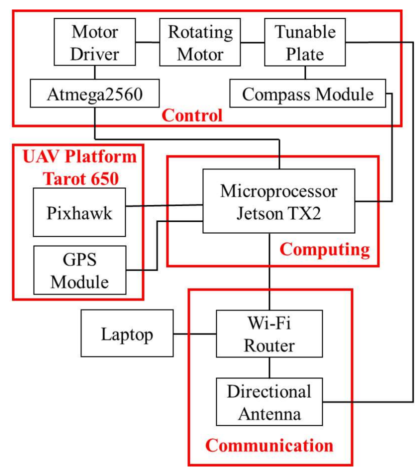
J. Xie, Y. Wan, K. Mills, J. J. Filliben, and F. Lewis, "A Scalable Sampling Method to High-dimensional Uncertainties for Optimal and Reinforcement Learning-based Controls," IEEE Control Systems Letters, vol. 1, no. 1, pp. 98-103, July 2017.

IMPLEMENTATION AND TESTING



(a) (b)





Testing Results

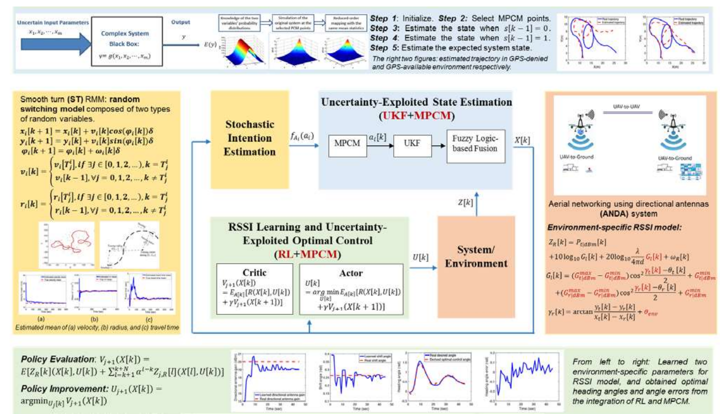
- 100m, 85Mbps
- 300m, 65Mbps
- 1km, 45Mbps
- 2km, 40Mbps
- 4km, 25Mbps

S. Li, M. Liu, C. He, Y. Wan, Y. Gu, J. Xie, S. Fu, and K. Lu, "The Design and Implementation of Aerial Communication Using Directional Antennas: Learning Control in Unknown Communication Environment," IET Control Theory and Application, accepted, October 2018.

J. Chen, J. Xie, Y. Gu, S. Li, S. Fu, Y. Wan, and K. Lu, "Long-Range and Broadband Aerial Networking using Directional Antenna (ANDA): Design and Implementation, IEEE Transactions on Vehicular Technology, Vol. 66, No. 12, pp. 10793-10805, December 2017.

COMMUNICATION AND CONTROL CO-DESIGN FOR LONG-DISTANCE AND BROAD-BAND UAV NETWORKING

- UAVs to provide long-distance broad-band on-demand emergency communication
- The control of directional antennas facilitates communication
- Received signal strength, the communication indicator, serves as measurement and goal function for control
- Communication measurement data learns the environmental-specific communication model, and distributed reinforcement learning is used for adaptive optimal control.
- Flight tests, water-proof design, and user-friendly interface design for technology transfer in the safety-critical emergency response application.



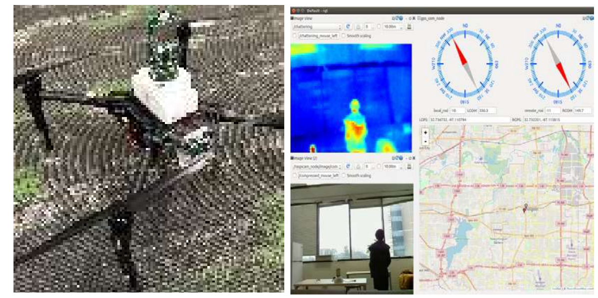
M. Liu, Y. Wan, S. Li, F. Lewis, and S. Fu, "Learning and Uncertainty-exploited Directional Antenna Control for Robust Long-distance and Broad-band Aerial Communication," IEEE Transactions on Vehicular Technologies, vol. 69, no. 1, pp. 593-606, January 2020.

