Johns Hopkins Engineering

Autonomous Personal Air Vehicle (APAV)

645.800 Systems Engineering Project

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Outline

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Biography

- Education
  - B.S. in Mechanical Engineering (May 2014) from the University of Maryland, College Park
  - M.S. in Systems Engineering (expected 2018) from Johns Hopkins University, Engineering for Professionals
- Experience
  - Perspecta (formerly Vencore, formerly The SI Org.) – [Aug 2014 to Oct 2018]
    - Systems Engineer
      - Supported systems engineering/integration lifecycle for the acquisition of a critical Command and Control software
    - Predictive Modeling Analyst
      - Analyzed detailed system and operational requirements of Geospatial Intelligence (GEOINT) systems through the use of the modeling and simulation
  - Johns Hopkins Applied Physics Lab (APL) – [Oct 2018 to Present]
    - Modeling and Simulation Analyst (FPS/KVQ)
      - Support to precision strike analysis. Modeling and analysis of radar systems and Integrated Air Defense Systems

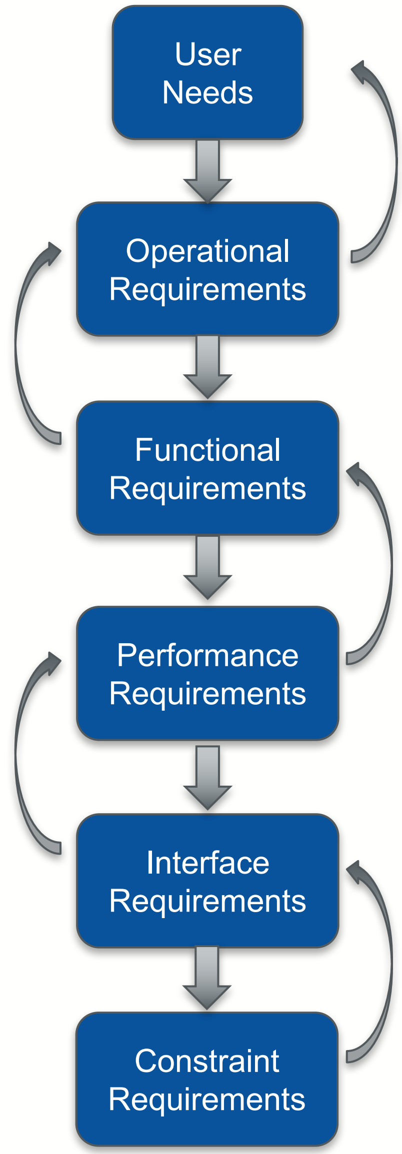
Introduction & Need for System

- The APAV system provides an alternative method of transportation which integrates various sensor packages with high-precision navigation in order to autonomously transport passengers and cargo
- The need:
  - Average U.S. commute times can reach up to 34.7 minutes one-way
  - Number of workers with commute times ≥45 min is growing at a faster rate than those with commute times <45 min
  - Longer commutes have been seen to be linked with increased rates of obesity, high cholesterol, high blood pressure, back and neck pain, divorce, depression and death
  - A study from the United States Department of Transportation attributes 94% of serious crashes to human choices
  - The APAV offers a fully-electric solution which helps address the rising concern of global warming and carbon emissions
    - Cars and trucks account for nearly one-fifth of all U.S. emissions, emitting 24 pounds of carbon dioxide and other global warming gases per gallon of gas

Requirements (1 of 2)

Approach

- Requirements generation approach:
  - Identify top-level User/Mission Needs
  - Decompose User Needs into:
    - Operational Requirements (mission and scope)
    - Functional Requirements (capabilities/tasks)
    - Performance Requirements (quantitative ability)
    - Interface Requirements (external interfaces)
    - Constraint Requirements (limitations, -ilities)
- Each requirement written to be unambiguous, verifiable, clear, and implementation-free
- Every requirement traceable back to User Needs
- Identified verification methods for each requirement (inspection, analysis, demonstration, test)



*Iterative Process

Requirements (2 of 2)

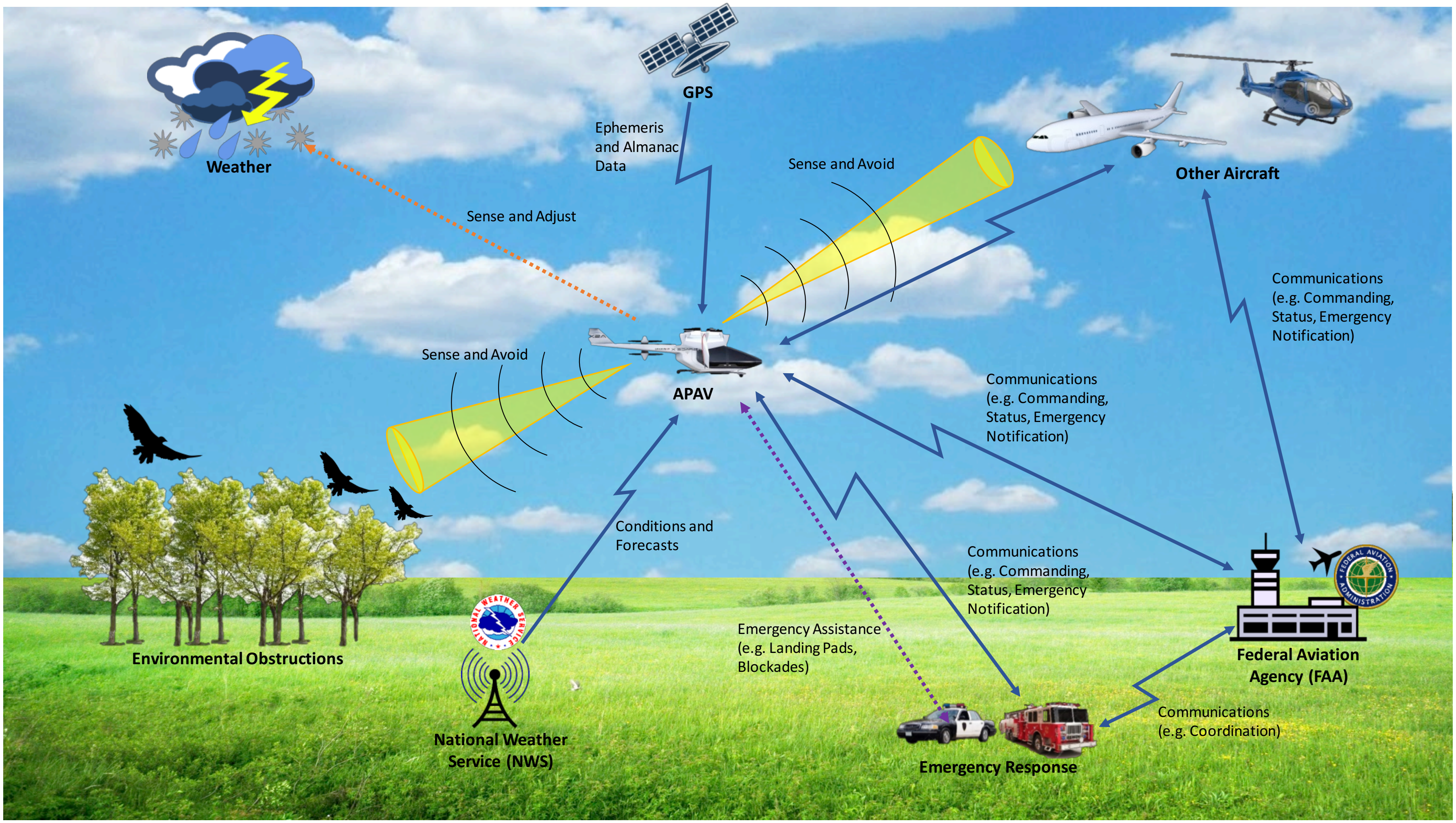
Sources and Stakeholders

- Sources for requirements generation:
  - Independent research
    - Societal Needs – Capability gaps
    - Existing technologies
  - User and Stakeholder Interviews/Surveys
- System Stakeholders:
  - Daily Commuters, Federal Aviation Administration (FAA), Federal Communications Commission (FCC)

	Total	Quantitative	% Quantitative	Binary	Qualitative
Requirements Analysis Report	123	76	62%	31	16
Functional Analysis Report	145	91	63%	37	17
Trade Study	149	95	64%	37	17
Conceptual Design Report	155	101	65%	37	17
Test Plan	155	102	66%	37	16
System Specifications	216	176	81%	40	0

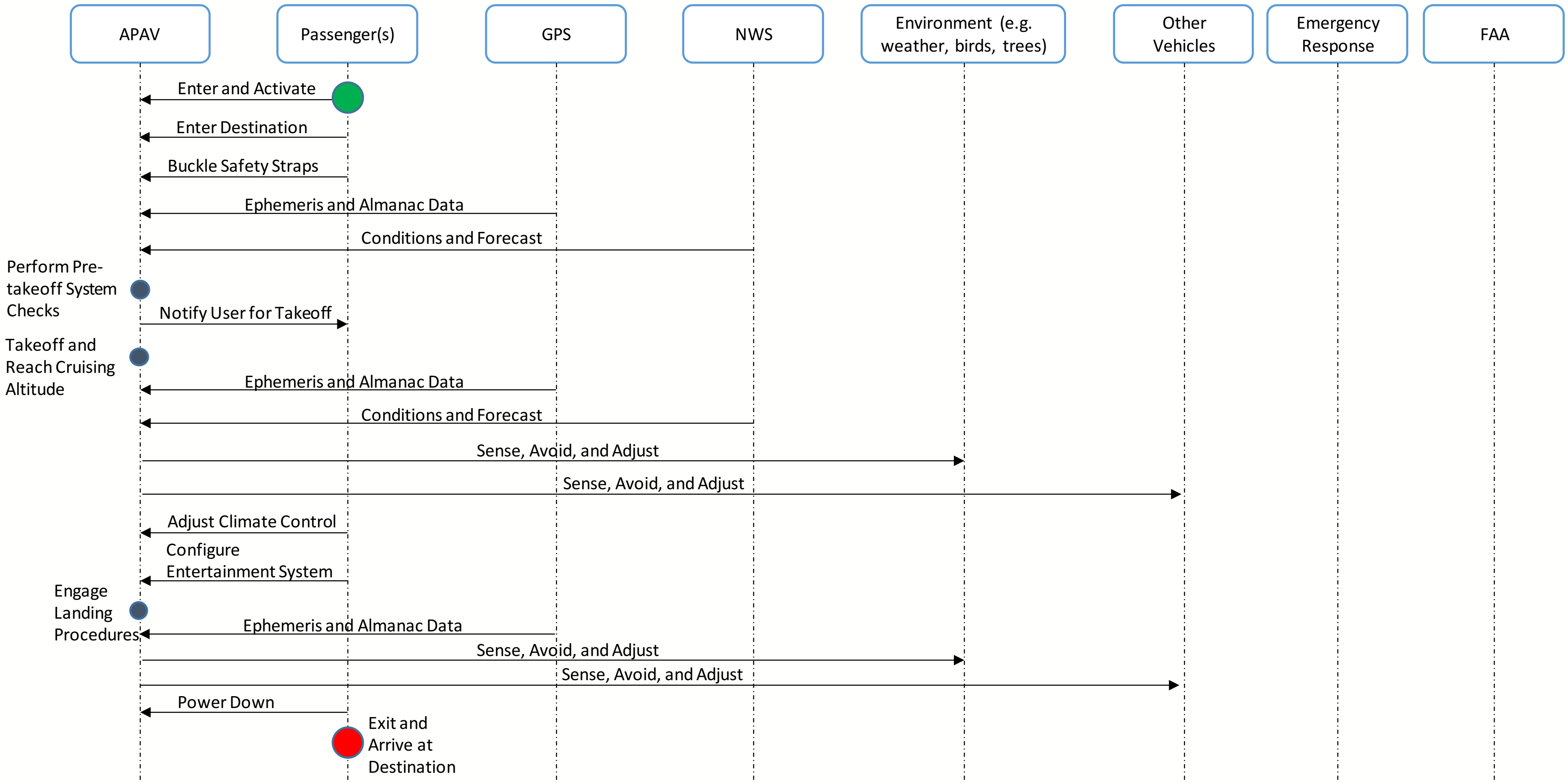
Concept of Operations (CONOPS) (1 of 3)

