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System and Component Level Flexibility of a Micro Air Vehicle: A Case Study in Flexible System Design using Change Propagation Analysis and Filtered Outdegree Methods

Jennifer M. Wilds, Massachusetts Institute of Technology
Room NE20-343, Cambridge, MA 02139
wilds@mit.edu

Nirav B. Shah, Massachusetts Institute of Technology
Room NE20-343, Cambridge, MA 02139
nbshah@mit.edu

Abstract

The design of complex systems often, if not always, occurs in a context that is uncertain -- needs change, technology evolves, and resources are uncertain. Much recent work has focused on design of systems that are able to deliver high value over time despite uncertainty. One commonly cited mechanism for doing so is to embed flexibility into system design. The design of a flexible system is described in terms of a new framework. Change propagation analysis is extended to allow analysis of systems with heterogeneous relationships between system components. Filtered outdegree analysis is presented as a method for quantifying flexibility at the system level. This paper is intended to provide a case example to supplement the theory development in Shah et al (2008). Change propagation methods and filtered outdegree are used to consider the formulation of real options for flexible system design for a Micro Air Vehicle (MAV).

1. Background

The US military is developing a micro air vehicle to provided reconnaissance and surveillance at a greater standoff distance. A micro air vehicle (MAV) is a less-than-one-pound unmanned air system equipped with a visual sensor. Conceptual design of the system continues to progress and formal requirements are being developed. Customers are willing to accept a less than optimal initial design, but ultimately would like to acquire one that can be adapted to changing operational needs. In addition, enabling technologies are evolving at a rapid rate relative to the program's production cycle.

Uncertainties. Key uncertainties were identified to analyze the design of the MAV within this uncertain context. Operational uncertainties considered are the required range and endurance, while technological uncertainties include the availability of advanced sensors and of high energy density power supplies. Based on these uncertainties, several change scenarios were identified as likely future environments in which the system may be required to operate. Three such scenarios enumerated below are the focus of this case study.

1. A technological change in the payload to enable day/night operations (CS #1)
2. A change in the data transmission standoff requirement (CS #2)
3. A change in the endurance requirement to allow entry into a new market (CS#3)

Physical Description. MAVs contain three major components: the air vehicle, the ground station, and the operator control unit, which is a software application providing a graphical user interface. The complexity of the interactions between the three components is beyond the scope of this analysis, thus for simplicity the system analyzed in this paper will be restricted to only the air vehicle and the ground station components. The air vehicle will include all components within the physical airframe, including the airframe itself. The analysis will be further limited to consideration of hardware components to improve or maintain performance, rather than modifications to the software algorithms within the autopilot, data link or mission controller.

The airframe can be decomposed into a series of objects, which can be described in terms of geometric and mass properties. Figure 1 shows the various components of the MAV airframe. A physical model of the air vehicle design was developed using MS Excel© by the USAF Academy (Bartolomei 2005) and validated by Air Force Research Laboratory, Munitions Directorate for a series of MAV platforms. The model accepts geometric and mass property inputs for components of the MAV to return performance objectives, such as endurance, range, and airspeed solutions. The model enables designers to quickly compute impacts to performance resulting from changes to the physical design.

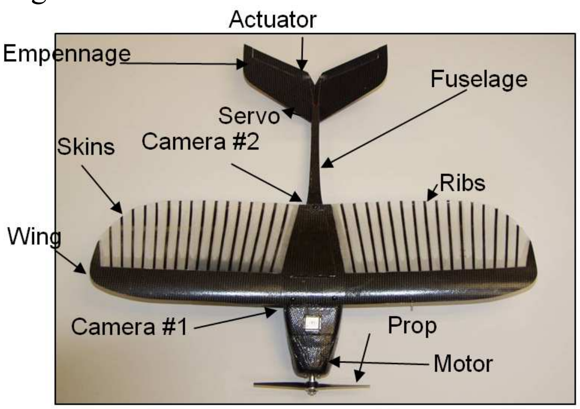


Figure 1. The Anatomy of a Micro Air Vehicle (Wilds et al 2007)

2. Application of Change Propagation Analysis

Clarkson et al. (2001) present a framework for analyzing the propagation of change throughout a system. Because change becomes more costly as the design matures due to integration efforts (i.e., a change to one part is more likely to affect multiple additional parts), it is advantageous to understand how the system will respond to future change and, if possible, create a design that is flexible to those changes. This paper will attempt to use the CPA method, along with the Change Propagation Index (CPI) introduced by Suh (2005) to identify candidates for embedded flexibility at the component level.

The Physical DSM. The first step of the analysis involves the creation of a DSM representing the MAV system. The DSM includes a physical decomposition of the ground station and the air vehicle to the component level, resulting in seventy-two nodes. Then, four types of relationships are recognized as existing between the physical components: power (electrical flows), data transmission (information flows), hardware interface (a spatial relationship indicating adjoining parts or physical connection), and "housing" (a geometric constraint relation indicating physical location). The result is a directed graph indicating the nodal relationships represented as edges. The matrix is sparsely populated; however the system as a whole is highly connected as a result of a tightly integrated system, as seen in Figure 2.

