Quantifying Flexibility for Architecting Changeable Systems

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Agenda

- Design of systems under uncertainty
- Assessing system flexibility using filtered out degree
- Finding flexible design leverage points using the change propagation index
- Conclusions and future work

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Uncertainty and Flexibility

Systems exist in uncertainty -- change is expected, but the future is unknown. Uncertainty provides both risks and opportunities.

Definition: A flexible system is one that can be changed by an external agent as response to a changing environment or internal state. (Ross 2008)

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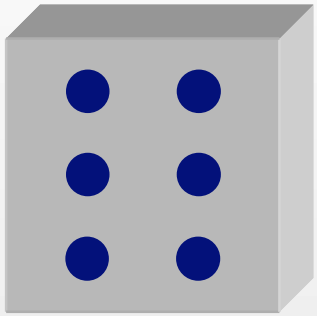
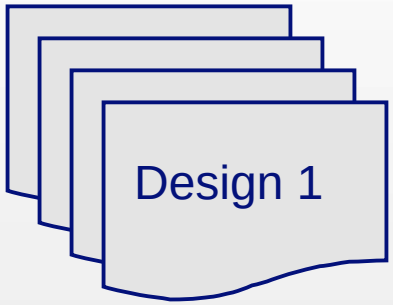
Three D's of flexible design

Real Option: The right, but not the obligation, to take some (design) action in the future



Dice: The uncertain future State of the system/context



Designs: Decisions (technical, programmatic and operational)

Discounting: The value of future benefits/costs as perceived today

The greater the variety of options I wish to have in the future, the more I may need to spend today to have those available

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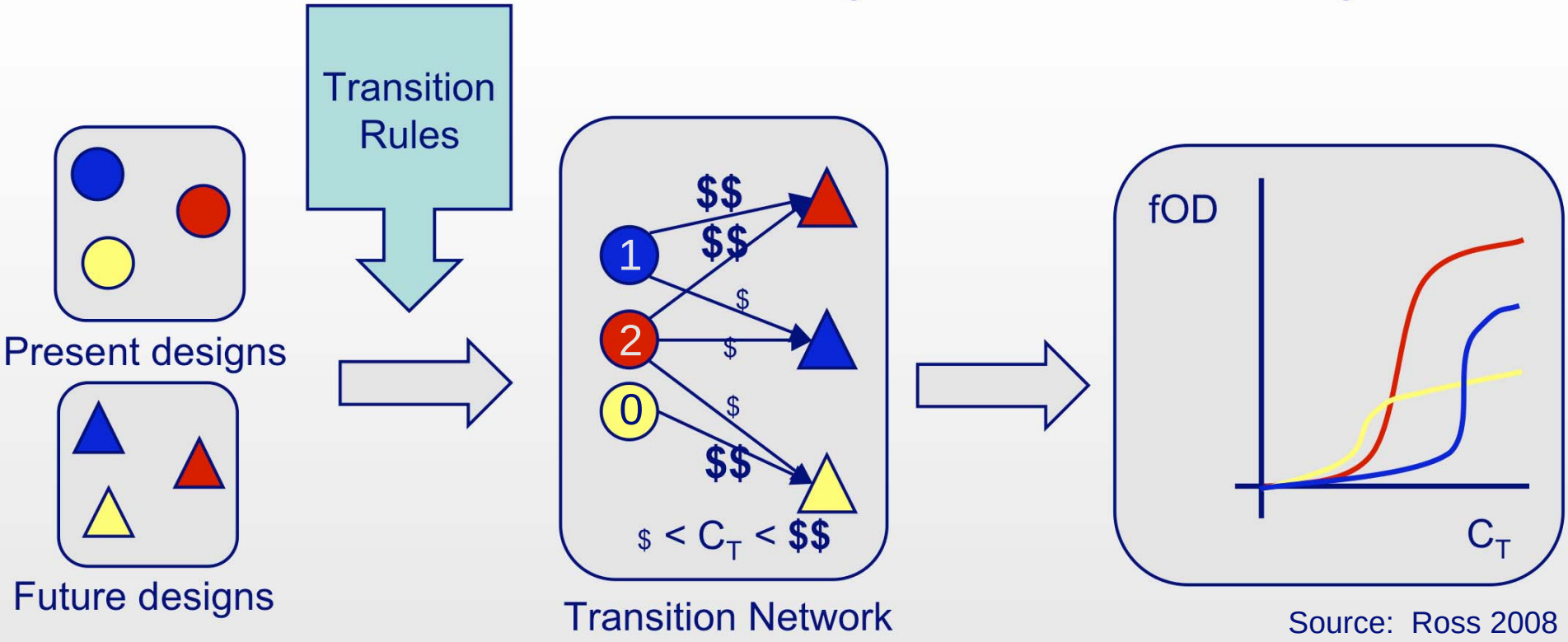
Using filtered out-degree to assess system flexibility



Source: Ross 2008

Does not address the value of having a particular option available only looks at the number of accessible future states

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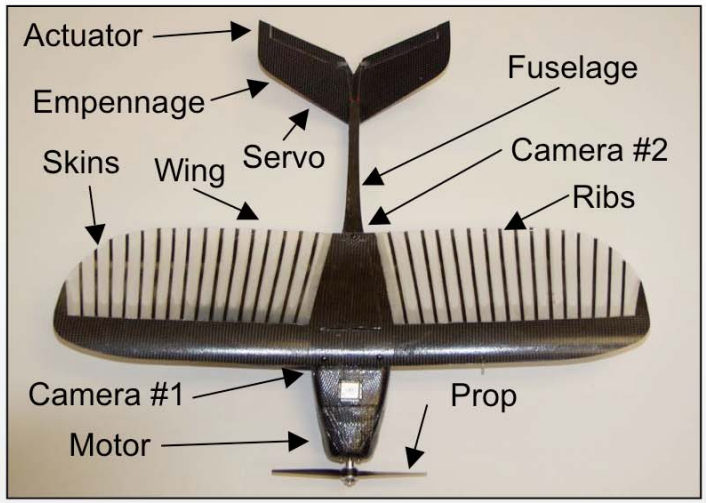
Case Study: Micro Air Vehicle

Change Scenario:

