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# Unmanned Aerial Systems Charrette Report

by Brett Piekarski, Rajneesh Singh, Robert Hebner, Hao Kang,  
and Elias Rigas



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# Unmanned Aerial Systems Charrette Report

by Brett Piekarski, Rajneesh Singh, Hao Kang and Elias Rigas  
*Vehicle Technology, CCDC Army Research Laboratory*

Robert Hebner  
*Center for Electromechanics  
University of Texas at Austin*

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<b>14. ABSTRACT</b> The US Army Combat Capabilities Development Command, Army Research Laboratory (CCDC-ARL), in collaboration with the University of Texas at Austin (UT), conducted a charrette focused on unmanned aerial systems (UAS). The charrette was an effort to build on existing activities and expertise in the ARL-South region to reduce the cost and time required for innovation. A Group 2-3 VTOLS UAS and Group 1-2 Air-launch UAS were presented as the challenge problem for discussions. The groups focused discussions on three areas: platform modeling and design, power systems, and sensors and payloads. The report summarizes the breakout groups' discussions on the challenge problems to identify technical gaps, answer science questions, and develop ideas to address gaps and questions. The charrette has stimulated new activities and provided useful information for ARL South to make significant impact and accelerate science and technology in this area.					
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## 1. Introduction

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The US Army Combat Capabilities Development Command, Army Research Laboratory (CCDC-ARL), in collaboration with the University of Texas at Austin (UT), conducted a charrette focused on unmanned aerial systems (UAS) on 25 Oct 2018 at the UT campus. The charrette was focused on answering several overarching questions as follows:

- 1) What will class 1–3 UAS will look and behave like in 2028 and beyond? What capabilities will they have?
- 2) What technology gaps are limiting this future vision today? What are the underlying basic research questions that must be addressed now to reach this future vision?
- 3) What are some potential innovative solutions to these questions? What is currently being worked within the ARL-South\* region and what is not?
- 4) What approaches could the researchers in the ARL-South region pursue as a whole to more rapidly and holistically address the research questions and close the gaps in technology?

The activity grew from the ARL-South Summit held in April 2018 at Rice University.<sup>1</sup> At that meeting, it became apparent that many of the universities participating in ARL-South activities had extensive research programs and interests in UAS. In addition, it is a growing topic of interest of the US Army, both in deployment and in research for future relevant capabilities. The charrette was an effort to build on existing activities and expertise to reduce the cost and time required for innovation.

## 2. Charrette Structure

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To address these questions, the charrette attendees (Appendix A) were organized into three breakout groups:

- 1) Platform Modeling and Design (to include fundamental efforts in aeromechanics)
- 2) Power Systems

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\*ARL South, part of the CCDC-ARL Open Campus initiative, is an effort to co-locate Army research and development personnel in the south central US to gain access to subject matter experts and technical centers and universities that are not well represented on the east coast.

3) Sensors and Payloads (to include communications)

The breakout groups met in three sessions over the course of the day. A full agenda is provided in Appendix B.

- 1) Session 1: Focus on what the hard problems are and underlying science issues preventing us from meeting Challenge Problems 1 and 2 today.
- 2) Session 2: Focus on what science and technology (S&T) is needed to solve questions raised in Session 1.
- 3) Session 3: Focus on the systems' view and interdependencies between technology areas.

The breakouts were given challenge problems to focus the breakout discussions.

1) Challenge Problem 1

a. Group 2–3: Vertical takeoff and landing (VTOL) UAS

Enable UAS with capabilities for diverse operations such as intelligence, surveillance, and reconnaissance (ISR), long-range reconnaissance, electronic warfare (EW) and counter-EW, communications relay, and payload delivery operations. Advanced technologies for improved performance (speed, payload, range, endurance, weight, low power), maneuverability (geometric footprint, turn radius), reliability (low vibratory loads), and survivability (acoustics signature).