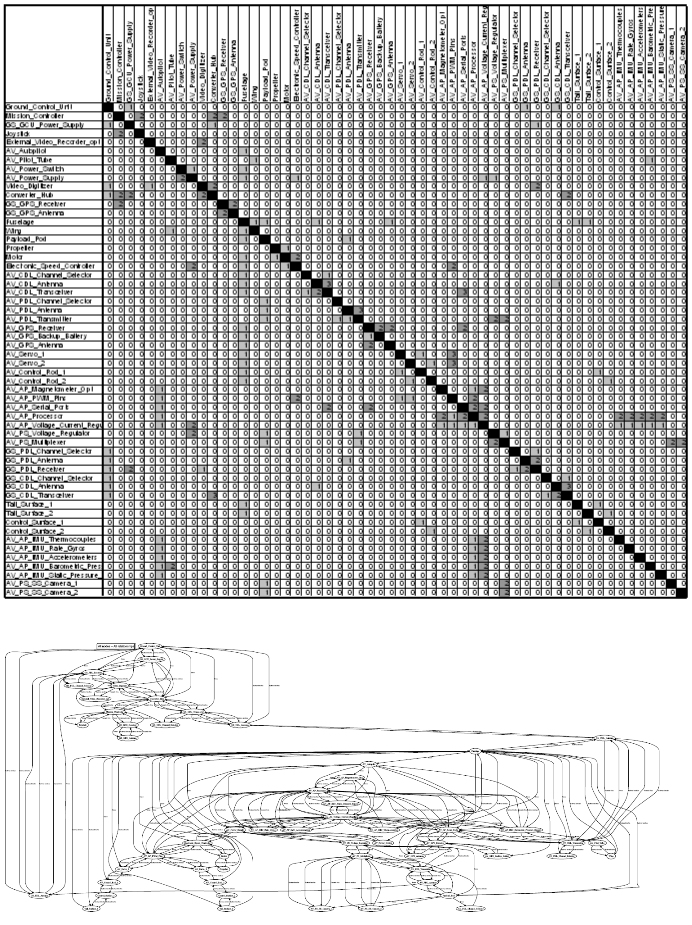


Figure 2. Design System Matrix (top) and Directed Graph (bottom) of the Micro Air Vehicle System

Change Scenarios. Change propagates when the tolerance margins of individual parameters are exceeded. (Eckert et al. 2004) Tolerance margins often include a design buffer, or contingency margin, which is used to absorb emergent changes that are not known at the time of design. Contingency margins are often decided based on primitive assessment of future uncertainties. Therefore, the first step in analyzing potential change propagation is identifying change scenarios based on the future uncertainties. This paper considers three change scenarios as previously defined. External uncertainties drive the internal changes within the system. Thus, change scenarios ask the question: "If component A is required to change due to resolved uncertainty, what other components will also change?" In this example, component A is the change initiator, or point where the change is introduced into the system. The question is answered based on the assessment of the perceived magnitude of change required as compared to the component's contingency margin. If the margin is exceeded, then change is propagated, however, if the margin is not exceeded, then change is absorbed. There may be multiple change initiators for a given change scenario. This occurs when the change is introduced into multiple components simultaneously.

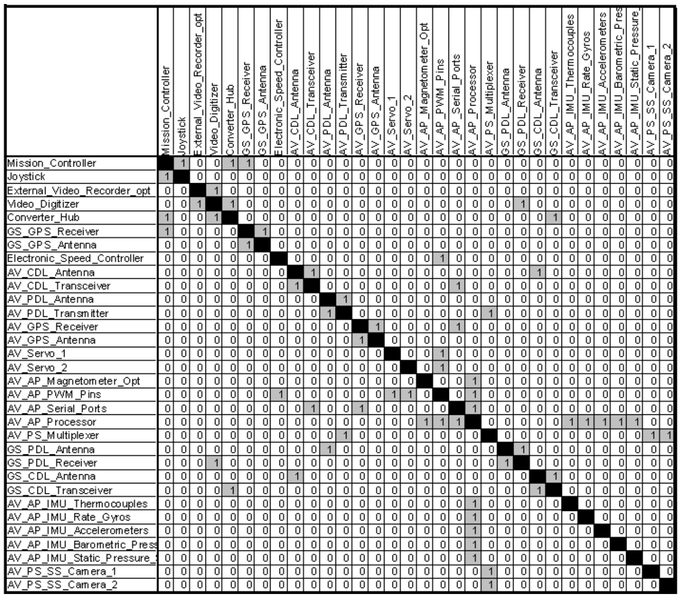
In this case study, an interview with a Subject Matter Expert (SME) was conducted to determine the change initiators for each of the change scenarios. The SME was asked to consider which components within the system would likely be changed in direct response to the change scenario. For example, the first change scenario (CS #1) considers a change in technology that is most likely a newly available sensor suite. The SME indicated that the existing sensor suite is the primary change initiator in the system in response to a new or upgraded sensor. In a less intuitive scenario, for example the third change scenario, the objective/functional requirements flow down to the physical components is necessary to identify the appropriate change initiators. In the case of a change in the endurance requirement (CS #3), the SME considered the components which directly contributed to the endurance computation, leading to five possible change initiators. Table 1 displays the identified change initiators for each respective change scenario.