System OV-1



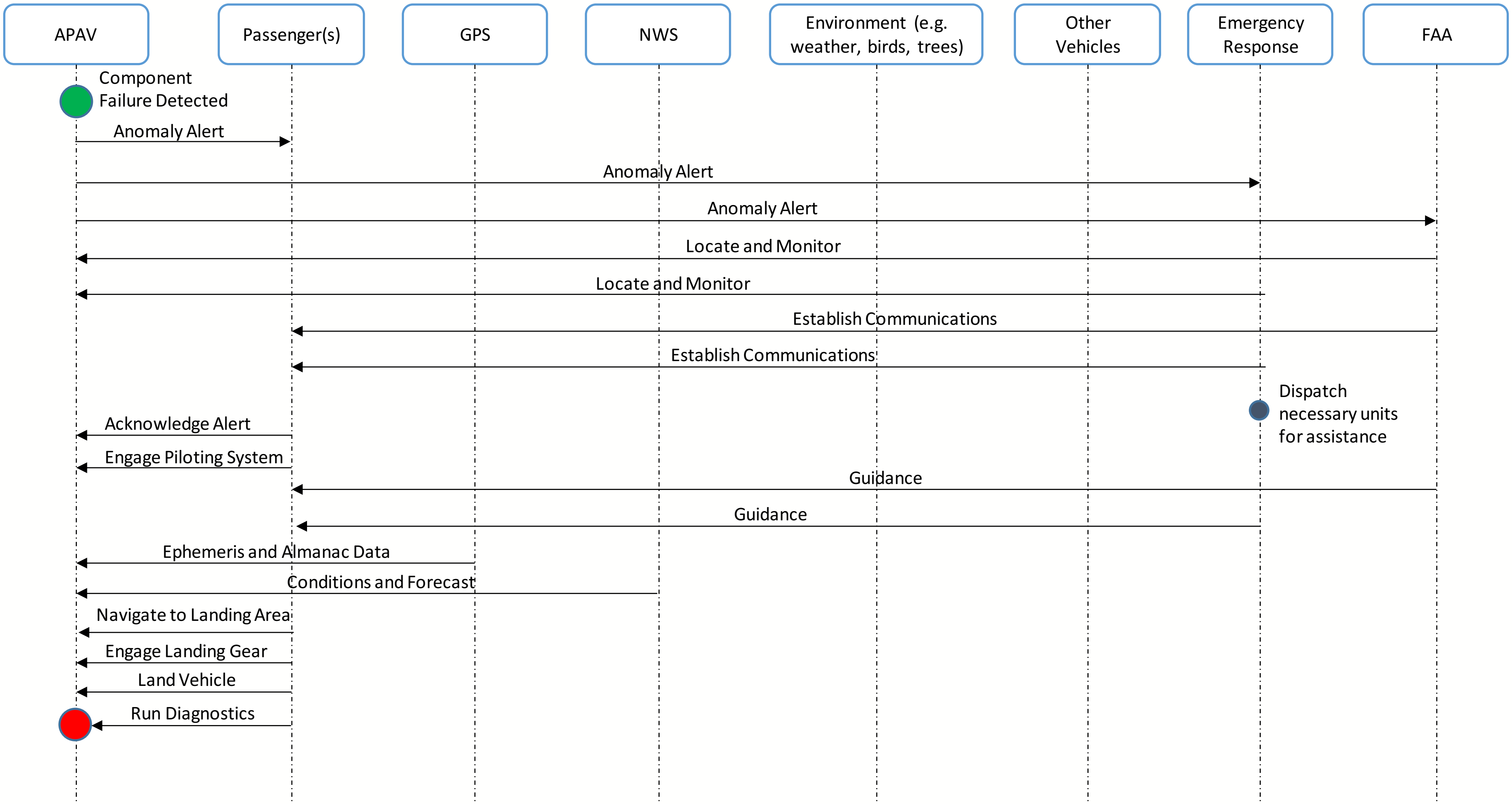
Concept of Operations (CONOPS) (2 of 3)

Scenario: Baseline



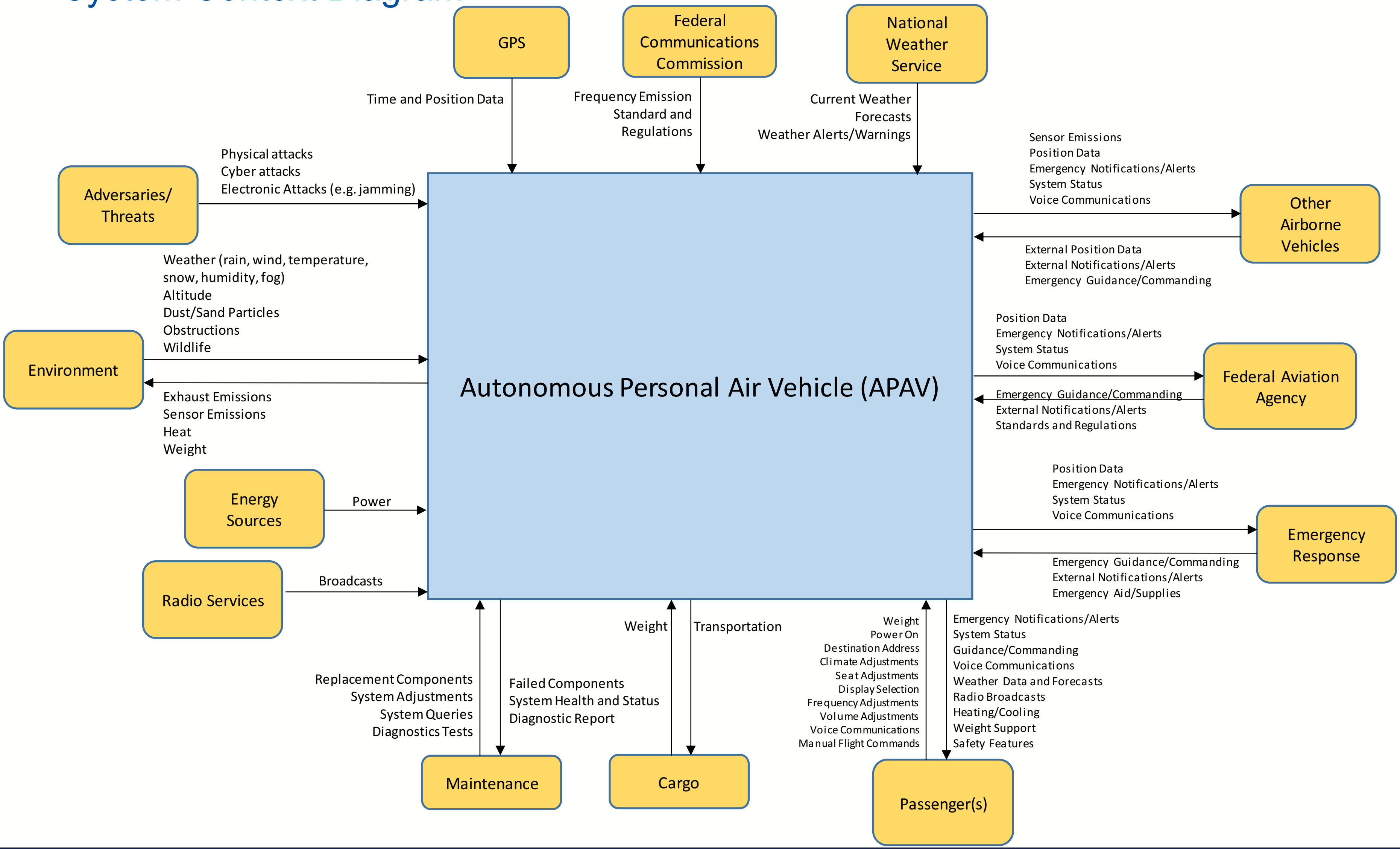
Concept of Operations (CONOPS) (3 of 3)