2) Challenge Problem 2

a. Group 1–2: Air-launch UAS

Address S&T challenges to launch a UAS from a 6-inch-diameter common launch tube (flexible rotor, unfolding mechanism), with robust flight control, increased flight endurance, and gust tolerance.

### **3. Outputs**

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The expectation was that the charrette would stimulate short-term activities and provide information useful in the longer term. It was successful in both areas. The new activities that were inspired by the charrette included:

- 1) The University of North Texas proactively engaged CCDC-ARL to leverage CCDC-ARL's hybrid-platform concept, as discussed at the



charrette, to focus their internal research on UAS. They will be using their expertise in materials and manufacturing to explore new designs and manufacturing methods using additive and other methods for future morphing design concepts. They will also explore uncertainty analysis and quantification, noise reduction (rotor designs), additive manufacturing-(AM)-assisted integration of strain sensors with wireless data communication to generate mechanical data streams to support platform designs, concepts for integration of 2-D printed batteries with drone structural elements, and concepts for integration of communication packages for mesh networks. A next step for this activity is to explore avenues under ARL South for scientists–faculty–student collaborations and broader participation from ARL South member institutions in building on current capability design and concepts.

- 2) The University of Texas at Austin and CCDC-ARL are collaborating on an effort to show how tools could be developed that permit unmanned aerial vehicle (UAV) designers to optimize the UAV power system, considering the platform design and anticipated mission set. Since the preponderance of UAV design is not done by power specialists, these tools show promise to help the designers design, build, and deploy more effective systems.

The effort to generate actionable information had three areas of emphasis:

- 1) Identify technical gaps and science questions related to the challenge problems.
- 2) Develop a set of innovative ideas that could address gaps and questions.
- 3) Recommend approaches where ARL South could make significant impact and accelerate S&T in this space. The following is a summary, by topic area, of the charrette breakout group discussions. Working documents are included in Appendix C for reference.

#### **4. Platform Modeling and Design**

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The platform group reached a consensus that Group 1–3 UAS are going to become increasingly ubiquitous in both military and civilian applications. Recent advances in emerging technologies, such as electric propulsion, electronics, and manufacturing will enable UAS with progressively improving capabilities. This is backed up by historical trends of vertical-lift aerial platforms evolving in conjunction with the component technological advances. Additionally, the group felt that the pace of vertical-lift UAS platform innovation is accelerating as the

community grows and begins to exploit the potential impact of such technologies. For example, multirotor UAS platforms with distributed electric propulsion were not practical until less than 10 years ago.

The group identified five key platform attributes of vertical-lift UAS that determine their ability to perform any mission as follows:

- **Geometric footprint:** Ability to perform a mission with geometric constraints on its footprint. This sets the upper limit on the available power and energy, as well as the lower limit on the power required. The ideal geometric footprint may be different for different phases of a given mission (e.g., efficient loiter vs. high-speed dash).
- **Efficiency:** Ability to achieve desired performance (speed, flight endurance, range, and payload capability) at low power consumption and with low empty-weight fraction.
- **Robustness:** Ability to both passively and actively reject external disturbances such as wind gusts; design of redundant systems with small weight penalty.
- **Agility:** Ability to perform high-rate maneuvers in constrained spaces or as required for obstacle avoidance at flight speeds.
- **Quieter operations:** Ability to maintain low acoustics signature for improved survivability and reduced community annoyance.

The group felt that UAS capabilities will improve across these five dimensions to enable aerial mobility of a useful payload (sensors, logistics, materiel, etc.) in all environments and terrain in an efficient manner.

#### 1) **Hard problems and underlying science issues**

The problem of developing a UAS platform can be described as selecting the number, location, size, and relative position on the vehicle of subcomponents, such as rotors, wings, control effectors, and power plant. Sizing of these components is performed to maintain force trim under various flight conditions with a goal of maximizing or meeting minimum threshold for the key attributes. For example, designing a vertical UAV for Challenge Problem 1 translates to choosing a configuration (e.g., quadcopter or tail-sitter) and then determining the rotor and wing characteristics (e.g., airfoil cross-section, span, etc.).