Table 1. Identified Change Initiators for Particular Change Scenarios

Change Scenario	Change Initiator(s)
Payload (CS#1)	▪ Payload Sensor Suite
Range (CS #2)	▪ Power Supply ▪ Comm Data Link Antennas ▪ Payload Data Link Antennas ▪ Payload Data Link ▪ Comm Data Link
Endurance (CS#3)	▪ Power Supply (AV) ▪ Propeller ▪ Motor ▪ Electronic Speed Controller (ESC) ▪ Wing

The SME was then asked to identify which of the relationship types (i.e., power, data transmission, etc.) are most directly affected in each change scenario. Because the DSM was limited initially to only four types of relationships, all four relationships were included in the analysis of each change scenario. However, in a more inclusive data set, filtering the connections that are not effected by the change scenario may reduce the computational complexity of the analysis.

Filtered Undirected Graphs. The next step of the analysis requires an algorithm that filters the DSM to include only the types of relationships affected in each change scenario. Recall that the DSM represents a directed connectivity graph. This graph may include relationship directions according to the system flows; however those directions may not be representative of the change flows depending on where the change is introduced in the system. Because changes can propagate both upstream and downstream from where the change initiator is located, the DSM must first be altered to reflect an undirected graph (i.e., the DSM is symmetric about the diagonal). Given a particular change scenario, the identified change initiators, and the respective relationship types affected by the change, the algorithm then searches the DSM for all defined connections between nodes matching the relationship type. The result is an undirected sub-graph including only the nodes within the new filtered network for each relationship type. For example, CS #1 has one change initiator (Payload Sensor Suite) and four relationship types (power, data transmission, hardware interface, houses). Therefore, four undirected sub-graphs are generated by the filtering algorithm for CS#1. Figure 3 depicts the filtered undirected matrix and subgraph for the data transmission relationship type for a change in the payload technology (CS#1). A total of twelve sub-graphs were created for this case study using four relationship types for each of three change scenarios.



	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	1	0	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	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	1	0	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
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
AV_GPS_Receiver	0	0	0	0	0	0	0	0	0	0	0	0	■	1	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
AV_Servo_1	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
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
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
AV_AP_Serial_Ports	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	■	1	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	1	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
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
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
GS_CDL_Transceiver	0	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
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
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
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
AV_AP_IMU_Barometric_Press	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
AV_AP_IMU_Static_Pressure_	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
AV_PS_SS_Camera_1	0	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
AV_PS_SS_Camera_2	0	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	■

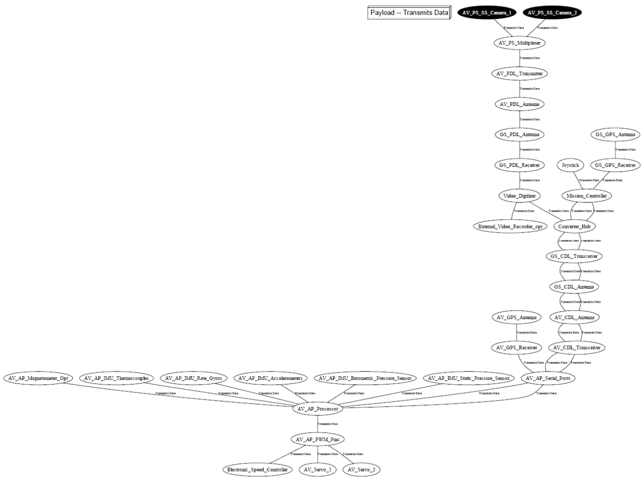


Figure 3. Undirected DSM (top) and Network Graph (bottom) for Payload Change Scenario (CS#1) Data Transmission

Additionally, a list of nodes and relationships for each subgraph is generated so that the SME can evaluate each of the included relationships by answering the question “Which direction does the change flow?” for a given change scenario and relationship type. Here, it is important to note that the SME’s response is dictated by the level of understanding of the overall system and the individual components. A thorough knowledge of the contingency margins within the system is ideal since the propagation of change is highly dependent on these margins. Then, using the perceived direction of change flow, a directed subgraph is created which will be used to calculate the CPI of each component within the filtered graph. This step allows the SME to explicitly document the perceived direction of change flow and provide reasoning for the elimination of any edge in the filtered graph. For example, in CS #1 the undirected subgraph for power indicates existing data flows from the ground station converter hub (Converter_Hub) to the ground station communications data link (GS_CDL_Transceiver), which then connects all components receiving information from the communications data link; however the SME indicated that the converter hub would effectively shield those components from any change in the payload data transmission since the communications data link operates on a different radio frequency than the payload data link. Therefore, those components were eliminated from the data transmission subgraph for CS #1. Figure 4 displays the directed filtered matrix and subgraph for CS#1 data transmission.