PREVIOUS PROTOTYPE SYSTEMS

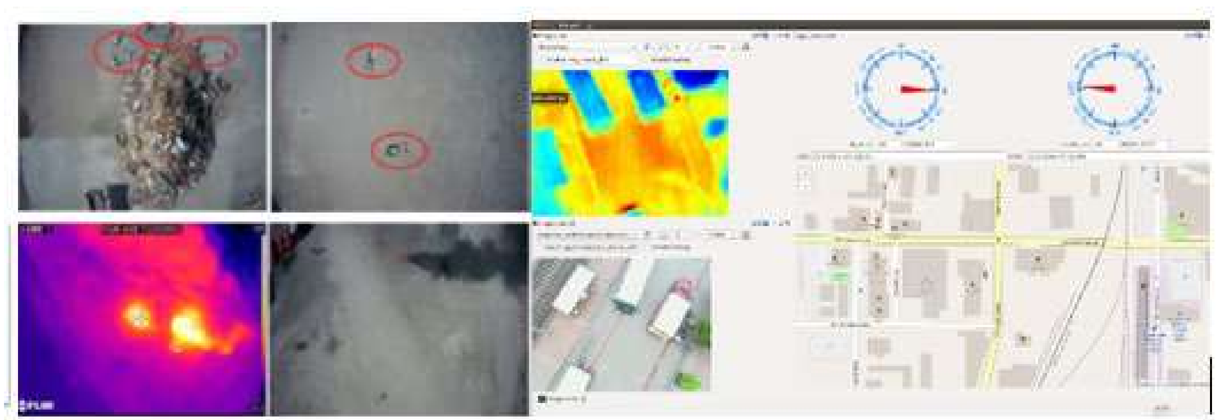
2014

2015

2016

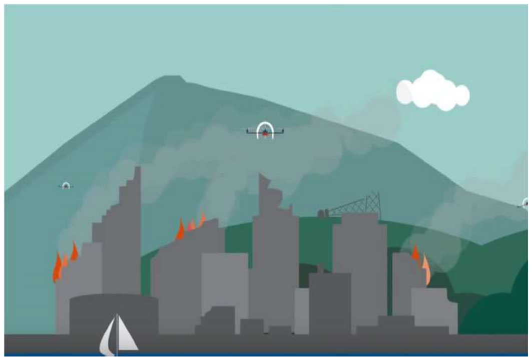


2017



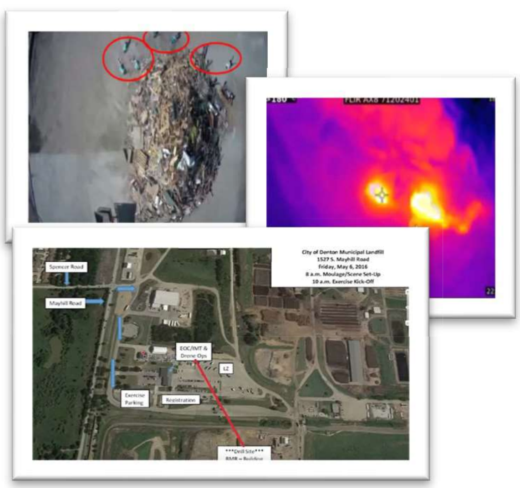
Various disaster drills & field tests

SAMPLE VIDEOS



https://www.youtube.com/watch?v=Yi_dK4iRCA4&t=15s

Concept Cartoon, Smart Emergency Response System, in collaboration with NI, Mathworks, Boeing, etc.



https://drive.google.com/open?id=0BwUF9xqKcA6NdWxqTmgtb2h3SUk

May 2016, with Denton Fire Department on the full-scale disaster drill, testing the use of UAS-carried WiFi for monitoring and resource allocation in a tornado scenario.