Scenario: System Failure – Manual Operations



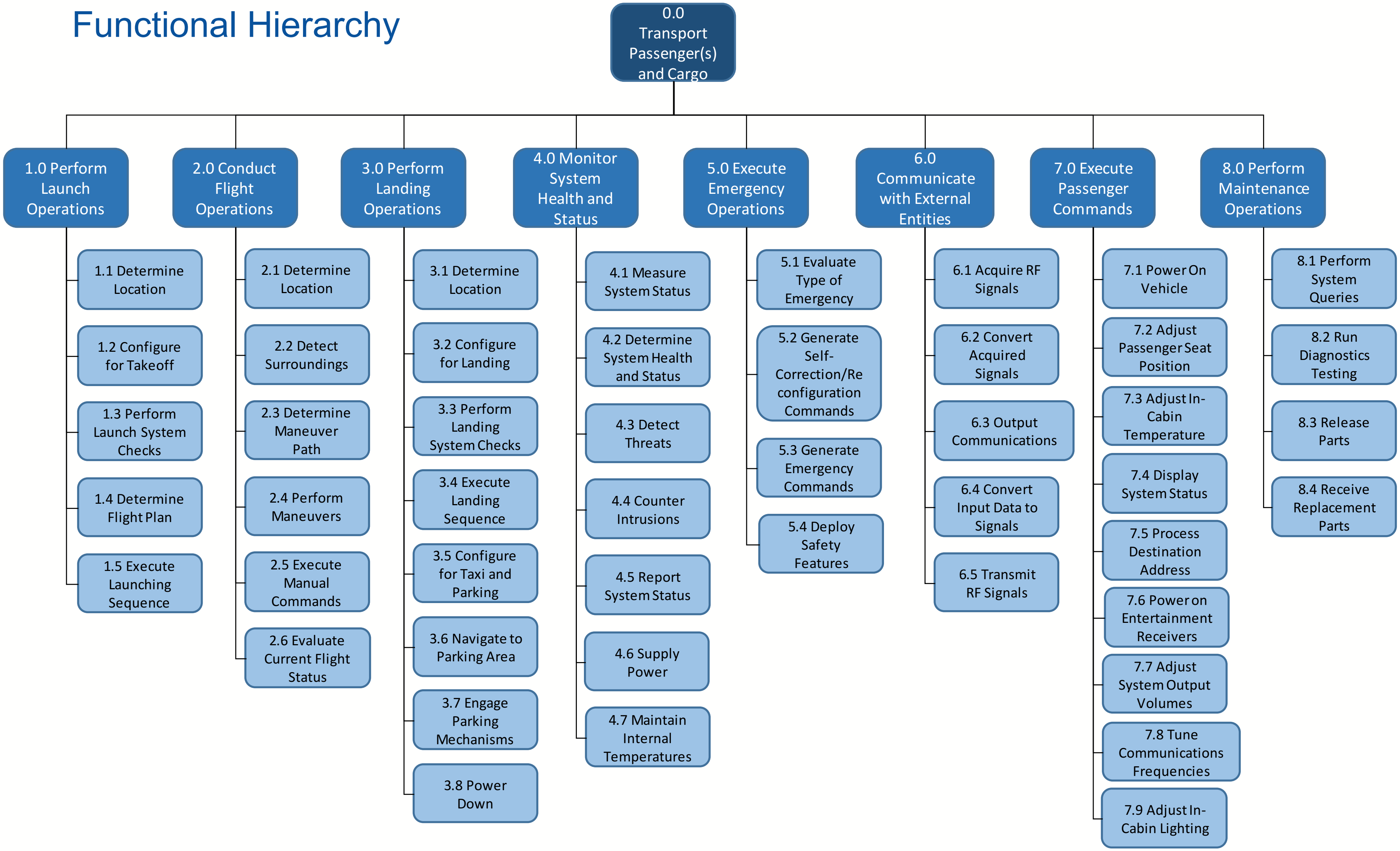
Functional Concept (1 of 6)

System Context Diagram



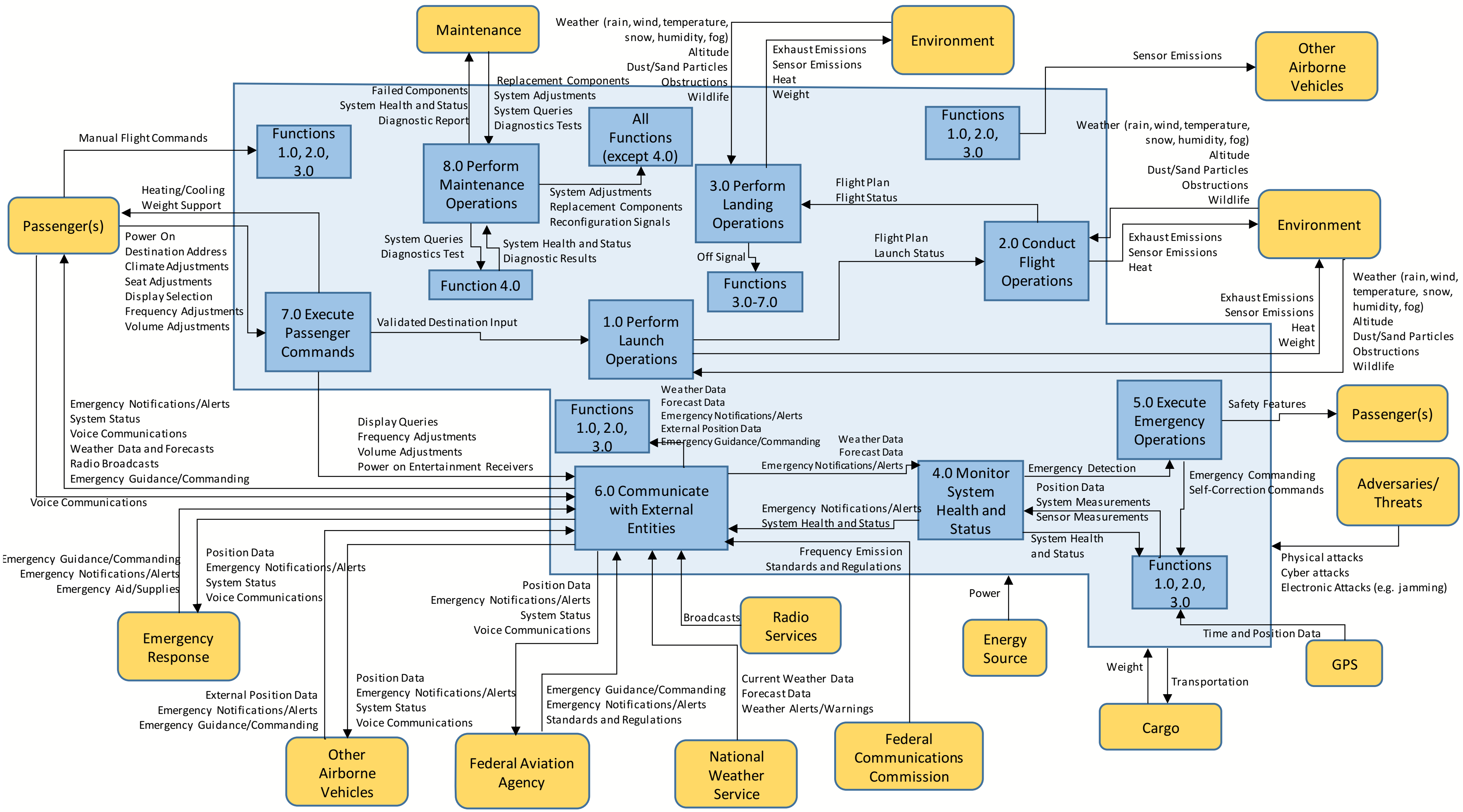
Functional Concept (2 of 6)

Functional Hierarchy



Functional Concept (3 of 6)

Top-Level Functional Block Diagram (FBD)



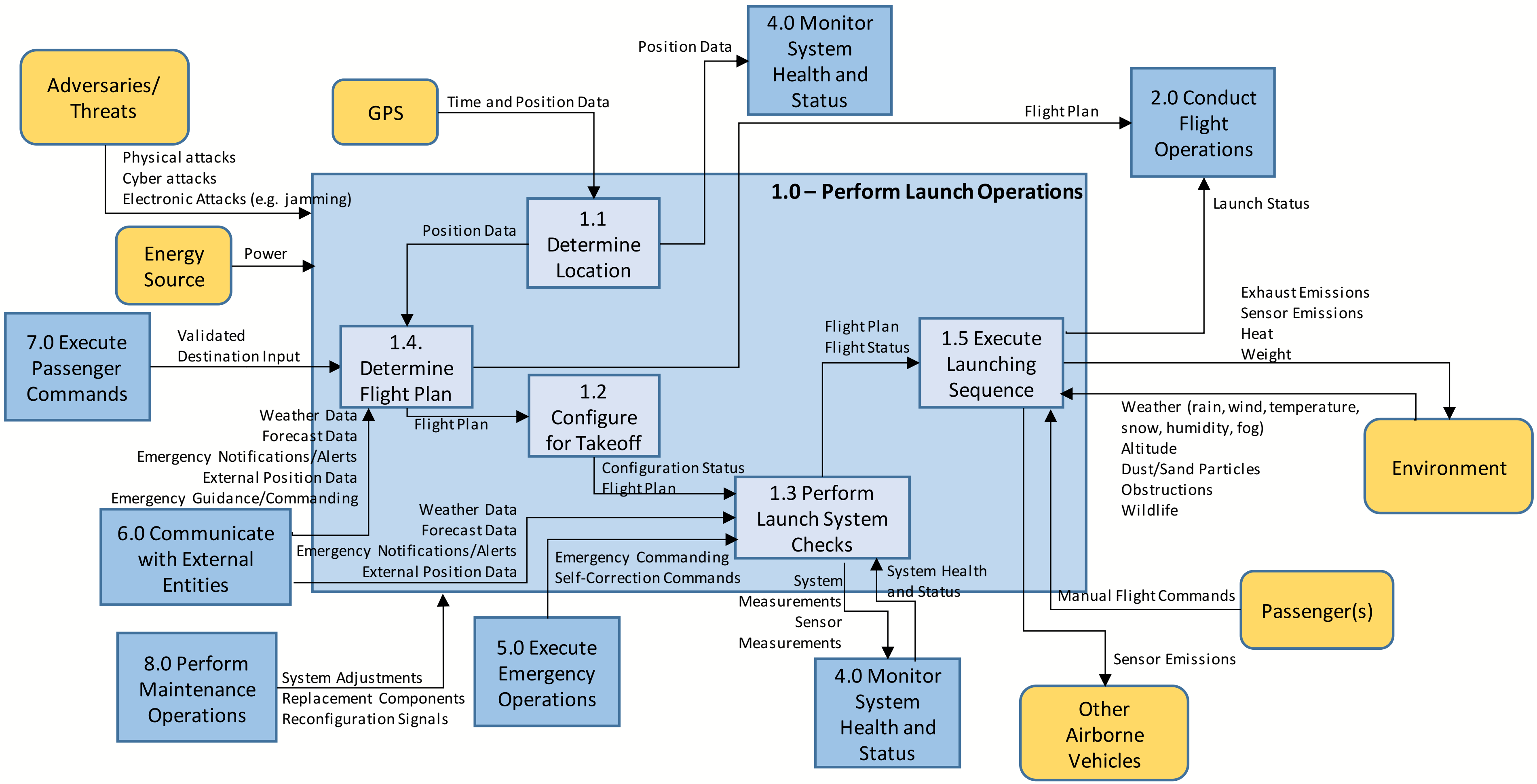
Functional Concept (4 of 6)

