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A Model for Assessing UAV System Architectures

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Abstract

There is a current need for Unmanned Aerial Vehicle (UAV) systems architecture generation and assessment models. Architecture assessment models that presently exist tend to be fractional and do not account for all dynamic attributes that should be considered in the architecture assessment. There are infinite possibilities of architecture assessment modeling methods that can be used to assess conceptual systems architecture. Developing a good architecture assessment model for evaluating the functional and systems architecture reduces system ambiguity while increasing the tangibility of the system. This paper will present an assessment model specifically for UAV systems and this model can also be adapted to virtually any type of complex adaptive system. On new complex UAV systems it is essential evaluate the appropriate Level of Autonomy (LOA) required to satisfy customer and mission requirements. The assessment model detailed in this paper combines known design heuristics with quantitative, qualitative, and visual representations that assess the probability that the generated architecture will meet performance and capability requirements. The architecture assessment model will assess and generate a combined score that will indicate if the architecture is acceptable or unacceptable. Future UAV systems may reach a LOA that would be considered as Artificial Intelligence (AI); and this pursuit will increase the need for advanced LOA architecture modeling and assessment.

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Keywords: Architecture Generation; Architecture Assessment; Unmanned Aerial Vehicle (UAV); Artificial Intelligence (AI)

1. Introduction

There are very few formal [1] and comprehensive architecture assessment models and new technology development of complex systems in the future will require them. Architecture assessment models are essential for new technology development that contains unwanted ambiguity and lack of architecture clarity. UAV assessment

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models that exist tend to be fractional and do not account for all dynamic aspects that should be considered in the architecture assessment. Science and technology is continuously growing, expanding, and evolving as System Architects explore new and exciting architecture concepts and visualizations that presently do not exist. There can be much risk and ambiguity associated with new technology development, however, there is also the potential for tremendous rewards when a breakthrough is achieved. The complex and dynamic nature of Unmanned Aerial Vehicle (UAV) systems greatly increases when the Levels of Autonomy (LOA) are considered [2] and the assessment model must include this very important capability attribute. It is predicted by many that future UAV may develop high LOA and become what would then be considered as Artificial Intelligence (AI). The dynamic interaction between the UAV and the operating environment of the UAV [3] must be taken into careful consideration and this must be included in the assessment of the key performance attributes that involve safety and survivability. The UAV systems concept architecture assessment model should also consider the complex and dynamic system hardware and software that would enable the UAV to fulfil complex mission requirements and potentially risky mission scenarios. Both Commercial and Military usage of UAVs is increasing and this is already presenting air traffic concerns. An effective architecture assessment model is essential for the development of new complex UAV architecture that involves increased mission capability and LOA.

1.1. Problem Statement

There is a current lack of systems architecture generation and assessment models made specifically for UAVs. Assessment models that do exist tend to be fractional and do not account for all dynamic aspects that should be considered in the UAV architecture. In the early stages of the architecture generation process it is essential to have an effective assessment model to determine whether the modeled system architecture is feasible and acceptable. The systems architecting process consists of scoping, aggregating, partitioning, integrating and finally validating systems architecture. Architecting process is the process by which standards, protocols, rules, system structures, and interfaces are created in order to achieve the requirements of a system [4]. The architecting process is the planning and building of structures to respond to a given need. The systems architecting process will guide the architecture generation process to ultimately create the artifact. Architecture is the conceptual model that defines the structure, behavior, and more views of the artifact (system).

The systems architecture can provide a plan from which products can be procured, and systems developed, that will work together to implement the overall system. The architecture assessment model developed in this paper can benefit the architecture generation process by reducing ambiguity in the early stages of architecture concept development. Developing a good architecture assessment model for evaluating the functional and systems architecture can help with the reductions in system ambiguity while increasing the tangibility of the system. This paper will attempt to generate and assess the UAV concept and construct a high level architecture assessment model that will be used to evaluate the new architecture concept. The assessment model will evaluate the tangibility of the generated architecture concept and assign a numerical score that will represent the architecture as a whole to determine if the architecture is unacceptable or acceptable.