- A technological change in the payload to enable day/night operations



Choose an airframe
Purchase initial lot

Operate with day payload

Adapt design for day/night

Purchase prod. Lot w/ Day/Night payload
Upgrade existing

Uncertainty as to air vehicle performance requirements during day/night mission

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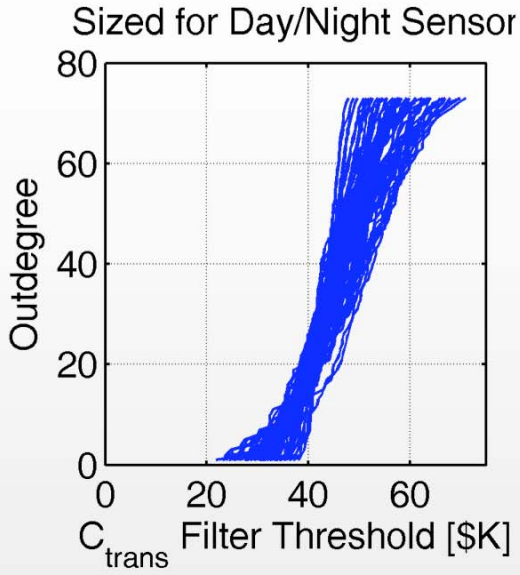
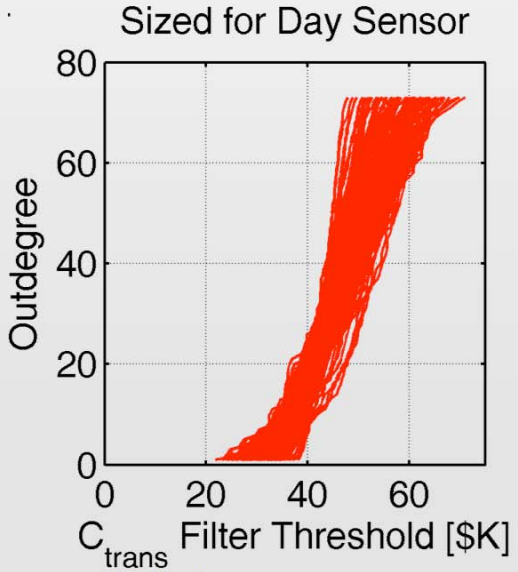
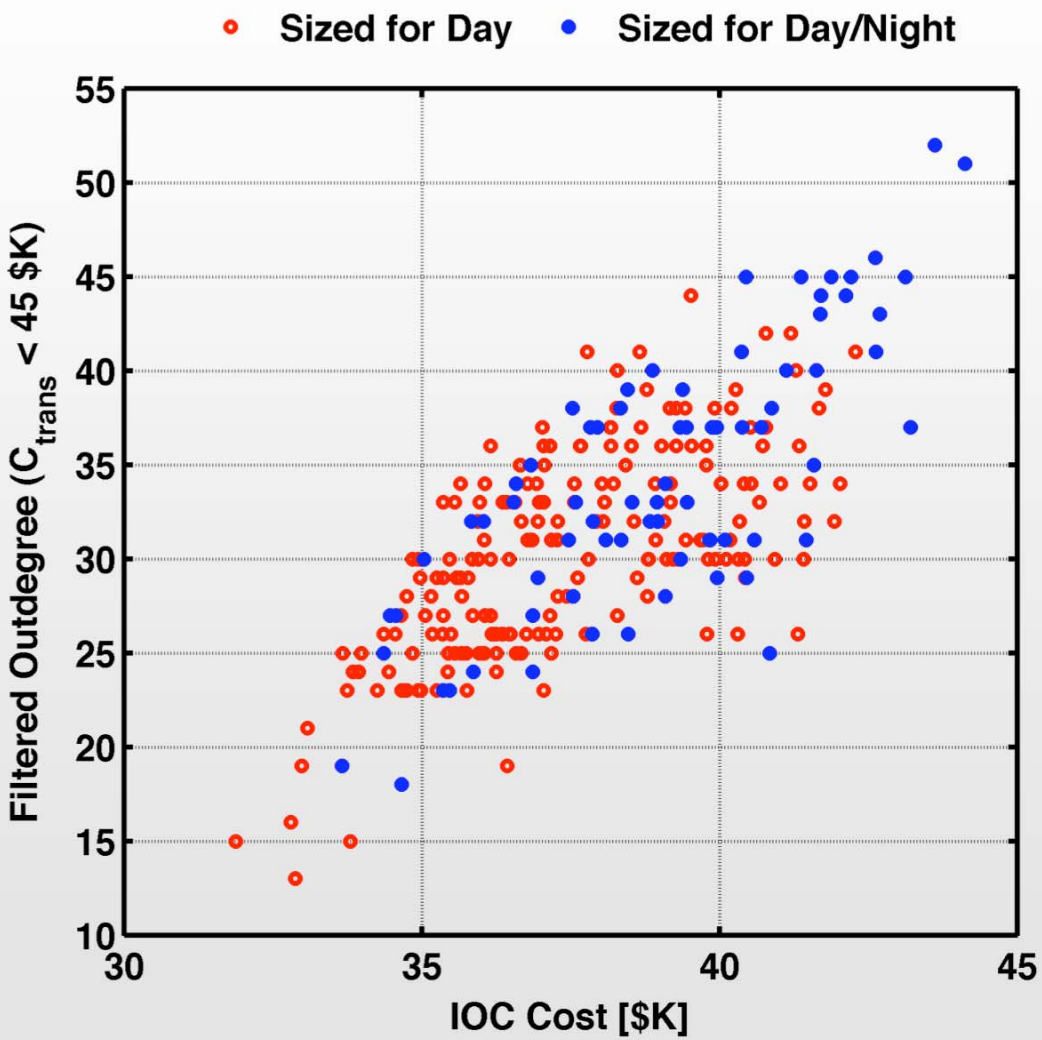
Increasing f-OD by embedding flexibility







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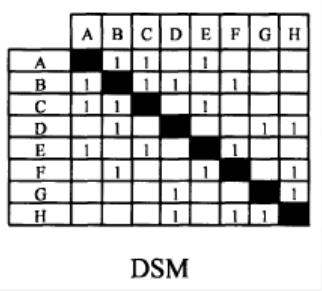
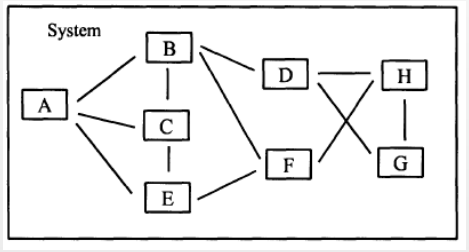
Change Propagation Method

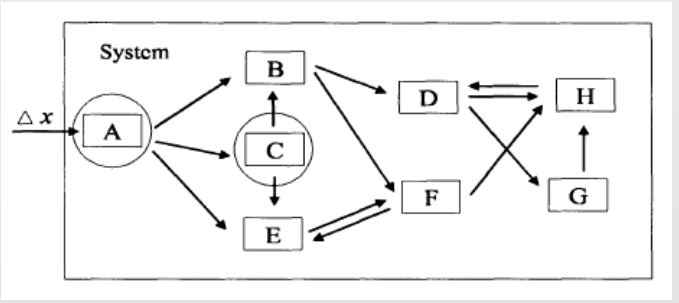
Change Propagation Method

1. Construct the Physical DSM.
2. Identify change scenarios from the system uncertainties.
3. Generate the undirected graph of the physical system.
4. Indicate the change flows based on expertise and experience.
5. Calculate component Change Propagation Index (CPI) and identify change behavior.
6. Calculate switch costs.
7. Formulate potential real options.



DSM





Source: Clarkson 2001, Suh 2005

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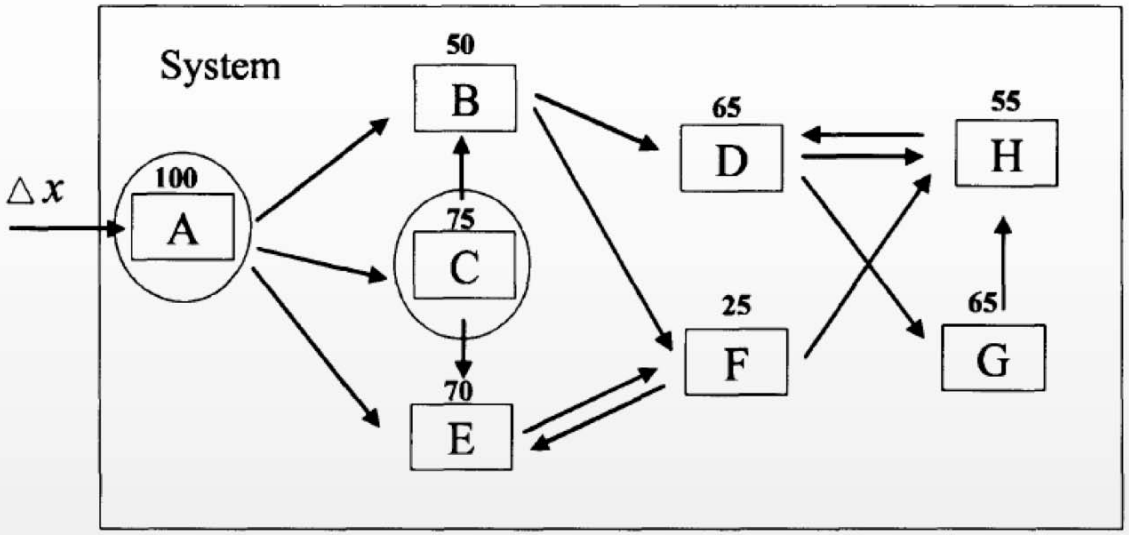
The CPI Heuristic



$$\mathrm{CPI}_i = \sum_{j=1}^{n_{out}} \Delta E_{out,j} - \sum_{k=1}^{n_{in}} \Delta E_{in,k}$$

Multipliers: A, C

Carriers: B, D, F, G

Absorbers: E, H

Source: Clarkson 2001, Suh 2005

Objective: Identify system components whose re-design will likely reduce system-level switch cost and thereby open up more switch possibilities at a given cost threshold

Switch cost: Reducing direct switch cost at the node level will reduce system-level switch cost

Multipliers: Reducing the propagation of changes by redesigning multipliers can reduce the components level switch costs that are incurred

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Limitations

- Actually determining change paths can be difficult for very complex DSMs
- Exponential growth in number of paths to be considered as one adds initiators
- Single edge type abstracts away details of how change is propagated
- Magnitude of change is not directly addressed

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Modified CPM

Change Propagation Method

1. **Construct the Physical DSM with multiple edge types.**
2. Identify change scenarios from the system uncertainties.
3. Generate the undirected graph of the physical system.
4. **Apply filtering for relationship types/change scenarios and generate subgraphs.**
5. Indicate the change flows for each subgraph.
6. Calculate component Change Propagation Index (CPI) and identify change behavior. (Suh 2005 & Giffin 2007)
7. **Observe CPI variations for multiple contexts.**
8. Calculate switch costs.
9. Formulate potential real options.