Top-Level N2 Diagram

Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power, Time and Position Data, Weather (rain, wind, temperature, snow, humidity, fog), Altitude Dust/Sand Partides, Obstructions, Wildlife, Manual Flight Commands	Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power, Time and Position Data, Weather (rain, wind, temperature, snow, humidity, fog), Altitude Dust/Sand Partides, Obstructions, Wildlife, Manual Flight Commands	Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power, Time and Position Data, Weather (rain, wind, temperature, snow, humidity, fog), Altitude Dust/Sand Partides, Obstructions, Wildlife, Manual Flight Commands	Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power	Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power	Physical attacks, Cyber attacks, Electronic Attacks (e.g. jamming), Power, Frequency Emission Standards and Regulations, Broadcasts, Current Weather Data, Forecast Data, Weather Alerts/Warnings, Emergency Guidance/Commanding, Emergency Notif/Alerts, Standards and Regulations, External Position Data, Emergency Aid/Supplies, Voice Communications,	Power On Destination Address Climate Adjustments Seat Adjustments Display Selection Frequency Adjustments Volume Adjustments	Replacement Components System Adjustments System Queries Diagnostics Tests	
1.0 Perform Launch Operations	Flight Plan Launch Status		Position Data System Measurements Sensor Measurements					Exhaust Emissions Sensor Emissions Heat Weight
	2.0 Conduct Flight Operations	Flight Plan Flight Status	Position Data System Measurements Sensor Measurements					Exhaust Emissions Sensor Emissions Heat
		3.0 Perform Landing Operations	Position Data System Measurements Sensor Measurements					Exhaust Emissions Sensor Emissions Heat Weight
System Health and Status	System Health and Status	System Health and Status	4.0 Monitor System Health and Status	Emergency Detection	Emergency Notif/Alerts System Health and Status		System Health and Status Diagnostic Results	Countermeasures
Emergency Commanding Self-Correction Commands	Emergency Commanding Self-Correction Commands	Emergency Commanding Self-Correction Commands		5.0 Execute Emergency Operations				Safety Features
Weather Data Forecast Data Emergency Notif/Alerts External Position Data Emergency Guidance/Commanding	Weather Data Forecast Data Emergency Notif/Alerts External Position Data Emergency Guidance/Commanding	Weather Data Forecast Data Emergency Notif/Alerts External Position Data Emergency Guidance/Commanding	Weather Data Forecast Data Emergency Notif/Alerts		6.0 Communicate with External Entities			Emergency Notif/Alerts System Status Voice Communications Weather Data and Forecasts Radio Broadcasts Position Data Emergency Guidance/Commanding
Validated Destination Input					Display Queries Frequency Adjustments Volume Adjustments Power on Entertainment Receivers	7.0 Execute Passenger Commands		Heating/Cooling Weight Support Power
System Adjustments Replacement Components Reconfiguration Signals	System Adjustments Replacement Components Reconfiguration Signals	System Adjustments Replacement Components Reconfiguration Signals	System Queries Diagnostics Test	System Adjustments Replacement Components Reconfiguration Signals	System Adjustments Replacement Components Reconfiguration Signals	System Adjustments Replacement Components Reconfiguration Signals	8.0 Perform Maintenance Operations	Failed Components System Health and Status Diagnostic Report

Functional Concept (5 of 6)

Level 1 Function - 1.0. Perform Launch Operations FBD



Functional Concept (6 of 6)

Traceability

- Traceability was maintained throughout functional analysis

Requirements to Functions Traceability

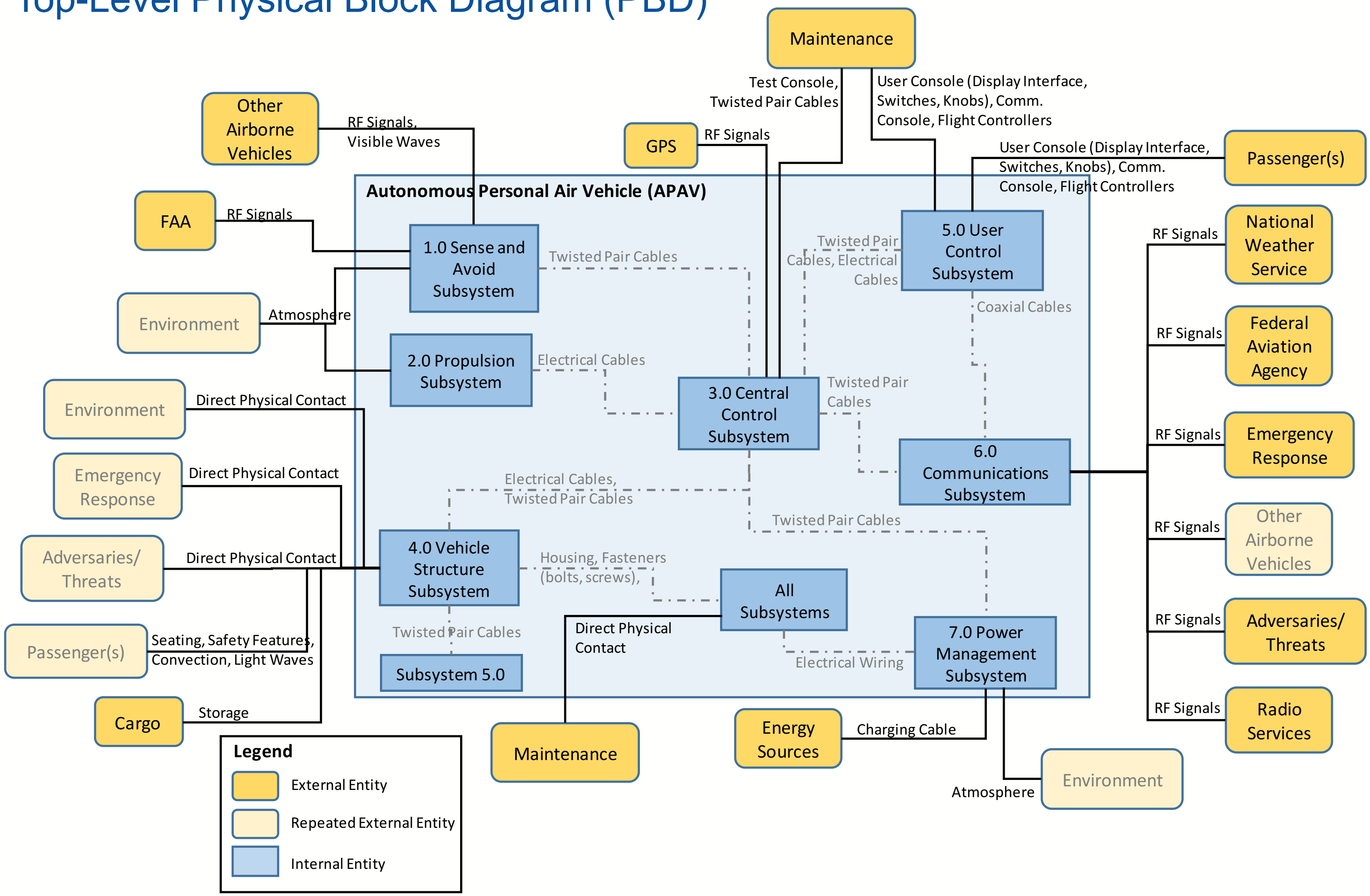
Req_ID	Subsystem/ Category	Description	Type (Binary, Quantitative, or Qualitative)	Verification _Method (I, A, T, or D)	Linked Functions
SA.001	Sense and Avoid	The sense and avoid subsystem shall locate stationary objects with a detection range of at least 1 mile.	Quantitative	D	Launch: [FUNC_1.5.1.1] Detect Surroundings [FUNC_1.5.2.1] Determine Maneuver Path Flight: [FUNC_2.2] Detect Surroundings [FUNC_2.2.6] Determine Maneuver Path Landing: [FUNC_3.3.5.1] Evaluate Ground Space [FUNC_3.3.5.2] Determine Location with Sufficient Space
PR.003	Propulsion	The propulsion subsystem shall have a power-to-weight ratio of at least 4 kW/kg per motor.	Quantitative	T	[FUNC_1.5] Execute Launching Sequence [FUNC_2.4] Perform Manuevers [FUNC_3.4] Execute Landing Sequence [FUNC_3.6] Navigate to Parking Area

Functions to Requirements Traceability

Function_ID	Level	Function_Name	Linking_Req_ID
0.0	0	Transport Passenger(s) and Cargo	
1.0	1	Perform Launch Operations	
1.1	2	Determine Location	[REQ_I.001] The system shall determine its location with an accuracy less than or equal to 0.5 meters based on signals received by GPS
1.1.1	3	Acquire GPS Signals	[REQ_O.016] The system shall enable communications within the UHF (300 MHz - 3 GHz) frequency band [REQ_I.001] The system shall determine its location with an accuracy less than or equal to 0.5 meters based on signals received by GPS [REQ_I.025] The system shall receive timing and location data in near real-time from GPS within the UHF band (300 MHz - 3 GHz)
1.1.2	3	Receive Timing and Location Data	[REQ_I.001] The system shall determine its location with an accuracy less than or equal to 0.5 meters based on signals received by GPS [REQ_I.025] The system shall receive timing and location data in near real-time from GPS within the UHF band (300 MHz - 3 GHz)

Physical Concept (1 of 5)

Top-Level Physical Block Diagram (PBD)



Physical Concept (2 of 5)