1.2. Review of Related Work

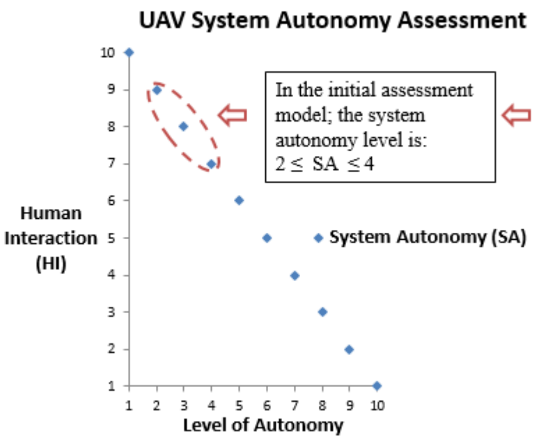
During system concept development is important to understand the relationship between human interaction and machine automation. Husar and Stacener [2] developed a two dimensional algorithmic methodology and related design tools that contribute to trade space assessment during the early stages of architecture development. The paper was specifically focused on assessing the correct LOA during the early stages of architecture development. Extensive research is made on the complex relationship between system autonomy and human interaction. UAV missions are becoming more complex and the LOA must increase and adapt to varying unknown situations. The correct LOA is critical to perform mission objectives safely and effectively and this paper illustrates the importance and of the LOA in the architecture development of UAV systems.

Dagli et al [5] describe the Smart Systems Architecting (SSA) approach for generating and assessing architecture alternatives and the objective of this approach is to effectively eliminate the system ambiguity to increase the tangibility of the systems architecture. Generating new complex systems is a challenge because new complex systems typically have high levels of ambiguity and they have numerous interactions and properties that are unchartered and undiscovered. The SSA approach seems viable in the reduction of the design free space and system ambiguity providing further clarity in system architecture definition. The SSA approach will influence the assessment model in this paper by targeting ambiguity. Systems Engineers often rely on heuristics because of the lack of architecture assessment models that are currently available.

Rodano and Giammarco [1] described that there are a multitude of modeling methods, however, determining if the model effectively represents the entire system architecture is a challenge. System models can be effectively derived primarily from the DoDAF Meta-Model (DM2) Conceptual Data Model [6]. The paper uses this model to formally assign know heuristics in a manner that can be modelled to assess the systems architecture. The model as described in this paper would be useful when defining systems architecture for UAV systems that have higher LOA.

1.3. Critical Model Considerations

The most important consideration of this model is how to assess the appropriate LOA. On new complex UAV systems it critical to analyse the trade space of architecture options to determine the appropriate level of autonomy (LOA) required to customer performance requirements [2]. The key to trade space definition begins with the customer's requirements. An assessment model is typically not required for UAV systems that fall below 2 on the Sheridan Autonomy Scale (see Figure 1). Most commercially made UAVs are constructed below level 2 LOA and in most cases you will only find UAVs that are level 4 LOA and above are manufactured specifically for military applications. The assessment model in the paper is modelled to access UAV with LOA that is between the range of two and four. The term System Autonomy (SA) represents the LOA of the UAV system collectively.



Sheridan Autonomy Scale

1 Computer offers no assistance; human does it all
2 Computer offers a complete set of action alternatives
3 Computer narrows the selection down to a few choices
4 Computer suggests a single action
5 Computer executes that action if human approves
6 Computer allows the human limited time to veto before automatic execution
7 Computer executes automatically then necessarily informs the human
8 Computer informs human after automatic execution only if human asks
9 Computer informs human after automatic execution only if it decides to
10 Computer decides everything and acts autonomously, ignoring the human

Note: Higher levels of LOA are desired for the UAV systems; they may also bring undesired system ambiguity, additional costs, and project risk. A UAV that reaches level 10 on the Sheridan Autonomy Scale would be considered Artificial Intelligence (AI).