	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
Mission_Controller	■	0	0	1	0	0	0	0	0	0	0
External_Video_Recorder_opt	0	■	1	0	0	0	0	0	0	0	0
Video_Digitizer	0	0	■	0	0	0	0	0	1	0	0
Converter_Hub	0	0	1	■	0	0	0	0	0	0	0
AV_PDL_Antenna	0	0	0	0	■	1	0	0	0	0	0
AV_PDL_Transmitter	0	0	0	0	0	■	1	0	0	0	0
AV_PS_Multiplexer	0	0	0	0	0	0	■	0	0	1	1
GS_PDL_Antenna	0	0	0	0	1	0	0	■	0	0	0
GS_PDL_Receiver	0	0	0	0	0	0	0	1	■	0	0
AV_PS_SS_Camera_1	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	■

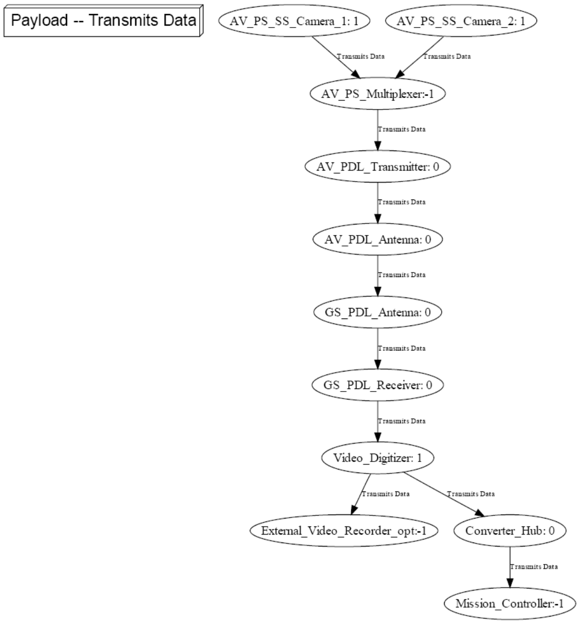


Figure 4. Direceted DSM (top) and Subgraph (bottom) for Payload Change Scenario (CS#1) Data Transmission

Multiple change initiators may result in multiple subgraphs for a given relationship type if there is a disconnect in the change flow. For example, CS #2 for the data transmission relationship, the payload data link

(AV_Payload_Data_Link and GS_Payload_Data_Link) transmits on a separate frequency than the communications data link (AV_Comm_Data_Link and GS_Comm_Data_Link) so the information flows are independent. The resulting subgraph will contain two change trees that are not connected as shown in Figure 5. Both trees should be considered in the analysis since other relationship types may link components within both change trees.

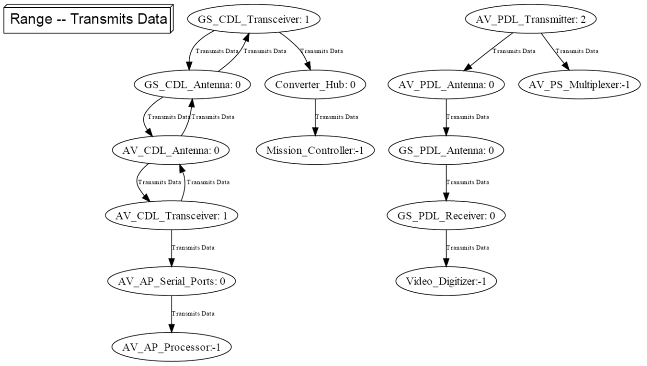


Figure 5. Directed Subgraph for Range Change Scenario (CS#2) Data Tranmission

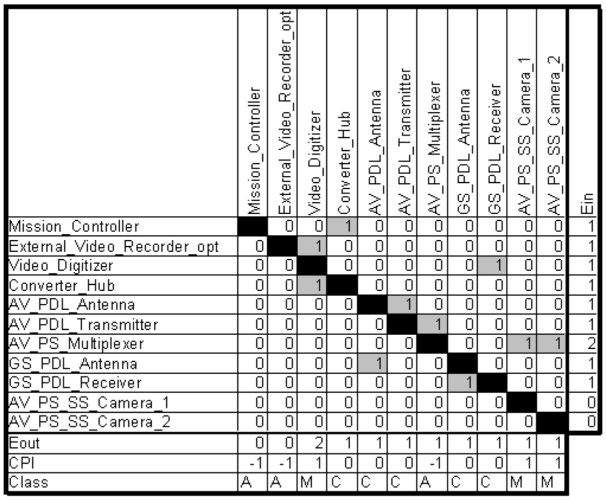
Identifying Change Multipliers/Carriers. Suh (2005) provides a process to calculate the CPI for each node in the filtered subgraph.

