Model-Based Systems Engineering for Target Vulnerability Assessment

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NDIA 27th Annual Systems & Mission Engineering Conference

October 28-31, 2023

Norfolk, Virginia

OUTLINE

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- Purpose
- Vulnerability Overview
- Target Information
- SysML Diagrams
- Conclusions

DISCLAIMER

The views presented are those of the speaker and do not necessarily represent the views of the U.S. Department of Defense or its components.

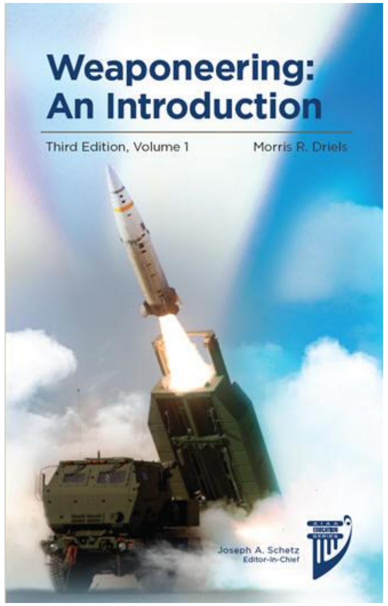
Purpose

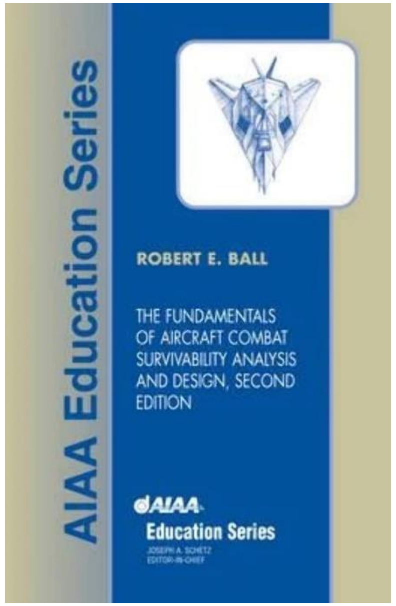
- To discuss Vulnerability, Lethality, Effectiveness
- To discuss Target Vulnerability Assessment, and it's significance
- To discuss how SysML diagrams can be used to improve Target Vulnerability Assessments

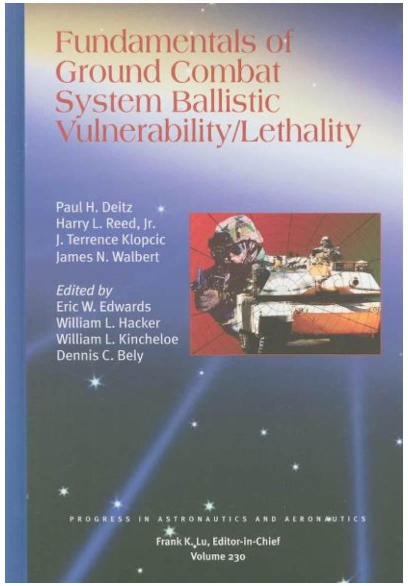
Vulnerability Overview

Weaponeering

- Weaponeering (portmanteau of weapon and engineering) is the field of designing an attack with weapons
- Defined as the process of determining the quantity of a specific type of lethal or nonlethal weapons required to achieve a specific level of damage to a given target, considering target vulnerability, weapon effect, munitions delivery accuracy, damage criteria, probability of kill and weapon reliability







Aerial Targets

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- Unmanned Aerial Vehicles (UAVs)
- Missiles
- Hypersonic Glide Vehicles (HGVs)
- Drones
- Balloons
- Inflatable Decoys
- Helicopters
- Spacecraft
- Other Space-Based Systems






Weapons

- **Kinetic weapons**: Can cause physical damage to targets, such as injuries or destruction of materials.
- Direct effects: Physical Damage, Blast/ Shockwave, Fragmentation, Thermal
- Examples:
  - Conventional Firearms
  - Explosives and Missiles
  - Artillery
  - Tanks



- **Non-kinetic weapons**: Can cause functional disruption without necessarily inflicting physical harm.
- Indirect effects: Physical Damage, Electronic Disruption, Degradation of Command and Control, Electromagnetic Pulses
- Examples:
  - Electronic Warfare (EW)
  - Directed Energy Weapons (DEW)
  - Cyber Weapons



Vulnerability-Lethality-Effectiveness

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Vulnerability
- The characteristics of an object that cause it to suffer functional degradation as a result of damage.
- Assessment characterizes the object to be enacted upon
- Data Products
  - Geometric Model
  - Bill of Materials
  - Fragility Curves
  - Failure Analysis Logic Tree (FALT)
  - Functional Effect

Weapon System
- Characterizes the object performing the damage
- Performance Data
- Data Products
  - Engagement Conditions
  - System Accuracy
  - Weapon Characterization

Lethality
- The ability of a munition to inflict damage on an object sufficient to cause functional degradation.
- Calculates the interaction between vulnerability data, weapon system damage, and environmental data
- Models:
  - Advanced Joint Effectiveness Model (AJEM)
  - Effectiveness Toolbox (ETB)
  - Kinetic Warhead Evaluation (KWEval)
  - Joint Mean Area of Effect (JMAE)

Effectiveness
- The measure of the ability of a weapon system to engage and inflict damage on an object sufficient to cause functional degradation.
- Calculates the degradation of lethality data due to weapon system accuracy.
- Models:
  - Effectiveness Toolbox (ETB)
  - Kinetic Warhead Evaluation (KWEval)
  - Advanced Joint Effectiveness Model (AJEM)
  - Joint RF Effectiveness Model (JREM)