The underlying science issues that make the problems hard can be grouped in the following areas:

- **Aerodynamics:** UAS rely on aerodynamic processes to generate forces for propulsion and control. These processes are governed by highly nonlinear equations and, as such, estimation of forces acting on various components is challenging with simpler (computationally efficient/reduced order) methods. The platform concept development is an iterative process and higher fidelity methods that require large computational time or resources are not practical. Additionally, significant aerodynamic interactions can occur between different vehicle components and inaccuracies in predicting forces can lead to errors in estimating vehicle attributes at the design stage. Variation of aerodynamic characteristics with scale Reynolds numbers introduces additional problems as extrapolation of measured or computed aerodynamic characteristics across large ranges of size may not be accurate. For the same reason, knowledge and conventional wisdom accumulated over the last several decades for traditional large rotorcraft may not be applicable to Group 1–3 UAS.
- **Structural Dynamics:** Structural components in a vehicle platform are designed to connect subcomponents and carry the loads under various flight conditions. A tradeoff is needed between the strength and weight of these components. Estimating weight of these structural components is a hard problem, especially for composite material that generally provides lightweight solutions. Physics-based methods are needed for accurate determination of structural characteristics without requiring large computational resources.
- **Aeroelasticity:** The need to minimize vehicle weight or constrain the geometric footprint necessitates the use of flexible structures. Such structures, when subjected to unsteady aerodynamic loads, can exhibit catastrophic aeroelastic instabilities under certain flight conditions. Avoiding onset of instabilities imposes limits on achieving the full potential of the platform concept. Understanding of the physical mechanisms of fluid-structure coupling is needed to overcome this problem. Underlying science issues are the phenomena of fluid flow transition, separation, and reattachment, and their coupling with moving boundaries.
- **Acoustics:** Accurate estimation of the noise signature involves two steps: prediction of the aerodynamics and subsequent evaluation of the acoustic sources. Propeller aerodynamic noise, and noise generated by flow interacting with various components, such as the rotor wing and

wing pylon, is required. While the effects of these noise sources have been individually studied by several researchers, evaluation of their complex interplay in a system that involves multiple rotors can result in nontrivial interference patterns. The magnitude of acoustic pressures are several orders of magnitude smaller than ambient pressure and thus the measurement or computation of acoustics is challenging. Additionally, sound reflection from solid boundaries or refraction/diffraction effects due to atmospheric conditions are mathematically complex and difficult to model. There are also questions of the appropriate metrics for quantifying the annoyance/detectability of UAS (e.g., A-weighted sound pressure level) and how to properly account for psychoacoustic effects (frequency masking, etc.).

- **Flight Stability & Control:** The stability of the vehicle during different phases of the mission, such as hover, cruise, and maneuvering flight, is an essential component for designing control surfaces and finding limits on the pilot control inputs (e.g., revolutions per minute (rpm) limits on the rotor or collective range). Aspects such as flight control, flight stability, and gust tolerance are not completely understood. The control problem for multirotor/multiwing concepts results in an overdetermined system and, therefore, the optimum control strategy can be mission specific and depends on the desired attributes. The curse of dimensionality makes developing optimum flight controllers difficult as the number of control surfaces/actuators increases.

## 2) **S&T needed to solve questions raised in Challenge Problem 1**

- Mathematical methods and algorithms to determine effects of aerodynamic interactions on forces generated on vehicle components, correlated with data gathered from reference systems but with the ability to extend to additional configurations.
- Artificial intelligence/machine learning (AI/ML) can have disruptive impact on platform configuration design space by enabling vehicle concepts with a large number (>100) of control effectors. Such vehicle concepts can achieve extreme improvements in multiple attributes such as agility and robustness. AI/ML algorithms for vehicle flight control and design process for concepts with redundant control effectors.
- Methods to explore the design space of vehicle concepts and conduct tradeoff analyses at varying levels of fidelity.