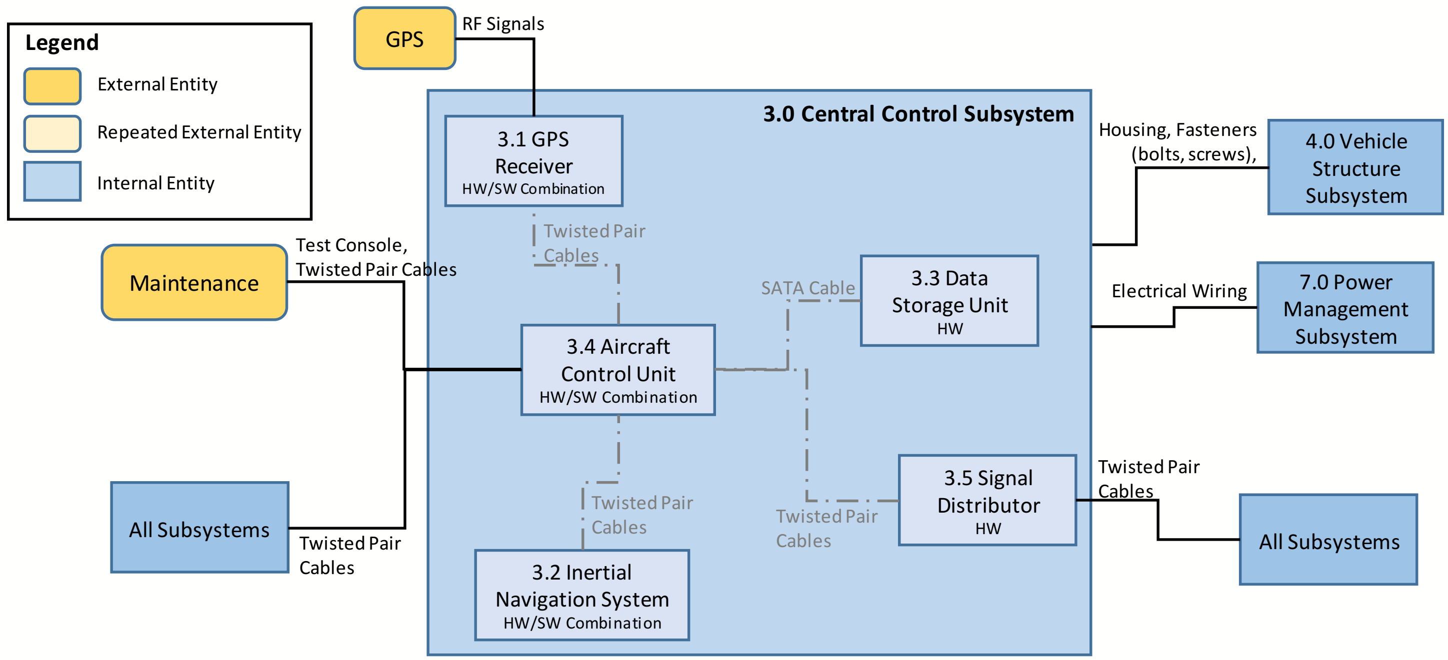
Top-Level N2 Diagram

RF Signals (position and weather data) Visible Waves		Location and Timing Data Maintenance Queries Maintenance Tests	Environment (heat, rain, snow, winds, dust, sand, humidity, etc.) Passenger Weight Cargo Weight Adversarial Attacks	User Input Commands (Destination Address Climate Adjustments Seat Adjustments Display Selection Frequency Adjustments Volume Adjustments) User Flight Commands User Voice Communications	RF Signals (Broadcast Data, Weather/Forecast Data, External Emergency Notif/Alerts, External Guidance/Commanding, External Position Data, External Voice Communications)	Electrical Power/Charge	
1.0 Sense and Avoid Subsystem		External aircraft position data Weather data EO/IR sensor detections Sense and avoid component measurements	Weight				RF Signals (position data)
	2.0 Propulsion Subsystem	Propulsion subsystem sensor measurements	Weight				Heat Thrust
Pointing Commands Power/Frequency Adjustments	Flight Commands (power output, speed)	3.0 Central Control Subsystem	Emergency Commands for safety units Landing gear control commands Wing/Stabilizer Commands Weight	System Status Emergency Notif./Alerts Guidance/Navigation	System Status Emergency Notif./Alerts Location Data	Power Distribution Commands	System Status Maintenance results Data logs/history
Housing/Structural Support	Housing/Structural Support	Structure component measurements Housing/Structural Support	4.0 Vehicle Structure Subsystem	Housing/Structural Support	Housing/Structural Support	Housing/Structural Support	Weight Storage Safety Features Seating Heating/Cooling Lighting
		Data Requests/Queries Flight Commands	Seat Adjustments Climate Adjustments Weight	5.0 User Control Subsystem	User Voice Communications Tuning Adjustments	Power On/Off Signals	System Status Emergency Notif./Alerts Guidance/Navigation User Voice Signals Broadcasts
		Comm. Component measurements External Emergency Notif./Alerts External Guidance/Commanding	Weight	External Voice Communications Signals Broadcast Data	6.0 Communications Subsystem		RF Signals (Voice Communications, System Status, Emergency Notif/Alerts, Location Data)
Electrical Power	Electrical Power	Electrical Power	Electrical Power Weight	Electrical Power	Electrical Power	7.0 Power Management Subsystem	Heat

Physical Concept (3 of 5)

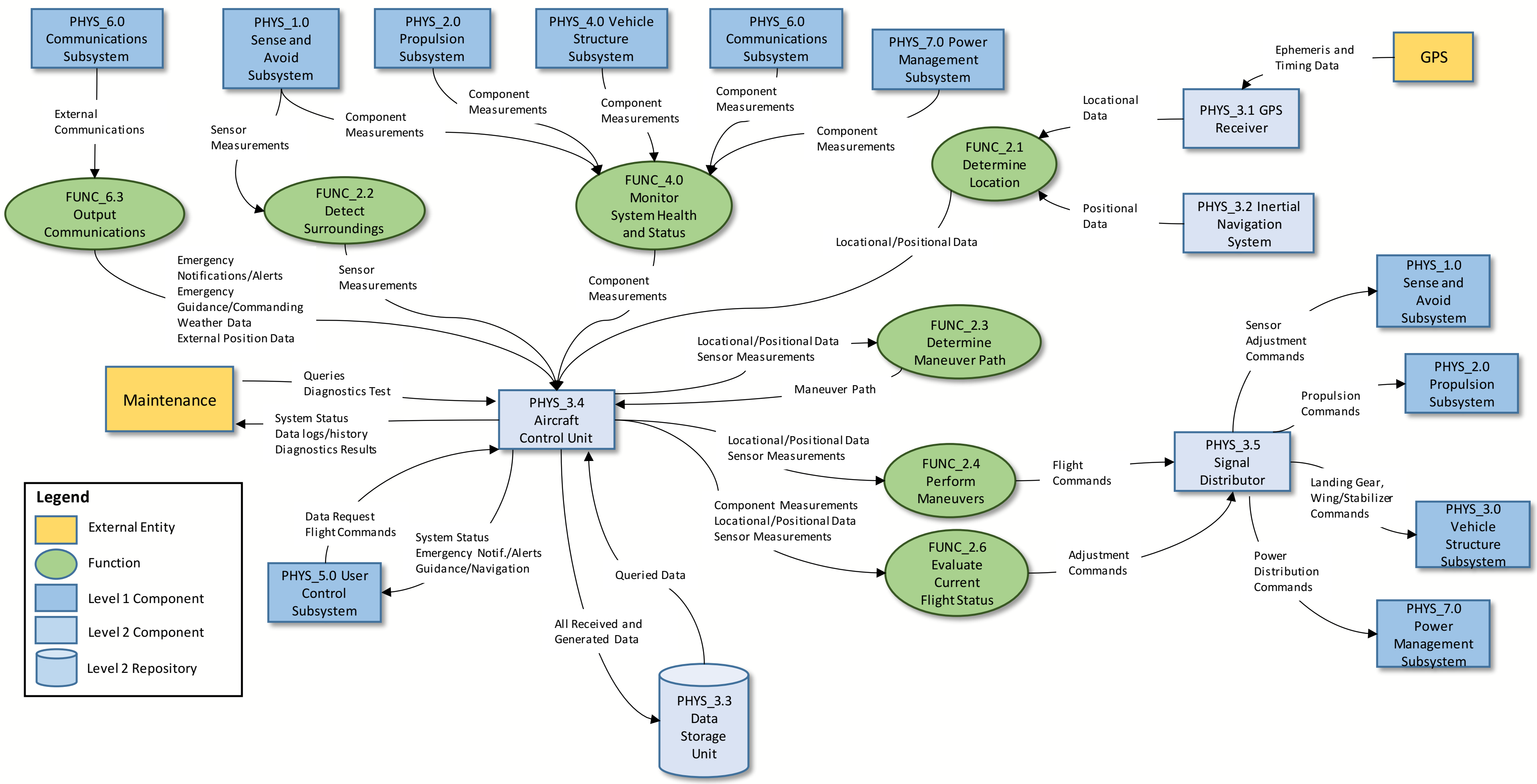
Central Control Subsystem PBD

- Depicts physical connections between subsystem components
- N2 diagram describes items passed between components



Physical Concept (4 of 5)

Central Control Subsystem - Aircraft Control Unit Data Flow Diagram (DFD)



Physical Concept (5 of 5)

Traceability

- Traceability was maintained throughout conceptual design

Requirements to Physical Component Traceability

Req_ID	Subsystem/ Category	Description	Type (Binary, Quantitative, or Qualitative)	Verification_ Method (I, A, T, or D)	Linked Physical Components
SA.001	Sense and Avoid	The sense and avoid subsystem shall locate stationary objects with a detection range of at least 1 mile.	Quantitative	D	[PHYS_1.1] ADS-B [PHYS_1.2] EO/IR Sensors
PR.003	Propulsion	The propulsion subsystem shall have a power-to-weight ratio of at least 4 kW/kg per motor.	Quantitative	T	[PHYS_2.1] Electric Motors
P.015	performance	The system shall compute flight routes within 10 seconds of receiving a destination address.	Quantitative	D	[PHYS_3.4] Aircraft Control Unit [PHYS_3.4.3] Microprocessor [PHYS_3.4.3.1] Navigation/Guidance Software

Physical Component to Requirements Traceability

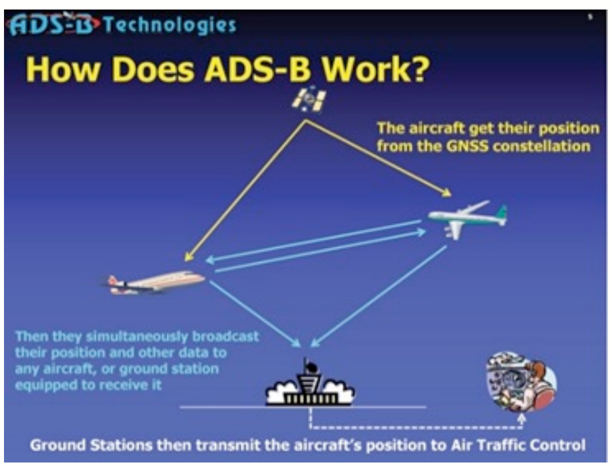
Phys_ID	Class	Level	Component_Name	Linking_Req_ID
1.0	Subsystem	1	Sense and Avoid Subsystem	
1.1	Component	2	ADS-B	
1.1.1	Configuration Item	3	ADS-B In Receiver	
1.1.1.1	Part	4	Antenna	[REQ_EI.033] The system shall receive external aircraft positional data and weather data from other airborne vehicles and ground air control stations at 1090 MHz.
1.1.1.2	Part	4	Signal Processor	[REQ_II.001] The sense and avoid subsystem shall send received external aircraft position data to the central control subsystem within 20 milliseconds of receipt.