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

Equation 1. Change Propagation Index

Nodes having a CPI > 0 are change multipliers, indicating that the node propagates more change than it absorbs. A CPI < 0 categorizes the node as a change absorber. While these two types of change behavior are typically the most interesting, change carriers, nodes having a CPI = 0, are also important when attempting to design flexible systems, since they effectively provide a pass through for change. Eckert et al. (2004) acknowledges that system components do not have a predetermined change behavior. Similarly, the CPI as a metric of the change behavior varies across change scenarios and the context in which the system is examined.

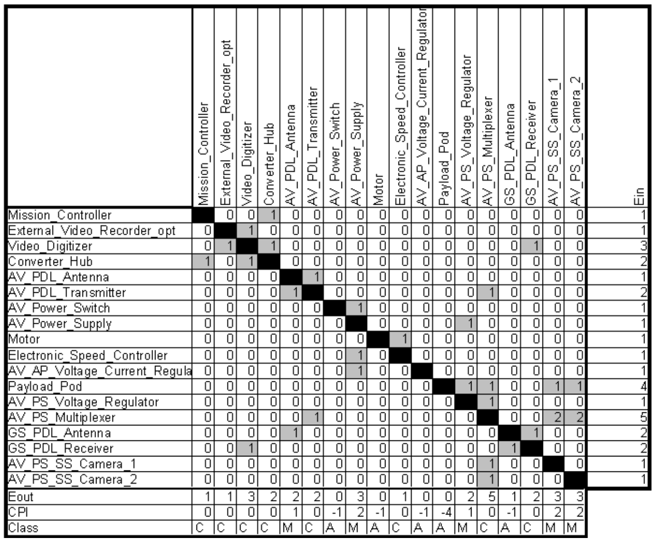
Filter by Relationship Type and Change Scenario. The CPI was first calculated for each node within the subgraphs that were filtered by relationship type for each change scenario. To complete the previous example, Figure 6 displays the CPI calculation given filtering for CS#1 data transmission.



	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	

Figure 6. CPI Calculation for Payload Change Scenario (CS#1) Data Transmission

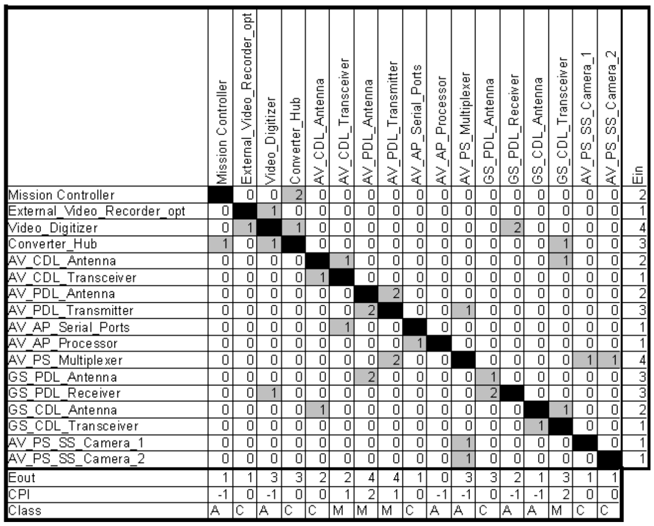
Filtered by Change Scenario. Eckert (2004) does not distinguish between the relationship type in the classifying of the change behavior (i.e., multiplier or absorber). Thus, an aggregated CPI was calculated by summing component CPI for each relationship type within the change scenario. This result provides an indication of which components are overall multipliers/carriers/absorbers for the change scenario, independent of the relationship type. Figure 7 displays the aggregated CPIs for CS#1 given three relationship types (power, data transmission, houses).