- Adaptive structures to enable in-flight vehicle reconfiguration for efficiency across the flight conditions and operating environments.
  - Lightweight material with adaptive structural properties.
  - Robust and efficient active fluid and structure control technologies for UAV platform concepts.
  - Structural design approaches to enable lightweight UAV platforms as well as provide accurate estimate of weight at the concept development stage.
  - Tools of varying fidelity for assessing flight dynamics and handling qualities at concept design stage/standards for handling qualities.
  - Understanding of Reynolds number effects on the aeromechanics and acoustics of vehicle components and their mutual interaction.
  - Understanding of acoustics sources, propagation, and perception relevant at different scales of UAV.
  - AM methods and material for UAV components for desired aerodynamic shape and structural strength.
  - Development and application of uncertainty quantification methods toward UAS concept design and performance predictions.
- 3) **Focus on the systems' view and interdependencies between technology areas**
- Power density or energy density of power system has a huge impact on the UAV platform concepts.
  - Transient response of electric motor or engine impacts the vehicle agility attributes (if rpm control is used).
  - Size, weight, and power of sensor systems will influence autonomous flight and navigation capabilities.
  - Propulsion system architecture and its effect on vehicle concept.

## 5. Power Systems

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In many ways, the approach to meet the power needs is agnostic to the challenge problems. It was quickly recognized that there were fundamental constraints that needed to be addressed including:

- UAVs are always going to need the smallest, lightest power system to meet the mission.
- Propulsion is likely to require a different power- and energy-use profile from that of any mission system on the UAV. The power system must supply both.
- Depending on the mission, power density or energy density may be the driver for power system size.
- The audible noise signature is likely to always be important.

Based on these discussions, several research directions were explored.

- 1) Power system design tools
  - a) Given a platform and a mission set, better tools are needed to calculate the best power system design and components.
    - i) An even better tool would permit both platform and power system trades to be made to get the optimum hardware to accomplish anticipated missions.
  - b) This is likely an engineering development task as tools exist in different areas of the transportation field. But none appear to be appropriate for this application.
  - c) Multi-objective optimization
    - i) Define state space
    - ii) Determine functions and metrics that need to be optimized
    - iii) Optimize constraints of subsystems
    - iv) Determine tools to optimize computational challenges (such as computational fluid dynamics, fluid-structure interaction, structures, thermal, etc.)
  - d) Develop power curves for various weights
    - i) Burst speed
    - ii) Non-steady-state environments
- 2) Advanced components leading to improvements in size, weight, and range
  - a) There is a robust set of components for combustion-based systems, electric power, and for some hybrid systems. But, there needs to be, and

there are likely opportunities for, improvements of these technologies for UAV applications.

- b) Research leading to improved structures, which could include:
    - i) Conformable hydrogen tanks
    - ii) Battery packs sharing structure with platform
  - c) Efficient and silent propellers
  - d) Improved motors
    - i) Composite structures
    - ii) Motors that minimize need for power electronics
    - iii) Varying power draws
    - iv) Flywheel-based technologies for power (50+ lb now)
  - e) Improved motor drives
  - f) Electromagnetic launch of platforms
  - g) Smaller cable plants
    - i) New materials
    - ii) Improved life assessment
    - iii) Improved definition of life requirements
    - iv) Optimal electrical environment
  - h) Ultracapacitors
  - i) Liquid molten reserves
  - j) Low-endurance (poor recharge cycle [10–100 cycles]), high-power battery
  - k) Jettison power source (limited one-use power sources)
  - l) Launch power versus cruise power challenges
  - m) Rotor turbulence used to generate power?
- 3) Improved management of power system effects
- a) Electromagnetic interferences from power electronic and other switching
    - i) Focus on elimination via package design
  - b) Thermal management
    - i) Enhance efficiency
    - ii) Improved airflow cooling
    - iii) Challenge increases for combustion systems, particularly at higher altitudes
  - c) Vibration management
    - i) Minimize the size and weight impact
- 4) Dynamic route selection
- a) Development of improved sensors and controls that enhance the ability to sense and exploit wind patterns when range and fuel economy are more important than speed