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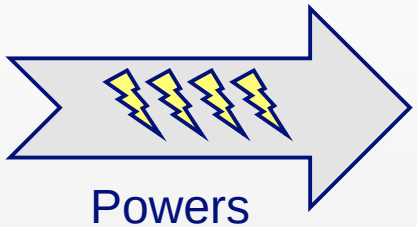
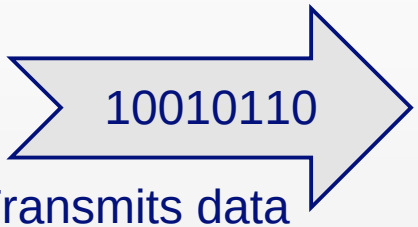
The Micro Air Vehicle Network Graph: System flows

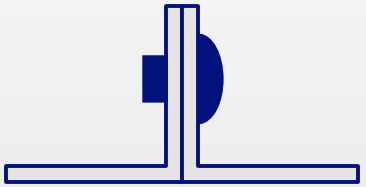
- 56 Nodes in Physical DSM
- 4 Relationship Types



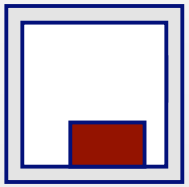
Powers



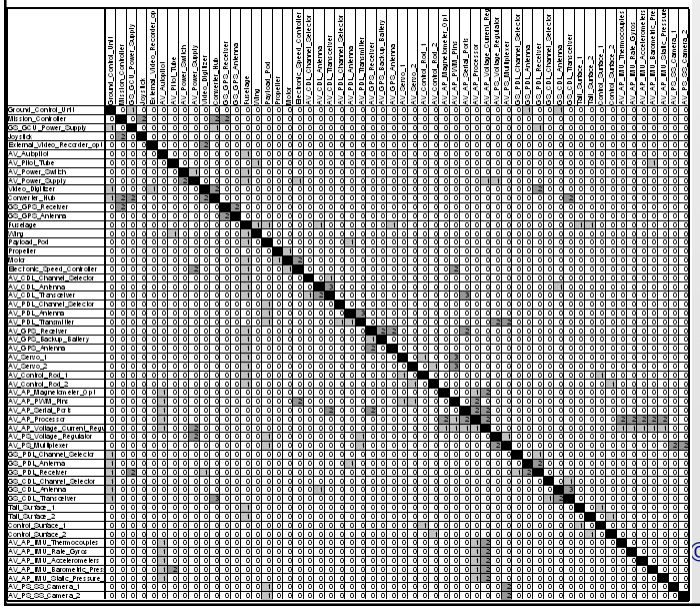
Transmits data

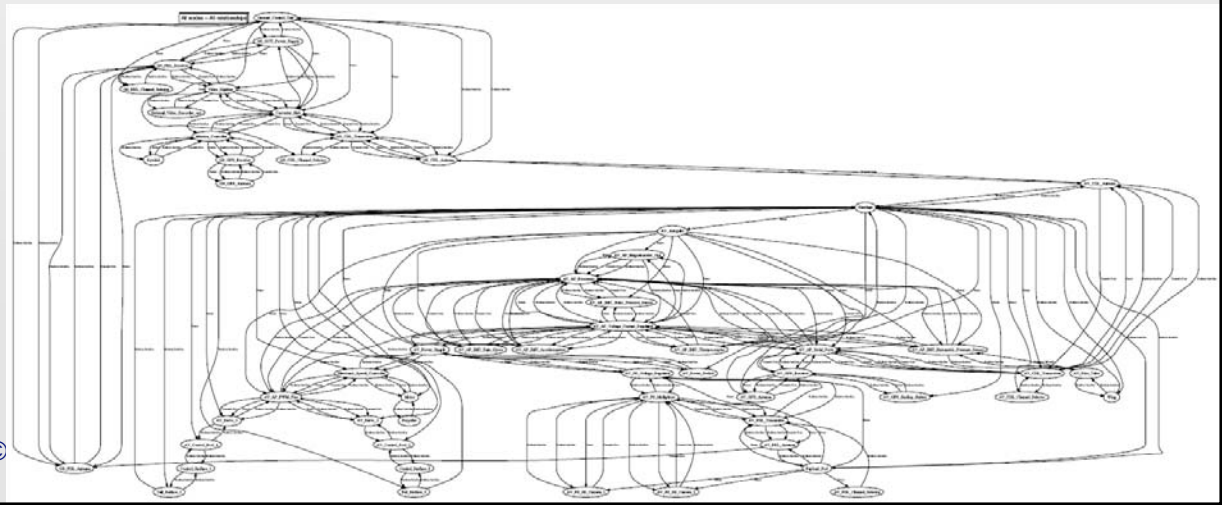


Hardware Interface



Houses





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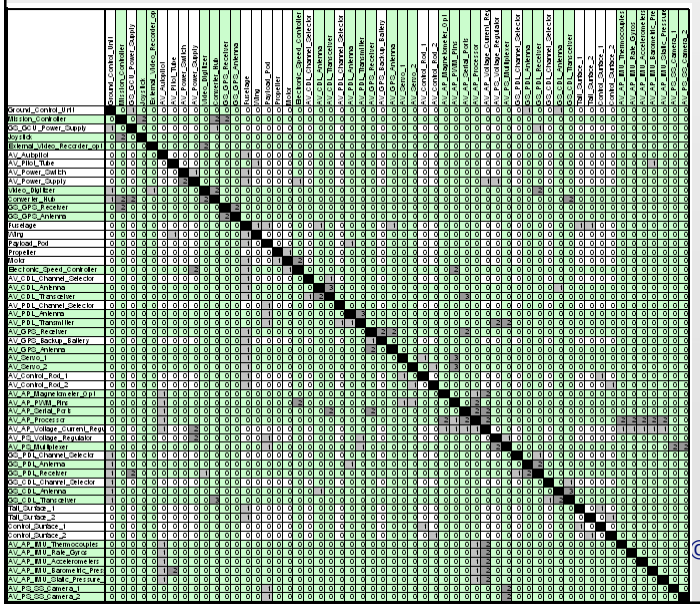
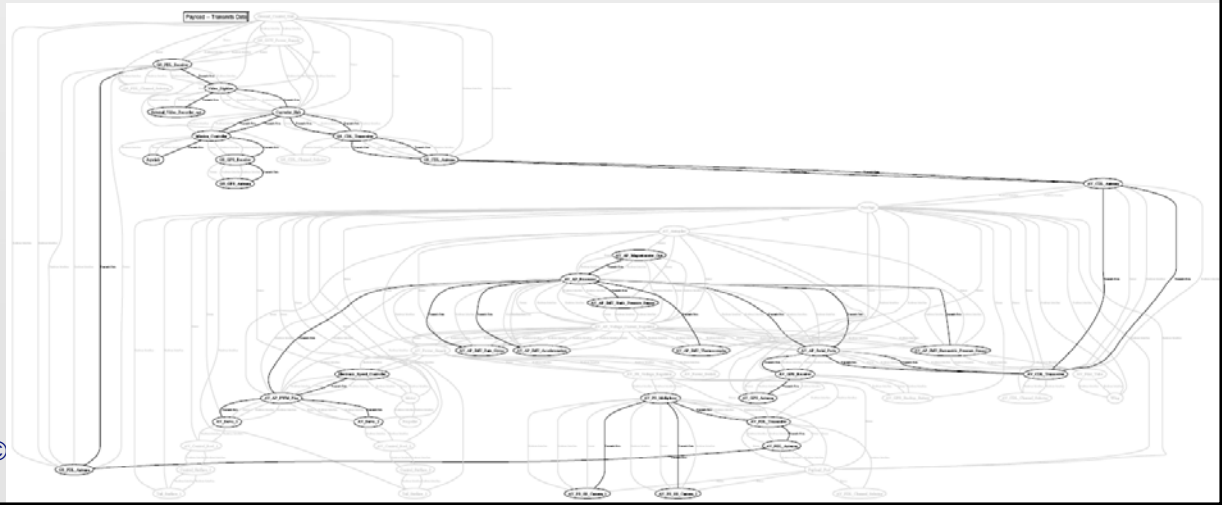
MAV Network Graph: Filtered for Payload Change Scenario

- 32 Nodes in Physical DSM
- 1 Relationship Type (“transmits data”)
- Initiators are the camera payloads