Fig. 1. UAV System Autonomy Assessment with Sheridan Autonomy Scale [2].

With the widespread interest in SA will undoubtedly increase the need for an increase in LOA in UAV systems. This assessment model may provide to be essential when the level of autonomy is increased further to LOA above level 6. The level of Human Interaction (HI) is inversely proportional to the LOA. The complexity of the UAVs operating environment makes the task more challenging as the system would have to be aware of air traffic conditions and terrain and be capable of making emergency evasive maneuvers to ensure the survivability of the UAV and to ensure mission success.

2. Proposed Model for UAV Architecture Assessment

The systems architecting generation process involves a several stages that lead to the reduction of systems ambiguity and the development of a conceptual systems architecture. In order to assess the systems architecture it first must be developed so this process will begin with architecture generation. In an unlimited resource environment; all architecture would eventually meet each engineering specifications and customer performance requirements. Unfortunately, most businesses and organizations operate where time, funding, and other resource constraints force tough design choices. The assessment model is used to assess the functional and system architecture at any given configuration and state of development to assess if it will meet customer performance requirements. The assessment model can be used to improve the architecture when deficiencies are observed, allowing the Architect to make necessary changes that are required. The UAV generation and assessment model involves the following six stages:

1. Customer Needs Statement
2. Customer Inputs Assessment
3. Development of the Functional Architecture
4. Development of the Attribute Tree
5. Development of the System Architecture
6. Assessment of the Systems Architecture using the UAV Assessment Model

The assessment model as illustrated in Figure 2 is an integrated assessment of the systems key performance attributes, functional/system architecture concepts, LOA assessment, and the DoDAF Meta-Model (DM2) Conceptual Data Model [6]. To assess architecture that has higher LOA, the DM2 can be used as a data model to determine the relationships between functions and their respective inputs/outputs and other types of interfaces. The LOA model can be used to determine the appropriate level of SA [2] in the UAVs capabilities that is required to perform mission objectives. Mission scenarios are used as an assessment method to determine the probability that the UAV can perform typical missions and this method can also to identify system deficiencies. The multiple assessment models are combined to rate the system as unacceptable, marginal, acceptable, or excellent.

The architecture assessment model is adaptable and can accommodate changes in functional and systems architecture as part of an evolutionary process. This model is designed to evolve and improve by the selective integration of individual assessment models. This model is a sum of several models (qualitative, quantitative, fuzzy, and visual) that assess different aspects of the system architectures to generate a score determined by weighted categories that allows comparison of different variations of functional and systems architecture concepts. Architecture concepts can be improved and assessed repeatedly until a desired architecture concept is realized.

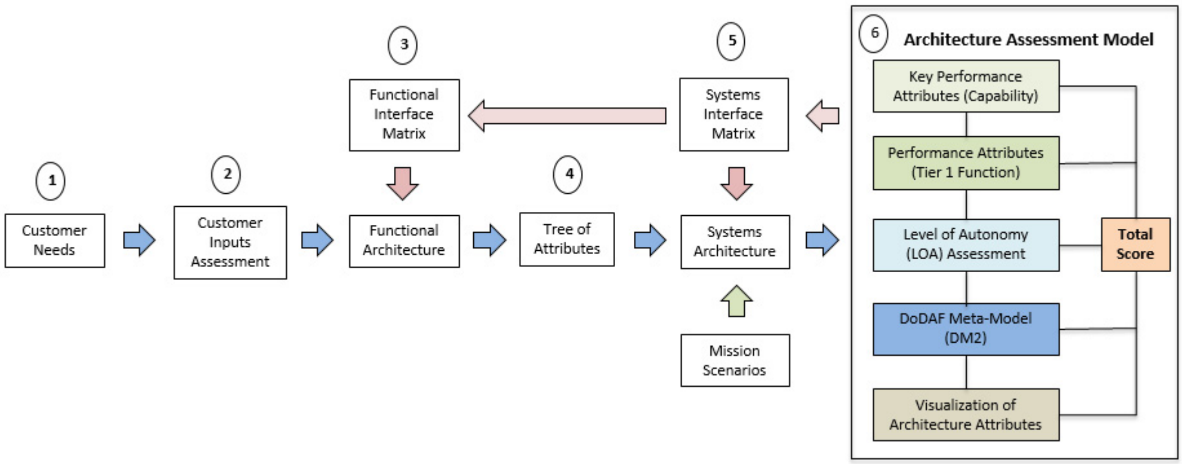


Fig. 2. UAV Architecture Generation and Assessment Process and Model Leading to Artifact Development.