$$P_h * P_{d/h} * P_{k/d} = P_k$$

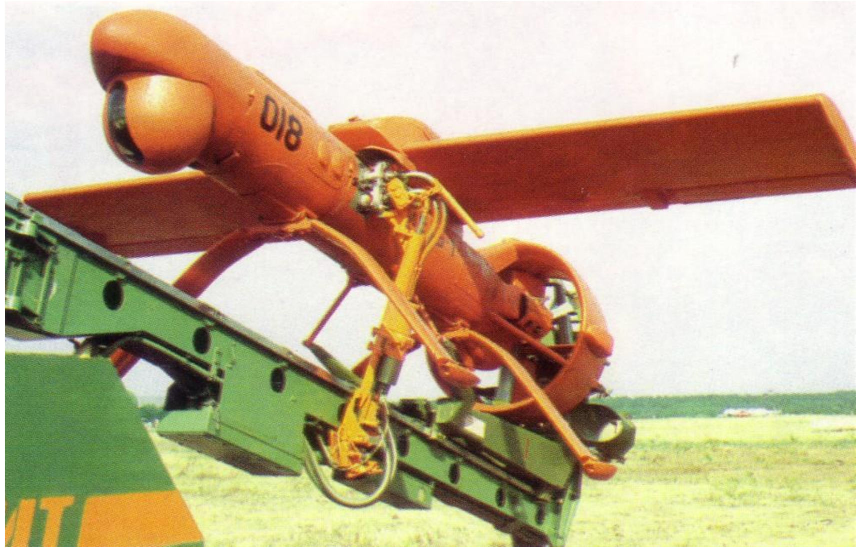
Accuracy — **Lethality** — **Effectiveness**

Target Vulnerability Assessment

1. Geometric Model (CAD): Defines size, location, and shape of each component
2. Component Material Descriptions: Bill of Materials (BOM)
3. Failure Modes and Effects Analysis (FMEA): Determines (for a given component and its failure mode) what effect does this have on the overall system performance
4. Failure Analysis Logic Tree (FALT): Defines which components are critical to a subsystem for threat functionality
5. Fragility Curves: Defines the component degradation due to a weapon effector (fragment, blast, etc.)
6. Functional Effects
   - Static: JTCG/ME Kill definitions (Mission, Recognizable, Mobility, etc.)
   - Dynamic: Threat response from damaged components to feed lethality calculations

Target Information

Target Unmanned Aerial Vehicles (UAV)



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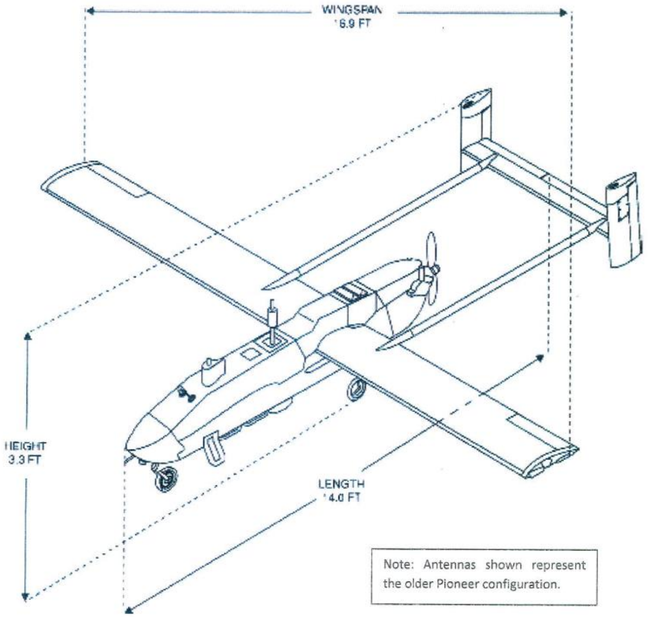
RQ-2 Pioneer UAV Background

- Utilized by the United States Navy, Marine Corps, and Army, deployed at sea and on land from 1986 until 2007.
- **Primary Function:** Reconnaissance, Surveillance, Targeting Acquisition (RSTA).
- **Contractor:** Pioneer UAV Inc.
- **Date Deployed:** December 1986 [*USS Iowa* (BB 61)]
- **Propulsion:** Sachs SF-350 gasoline engine, 26 horsepower
- **Length:** 14.0 ft (4.2672 meters).
- **Wingspan:** 16.9 ft (5.15 meters).
- **Weight:** Max design gross take-off: 416 pounds (188.69 kg).
- **Airspeed:** 110 knots (109.37 mph, 176 kph).
- **Ceiling:** 15,000 feet (4,572 meters).
- **Range:** 100+ nautical miles (115+ statute miles, 185+ km).
- **Sensors:** 12DS, POP-200, POP-300



SysML Diagrams

Problem

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- A significant part of the Vulnerability Analysts' time is spent doing front-end work to describe the functionality of components and systems
- There is a need for diagrams depicting the interactions between various systems: electrical, fuel, pneumatic, hydraulic, controls, etc.
- Example:
  - The hydraulic system interacts with the fuel system for a particular threat. How would the loss of the relief valve affect system behavior from a kill perspective?
- This is hard to discern from the current functional description. The analyst has to create a drawing depicting the interaction and the flow of energy between both systems
- There is a shortage of missile system expertise (knowledge deficit) due to attrition (retirement, transfer, etc.)

Proposed Solution

- Utilize SysML to create diagrams to better illustrate system behavior by depicting energy flow between components and systems. This will lead to a higher fidelity functional description
- Structural diagrams will be used to minimize complexity
- Payoff
  - Facilitate accurate analysis
  - Help identify the location of components missing from the CAD
  - Save time (Minimize back and forth) once the process is developed
  - Develop Subject Matter Expertise