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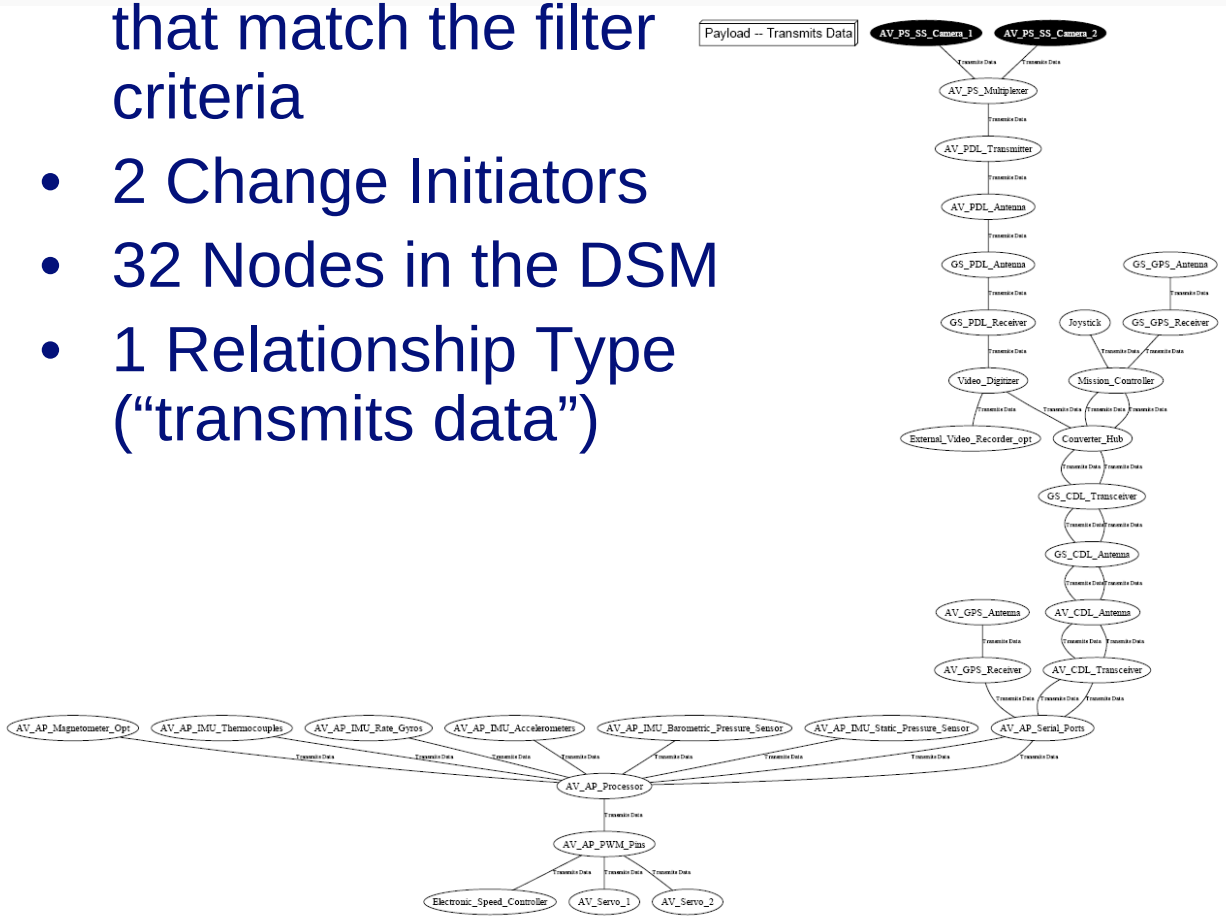
DSM- Payload Data Transmission Filtered for Change Initiators

- Reduced graph to only those nodes and edges that match the filter criteria
- 2 Change Initiators
- 32 Nodes in the DSM
- 1 Relationship Type ("transmits data")



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Mission_Controller		1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Joystick	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
External_Video_Recorder_opt	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Video_Digitizer	0	0	1		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
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GS_GPS_Receiver	1	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GS_GPS_Antenna	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electronic_Speed_Controller	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_CDL_Antenna	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
AV_CDL_Transceiver	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
AV_PDL_Antenna	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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AV_Servo_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_Servo_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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GS_PDL_Receiver	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0
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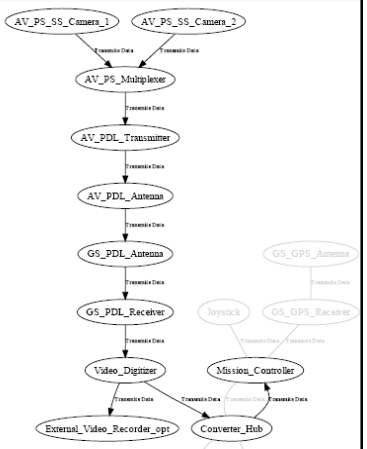
DSM- Payload Data Transmission Filtered with Change Flows

- Expert knowledge applied to indicate change path for given scenario
- 2 Change Initiators
- 10 Change flows
- 11 Nodes in the DSM
- 1 Relationship Type ("transmits data")



	Mission_Controller	Joystick	External_Video_Recorder_opt	Video_Digitizer	Converter_Hub	GS_GPS_Receiver	GS_GPS_Antenna	Electronic_Speed_Controller	AV_CDL_Antenna	AV_CDL_Transceiver	AV_PDL_Antenna	AV_PDL_Transmitter	AV_GPS_Receiver	AV_GPS_Antenna	AV_Servo_1	AV_Servo_2	AV_AP_Magnetometer_Opt	AV_AP_PWM_Pins	AV_AP_Serial_Ports	AV_AP_Processor	AV_PS_Multiplexer	GS_PDL_Antenna	GS_PDL_Receiver	GS_CDL_Antenna	GS_CDL_Transceiver	AV_AP_IMU_Thermocouples	AV_AP_IMU_Rate_Gyros	AV_AP_IMU_Accelerometers	AV_AP_IMU_Barometric_Pres	AV_AP_IMU_Static_Pressure_	AV_PS_SS_Camera_1	AV_PS_SS_Camera_2
Mission_Controller		1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Joystick	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
External_Video_Recorder_opt	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Video_Digitizer	0	0	1		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Converter_Hub	1	0	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
GS_GPS_Receiver	1	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GS_GPS_Antenna	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electronic_Speed_Controller	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_CDL_Antenna	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
AV_CDL_Transceiver	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
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AV_PDL_Transmitter	0	0	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
AV_GPS_Receiver	0	0	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_GPS_Antenna	0	0	0	0	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_Servo_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_Servo_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_AP_Magnetometer_Opt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_AP_PWM_Pins	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_AP_Serial_Ports	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0
AV_AP_Processor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1		0	0	0	0	0	1	1	1	1	1	0	0	
AV_PS_Multiplexer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	1	1	
GS_PDL_Antenna	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0
GS_PDL_Receiver	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0
GS_CDL_Antenna	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0
GS_CDL_Transceiver	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0		0	0	0	0	0	0	0	0
AV_AP_IMU_Thermocouples	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0		0	0	0	0	0	0	0
AV_AP_IMU_Rate_Gyros	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0		0	0	0	0	0	0
AV_AP_IMU_Accelerometers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	0
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AV_PS_SS_Camera_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		0	0
AV_PS_SS_Camera_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0		0

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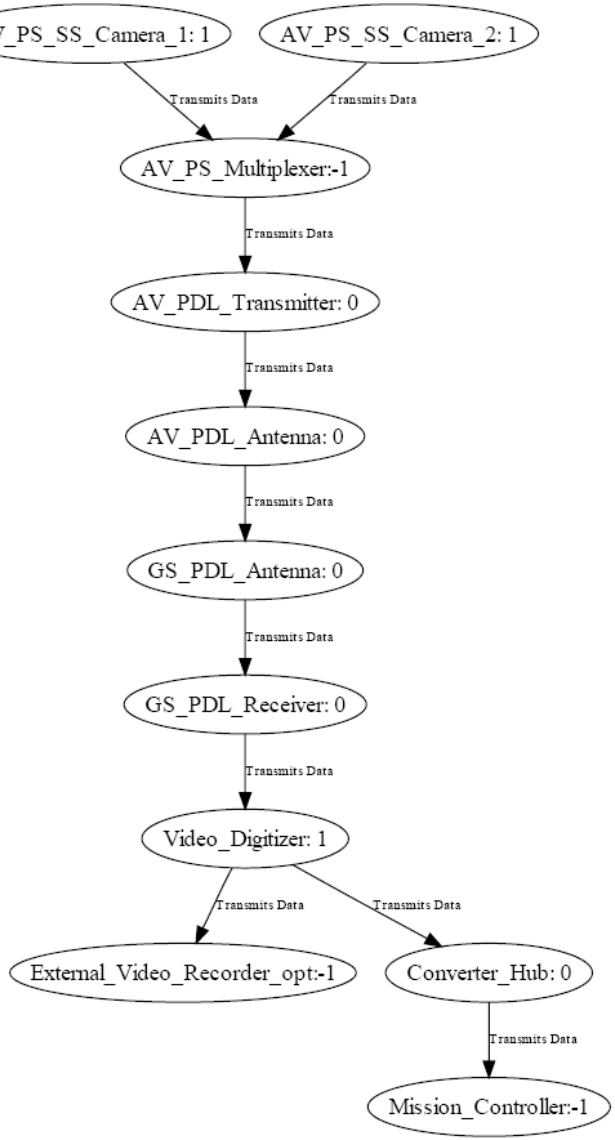
CPM- Payload Data Transmission

Payload -- Transmits Data

$$\mathrm{CPI}_i = \sum_{j=1}^{n_{out}} \Delta E_{out,j} - \sum_{k=1}^{n_{in}} \Delta E_{in,k}$$

	Mission_Controller	External_Video_Recorder_opt	Video_Digitizer	Converter_Hub	AV_PDL_Antenna	AV_PDL_Transmitter	AV_PS_Multiplexer	GS_PDL_Antenna	GS_PDL_Receiver	AV_PS_SS_Camera_1	AV_PS_SS_Camera_2	Ein
Mission_Controller		0	0	1	0	0	0	0	0	0	0	1
External_Video_Recorder_opt	0		1	0	0	0	0	0	0	0	0	1
Video_Digitizer	0	0		0	0	0	0	0	1	0	0	1
Converter_Hub	0	0	1		0	0	0	0	0	0	0	1
AV_PDL_Antenna	0	0	0	0		1	0	0	0	0	0	1
AV_PDL_Transmitter	0	0	0	0	0		1	0	0	0	0	1
AV_PS_Multiplexer	0	0	0	0	0	0		0	0	1	1	2
GS_PDL_Antenna	0	0	0	0	1	0	0		0	0	0	1
GS_PDL_Receiver	0	0	0	0	0	0	0	1		0	0	1
AV_PS_SS_Camera_1	0	0	0	0	0	0	0	0	0		0	0
AV_PS_SS_Camera_2	0	0	0	0	0	0	0	0	0	0		0
Eout	0	0	2	1	1	1	1	1	1	1	1	
CPI	-1	-1	1	0	0	0	-1	0	0	1	1	
Class	A	A	M	C	C	C	A	C	C	M	M	