Trade Study (1 of 6)

Introduction and Alternatives

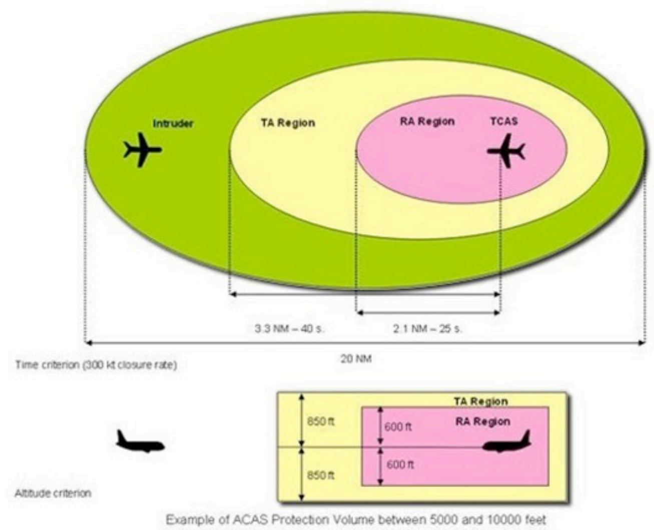
- Trade space existed for the various risk areas of the APAV, requiring the evaluation of alternatives to determine the most feasible and cost-effective solution
- Formal trade analysis was conducted for the sense and avoid subsystem of the APAV
- Alternatives included:
  - Electro-optical/Infrared (EO/IR) Sensor Package
  - Automatic Dependent Surveillance – Broadcast (ADS-B)
  - Airborne Sense-and-Avoid (ABSAA) Radar
  - Traffic Alert and Collision Avoidance System (TCAS II)

Example EO/IR Sensor



Basic ADS-B explanation

Example ABSAA

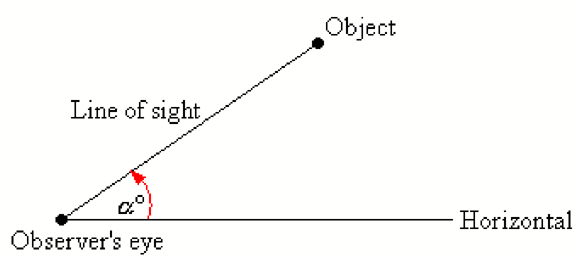


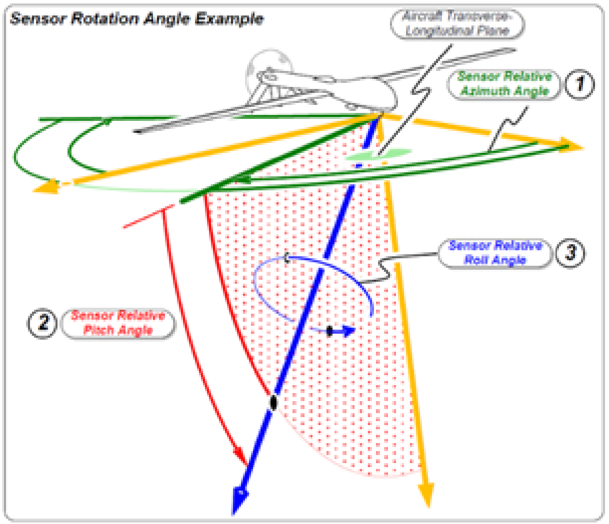
Basic TCAS II explanation

Trade Study (2 of 6)

Selection Criteria

- Selection criteria was based on the system requirements of the APAV system and these criteria represent the major characteristics for sense and avoid capabilities
  - **Field of View (FOV)** - the observable area of a sensor, broken down by:
    - Azimuth Range - the angle measured between the vehicle direction of travel and the projected line-of-sight (LOS) to the target
    - Minimum Elevation - the angle between the ground and the LOS to the object
  - **Detection Range** - the furthest distance an object could be detected
  - **Detection Accuracy** - measurement of the error in the detection range
  - **Weight** – weight of the system
  - **Power** – power consumed by the system





Trade Study (3 of 6)

Selection Criteria Traceability

Req_ID	Description	Related Criteria
SA.007	The sense and avoid subsystem shall sense objects within an azimuth range of at least ± 90° referenced from the direction of travel.	Azimuth Range
SA.008	The sense and avoid subsystem shall sense objects within an azimuth range of at least ± 90° referenced from the opposite direction of travel.	Azimuth Range
SA.009	The sense and avoid subsystem shall sense objects within a minimum elevation angle of 20° or less.	Minimum Elevation
SA.001	The sense and avoid subsystem shall locate stationary objects with a detection range of at least 1 mile.	Detection Range
SA.003	The sense and avoid subsystem shall locate moving objects with a detection range of at least 0.5 miles.	Detection Range
SA.005	The sense and avoid subsystem shall track moving objects with a detection range of at least 0.5 miles.	Detection Range
SA.002	The sense and avoid subsystem shall locate stationary objects with a detection range accuracy of +/- 1 ft or less.	Detection Accuracy
SA.004	The sense and avoid subsystem shall locate moving objects with a detection range accuracy of +/- 1.5 ft or less.	Detection Accuracy
SA.005	The sense and avoid subsystem shall track moving objects with a detection range accuracy of +/- 1.5 ft or less.	Detection Accuracy
C.012	The system shall have full operations (e.g. takeoff, flight, landing, detecting, communications) while under minimum loading conditions (one average sized passenger and no cargo) for a range of at least 400 miles before requiring power replenishment.	Weight
O.013	The system shall have an empty weight of no more than 2500 lbs.	Weight
O.014	The system shall have a maximum takeoff weight (including passengers and cargo) of 3500 lbs.	Weight
O.012	The system shall have full operations (e.g. takeoff, flight, landing, detecting, communications) while under minimum loading conditions (one average sized passenger and no cargo) for a range of at least 400 miles before requiring power replenishment.	Power
PR.001	The propulsion subsystem shall output power of at least 260 kW per motor.	Power

Trade Study (4 of 6)

Criteria Weighting

- Normalized criteria weights were generated by following the Nth-root Pair-wise comparison method

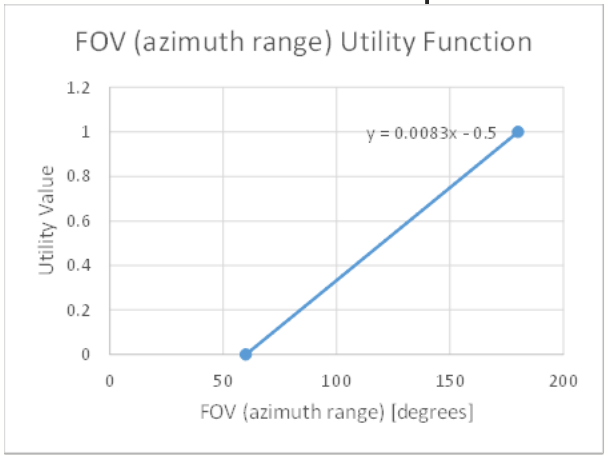
Value	Meaning	Definition
1	Equal Importance	Both alternatives contribute equally to the objective
3	Moderate Importance	Experience and judgement give a slight edge to one alternative
5	Strong Importance	Experience and judgement strongly favor one alternative
7	Very Strong Importance	Activity strongly favored and its dominance is demonstrated in practice
9	Absolute Importance	Evidence favoring one alternative is highest possible

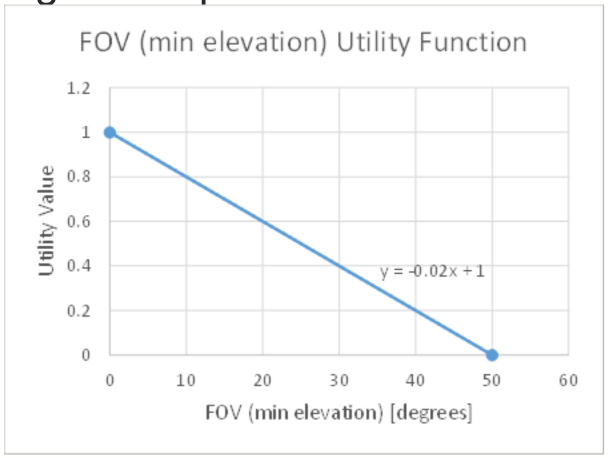
	FOV (azimuth range)	FOV (min elevation)	Detection Range	Detection Accuracy	Weight	Power	**Row Value Products**	**Nth root of Row Value Products**	**Normalized Weighting Factor**
FOV (azimuth range)	1	1	2	2	3	3	36	1.817	**0.269**
FOV (min elevation)	1	1	2	2	3	3	36	1.817	**0.269**
Detection Range	0.5	0.5	1	2	2	2	2	1.122	**0.166**
Detection Accuracy	0.5	0.5	0.5	1	2	2	0.5	0.891	**0.132**
Weight	0.333	0.333	0.5	0.5	1	0.5	0.013889	0.490	**0.073**
Power	0.333	0.333	0.5	0.5	2	1	0.055556	0.618	**0.091**
							Sum:	6.756	1.000

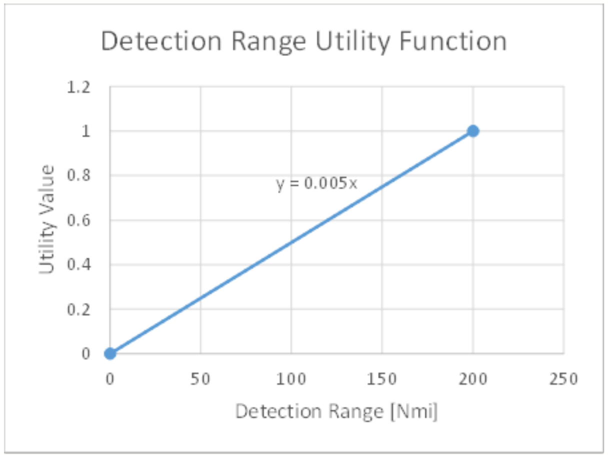
Trade Study (5 of 6)

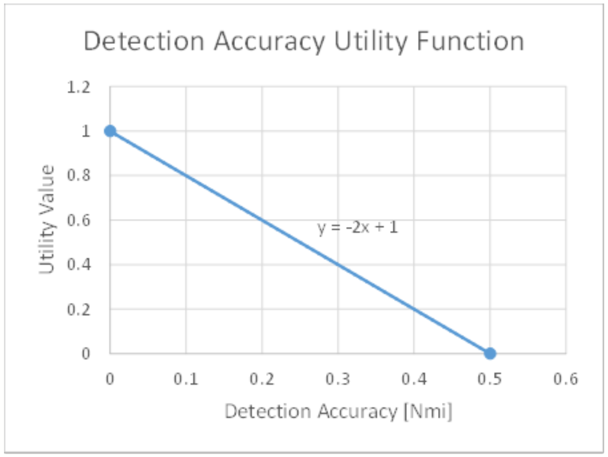
Utility Curves

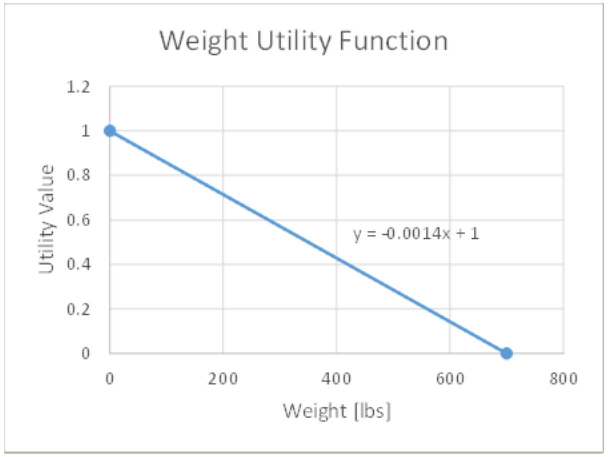
- Utility functions used to translate an alternative's raw score against a criterion to a utility score
- Curves developed according to independent research and assumed to be linear