Vulnerability MBSE Workflow

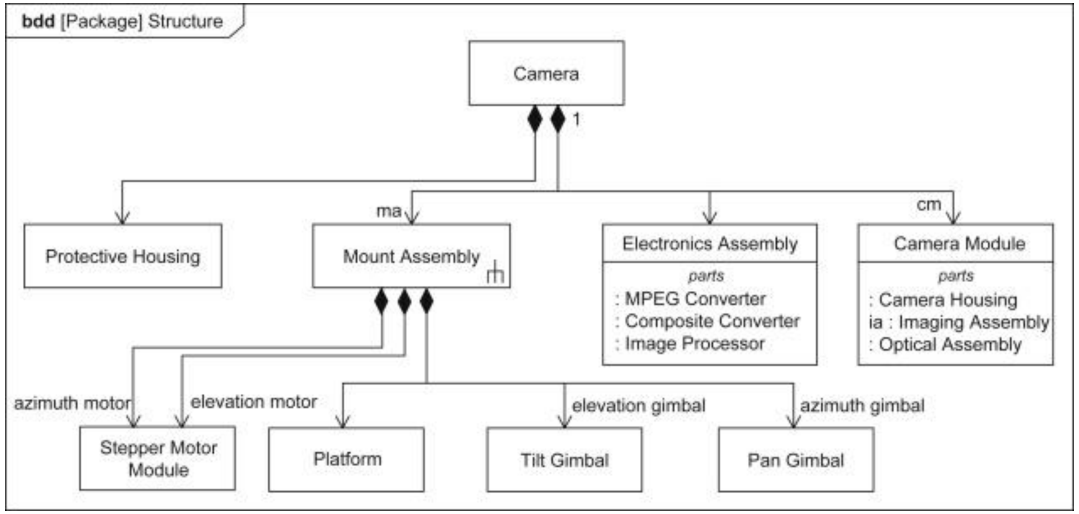
1. Generate the BOM from the CAD
2. Create a preliminary functional description from the available resources that identifies system functions
3. Develop an ontology
4. Create BDDs utilizing functional decomposition
5. Develop IBDs with flow ports and item flow to illustrate the flow of energy
6. Fill in gaps using technical expertise
7. Revise the preliminary functional description using the SysML diagrams

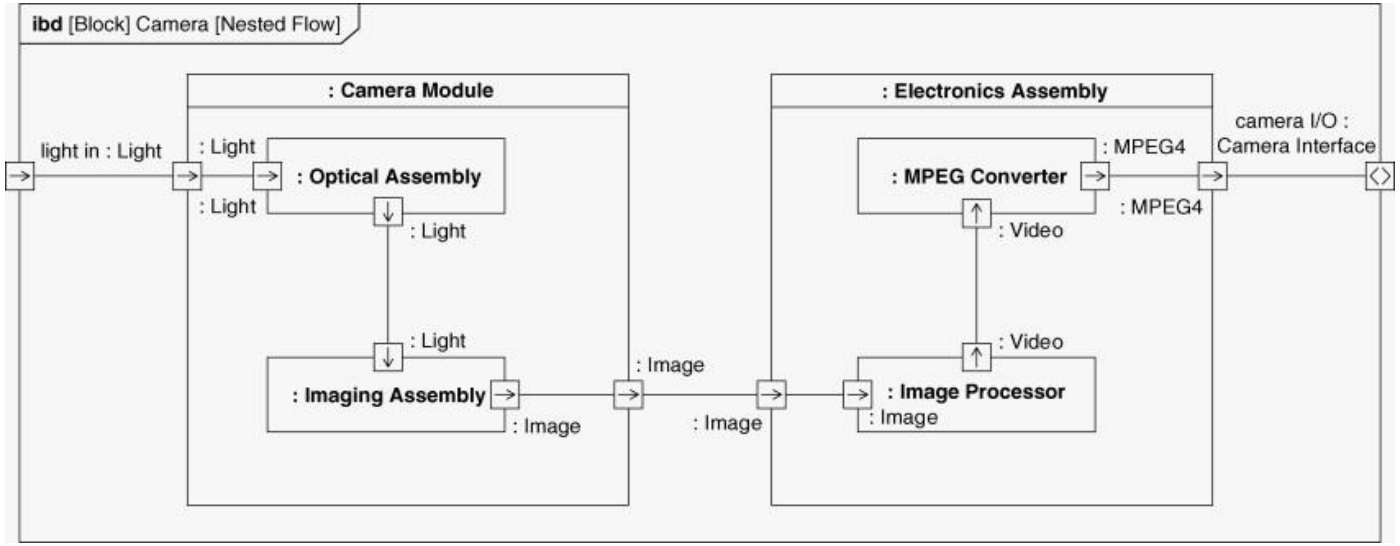
Vulnerability Ontology Development

- **Goal**: To develop a vulnerability ontology that will be used to inform MBSE development
- **Definition**: Ontologies provide descriptions of concepts and their relationships for a domain of interest
- **Rationale**: Ontology is an enabler of good modeling in that it focuses on establishing well-defined domain concepts in terms of the terminology, definitions, and relationships
  - Provides the concepts used to describe the domain
  - Defines the concepts which enables better model sharing
  - Standardizes the domain language
  - Standardized ontologies makes concepts precise, enables better model sharing