Aggregation of Change Propagation Index (CPI)

- Above steps are repeated across all change scenarios, switch costs estimated and CPI normalized (Giffin 2007) to allow aggregation
- CPI can be aggregated by:
  - Component CPI for given change scenario and relationship type across multiple initiator sets
  - Component CPI for a given change scenario
  - Component CPI for a given relationship type
  - Component CPI for all change scenarios/relation types
- Interpretation of aggregated CPI is an area of ongoing research
  - High aggregate CPI seems to indicate likely candidates for redesign to reduce transition cost

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Aggregation Results

- Considered two additional change scenarios: Endurance and range
- Aggregated across all scenarios and relations

Sum of nCPI	Relation			
Component	Houses	Powers	Transmits Data	Grand Total
AV_Power_Supply	2.0	2.5	con	4.5
AV_PS_SS_Camera_2	1.0	1.0	1.0	3.0
AV_PS_SS_Camera_1	1.0	1.0	1.0	3.0
Electronic_Speed_Controller	2.0	0.0	con	2.0
AV_PS_Voltage_Regulator	2.0	0.0	con	2.0
AV_PDL_Transmitter	1.0	0.0	1.0	2.0

Expert confirmed that the Air Vehicle Power Supply caused great difficulty in managing all the changes that occurred to the system in its life-cycle

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Conclusions

- Flexibility is a key consideration in system design in an uncertain world
- Filtered outdegree can be used to quantify flexibility
  - Demonstrates the tradeoff between upfront costs and future transitions costs
- CPI can be used to identify aspects of the system design where embedding real options may be yield greater flexibility
  - Filtering reduces the cognitive demand on the expert specifying the change path
  - Multiple edge-types allow are more complete representation of all the changes that occur

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Future work

- Combine change propagation and filtered outdegree / real options valuation into a holistic system and component level framework for the design of flexible systems
- Characterize the different methods of aggregating CPI and develop guidance for interpretation by the practitioner
- Explore different way in which design can be modified to create options

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Backup Slides

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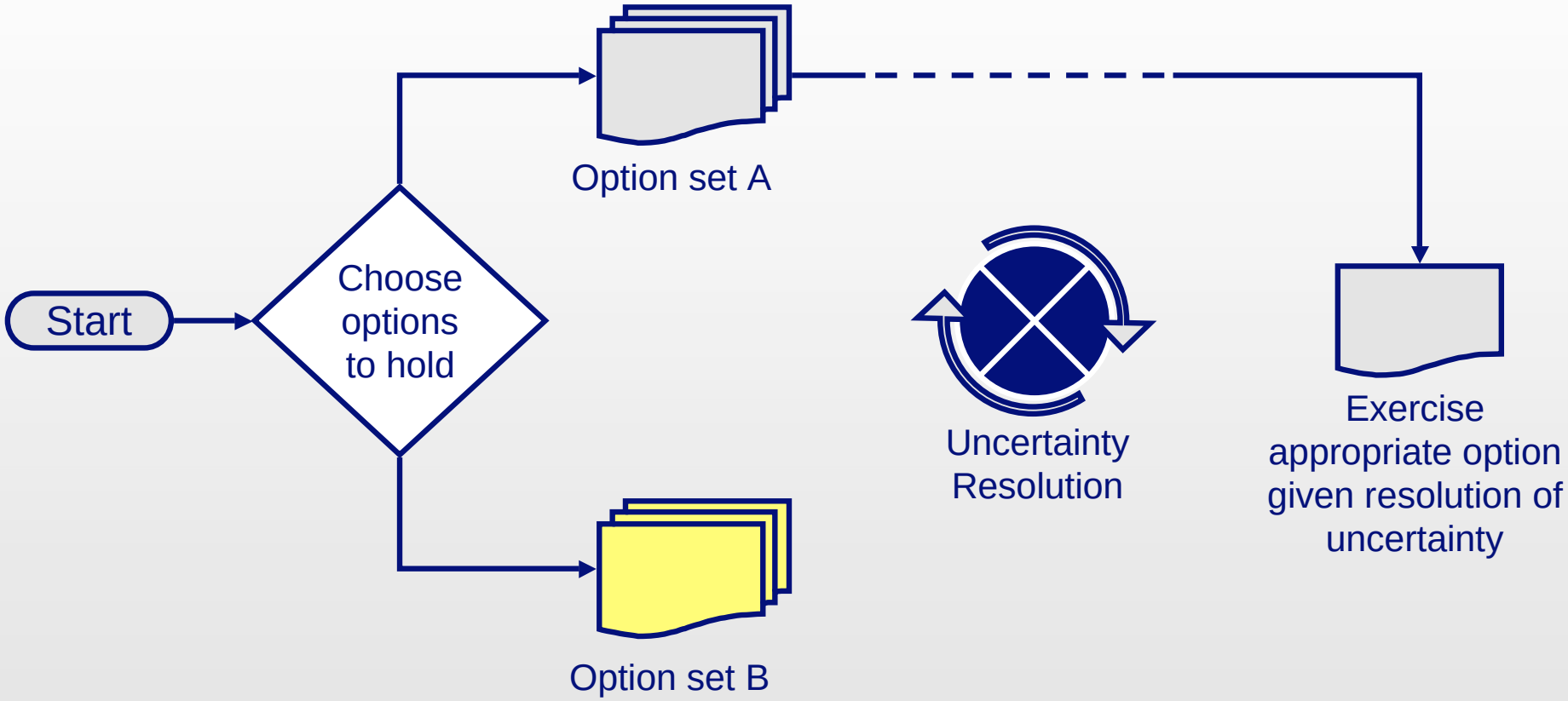
Flexible (Real option) design timeline



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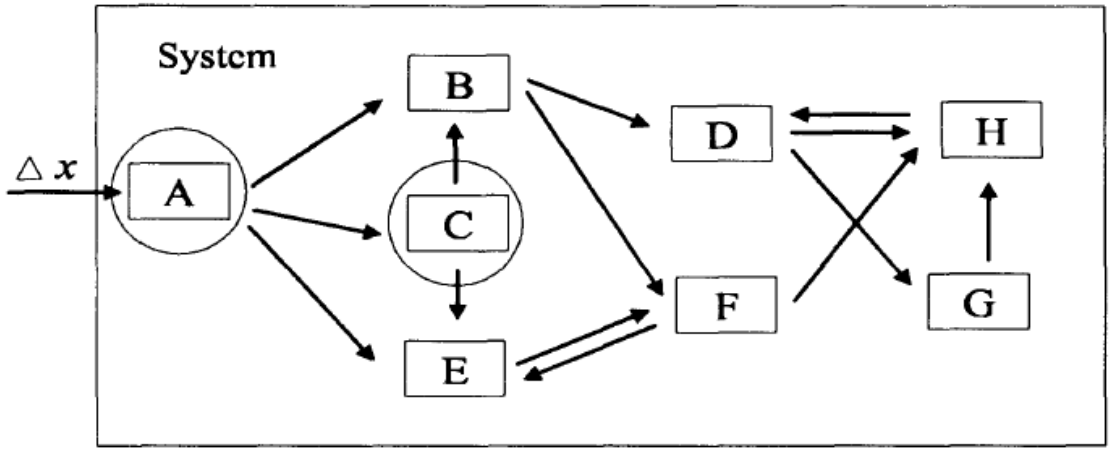
Change Behaviors



Multiplier: A, C

Carrier: B, D, F, G

Absorber/Constant: E, H

Source: Suh, 2005

Figure 3-5: Change Propagation Due to Δx

- Multiplier = “generate more changes than they absorb”
- Absorber = “absorb more change than they themselves cause”
- Carrier = “absorb a similar number of changes to those that they cause themselves.”
- Constant = do not generate nor absorb changes

Source: Eckert, 2004

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Change Propagation: Switch Costs

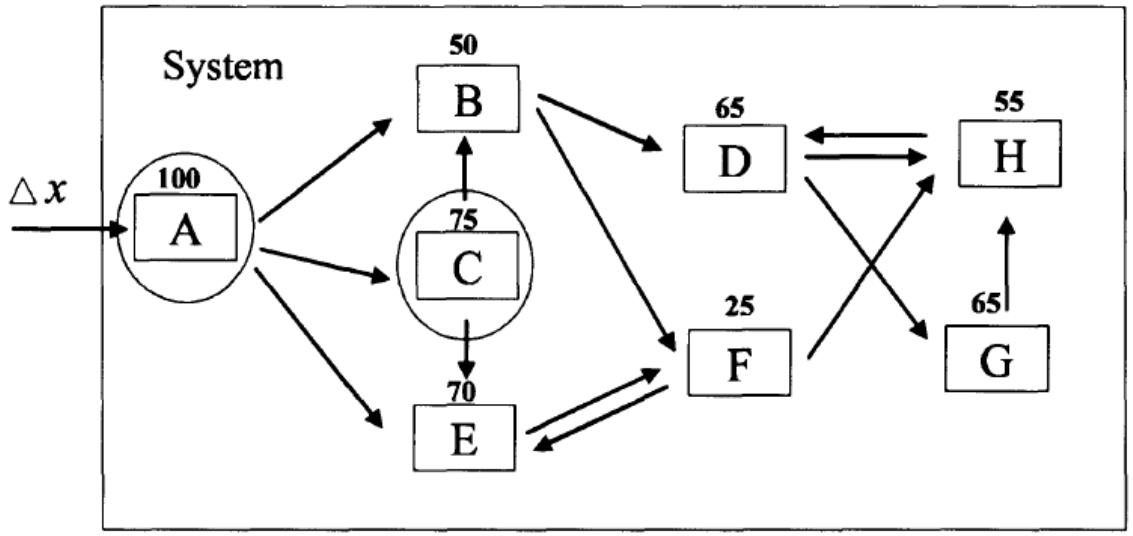

Figure 3-7: Economic Impact of the System for Δx

Switch Cost = indicates the economic consequence of change Δx

- Consider not only the direct cost of the change, but indirect costs also!