- i) Intelligent path planning to maximize power savings
  - ii) Use environment/weather to advantage relative to power use
- 5) Concepts
  - a) Modular approaches to power systems
    - i) Mission packages for energy (packetize)
  - b) Swap out power sources based on missions
  - c) Testbeds to explore integration and h/w in the loop
  - d) Low–high voltage constructs (what is the right voltage?)
  - e) Integration issues including structures, batteries, sensors, and corresponding interdependencies
  - f) Explore platform configurations in combination with various power combinations

Finally, there was discussion as to how to accelerate the progress via collaboration. The important items discussed were that collaboration always takes money, but funding does not inevitably lead to collaboration. Suggestions were to:

- Invigorate and expand existing collaborations;
- Look for opportunities for joint funding; and
- Collaboratively accelerate innovations beyond individuals.

## **6. Sensors and Payloads (to include Communications)**

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### **6.1 Challenge Problem 1: Focused on Group 2–3 VTOL UAS**

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Breakout Session 1 started with a discussion to revisit the challenge problems to define them from a sensors and payload perspective. The Group 2–3 VTOL UAS was viewed as a long-range ISR mission. Several platform characteristics were captured as necessary to meet the challenge objective to include:

- A platform that is 100+ km mission capable
- Single-platform mission capable (expandable to multiple for multiple targets or larger areas)
- 50-lb class platform or smaller
- Affordable construction and design to support attributable mission potential
- Either fixed wing or hybrid design to meet potential mission profiles
- Ability to perch desired



- Ability to send real-time data preferred, although potentially not feasible. Alternative was Dropbox or coordination with unmanned ground vehicle concepts.

Based on this characterization of the UAS platform, discussion focused on what the major challenges are to complete the long-range ISR mission. These included:

- Communication to/from platform and how to get information out from the sensor payloads (e.g., real time or download at end of mission)
- Stealth to include signature of platform and emission of sensor payloads
- Ability to localize (self and threats)
- Ability to autonomously navigate, to include night and GPS, denied operations over long distance and through complex environments
- Trade space of fixed wing and VTOL and the need for high maneuverability and control at point of ISR mission (e.g., ISR maneuver in dense urban areas, perch and stare missions, etc.)
- Ability to identify threats and assess risks
- On-board processing to support autonomy, AI for decision making, and so on
- Size, weight, and power constraints
- Resilience to operate in a contested environment and in face of adversarial actions (EW, jamming, counter-UAS, etc.)
- Scalability to large numbers of targets

## **6.2 Challenge Problem 2: Group 1–2 Air-Launch UAS**

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The Group 1-2 air-launch UAS was viewed as a teaming activity between multiple platforms. Several platform characteristics were captured as necessary to meet the challenge objective as follows:

- System could include heterogeneous platforms (large/small, manned/unmanned)
- Numbers of systems expected in the range of 2–10 per large launching platform. Swarm behavior potentially desired from groups of systems (system of systems including 10+ platforms)

- Platforms need autonomous maneuvering capability and to be able to operate with minimal communications
- Should be able to perform heterogeneous or layered behaviors and capabilities
- The ability to perform distributed control and processing is desired
- Needs to have autonomous and AI capabilities to enable mission adaptability
- Needs to consider human in the loop as both a mission commander and teammate (e.g., perception input)
- Needs to consider air space deconfliction
- Needs to consider mission platform and payload power profiles
- Needs long endurance with low signature

Based on this characterization of the Air-Launch UAS mission, the discussion focused on what the major challenges are to complete the UAS teaming operation. These included:

- Conflict resolution
- Understanding team capability at any given time, functional allocation of resources given the team at that moment, and the context of the mission environment
- Human-agent teaming issues such as trust and understanding of team and individual behaviors and how to integrate with humans at varying levels from commanders, to teammates, to bystanders
- Common world model and representations of the world that are understandable by humans and platforms. The level of abstraction needed to share multimode sensory inputs.
- Shifting and reallocations of tasks; what happens when tasks cannot be completed
- Latency of information and data sharing (to include localization, platform state, and perception data)
- Predicting mission effectiveness and understanding growth in uncertainty across systems
- Communications: how often, how much

- Interoperability of component technologies and platforms given potentially different vendors; need for open architectures
- Scalability of algorithms for small platforms
- Cybersecurity
- Test, evaluation, verification, and validation for autonomous systems software
- Small platform with long endurance (4–8 h) and high speed (>100 knots)
- Low acoustics, visual, and heat signature

## **7. Technology Solutions**

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Based on the discussions of relevant missions, needed platform characteristics, and underlying research challenges, the following were identified as potential areas for investment to overcome them.

- Multispectral communications
- Variable bandwidth communications based on resources available, quality of service needed, and mission needs given context of mission at that moment
- Daisy-chained communications
- Directional communications for security
- Game theory to address incomplete information
- Edge and distributed computing
- AI planners for low-level control based on high-level constraints
- Software-defined networks
- Task allocation methods
- Nonconsensus methods for decision making
- Adaptive platform- and mission-level controls
- Context-aware communications and control
- Infrastructure: reconfigurable and delivery methods

- Formal methods for test and evaluation, verification and validation, explainable AI, model-based simulations
- Trust in human-agent teaming
- Fidelity of information between agents
- Data fusion for heterogeneous agents and sensors
- Passive sensor-based solutions (navigation and ISR across all environments)
- Layered approaches to scalability
- Co-design across tech areas—systems-of-systems approach
- Multifunctional structures
- Routing—given operational environments and mission constraints
- Standardization (handshakes, comms, what makes up a team)
- Cooperative simultaneous localization and mapping (heterogeneous solutions, nonGPS solutions, austere and night operations)
- Multiconfigurations
- Unconventional configurations for long endurance and high speed
- Modular electric power systems (battery)

## 8. References

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1. Maupin H. US Army Research Laboratory (ARL) South Partnership Summit 2018. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2018 Apr. Report No.: ARL-SR-0413.

## **Appendix A. Attendees**

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This appendix appears in its original form, without editorial change.

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Prefix	First Name	Last Name	Title	Department
<b>Army Futures Command</b>				
Mr.	Rex	Eiserer	Liason	
<b>Army Research Laboratory</b>				
Dr.	Christopher	Cameron	Postdoctoral Fellow	Vehicle Technology Directorate
Dr.	Hao	Kang	Lead, Rotocraft Aeroelasticity Team	Vehicle Technology Directorate
Ms.	Heidi	Maupin	Director, ARL South	
Dr.	Brett	Piekarski	Senior Campaign Scientist	Sciences for Maneuver Campaign
Mr.	Elias	Rigas	Division Chief, Vehicle Applied Research Division	Vehicle Technology Directorate
Dr.	Edward	Shaffer	Division Chief	Energy and Power Division
Dr.	Rajneesh	Singh	Research Aerospace Engineer	
<b>Clarkson Aerospace &amp; Rice University</b>				
Dr.	Baburaj	Eranezhuth	Director of Materials Research	
<b>New Mexico State University</b>				
Dr.	Igor	Dolgov	Associate Professor	Psychology
Dr.	Liang	Sun	Assistant Professor	Mechanical and Aerospace Engineering
<b>Texas A&amp;M University</b>				
Dr.	Moble	Benedict	Assistant Professor	Aerospace Engineering
Dr.	Swaroop	Darbha	Professor	Mechanical Engineering
<b>Texas Tech University</b>				
Dr.	Stephen	Bayne	Professor, ARL South Researcher	Center for Pulsed Power & Power Electronics
Dr.	Michael	Giesselmann	Professor & Chair	Department of Electrical & Computer Engineering
<b>U.S. Army AMRDEC</b>				
Mr.	Tom	Bernal	Mechanical Engineer	Aviation Development Directorate
<b>University of North Texas</b>				
Dr.	Diana	Berman	Assistant Professor	Materials Science and Engineering
Dr.	Kamesh	Namuduri	Professor	Electrical Engineering
Dr.	Hamid	Sadat	Assistant Professor	Mechanical and Energy Engineering
Dr.	Hector	Siller	Assistant Professor	Engineering Technology
<b>University of Oklahoma</b>				
Dr.	Andrea	L'Afflitto	Assistant Professor	Aerospace and Mechanical Engineering
<b>University of Texas at Arlington</b>				
Dr.	Yan	Wan	Associate Professor	Electrical Engineering
<b>University of Texas at Austin</b>				
Ms.	Liz	Arredondo	Executive Assistant	Center for Electromechanics
Dr.	Evan	Erickson	Research Fellow	Texas Materials Institute
Mr.	Michael	Godwin	Program Administrator	Vice-President for Research
Ms.	Monique	Gregory	Associate Director for Research Relations	Cockrell School of Engineering
Dr.	Bob	Hebner	Director	Center for Electromechanics