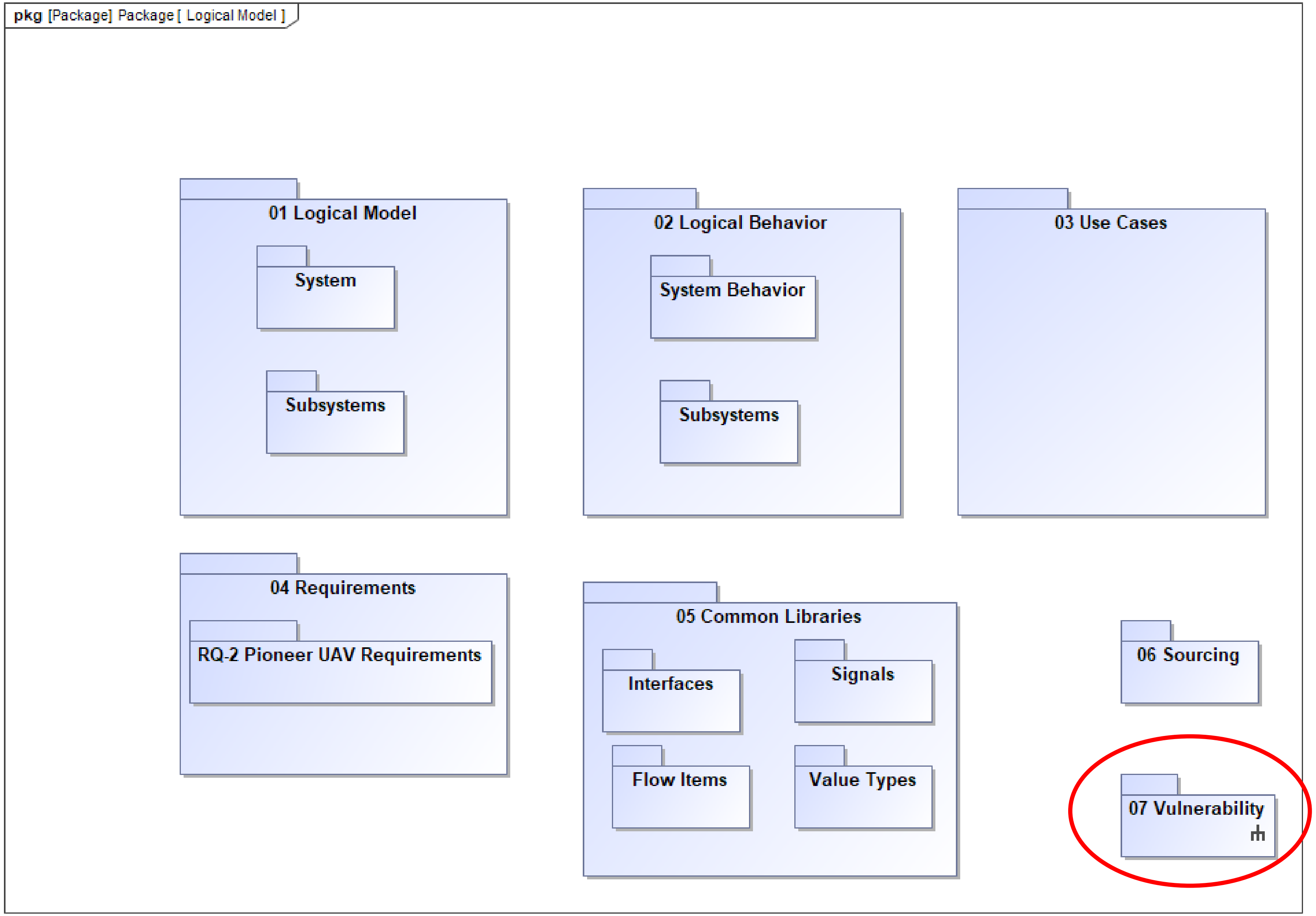
BDDs and IBDs

- **Block Definition Diagram (BDD)**: A static structural diagram that shows system components, their contents (Properties, Behaviors, Constraints), Interfaces, and relationships.
- **Internal Block Diagram (IBD)**: An Internal Block Diagram is a static structural diagram owned by a particular Block that shows its encapsulated structural contents: Parts, Properties, Connectors, Ports, and Interfaces.



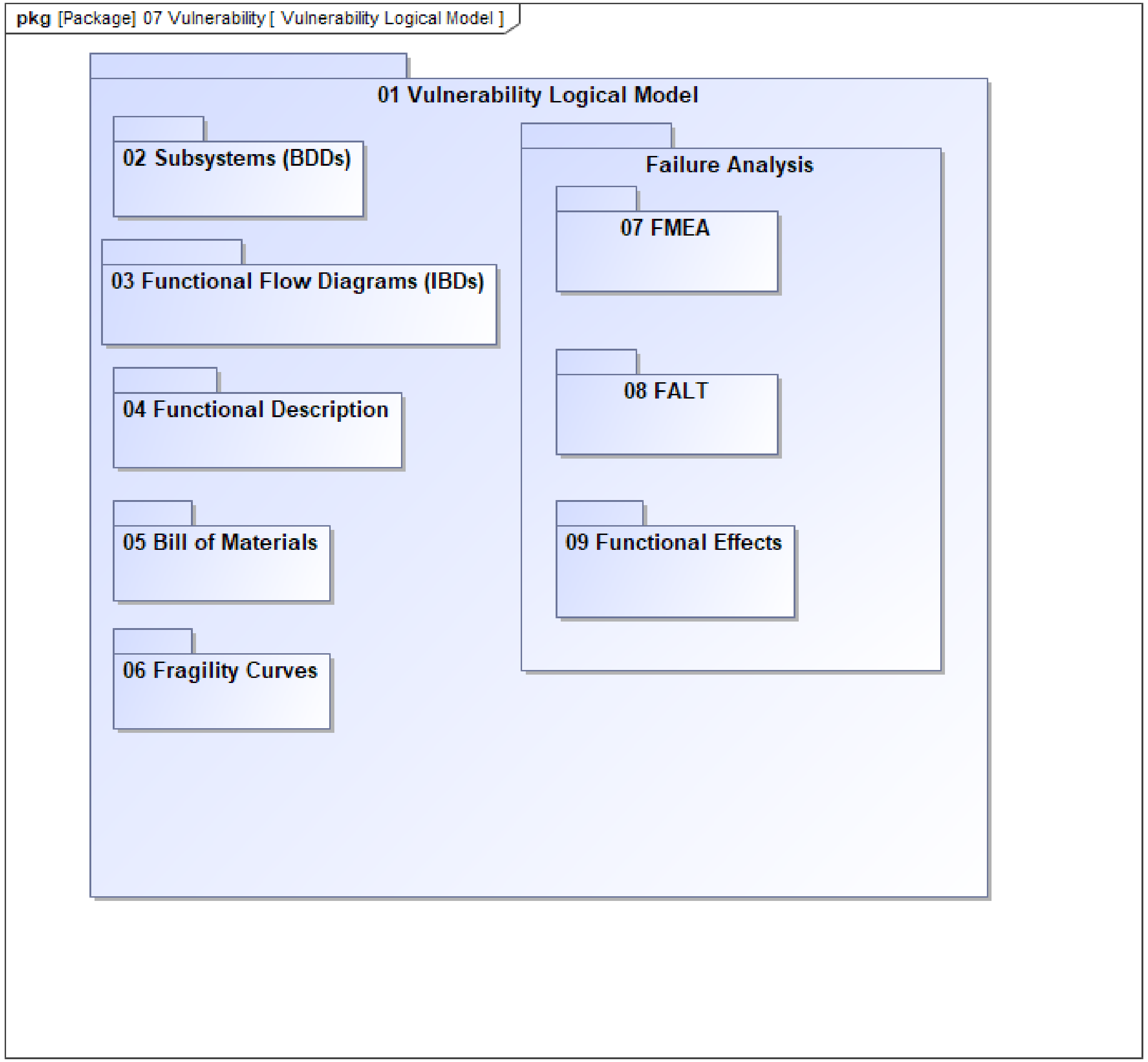


UAV Logical Model



Vulnerability Logical Model

- **Subsystems (Package)**
  - Subsystems (BDD, IBD)
- **Functional Description (Package)**
  - Functional Description (Matrix)
- **SysML Diagrams (Package)**
  - Functional Flow Diagrams
    - Structural Diagrams: Block Definition, Internal Block, Package
    - Behavioral Diagrams: Use case, Activity, Sequence, State Machine
    - Constraint Diagrams: Requirements, Parametric
- **Bill of Materials (Package)**
  - Bill of Materials (BOM) (Matrix)
- **Failure Analysis (Package)**
  - FMEA (BDD, IBD, Matrix)
  - Failure Modes (BDD, Matrix)
  - FALT (To Be determined)