Source: Suh, 2005

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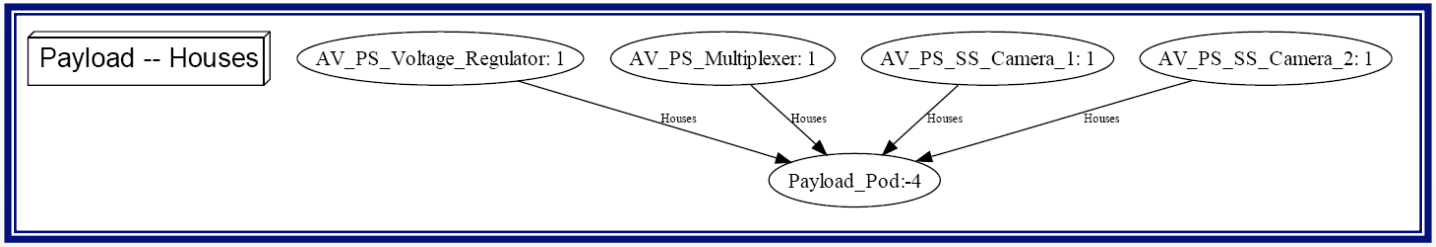
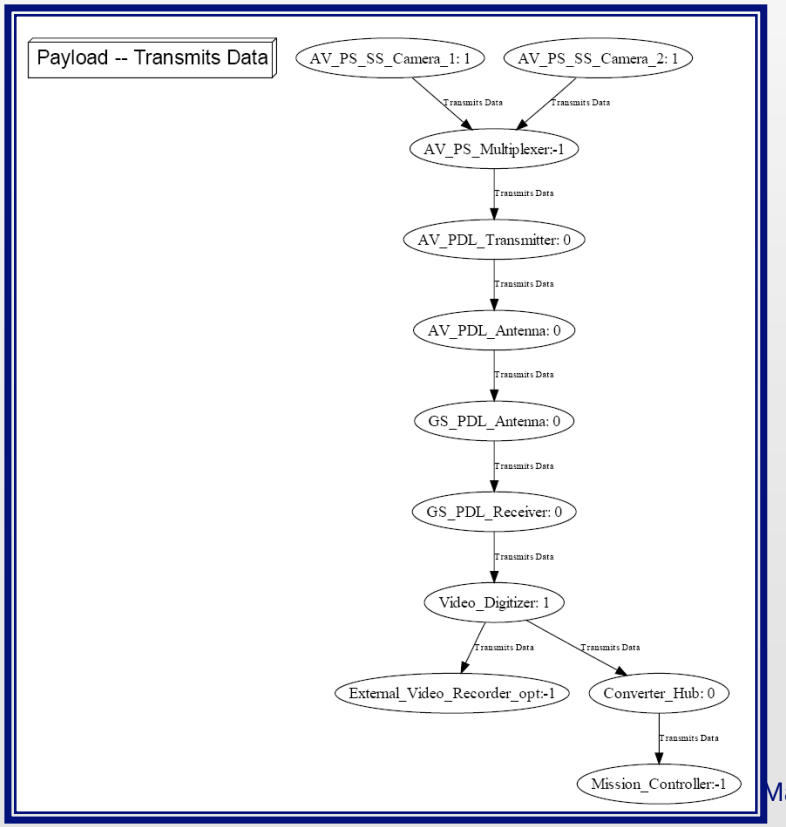
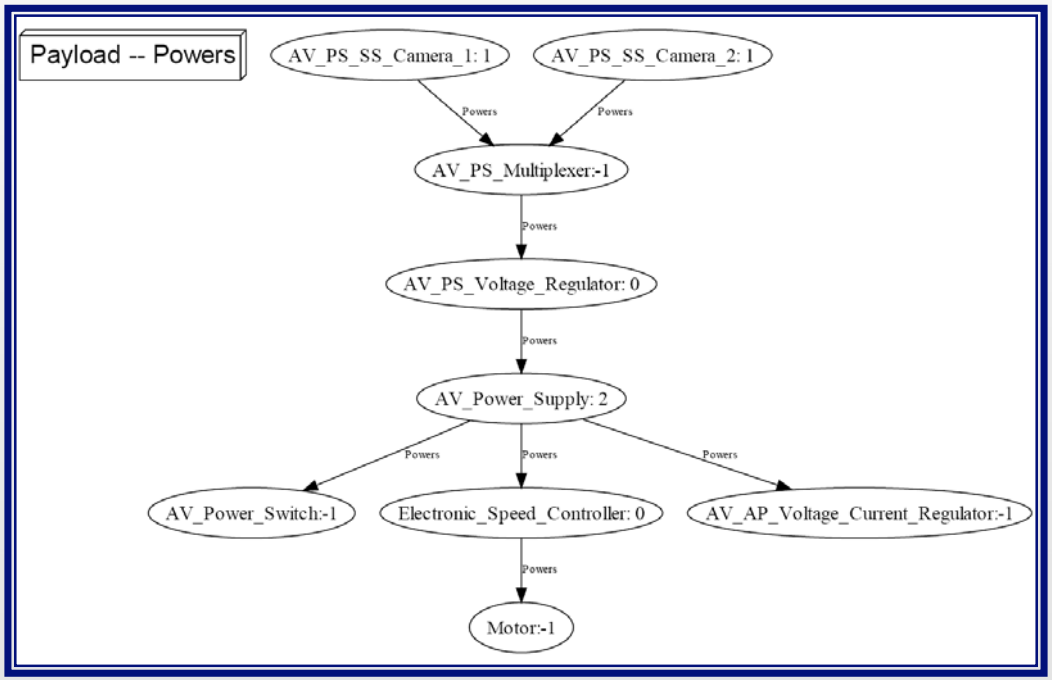
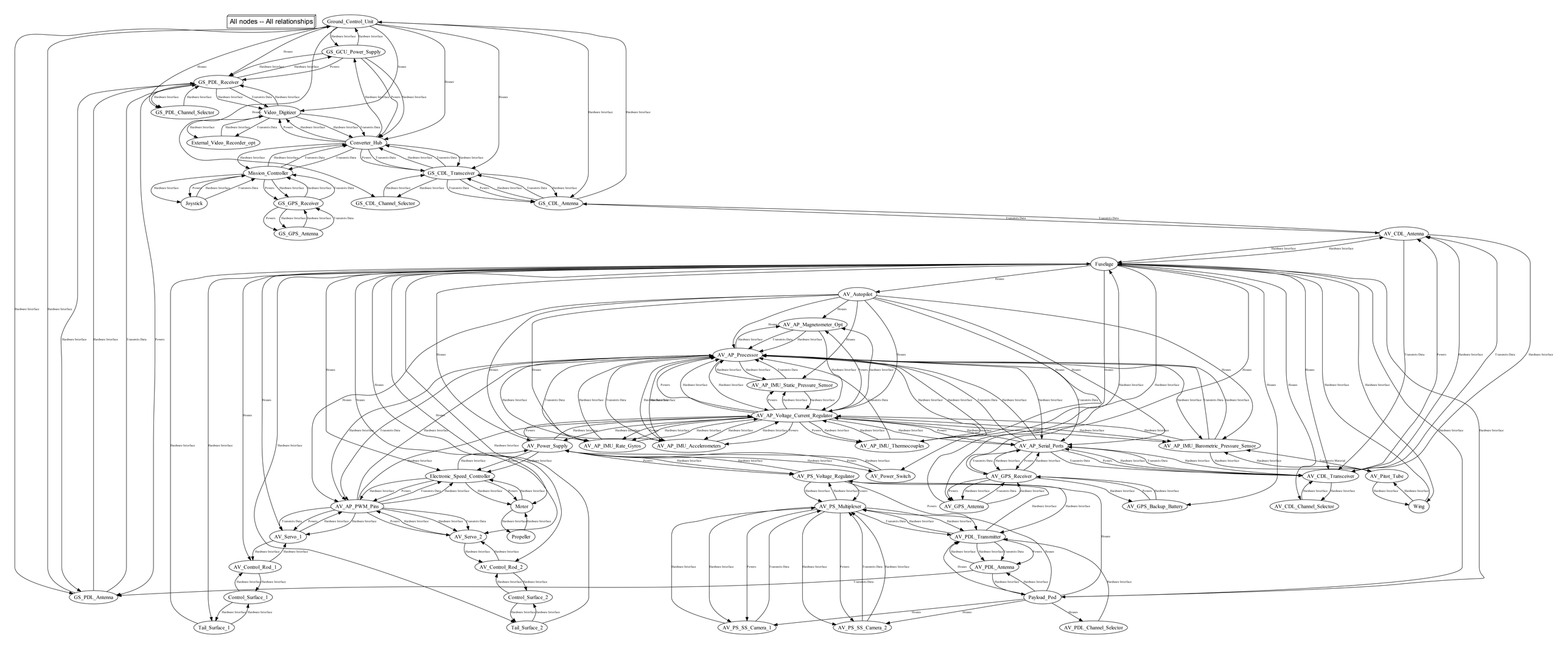
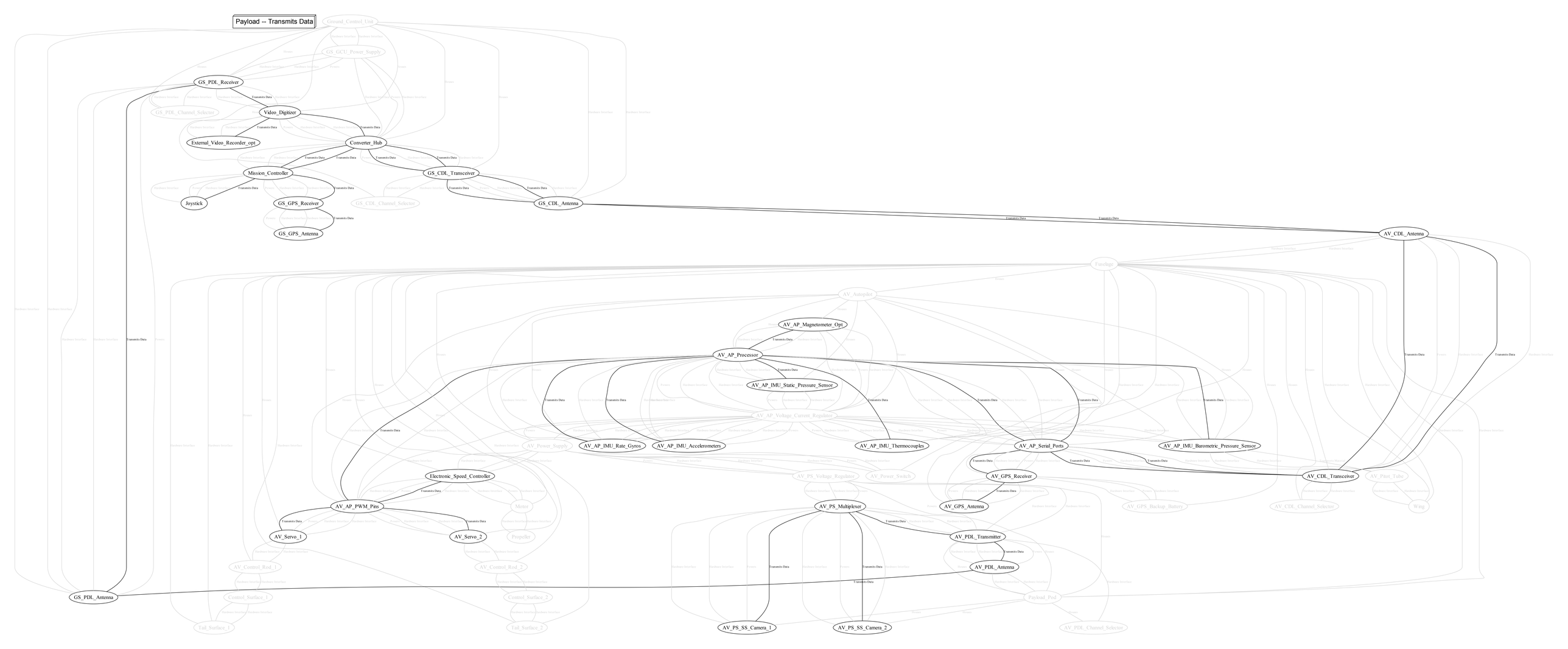
All Relationship Types for a Given Change Scenario