3. Solution of the Proposed Model

The systems architecting generation process involves several stages that lead to the reduction of system ambiguity and the effective use of the trade space assignments. The assessment model is used to assess the functional and systems architecture at any given configuration. The architecture process is always evolving, adapting, and improving the system architecture throughout the generation stages. After the customer needs have been assessed and the architecture generation phase is initiated; it is important to create a tangible concept that fulfils customer requirements. Systems scoping and system aggregation translates the customer needs into specific key performance attributes such as modularity, reliability, robustness, flexibility, and survivability. Requirements are converted into functions (each requirement can be a function). Functions and sub functions are arranged in accordance to the key performance attributes (capability) and performance attributes (Tier 1 function) and then functions are grouped to create a baseline UAV functional architecture as shown in Figure 3. The functional architecture is then verified using a functional interface matrix and also by using the DM2 [6]. This matrix serves as a primary assessment of the functional architecture and allows instant modifications to be made and to determine the validity of functional interfaces.

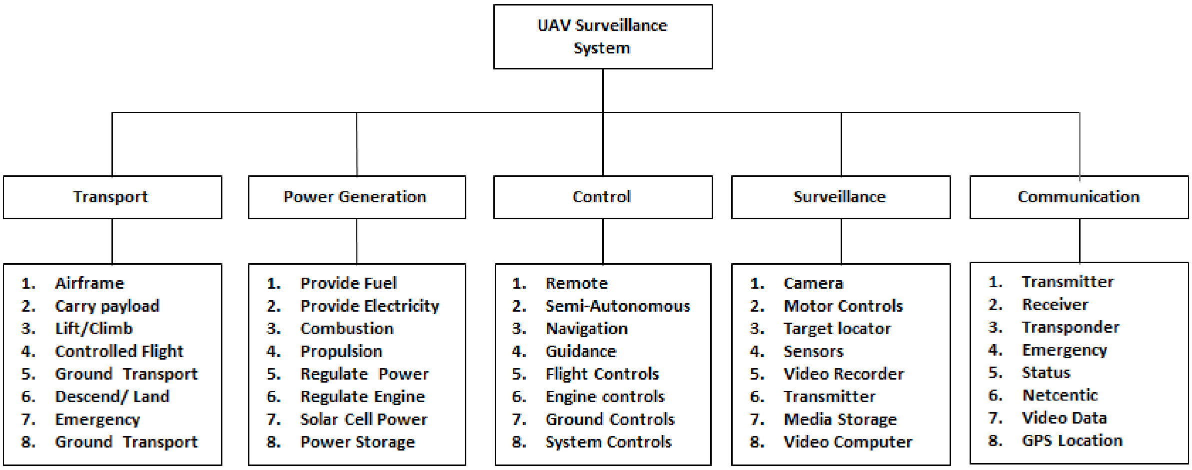


Fig.3: UAV Baseline Functional Architecture Partitioned by Performance Attributes (Tier 1 Function).

The architecture development process continues on with the development of an attribute tree when an acceptable functional architecture is generated. The baseline functional architecture is then converted into an attribute tree as shown on Figure 4. This attribute tree is the midpoint between the functional and system architectures. The attribute tree partitions and aggregates the key performance attributes into three categories:

1. MOE – Measure of Effectiveness (Operational/User Requirement)
2. MOP – Measure of Performance (System Requirements)
3. TPM – Technical Performance Measure

MOEs are measures of operational effectiveness and suitability in terms of operational outcomes. MOPs are derived from MOEs and characterize physical or functional attributes relating to the execution of the mission or function. TPMs are derived from MOPs, and are selected as being critical from a periodic review and control standpoint. Figure 4 represents the attribute tree and for the UAV system with MOEs, MOPs and TPMs also mapped for a convenient visual overview. The attribute tree provides initial validation of the prior assessment model shown on Figure 2 item 4.