RQ-2 Pioneer UAV Sub-systems

- **Flight Control System (FCS):**
  - Autopilot, Sensors, GPS/Navigation
- **Propulsion System:**
  - Motors, Propellers/Rotor Blades, Electronic Speed Controllers (ESCs)
- **Power System:**
  - Battery, Power Distribution Board, Voltage Regulators
- **Communication System:**
  - Telemetry, Remote Control (RC) Links, Data Link
- **Navigation and Guidance System:**
  - Inertial Measurement Unit (IMU), Compass/Magnetometer, Barometer/Altimeter
- **Sensors and Payloads:**
  - Camera, LIDAR, Infrared Sensors, Radar
- **Structural System:**
  - Frame, Landing Gear, Enclosures
- **Software System:**
  - Flight Management Software, Ground Control Software, Firmware

- **Navigation and Guidance System:**
  - Inertial Measurement Unit (IMU), Compass/Magnetometer, Barometer/Altimeter
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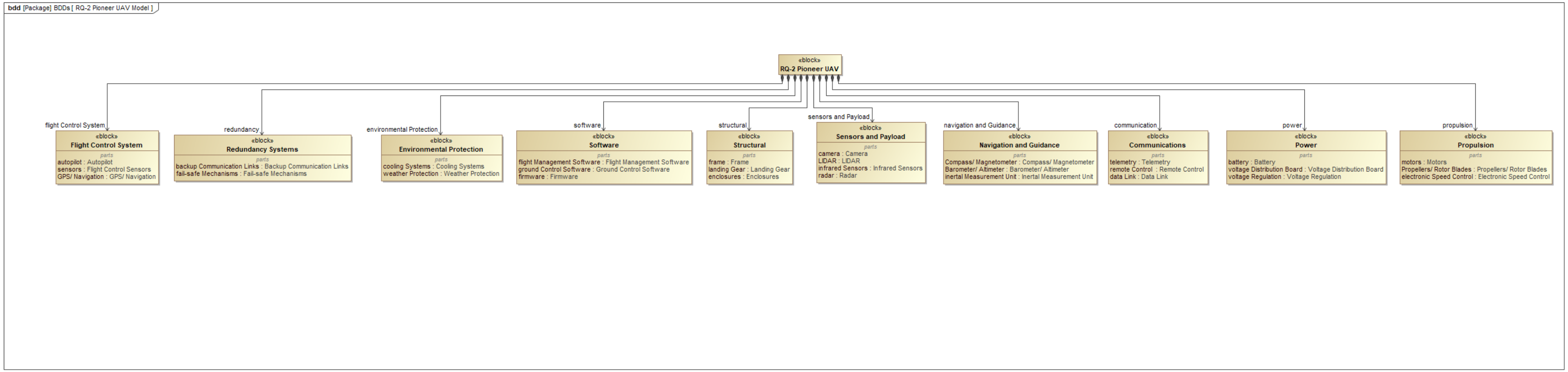
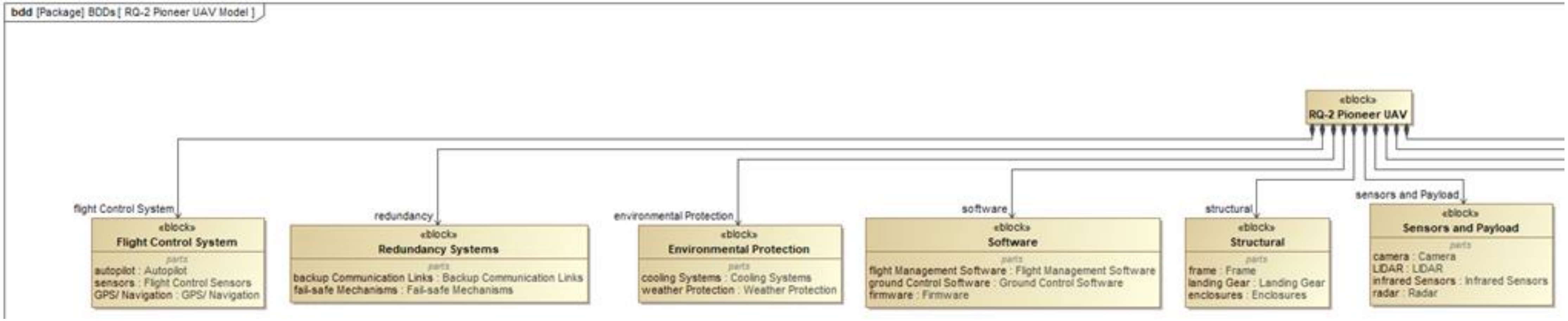
- **Structural System:**
  - Frame, Landing Gear, Enclosures
- **Software System:**
  - Flight Management Software, Ground Control Software, Firmware