	Mission_Controller	External_Video_Recorder_opt	Video_Digitizer	Converter_Hub	AV_PDL_Antenna	AV_PDL_Transmitter	AV_Power_Switch	AV_Power_Supply	Motor	Electronic_Speed_Controller	AV_AP_Voltage_Current_Regulator	Payload_Pod	AV_PS_Voltage_Regulator	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	0	0	0	0	0	0	0	1
External_Video_Recorder_opt	0	■	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Video_Digitizer	0	1	■	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
Converter_Hub	1	0	1	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
AV_PDL_Antenna	0	0	0	0	■	1	0	0	0	0	0	0	0	0	0	0	0	0	1
AV_PDL_Transmitter	0	0	0	0	1	■	0	0	0	0	0	0	0	1	0	0	0	0	2
AV_Power_Switch	0	0	0	0	0	0	■	1	0	0	0	0	0	0	0	0	0	0	1
AV_Power_Supply	0	0	0	0	0	0	0	■	0	0	0	0	1	0	0	0	0	0	1
Motor	0	0	0	0	0	0	0	0	■	1	0	0	0	0	0	0	0	0	1
Electronic_Speed_Controller	0	0	0	0	0	0	0	1	0	■	0	0	0	0	0	0	0	0	1
AV_AP_Voltage_Current_Regula	0	0	0	0	0	0	0	1	0	0	■	0	0	0	0	0	0	0	1
Payload_Pod	0	0	0	0	0	0	0	0	0	0	0	■	1	1	0	0	1	1	4
AV_PS_Voltage_Regulator	0	0	0	0	0	0	0	0	0	0	0	0	■	1	0	0	0	0	1
AV_PS_Multiplexer	0	0	0	0	0	1	0	0	0	0	0	0	0	■	0	0	2	2	5
GS_PDL_Antenna	0	0	0	0	1	0	0	0	0	0	0	0	0	0	■	1	0	0	2
GS_PDL_Receiver	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	■	0	0	2
AV_PS_SS_Camera_1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	■	0	1
AV_PS_SS_Camera_2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	■	1
Eout	1	1	3	2	2	2	0	3	0	1	0	0	2	5	1	2	3	3	
CPI	0	0	0	0	1	0	-1	2	-1	0	-1	-4	1	0	-1	0	2	2	
Class	C	C	C	C	M	C	A	M	A	C	A	A	M	C	A	C	M	M	

Figure 7. CPI Calculation for Payload Change Scenario (CS#1) Given Three Relationship Types

Filtered by Relationship Type. Another context for CPI analysis may include examining the change behaviors of the nodes for each relationship type across all change scenarios. A calculation of CPI given this context would require summing the CPI for each node in all of the data transmission subgraphs (ie data transmission subgraphs for CS#1, CS#2, and CS#3). Figure 8 displays the CPI calculation filtered only by the relationship type data transmission.



	Mission Controller	External_Video_Recorder_opt	Video_Digitizer	Converter_Hub	AV_CDL_Antenna	AV_CDL_Transceiver	AV_PDL_Antenna	AV_PDL_Transmitter	AV_AP_Serial_Ports	AV_AP_Processor	AV_PS_Multiplexer	GS_PDL_Antenna	GS_PDL_Receiver	GS_CDL_Antenna	GS_CDL_Transceiver	AV_PS_SS_Camera_1	AV_PS_SS_Camera_2	Ein
Mission Controller	■	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
External_Video_Recorder_opt	0	■	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Video_Digitizer	0	1	■	1	0	0	0	0	0	0	0	0	2	0	0	0	0	4
Converter_Hub	1	0	1	■	0	0	0	0	0	0	0	0	0	0	1	0	0	3
AV_CDL_Antenna	0	0	0	0	■	1	0	0	0	0	0	0	0	0	1	0	0	2
AV_CDL_Transceiver	0	0	0	0	1	■	0	0	0	0	0	0	0	0	0	0	0	1
AV_PDL_Antenna	0	0	0	0	0	0	■	2	0	0	0	0	0	0	0	0	0	2
AV_PDL_Transmitter	0	0	0	0	0	0	2	■	0	0	1	0	0	0	0	0	0	3
AV_AP_Serial_Ports	0	0	0	0	0	1	0	0	■	0	0	0	0	0	0	0	0	1
AV_AP_Processor	0	0	0	0	0	0	0	0	1	■	0	0	0	0	0	0	0	1
AV_PS_Multiplexer	0	0	0	0	0	0	0	2	0	0	■	0	0	0	0	1	1	4
GS_PDL_Antenna	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	3
GS_PDL_Receiver	0	0	1	0	0	0	0	0	0	0	0	2	■	0	0	0	0	3
GS_CDL_Antenna	0	0	0	0	1	0	0	0	0	0	0	0	0	■	1	0	0	2
GS_CDL_Transceiver	0	0	0	0	0	0	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	1	0	0	0	0	■	0	1
AV_PS_SS_Camera_2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	■	1
Eout	1	1	3	3	2	2	4	4	1	0	3	3	2	1	3	1	1	
CPI	-1	0	-1	0	0	1	2	1	0	-1	-1	0	-1	-1	2	0	0	
Class	A	C	A	C	C	M	M	M	C	A	A	C	A	A	M	C	C	

Figure 8. CPI Calculation for Relationship Type Data Transmission Given All Three Change Scenarios

Formulate Real Options. Using the CPI calculations above, the designer can begin to formulate real options for flexible design. Suh (2005) suggests looking first for change multipliers or components that the multipliers are propagating change to, and adjusting their contingency margins to absorb the change, thus making the system more robust to the change scenario. Similarly, designers could seek out change multipliers to locate where it might be good to embed flexibility in order to change the propagation paths. In the event that the change multipliers cannot be modified or if the change propagation paths are not altered by the possible modifications, then an option to modify surrounding change carriers may provide the desired outcome. While this approach to creating options is dependent on the goal/benefit of exploiting the options (i.e., to reduce the cost impact of the change on the system or to allow for the system to adopt new capabilities in the future), utilizing the results of the CPA can assist designers in: 1) identifying potential locations for options and 2) providing an improved estimate of the switch costs associated with the option due to the inclusion of the change paths. Once real options have been formulated, they can then be valued using ROA tools. In some cases, the switch cost of implementing an option may be more than the perceived benefit of the changed design when compared to other designs, and this will be observed in the valuation of such options. Wilds et al. (2007) provides an example of the valuation of real options "in" a system using three different ROA tools.