Mr.	Johnny	Holden	Media and Outreach Specialist	Cockrell School of Engineering
Mr.	Mike	Lewis	Senior Engineering Scientist	Center for Electromechanics
Dr.	Wangda	Li	Postdoctoral Fellow	Texas Materials Institute
Dr.	Jayant	Sirohi	Associate Professor	Aerospace Engineering and Engineering Mechanics
Dr.	Charles	Tinney	Research Scientist	Applied Research Laboratories
<b>University of Texas at El Paso</b>				
Dr.	Vinod	Kumar	Associate Professor	Mechanical Engineering
Dr.	Oscar	Mondragon	Clinical Associate Professor	IMSE, College of Engineering
<b>University of Texas at San Antonio</b>				
Dr.	Mauricio	Gomez	Assistant Professor in Practice	Department of Computer Science



## **Appendix B. Charrette Agenda**

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0830–0900: ARL introduction of two scenarios and high-level platform requirements

0900–1030: Initial subgroup discussions. The initial subgroups will be platforms, power, and sensors. The interests and expertise of the self-selected members of the groups are expected to lead to further subdivision or redefinition. The focus is not on designing a UAS to specifications but ideas that will drive future specifications.

1030–1100: Brief progress reports

1100–1230: Subgroup discussions #1: Examine the potential advances that have been identified in two ways. First, are there enough ideas and are they sufficiently innovative that they may make a relevant difference? Second, what research and development is needed to make the ideas plausible?

1230–1330: Lunch

1330–1400: Brief outs of subgroup discussions

1400–1530: Subgroup discussions #2: Coordinate ideas across groups, refine the topics of interest to the individual subgroup, and develop a specific set of follow-up steps for the next two months to effectively communicate the potential of your concepts.

1530–1600: Subgroup discussions #2 brief outs

1600: Adjourn

## **Appendix C. Working Documents for Topic Areas 2 and 3**

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C.1 Working Documents for Topic Area 2: Power Systems

How much power for payload

- + Computational
- passive sensor
- + EW Payloads
  - Tech
  - + Platform

read many power load to can-ops

- Simulation multi-ops

Modular power solutions

- on-demand design
- adaptable
- EMI - from switching
- Heat distro
- Vibration loading for sensors
- ALE worse case is w/ being carried

Sensor location

- where should they be
- what are they doing
- sense state for adaptive systems

Trade Platform Config VS Power solution

CBM

right metrics to capture overall pers config signature

Co-loading for sensors for ALE

- prioritization common to ALE launched backwards

⇒ MURI

⇒ NSF Center

⇒ Student Rotations Problem

- Formation control
- scale missions
- Challenge - cooperation
- WP approach
- Design challenge
- Shared knowledge space
- Trade space analysis tools