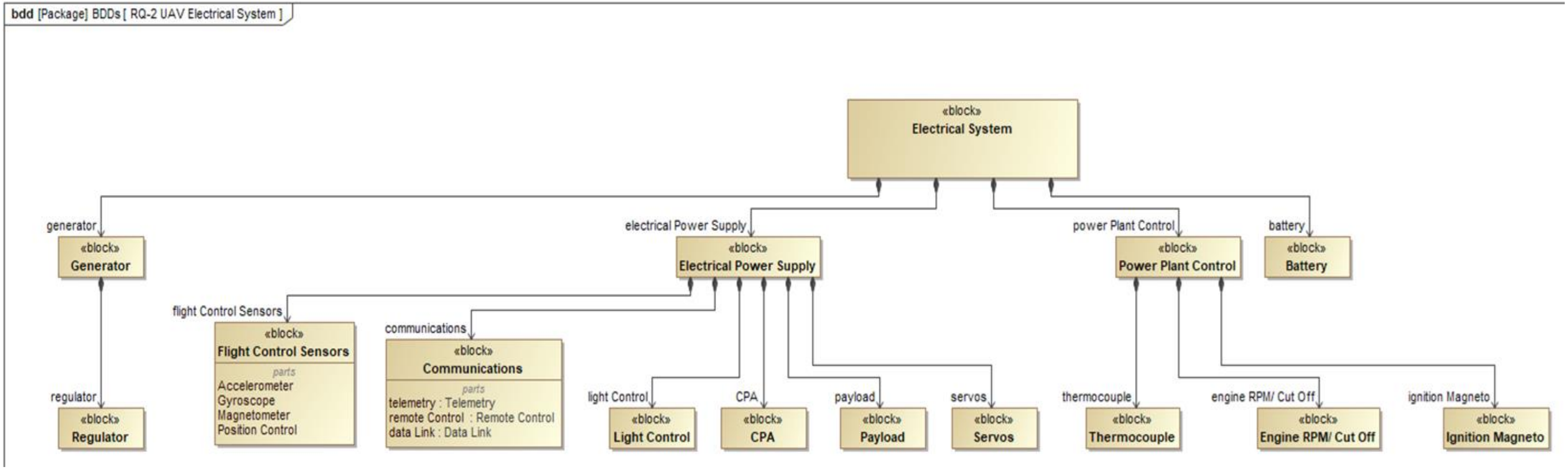
- **Environmental Protection System:**
  - Cooling Systems, Weather Protection
- **Redundancy Systems (for higher reliability):**
  - Backup Communication Links, Fail-safe Mechanisms

BDD: RG-2 Pioneer UAV





BDD: RQ-2 Pioneer UAV Electrical System



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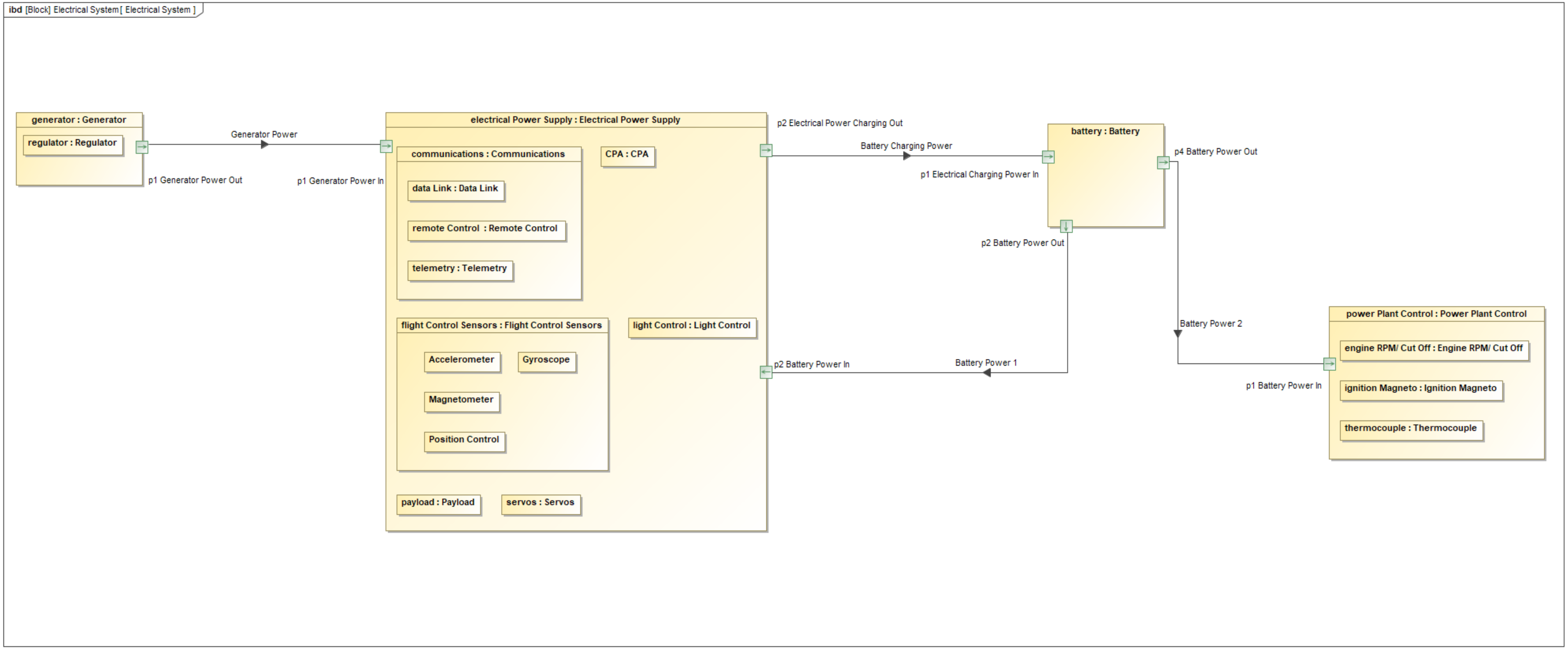
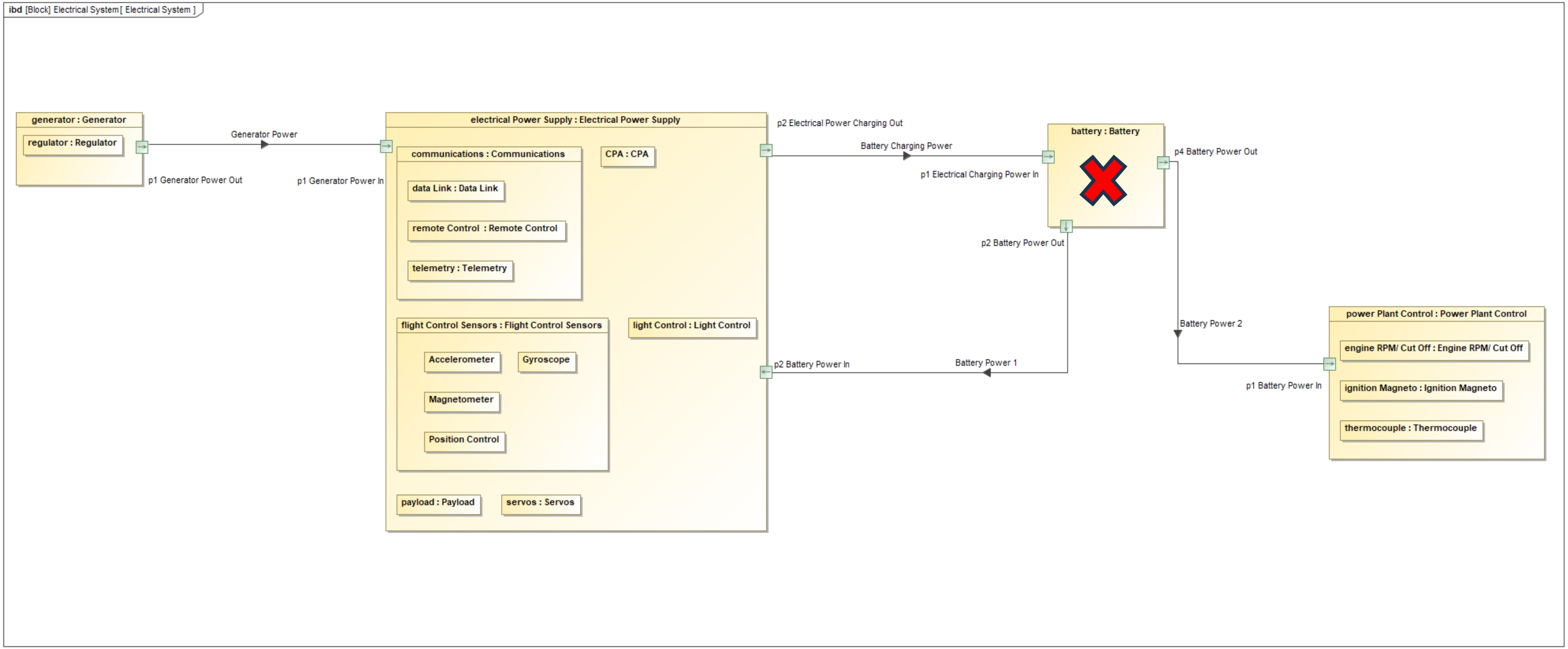
IBD: RQ-2 Pioneer UAV Electrical System