Application of Filtered Out Degree Method

The above discussion of CPA took a bottom-up approach to the problem of flexible system design. CPA focused on the structure and connectivity of system components and then attempted to determine beneficial modification to the structure to limit the impact (and/or take advantage of the upside) of uncertainty on future system performance and cost. Designers can also considers flexibility of the system architecture as a whole. The filtered-out-degree measure described above takes this approach comparing different solution of the MAV system as whole and measure the apparent changeability of the variants. To examine the usefulness of such a metric, a filtered-OD analysis was conducted on the MAV system. Only the results for the first change scenario (CS#1) will be presented here. Analysis for the other scenarios was conducted in a similar fashion.

To compute the filtered-OD, a system model was developed using the Multi-Attribute Tradespace Exploration technique (Ross, 2008). This resulted in a set of 438 distinct designs of the aircraft (different geometries as well internal components). These designs were assessed with respect to their cost and key performance attributes as identified by the decision maker[1] (DM). The DM identified three attributes, aircraft range, endurance and payload capability, as the most important is choosing design. The tradespace contained designs that included a simple payload (daytime imaging only) as well as those that included an advanced (Day and night capable) payload.

CS#1 is further detailed such that initially only the day-capable payload is available and that later the day-night capable may become available. Initial production will be for 50 units, followed by another 100 units once the day-night payload becomes available. Should the new payload be adopted, the initial production lot will be upgraded to include it. There is uncertainty as to the DM preferences with respect to range and endurance once the new payload becomes available.

Given this refined scenario, filtered-OD provides a mechanism for identifying day-capable design that can be upgraded to large variety of day-night capable design. The filtered-OD is defined as the number of day-night capable design a particular day-only design can be transformed subject to a constraint on cost of transformation. This information is valuable to the designer who may have a good sense of the DM's cost but is uncertain as to the performance requirements given the new payload – the designer knows that they will need to change the design, but lack sufficient information to determine which changes are most valuable to the DM. Designs with greater filtered-OD at a given cost have greater apparent flexibility[2]. An OD function is also defined by varying the cost threshold for permissible transitions. The resulting graph (Figure 9) comparing OD functions of the day-capable designs aides in visualizing the trade-off between flexibility and cost to achieve that flexibility.

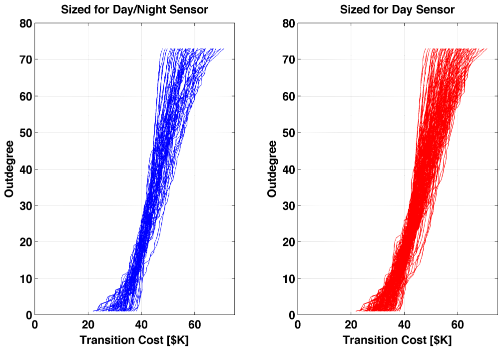


Figure 9. Outdegree as Function of Transition Cost for Payload Change Scenario

Should the designers find the observed OD function are of too high a cost or do not produce sufficient variety of transition possibilities, they can investigate embedding real options into the designs. These options serve as path enablers reducing the cost of transition

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[1] The former government program manager for the system on which to exercise was based served as the proxy for the decision maker.

[2] The term flexibility is used here instead of the more general changeability because the particular type of transition under consideration involves an intervention by an external agent to change the payload.

thereby increasing the f-OD. Of course, having these options may require additional initial expense, but that may be justified by the additional flexibility. As an example consider an alternative design of the day-capable MAV that includes a larger payload bay to ease upgrade to the day-night capable MAV. Figure 10 shows the OD functions for this set of designs compared to those that only considered the day imaging payload. Note the reduction of transformation cost for given f-OD.

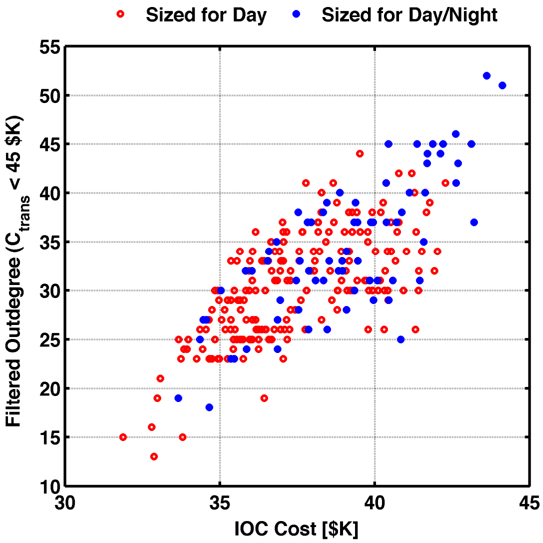

Figure 10. OD Functions for Payload Change Scenario

Valuing Flexibility Using Real Options Analysis

Real options analysis tools can be used to value options at predetermined time to suggest potential decision paths. These decision paths are strongly influenced by uncertainty models and the ability to estimate the associated switch costs. Three types of real options analysis tools include Net Present Value (NPV) calculations, Decision Analysis and binomial lattice methods.