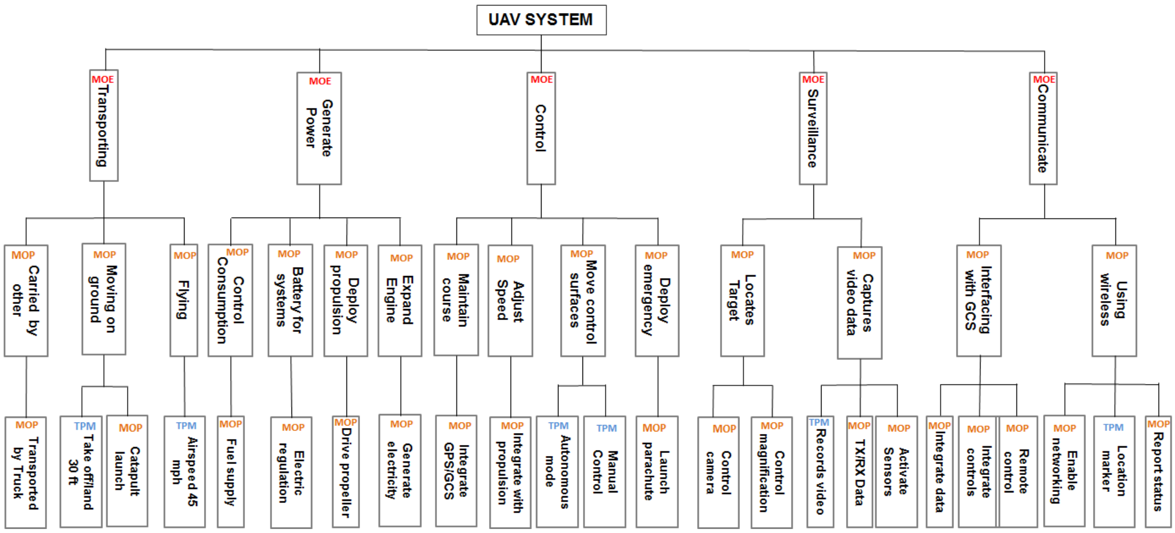


Fig. 4. Attribute Tree with mapped with MOEs, MOPs and TPMs for the UAV System Architecture Concept.

The next stage in the architecture generation process is the development of the high level UAV system architecture hierarchy. The attribute tree is converted into system modules through aggregation and system partitioning. Functional architecture and performance attributes are both converted into system components. The systems architecture is created by partitioning the major system modules into a tiered hierarchy; that the system indicated has the capability to perform the functions and sub functions of the system and the capability UAV system as a whole. This systems architecture model is validated using interface matrixes and the DM2 for aspects of the system that ambiguity still exists. The level of ambiguity is directly proportional to the level of SA. The level of autonomy that was selected is between levels 2 through 4 as shown on Figure 1. A model of the systems architecture concept in then generated and represented in a manner that represents the tiered hierarchy and interfaces between systems as shown on Figure 5.