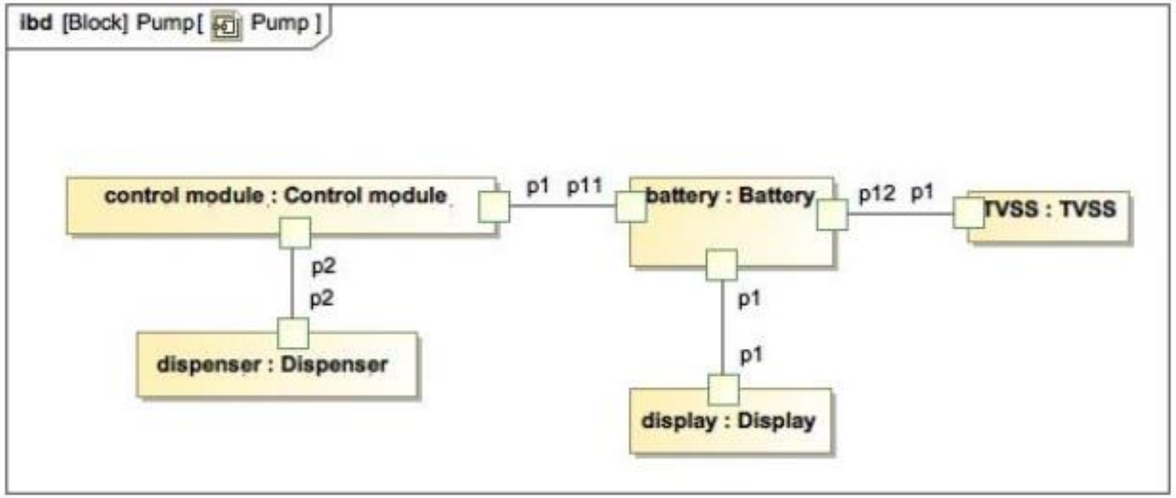
IBD: RQ-2 Pioneer UAV Electrical System

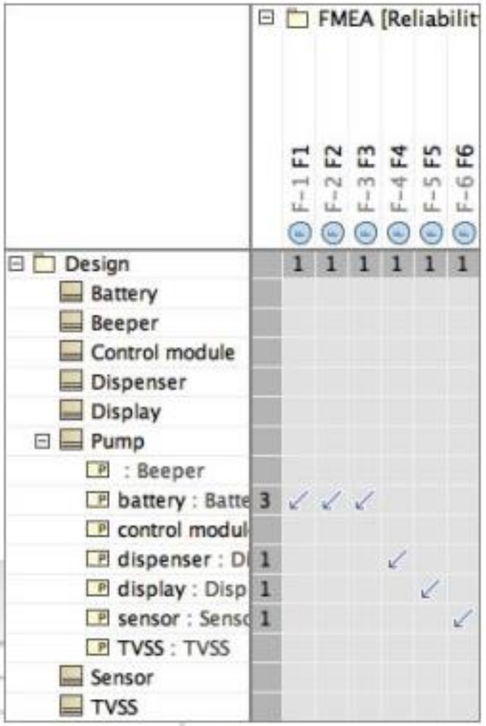


Vulnerability FMEA/FALT Generation Model

- **FMEAs and FALTs can be generated from SysML diagrams**
- **Develop a Vulnerability Model that generates FMEAs using a Standard Plugin**
  - Pros
    - Aid the Vulnerability Analyst
    - May aid in damage states analysis/ development
    - Time Saver
    - Customizable to standardize language
    - Traceability to the Design
    - Traceability to a Standard
    - Leverage a library of components with common failure modes
    - Easy applicable to new/ existing ATEP models
  - Cons
    - Some development may be required depending on the level of functionality