Resources  
Workshop

**C.2 Working Documents for Topic Area 3: Sensors and Payloads  
(to include communications)**

Long Range JSR  
 - 100+ Km  
 - Single platform  
 - ~50/b class or less / <sup>Attributable</sup> Resources  
 - Contested - GPS denial  
 - Fixed/hybrid  
 - Perch  
 - Ideal - Real time  
 What is realistic  
 - drop box (Solution)  
 - UGS

Problems  
 1) Communication / info Out  
 2) Stealth - Passive sensors  
 3) Localization - Night operations  
 - Navigation - self det threats  
 4) Trade VTOL/fixed - controls highly maneuverable  
 5) Risk assessment - threats  
 6) Processing / duration / AI/ML  
 7) SWaP  
 8) Resilience  
 9) Scalability in # of targets

Solutions - LR - AT  
 1) Multispectral Comms (C)  
 II - BW & quality of service  
 2) Daisy chain Comms (C)  
 3) Multi-modal - directional comms  
 4) Geometry to address incomplete info  
 5) edge / distributed computing  
 6) AI Planner for low level control  
 possible on high level constraints  
 ex: hidden Park models  
 7) Software defined network <sup>Hierarchical</sup> AT

7) Software defined network <sup>Hierarchical</sup> AT  
 8) TASK allocation  
 - a lot of techniques  
 9) non-consensus method (dine)  
 10) adaptive controls (missile control)  
 - when to interact  
 11) context aware comms/control  
 12) Infrastructure  
 - feature configurable  
 - delivery methods  
 13) formal methods for T&C  
 - during build - model based simulation  
 - operations  
 - explainable AI

Teaming

- 1) Heterogeneous Large <sup>Planned/Unplanned</sup> & Small
- 2) #s 2-10's (Swarm)
- 3) limited comms
- 4) heterogeneous behavior capabilities <sup>Structural</sup>
- 5) dist. control/access
- 6) Real Time Mission adapts
- 7) Human in Loop <sup>Air space domain</sup>

Problems

Conflict Resolution/Adaptable  
 Understanding Team Capabilities  
 Timely Local/Team  
 ↑ function Allocation

- 1) HAT - <sup>Trust</sup> common representations  
 abstractions - Language
- 2) Latency of info
- 3) Shifting / Task reallocation  
 - what happens when a task cannot be done?
- 4) Uncertainty Growth - Mission <sup>flexible</sup> <sup>robust</sup>  
 Probabilistic vs deterministic
- 5) Comms - how often/how much  
 - Local/Global HAT

- 6) Uncertainty Growth - Mission <sup>flexible</sup> <sup>robust</sup>  
 Probabilistic vs deterministic
- 7) Comms - how often/how much  
 - Local/Global HAT
- 8) Different vendor integration
- 9) Scalability - algorithms with <sup>robustness</sup>
- 10) Humans as commanders <sup>teamwork</sup> <sup>standards</sup>
- 11) Cyber Security
- 12) TEWY

- build trust in HAT  
 ↳ ability of info between agents
- Data Fusion (heterogeneous agents)
- Passive Sensor based solid forms  
 for Mav/ISR across  
 all environments
- Layered approaches to  
 scalability
- Co-design across tech areas  
 systems & systems
- Multi functional structures
- Rating given operational environment  
 mission duration constraints

- Standardization - handshakes  
 - comms  
 - what makes up a team
- Cooperative SLAM  
 - heterogeneous solutions  
 - non-GPS/SLAM solutions  
 - Anstare, MIGHT
- PAC Loops

## List of Symbols, Abbreviations, and Acronyms

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2-D	two-dimensional
AI	artificial intelligence
AM	additive manufacturing
CCDC-ARL	US Army Combat Capabilities Development Command, Army Research Laboratory
EW	electronic warfare
GPS	global positioning system
ISR	intelligence, surveillance, and reconnaissance
ML	machine learning
rpm	revolutions per minute
S&T	science and technology
UAS	unmanned aerial systems
UAV	unmanned aerial vehicle
UT	University of Texas at Austin
VTOL	vertical takeoff and landing

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