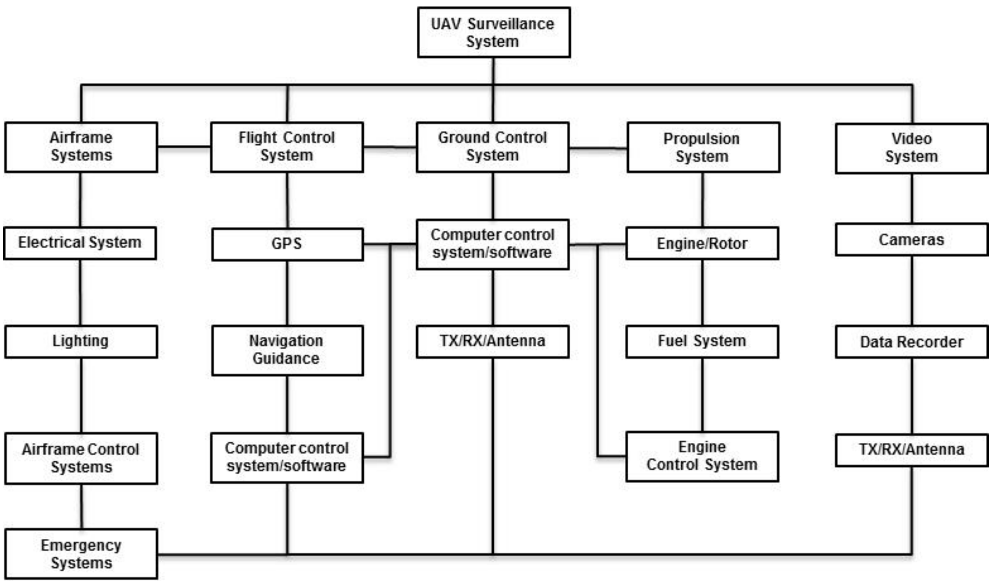


Fig. 5. UAV System Architecture Hierarchy Leading to Concept Development

The system architecture concept is assessed using the assessment model that is illustrated on Figure 2 item 6. The key performance attributes (capability and Tier 1 Function) are rated using known heuristics and various modeling methods and then represented with a numeric score with Kiviat charts as shown on Figure 6 below. The LOA is assessed by the probability that the system will perform in the acceptable range that will satisfy customer requirements. The DM2 combined with system and functional interface matrixes are used to assess the relationships between functions and their respective inputs/outputs and other types of interfaces. The visualization of architecture attributes (VAA) is the rating that the architecture will meet each engineering specification and customer performance requirements on time, on schedule, and on budget. Scenario based assessments consist of a multitude of "what if" scenarios [3] and the assessment on how the UAV system is able to respond. Scenarios would include narratives as "What if the UAV loses ground control station (GCS) signal?" "What if the UAV loses power?" Scenario based assessments are essential for UAV systems that increase in LOA above level 2. In this model, The UAV architecture is acceptable if the total score is above 80% and with an acceptable score in each category of the model. The assessment model could later be expanded and adapted for future UAV architecture considerations.

UAV Architectecture Assessment Model					
Model Type	Capability	Description	Acceptable	Max	Actual
Key Performance Attributes	KP1	Modularity	3.5	5	4
	KP2	Reliability	4	5	4.5
	KP3	Robustness	4	5	4.25
	KP4	Flexibility	4	5	4.5
	KP5	Survivability	3.5	5	4
Model Type	Function	Description	Acceptable	Max	Actual
Quantitative Fuzzy Qualitative	PA1	Transport	4	5	4.25
	PA2	Communicate	4	5	4.25
	PA3	Power	4	5	4
	PA4	Surveillance	4.25	5	4.5
	PA5	Control	4.25	5	4
Model Type	Category	Description	Acceptable	Max	Actual
Quantitative	LOA	System Autonomy	4	5	4.25
Quantitative	Modified DM2	DoDAF Meta-Model (DM2)	4	5	4.25
Fuzzy	VAA	Visualization of Architecture Attributes	4	5	4.13
Model Type	Scenario Category		Acceptable	Max	Actual
Scenario Based Assessment	Search and Rescue		80	100	85
	Border Patrol		80	100	90
	Tactical Law Enforcement		80	100	85
	Maritime Surveillance		80	100	90
Totals			371.5	465	404.88
Overall Score Percentage					87.07