FMEA Generation Example





FMEA Table

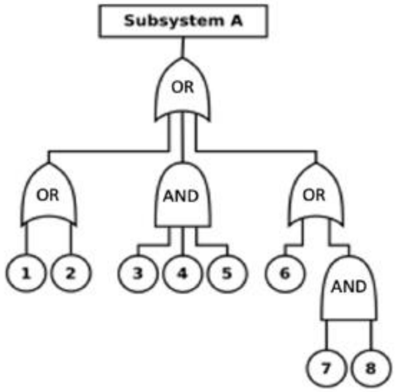
#	Id	Name	Classification	Item	Subsystem	Failure Mode	
1	F-1	F1	electrical	battery : Battery	Pump	Unable to be charged	
2	F-2	F2	electrical	battery : Battery	Pump	Voltage error	
3	F-3	F3	electrical	battery : Battery	Pump	Unable to be charged	
4	F-4	F4	electrical	dispenser : Dispenser	Pump	Pumps inaccurate size/rate of dose (including "f...	Air in line
5	F-5	F5	electrical	display : Display	Pump	Broken keypad	
6	F-6	F6	electrical	sensor : Sensor	Pump	Drop in sensitivity	High glucose-level undete Low glucose-level undetec

Risk Table

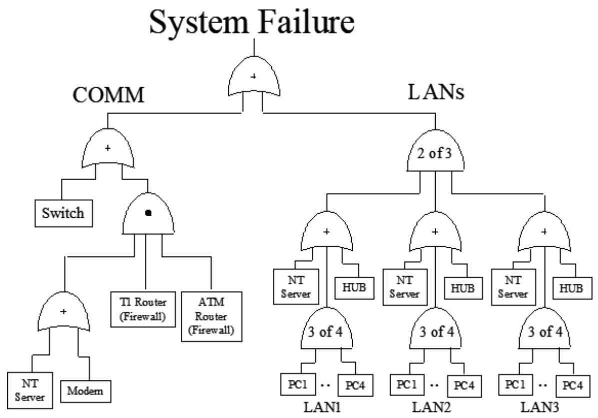
#	Id	FMEA Reference	Initiating Cause	Hazard	Sequence Of Event	Haza
1	R-1	F-1 F1	Discharged battery leads to coma or de	A Dose	Battery has sank	The user receives less insulin tha
2	R-2		Discharged battery leads to decreased	A Dose	Battery has sank	The user receives less insulin tha
3	R-3		Discharged battery leads to minor orgar	A Dose	Battery has sank	The user receives less insulin tha
4	R-4		R4	B Electromagnetic energy(ESD)	(1) Electrostatically...	Failure to deliver insulin unknowr

FALT Generation

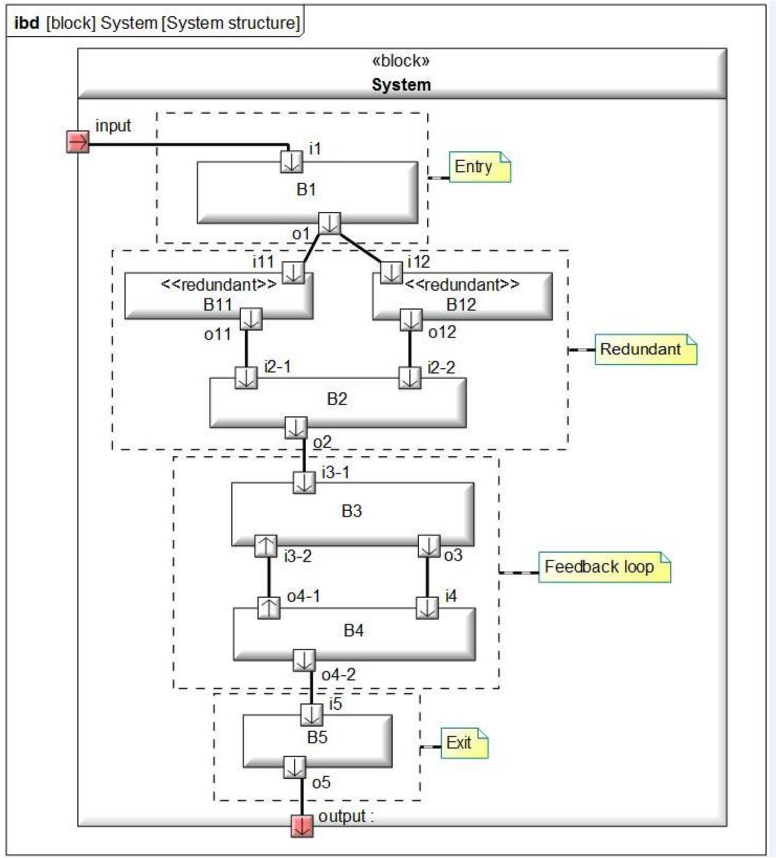
- FALTs are used to model the specific combination of subsystems required for the target system to function
  - These combinations are based on knowledge about how subsystems are connected to form a functioning system
- Inputs to FALTS are subsystem P_k values
  - Three types of gates in FALTs: AND, OR, & voting gate (M-of-N)
  - At each node, combinational logic is used to combine probabilities from P_k curves of constituent subsystems
  - P_k values for each constituent "roll up" to produce an overall P_k value for the target system



Classic Fault Tree Diagram



Example System FALT



FALT Depiction Using an IBD

Conclusions

- CAD diagrams and target documentation are the primary inputs when performing vulnerability assessments
- This information does not show the interactions between subsystems and how they affect the system as a whole
- SysML Diagrams are being used to fill these gaps
  - BDDS are used to outline the aircraft's hierarchical component structure, including subsystems like avionics, propulsion, control surfaces, and communications.
  - IBDs show how components interact and exchange information or energy. They can depict connections and interactions between components within the aircraft, such as how sensors communicate with avionics
- Future Work will incorporate behavioral diagrams into the analysis