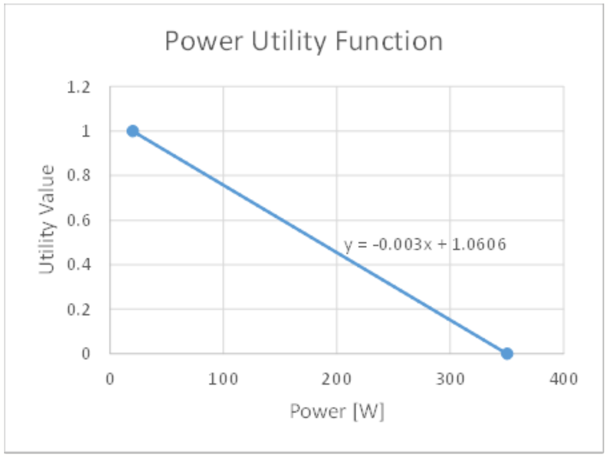












Trade Study (6 of 6)

Results

- Based on analysis, ADS-B provided the highest operational utility and cost-effectiveness

			EO/IR			ADS-B			ABSAA RADAR			TCAS II		
Criteria	**Units**	**Weight**	Raw Score	Utility Value	Weighted Utility Score	Raw Score	Utility Value	Weighted Utility Score	Raw Score	Utility Value	Weighted Utility Score	Raw Score	Utility Value	Weighted Utility Score
FOV (azimuth range)	[degrees]	0.269	110	0.417	0.112	180	1.000	0.269	110	0.417	0.112	180	1.000	0.269
FOV (min elevation)	[degrees]	0.269	15	0.700	0.188	0	1.000	0.269	30	0.400	0.108	0	1.000	0.269
Detection Range	[Nmi]	0.166	5	0.025	0.004	150	0.750	0.125	10	0.050	0.008	40	0.200	0.033
Detection Accuracy	[Nmi]	0.132	0.01	0.980	0.129	0.05	0.900	0.119	0.1	0.800	0.106	0.4	0.200	0.026
Weight	[lbs]	0.073	600	0.143	0.010	20	0.971	0.071	21	0.970	0.070	22	0.969	0.070
Power	[W]	0.091	27	0.979	0.089	250	0.303	0.028	50	0.909	0.083	80	0.818	0.075
Operational Utility Function (weighted sum)			0.534			**0.879**			0.487			0.743		
Cost [$]			19000			8000			21000			20000		
Cost-Effectiveness Selection Function (weighted sum/cost)			0.000028			**0.000110**			0.000023			0.000037		

- Sensitivity analysis
  - Set weights for each criterion to zero and reevaluated performance
  - ADS-B continued to provide the highest operational utility and cost-effectiveness
- Further analysis
  - ADS-B is heavily reliant on the factor that it only communicates with other ADS-B equipped aircraft of stations
  - This limits the ability of sense and avoidance for non-aircraft entities
  - Additional analysis needed to assess potential combinations of sense and avoid systems (e.g. ADS-B with EO/IR)

Risk Management (1 of 3)

Approach

- Managed and followed risks throughout each phase of design
- Followed Kossiakoff approach for defining likelihood and consequence
- Total of 8 risks remain at final assessment
  - 5 Technical
  - 1 Operational
  - 2 Programmatic

Level	Likelihood	Description
1	Not Likely	Will effectively avoid or mitigate this risk based on standard practices
2	Low Likelihood	Have usually mitigated this type of risk with minimal oversight in similar cases
3	Likely	May mitigate this risk, but work-arounds will be required
4	Highly Likely	Cannot mitigate this risk, but a different approach might
5	Near Certainty	Cannot mitigate this type of risk; no known processes of work-arounds are available

	Impact To:		
Level	**Performance**	**Schedule**	**Cost**
1	Minimal or No Impact	Minimal or No Impact	Minimal or No Impact
2	Minor performance shortfall, same approach retained	Additional activities required, able to meet key dates	Budget increase or unit production cost increase <1%
3	Moderate performance shortfall, but work-arounds available	Minor schedule slip, will miss needed dates	Budget increase or unit production cost increase <5%
4	Unacceptable, but work-arounds available	Project critical path affected	Budget increase or unit production cost increase <10%
5	Unacceptable; no alternatives exist	Cannot achieve key project milestones	Budget increase or unit production cost increase >10%

Risk Management (2 of 3)

Risk Overview

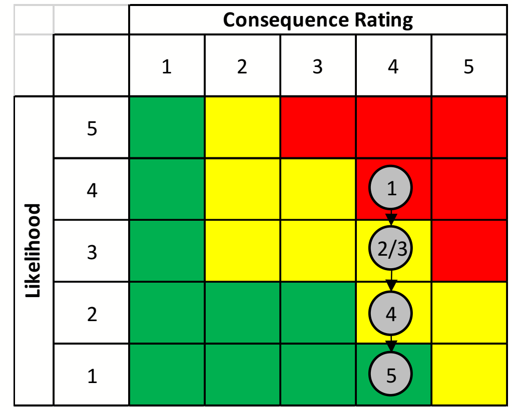
Risk ID	Type	Title	Risk Statement	Risk Description	Initial Likelihood	Initial Consequence	Final Likelihood	Final Consequence
R-001	T	Immature Electronic Flight Technologies	If current electronic power source technologies are insufficient to support all operations of a passenger aircraft, then the system may be unable to meet desired emissions standards and changes to the system design will be incurred.	Autonomous flight technologies, let alone fully-electronic autonomous flight technologies are still relatively new advanced concepts in today's industry. Current technologies may not be sufficient in being able to deploy a fully electric autonomous passenger aircraft.	4	4	2	4
R-002	T	In-Flight Collision	If autonomous avoidance technologies are immature and unable to properly operate in various environmental conditions (day, night, rain, snow, winds), then the APAV will be unable to provide full autonomy and safety to the passengers.	Autonomous aircraft face the potential of colliding with other airborne objects such as birds, drones, or other debris. If an object collides with the system, it may cause a system failure, posing a threat to the passenger(s).	3	4	2	3
R-003	T	Cyber Attacks	If protective and reliable network security is not implemented across the system, then cyber attacks could result in loss of flight control, loss of communications, and violation of passenger safety.	The APAV contains several external facing interfaces which can be targeted by cyber attacks, or other forms of electronic attacks (i.e. jamming).	3	5	1	4
R-004	O	Electronic Attacks	If electronic attacks (e.g. jamming) are successful against the APAV, then the system will be unable to establish stable communications links with external entities, leading to adverse impacts on safety and awareness.	The APAV contains several external facing interfaces which can be targeted by cyber attacks, or other forms of electronic attacks (i.e. jamming). Successful attacks can result in loss of positional data, loss of communications, and reduced safety.	3	4	1	4
R-005	T	Modularity/Standardization	If components within the system are non-standard and unique, then the system will have less modularity and require specialized tools and higher maintenance detail.	The APAV is a relatively new concept which may utilize newer technologies. Using new technologies poses a risk that non-standardized parts are used and specialized equipment will be required for production and maintenance.	3	3	1	2
R-006	T	Constraining Policies, Standards, & Regulations	If current FAA policies and standards pose overly constraining requirements, the APAV design may be constrained to certain implementations or designs.	Due to the new concept of autonomous air transportation, policies, standards, and regulations to manage personal autonomous aircraft may not be fully developed or in place. Existing governance may be too restrictive and/or new governance may need to be developed in order to accommodate this concept.	3	4	1	4
R-007	P	Societal Shift to Concept	If the system is unable to gain societal approval and trust, then continued development and production of the system will cease.	Being a newer concept, electronic autonomous aircraft may pose affordability concerns to the public. Additionally, society may have difficulty trusting the safety of the autonomous aircraft and may therefore reject this system.	4	5	1	5
R-008	P	On-time completion of Capstone Project	If personal tasks (e.g. work, travel) take up more time than anticipated, then the completion of deliverables will be delayed.	Given the large time commitment of this project and the combination of busyness in personal life, I may not be able to achieve all milestones in the intended timeframe. Additionally, given that I have not gained approval of my proposal prior to the start of the semester, my schedule has already been set back.	2	4	1	4

Risk Management (3 of 3)

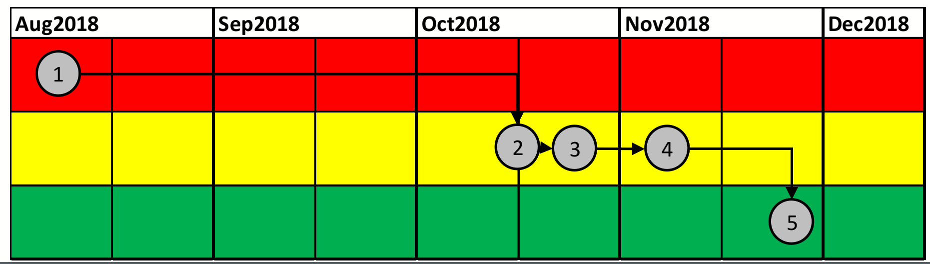
Risk 001 (Immature Electronic Flight Technologies) Review

Risk ID: R-001
Risk Title: Immature Electronic Flight Technologies
Risk Type: Technical

Risk Statement: If current electronic power source technologies are insufficient to support all operations of a passenger aircraft, then the system may be unable to meet desired emissions standards and changes to the system design will be incurred.
Risk Description: Autonomous flight technologies, let alone fully-electronic autonomous flight technologies are still relatively new advanced concepts in today's industry. Current technologies may not be sufficient in being able to deploy a fully electric autonomous passenger aircraft.