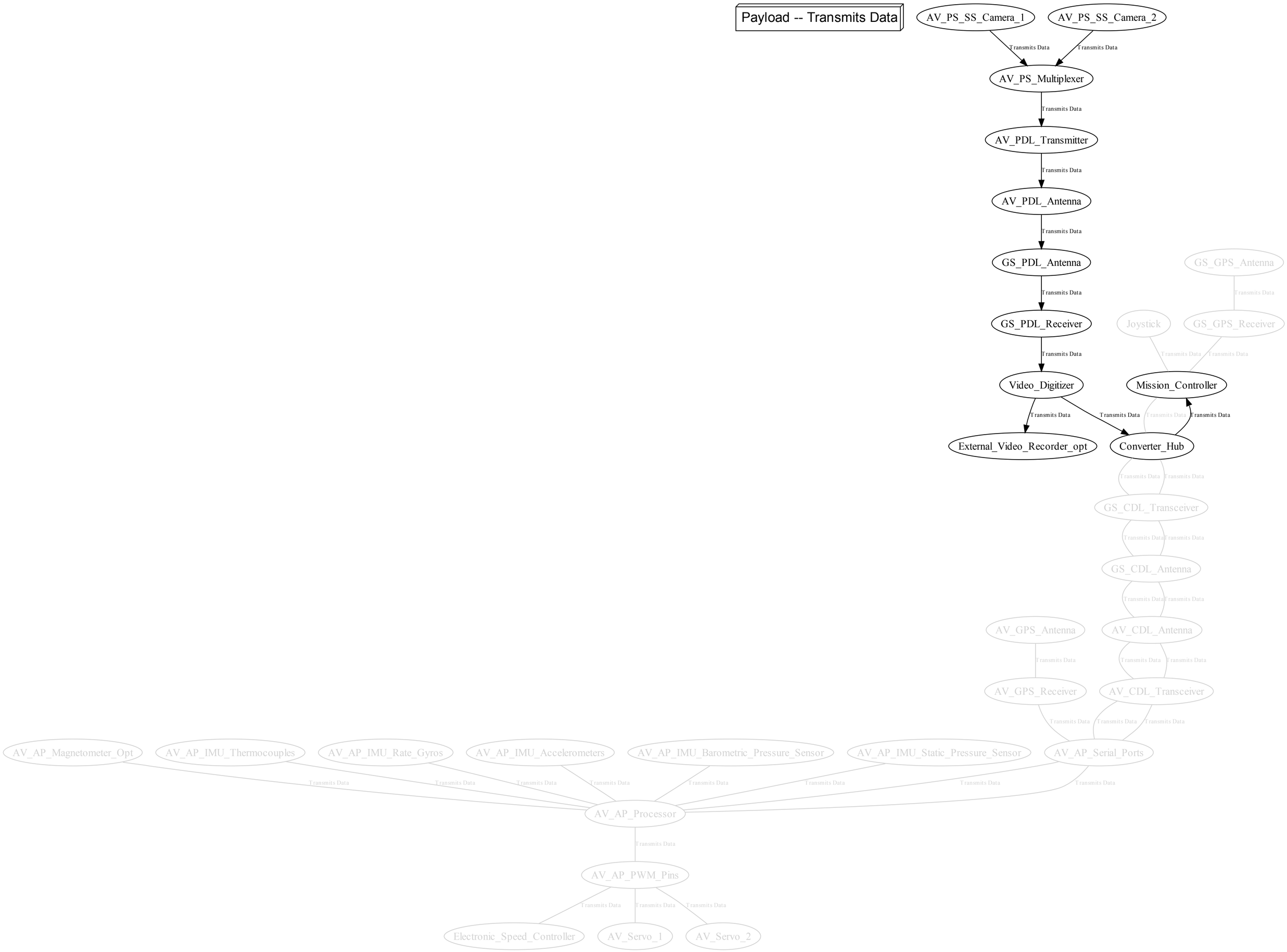

All nodes -- All relationships
Ground_Control_Unit
GS_GCU_Power_Supply
GS_PDL_Receiver
GS_PDL_Channel_Selector
Video_Digitizer
External_Video_Recorder_opt
Converter_Hub
Mission_Controller
Joystick
GS_GPS_Receiver
GS_GPS_Antenna
GS_CDL_Transceiver
GS_CDL_Channel_Selector
GS_CDL_Antenna
GS_PDL_Antenna
AV_CDL_Antenna
Fuselage
AV_Autopilot
AV_AP_Magnetometer_Opt
AV_AP_Processor
AV_AP_IMU_Static_Pressure_Sensor
AV_AP_Voltage_Current_Regulator
AV_Power_Supply
AV_AP_IMU_Rate_Gyros
AV_AP_IMU_Accelerometers
AV_AP_IMU_Thermocouples
AV_AP_Serial_Ports
AV_AP_IMU_Barometric_Pressure_Sensor
Electronic_Speed_Controller
AV_PS_Voltage_Regulator
AV_Power_Switch
AV_GPS_Receiver
AV_CDL_Transceiver
AV_Pitot_Tube
AV_AP_PWM_Pins
Motor
AV_PS_Multiplexer
AV_GPS_Antenna
AV_GPS_Backup_Battery
AV_CDL_Channel_Selector
Wing
AV_Servo_1
AV_Servo_2
Propeller
AV_PDL_Transmitter
AV_Control_Rod_1
AV_Control_Rod_2
AV_PDL_Antenna
Control_Surface_1
Control_Surface_2
Payload_Pod
Tail_Surface_1
Tail_Surface_2
AV_PS_SS_Camera_1
AV_PS_SS_Camera_2
AV_PDL_Channel_Selector
Houses
Hardware Interface
Transmits Data
Powers