https://drive.google.com/file/d/0B8CmKICcUSz_Ny03S1YyODJQdHM/view?usp=sharing

May 2014, With Austin Fire Department and WPI on UAV in coordination with robot for S&R

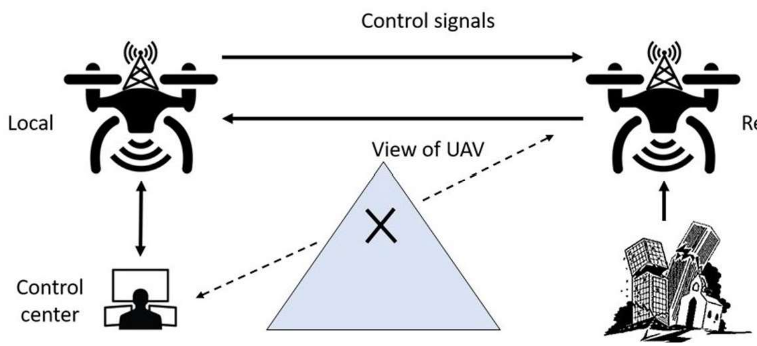
https://drive.google.com/file/d/0BwUF9xqKcA6NYXhBRDZRY3laMlE/view?usp=sharing

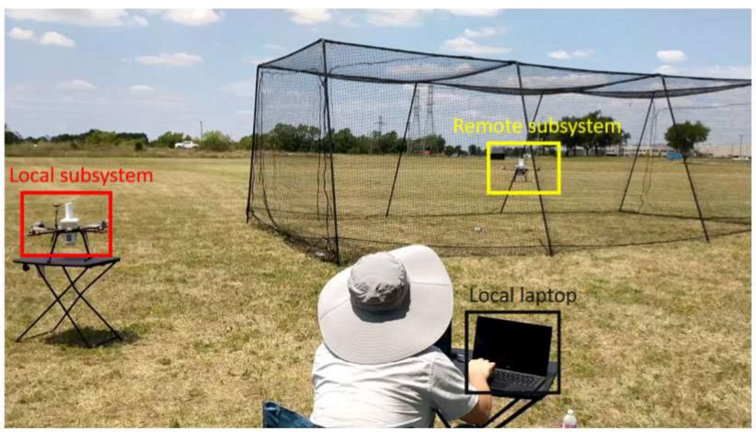
February 2016, with Tarrant County Fire Service Training Center, Filmed by Canada Discovery Channel on three scenarios: flooding water, fighting fires, and car accident

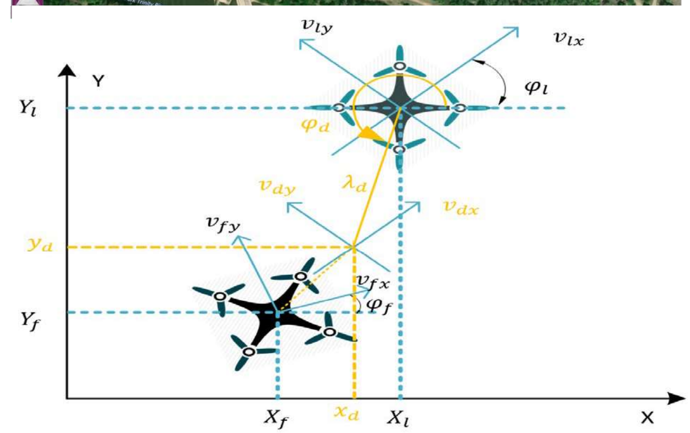
APPLICATION BUILT ON THE AERIAL COMMUNICATION USING DIRECTIONAL ANTENNAS (ACDA) SYSTEM

Beyond Visual Line of Sight Control

Multi-UAV Formation







S. Li, Y. Gu, B. Subedi, C. He, Y. Wan, A. Miyaji, and T. Higashino, "Beyond Visual Line of Sight UAV Control for Remote Monitoring using Directional Antennas," accepted by IEEE GLOBECOM 2019 Workshop on Computing-Centric Drone Networks, Waikoloa, Hawaii, December 2019.