Initial Likelihood: 4
Initial Consequence: 4
Current Likelihood: 2
Current Consequence: 4



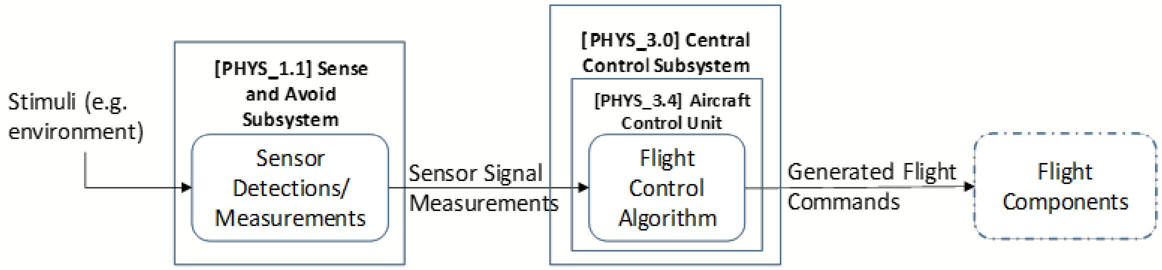
Mitigation Plan:

1. Conduct research on currently available electric aircraft technology
2. Perform trade analysis to identify feasible power source options for a fully-electric passenger aircraft
3. Identify potential alternatives to fully-electric power sources (e.g. hybrid)
4. Perform additional trade analysis to determine best overall solution for the power source.
5. Design and develop most feasible solution to meet performance objectives and safety

Further Assessment:
At this point in the system development, trade studies have been carried out and a feasible electric power source alternative has been identified to power the APAV. Following the trade studies, requirements were developed capture these alternatives and ensure the proper development of the power source.

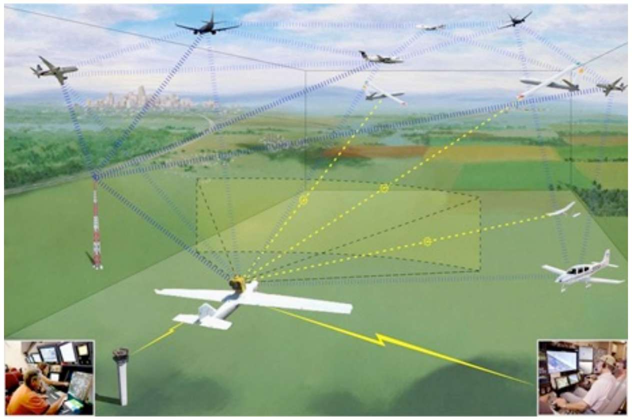
Test Plan (1 of 2)

- **Scope:** Describe the test and evaluation efforts needed to verify the sense and avoid capabilities of the APAV, implemented by the Sense and Avoid Subsystem and Aircraft Control Unit (ACU) of the Central Control Subsystem



- Testing planned as three major phases:
  - Phase 1 – virtual modeling and simulation
  - Phase 2 – controlled environmental testing
  - Phase 3 – flight testing
- **Test Objectives:** Requirements verification, risk reduction (R-002 – In-Flight Collision), and technological readiness demonstration
  - Success criteria and desired metrics each trace to system requirements
  - All relevant requirements include a desired test result
  - Example metrics include: max detection range, min detection accuracy, min avoidance distance, max temperature, max visibility

Test Plan (2 of 2)



Virtual Simulation Example

- **Test Environment:**
  - Phase 1: Virtual environment, integrated development environment (IDE)
  - Phase 2: Environmental testing facility (e.g. McKinley Climatic Laboratory)
  - Phase 3: Controlled live operational environment
- **Test Equipment**
  - Phase 1: Computers, power supplies
  - Phase 2: Weather simulators (e.g. wind, temperature, humidity, rain, snow, fog, etc.), stress sensors (e.g. load sensor, thermometers, hygrometer, barometer), computers, detection entities, artificial signal generators, control stations, power supplies
  - Phase 3: ADS-B Out transmitters, artificial obstacles (air and ground), safety equipment (guards, nets), ground control station
- **Test Articles and Subjects**
  - ADS-B, EO/IR Sensors, Sensor Component Detectors, ACU, APAV Prototype
  - Flight Control S/W Developer, Senior Design Engineer, T&E Analyst, Flight Operator, Development Technician, Emergency Response

McKinley Climatic Lab F-22 Test

System Specification (1 of 2)

Requirements Summary

- Total of 216 requirements
  - ~76% increase in requirements since the completion of the Requirements Analysis Report (RAR)
  - Requirements added, modified, and deleted throughout the course of the system development
  - Maintained traceability throughout each phase
- 81% of requirements are quantitative as compared to 62% at the completion of the RAR

	Total	Quantitative	% Quantitative	Binary	Qualitative
Requirements Analysis Report	123	76	62%	31	16
Functional Analysis Report	145	91	63%	37	17
Trade Study	149	95	64%	37	17
Conceptual Design Report	155	101	65%	37	17
Test Plan	155	102	66%	37	16
System Specifications	**216**	**176**	**81%**	**40**	**0**

System Specification (2 of 2)

Key Performance Parameters (KPPs)

Req_ID	Description	Rationale	Type (Binary, Quantitative, or Qualitative)	Verification Method (I, A, T, or D)
C.001	The system shall have an operational availability of at least 0.9999.	Users expect a high level of system effectiveness and have a need for the system to be readily available as a transport vehicle.	Quantitative	A
C.002	The system shall have a Mean Time To Failure (MTTF) of at least 400,000 traveled miles.	Road vehicles typically last around 200,000 miles. Given the system travels through air the MTTF was determined to be higher. MTTF measured in units of miles traveled instead of time.	Quantitative	A
C.003	The system shall have a fault detection rate of at least 99%.	Safety is a large concern to commuters; the autonomy of the vehicle must also include self-detection of anomalies.	Quantitative	T
F.001	The system shall conduct fully autonomous sense, avoid, and maneuvering during flight through day and night conditions.	A main objective of the APAV is to provide autonomy and minimize the need for human contribution. The system should be operable in day or night conditions.	Binary	D
F.009	The system shall transport passengers and cargo with travel times at least 20% faster than a personal road vehicle would achieve over the same distance.	A major objective of the system is to provide a faster mode of transportation to commuters.	Quantitative	A
P.014	The system shall deploy emergency safety features within 0.1 seconds of detecting a critical fault.	Safety is a large concern to commuters; safety features must be present to keep injuries at a minimum.	Quantitative	D
O.012	The system shall have full operations (e.g. takeoff, flight, landing, detecting, communications) while under minimum loading conditions (one average sized passenger and no cargo) for a range of at least 400 miles before requiring power replenishment.	As an air vehicle, this system is expected to provide at least the same range as a typical road vehicle on one tank of gas (average tank size is 16 gallons and average mpg is 24.7)	Quantitative	D
O.020	The system shall enable operations under various environmental conditions, to include: i. Altitudes ranging from at least 0 to 40,000 ft above sea level ii. Rainfall of at least moderate intensity (0.4 inches per hour) iii. Temperatures ranging from at least -20°F to 130°F iv. Humidity ranging from 0% to 100% v. Snowfall of at least Category 1 on the NESIS scale (by NOAA) vi. Winds up to at least 50 knots, steady winds up to at least 40 knots, and gust spreads up to at least 15 knots vii. Visibilities of 0.5 statute miles or less during the day viii. Visibilities of 1 statute mile or less during the night ix. Sand and dust concentrations of at least 0.5 grams per meters cubed	Air travel is subject to various environmental conditions and the system should be able to provide availability to the commuters through these various conditions.	Quantitative	D

Summary of Final Concept and Further Work

- User Needs and independent research served as the basis for the system development
- Additional review from subject matter experts (SMEs) are needed
- Recommend the following next steps:
  - Perform additional formal trade analysis of:
    - Propulsion Subsystem motors
    - Power Management Subsystem batteries
    - Vehicle Structure Subsystem safety features
  - Develop high-level cost estimations for projected development and manufacturing costs
  - Conduct system reviews for each major phase (based on DoD readiness events)
    - System Requirements Review (SRR)
    - System Functional Review (SFR)
    - Preliminary Design Review (PDR)

Lessons Learned

- Be consistent with tracking and assessing schedule
- Include extra time buffers in your schedule
- Learn a Systems Engineering tool (e.g. CORE)
  - A lot of time was spent on manually tracing between requirements, functions, and physical components
  - Much time was also spent looking for places where updates/modifications needed to be carried over
- Systems Engineering is a team effort
- Practice proper configuration management (version control)
  - The iterative nature of SE results in many changes which should be documented for reference

Recommendations

- If possible, consider offering an elective which teaches the use of System Engineering tools (e.g. CORE, DOORS)
  - This may give students more incentive to use these tools for this course
  - These tools may help students maintain consistency and traceability, as well as improve the overall quality of work
- Send reminders to keep students motivated and thinking about this course prior to enrolling
  - Access to blackboard site is given while taking the 5th core course (typically the mid-point of the program for most), but then the capstone course was never mentioned again
  - Getting the proposal done prior to the beginning of the course gives students more time to work on the other deliverables

Questions?

References

- ADS-B Technologies LLC. (2018). What is ADS-B? Retrieved December 1, 2018 from website: http://www.ads-b.com/
- Designboom. (2018). Researchers Test Cars and Planes in Extreme Weather Conditions Inside Lab. Retrieved November 4, 2018 from website: https://www.designboom.com/technology/mckinley-climatic-laboratory-07-27-2017/
- Desjardins, J. (2018). Visualizing the Average Commute Time in U.S. States and Cities. Visual Capitalist. Retrieved August 20, 2018, from website: http://www.visualcapitalist.com/average-commute-u-s-states-cities/
- Dronelife. (2015). NASA to Test Sense-and-Avoid Technology for Drones. Retrieved November 4, 2018 from website: https://dronelife.com/2015/06/29/nasa-to-test-sense-and-avoid-technology-for-drones/
- Ingraham, C. (2017). The American Commute is Worse Today Than its Ever Been. Washington Post. Retrieved August 20, 2018, from website: https://www.washingtonpost.com/news/wonk/wp/2017/02/22/the-american-commute-is-worse-today-than-its-ever-been/?utm_term=.2307886f0a28
- Kossiakoff, A. (2011). Systems Engineering Principles and Practice. Second Edition. John Wiley & Sons.
- NAVSEA (2017). NSWC Crane Hosts Surface Electro-Optics/Infrared (EO/IR) Standards Profile Review. Retrieved December 1, 2018 from website: https://www.navsea.navy.mil/Media/News/Article/1243556/nswc-crane-hosts-surface-electro-opticsinfrared-eoir-standards-profile-review/
- Traffic Avoidance Collision System. (2018). Wikipedia. Retrieved December 1, 2018 from website: https://en.wikipedia.org/wiki/Traffic_collision_avoidance_system
- Union of Concerned Scientists (UCS). (2018). Car Emissions & Global Warming. Retrieved August 20, 2018 from website: https://www.ucsusa.org/clean-vehicles/car-emissions-and-global-warming#.W3tlm-hKhPY