Payload -- Transmits Data
Ground_Control_Unit
GS_GCU_Power_Supply
GS_PDL_Receiver
GS_PDL_Channel_Selector
Video_Digitizer
External_Video_Recorder_opt
Converter_Hub
Mission_Controller
Joystick
GS_GPS_Receiver
GS_GPS_Antenna
GS_CDL_Transceiver
GS_CDL_Channel_Selector
GS_CDL_Antenna
GS_PDL_Antenna
AV_CDL_Antenna
Fuselage
AV_Autopilot
AV_AP_Magnetometer_Opt
AV_AP_Processor
AV_AP_IMU_Static_Pressure_Sensor
AV_AP_Voltage_Current_Regulator
AV_AP_IMU_Rate_Gyros
AV_AP_IMU_Accelerometers
AV_AP_IMU_Thermocouples
AV_Power_Supply
AV_AP_Serial_Ports
AV_AP_IMU_Barometric_Pressure_Sensor
AV_PS_Voltage_Regulator
AV_Power_Switch
AV_GPS_Receiver
AV_CDL_Transceiver
AV_Pitot_Tube
Electronic_Speed_Controller
AV_AP_PWM_Pins
Motor
AV_GPS_Antenna
AV_GPS_Backup_Battery
AV_CDL_Channel_Selector
Wing
AV_PS_Multiplexer
AV_Servo_1
AV_Servo_2
Propeller
AV_PDL_Transmitter
AV_Control_Rod_1
AV_Control_Rod_2
AV_PDL_Antenna
Control_Surface_1
Control_Surface_2
Payload_Pod
Tail_Surface_1
Tail_Surface_2
AV_PS_SS_Camera_1
AV_PS_SS_Camera_2
AV_PDL_Channel_Selector
Transmits Data
Power
Hardware Interface

Payload -- Transmits Data

AV_PS_SS_Camera_1
AV_PS_SS_Camera_2
AV_PS_Multiplexer
AV_PDL_Transmitter
AV_PDL_Antenna
GS_PDL_Antenna
GS_PDL_Receiver
GS_GPS_Antenna
GS_GPS_Receiver
Joystick
Video_Digitizer
Mission_Controller
External_Video_Recorder_opt
Converter_Hub
GS_CDL_Transceiver
GS_CDL_Antenna
AV_GPS_Antenna
AV_CDL_Antenna
AV_GPS_Receiver
AV_CDL_Transceiver
AV_AP_Magnetometer_Opt
AV_AP_IMU_Thermocouples
AV_AP_IMU_Rate_Gyros
AV_AP_IMU_Accelerometers
AV_AP_IMU_Barometric_Pressure_Sensor
AV_AP_IMU_Static_Pressure_Sensor
AV_AP_Serial_Ports
AV_AP_Processor
AV_AP_PWM_Pins
Electronic_Speed_Controller
AV_Servo_1
AV_Servo_2

Transmits Data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AV_PS_SS_Camera_1
AV_PS_SS_Camera_2
AV_PS_Multiplexer
AV_PDL_Transmitter
AV_PDL_Antenna
GS_PDL_Antenna
GS_PDL_Receiver
Video_Digitizer
External_Video_Recorder_opt
Converter_Hub
Mission_Controller
Joystick
GS_GPS_Antenna
GS_GPS_Receiver
GS_CDL_Transceiver
GS_CDL_Antenna
AV_GPS_Antenna
AV_CDL_Antenna
AV_GPS_Receiver
AV_CDL_Transceiver
AV_AP_Magnetometer_Opt
AV_AP_IMU_Thermocouples
AV_AP_IMU_Rate_Gyros
AV_AP_IMU_Accelerometers
AV_AP_IMU_Barometric_Pressure_Sensor
AV_AP_IMU_Static_Pressure_Sensor
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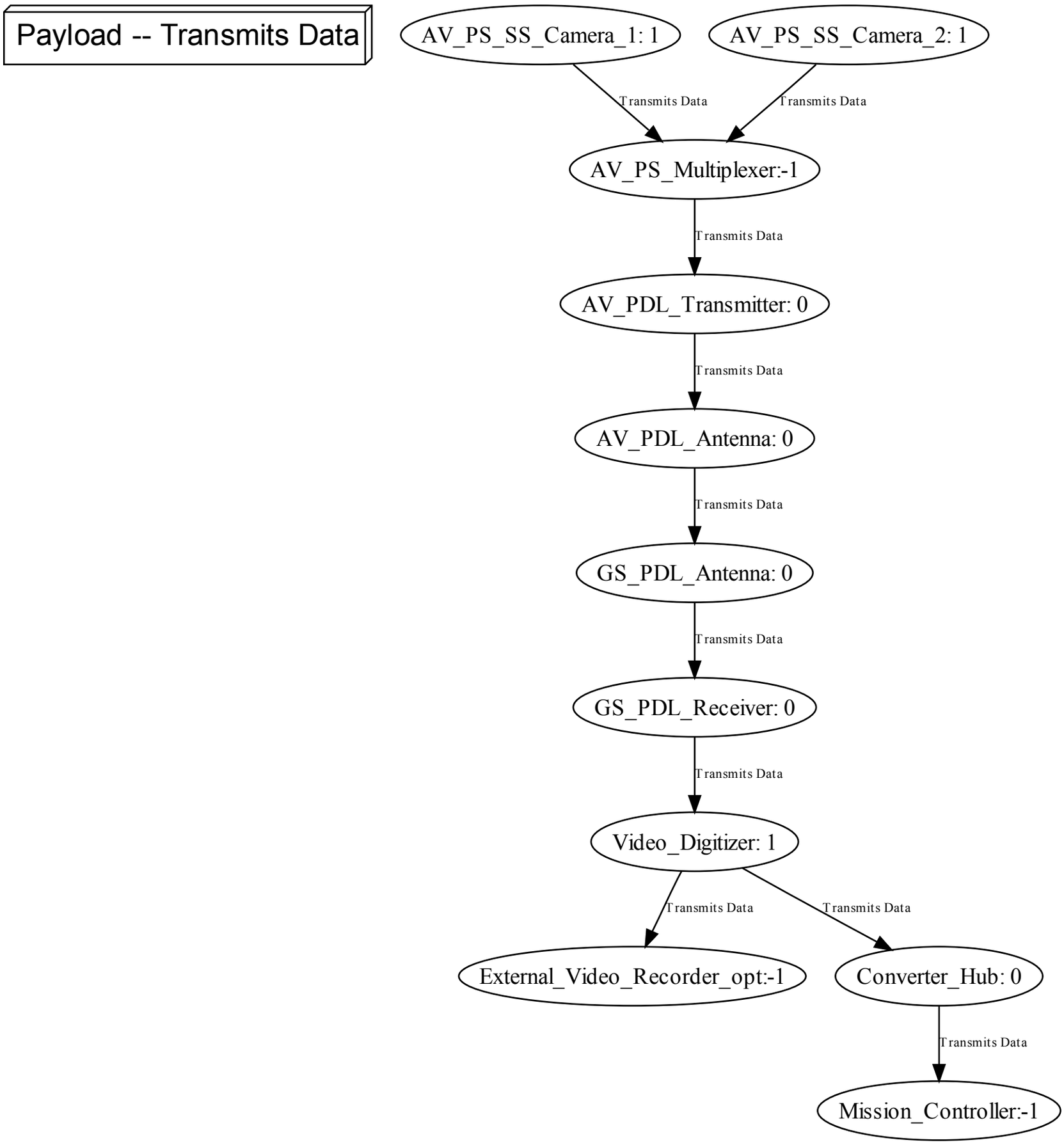
AV_AP_Processor
AV_AP_PWM_Pins
Electronic_Speed_Controller
AV_Servo_1
AV_Servo_2
Transmits Data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Transmits Data
Transmits Data
AV_PS_Multiplexer:-1
Transmits Data
AV_PDL_Transmitter: 0
Transmits Data
AV_PDL_Antenna: 0
Transmits Data
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Transmits Data
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Transmits Data
Transmits Data
External_Video_Recorder_opt:-1
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