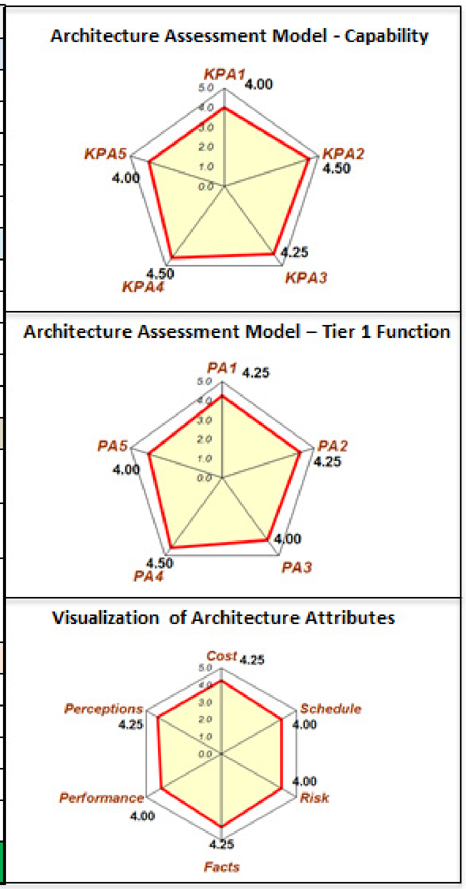


Fig. 6. UAV System Architecture Assessment Model Leading to Concept Development.

4. Conclusions

The systems architecting generation process involves several stages that lead to the reduction of systems ambiguity. In order to assess the systems architecture it first must be developed. The assessment model detailed in this paper assists with the generation and assessment of systems architecture concepts. The assessment model as shown on Figure 2 consists of multiple integrated assessment models and tools that are effective in developing acceptable new system architectures. Uncertainty is inherent in complex adaptive system design; especially UAV systems that have high LOA. Heuristics are specialized tools that can reduce but not eliminate ambiguity on concepts that have no precedence to learn from. The assessment model will assist with uncertainly by using qualitative and quantitative models used in conjunction with DM2 models, mission scenarios, and interface matrixes. Continuous progression on many fronts is an organizing principle of architecture models and supporting activities that lead to acceptable architecture configurations.

The scoring used in this process was considering a LOA of $2 \leq$ SA ≤ 4 and LOA below this range would have produced a higher score because of greatly reduced of system ambiguity. The operating environment of the UAV presents high levels of uncertainly and will increase in the future when air traffic will multiply. The assessment model can be revised and expanded to consider increased system complexity and autonomy. Mission Scenarios are extremely effective in assessing the system architecture by visualizing them in the real world operating environments. There is much uncertainty with operating conditions, weather conditions, and objects in the proximity of the UAVs flight path. Mission's scenarios are effective means of assessing new advanced architecture generation concepts for future adaptive UAV systems.

The architecture generation and assessment model used to assess the functional and systems architecture can be utilized at any given configuration. The assessment model can be used to improve the architecture when deficiencies are observed; allowing the architect to make necessary improvements as required. The architecture process is always evolving, adapting, and improving the system architecture throughout the concept generation stages. It is important to create a tangible design that fulfils systems requirements. It is also desired to achieve and elegance [8] in system functionality my cleverly aligning functional interfaces and increasing efficiency.

4.1. Future Work

The increase of science and technology always presents the challenge to generate architecture to bring technology to the next level. The need for systems architecture assessment models will certainly increase with the research and development of UAV systems that will require increased LOA. The UAV market is expected to grow dramatically by 2020 and beyond. The assessment model may help with the reduction of ambiguity during the concept generation phase. As the model matures it will integrate known technology with developmental concepts in the hopes to pioneer the way for new technology development. This architecture tool may prove useful in new technology development by adding tangibility to fuzzy models until an acceptable architecture is realized. There is a present lack of comprehensive UAV assessment models and the architecture assessment model detailed in this paper may grow and evolve into a universal model that could assess virtually any system. The model described in this paper is just a starting point and further research and development will follow. Future developments may include detailed qualitative models and fuzzy models that will supply additional assessment inputs for complex new concept development; in particular hardware and software architecture that will increase the UAV LOA.

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