NPV is the total of the present values of all future amounts, typically representing the total yearly profits discounted to present value. Discounting typically involves reducing future profits by a discount rate, or factor, on an annualized basis to account for the fact that a dollar tomorrow is worth less than a dollar today. The calculation is very sensitive to the chosen discount rate and the discount rate is typically treated as a constant over the period of analysis. The discount rate is often very difficult to determine from a political perspective, due to adjustment for perceived risks, though not difficult to calculate from a technical perspective. Discount rates are often set by high-level management or decision makers. (de Neufville 1990)

Decision Analysis (DA) accounts for the value of flexibility by structuring possible contingent decisions in a decision tree. Designers then choose the solution that offers the best expected value, a weighted average of the outcomes by their probability of occurrence (de Neufville, 1990). Wang (2005) points out that the expected value is based on an NPV calculation, and thus suffers from the same challenge of determining and using a fixed discount rate.

Binomial lattice method is based on a collapsed representation (i.e., later states are a multiple of earlier states) of the evolution of contingent decisions. This method assumes path independence and requires knowledge of the volatility and predicted growth rates of the modeled uncertainties. However, this information is not readily available for new and emerging technologies due to the absence of historical data. Furthermore, the lattice method assumes a constant expected growth rate, which is not typical of newly emerging technologies.

Wilds et al. (2007) uses NPV, DA, and binomial lattice method to provide an example of how to apply real options "in" a design. The paper includes a comparative assessment of the three ROA tools noted in this paper using a single MAV case study with comparable real options to those discussed in this paper. Wilds et al. (2007) conveys the importance of considering the assumptions of each method, with respect to known and unknown information, in order to carefully select the best ROA tool for valuing options.

Conclusions

CPA, as extended from the cited work, allows the designer to investigate how possible changes will impact the structure and behavior of a system design. The method outlined can aid designers in identifying system components that have some likelihood of changing. Designers can focus efforts on reducing change costs and impacts by embedding options into the design. Using the multipliers and carriers as guides, designers can develop potential options for inclusion, and then use ROA to determine which options generate sufficient benefits to justify costs. CPA does have some limitations, however. CPA results are highly sensitive to the particular set of change scenarios considered. If changes cannot be well represented or characterized, the analyst may miss identifying the change initiator or incorrectly propagate the change. CPA also relies upon representation of a system as a static graph of interactions between components (the DSM). Complex systems that change structure or behavior in response to changing contexts, i.e. self-modifying or intelligent systems, may not be easily represented using such a construct. Furthermore, traditionally DSMs only represent binary relationships between components. In complex systems, there may be multiple types of relationships between components. For example, two components may be physically connected, as well as exchange electrical energy. In different change scenarios, one type of relationship may result in change propagation, while the other does not. System representation that explicitly includes multiple relationship types, and filtering by those types when analyzing changes, helps to mitigate this issue. However, dealing with change scenarios that involve multiple relationship types is an ongoing research challenge.

CPA and f-OD can be used in concert to increase flexibility at a system level. Designers can use change scenarios to motivate system transition options or paths, and use f-OD to find system designs that are more flexible. The OD function can provide decision makers with a visual representation of the tradeoff between cost incurred in exercising transitions and the variety of transitions available from which to choose. Since the cost of transition is directly related to the changes in the system that occur during a transition, CPA can be used to determine where in the system those costs are being incurred, and to identify portions of the system that could benefit from redesign (e.g. through the addition of options) to reduce transition costs and/or to increase the variety of transitions available at a given cost. Taken together, CPA and f-OD can be used to help guide designers to generate and place real options to enable valuably flexible systems.

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Biographies

Jennifer Wilds is a dual Masters Candidate at Massachusetts Institute of Technology in Engineering Systems Division and Aeronautics and Astronautics. She is studying Technology and Policy with applications to DoD Acquisitions with emphasis on UAV applications. She is a civil servant in the US Air Force with experience in MAV development.

Nirav Shah is a graduate student at MIT pursuing a Ph.D in Aeronautics and Astronautics. A member of the SEAri research cluster and supported by MIT's Lean Aerospace Initiative, his research focuses on architecture of systems of systems. In particular, he is studying the impact of coupling in the physical, functional, and organizational spaces on system evolution. His work experiences include positions at Los Alamos National Laboratory and with Booz Allen Hamilton. Nirav received an S.B. (2001) degree and an S.M. (2004), both in Aeronautics and Astronautics, from MIT.