A FRAMEWORK FOR THE DESIGN OF THE AIRCRAFT INSPECTION INFORMATION ENVIRONMENT

Prasad Prabhu
and
Colin G. Drury
State University of New York at Buffalo
Department of Industrial Engineering

1.0 INTRODUCTION

From the extensive series of task analyses performed during site visits to aircraft inspection operations (Shepherd, et al., 1991) it became clear that supplying the inspector with appropriate information was a key contribution to inspector reliability. Information reaches the inspector through a variety of pathways, such as documentation, training and job aids which are subject to separate studies within the FAA/OAM program. For example, at this conference there are papers on training (Drury and Gramopadhye, 1992) and workcard design (Patel, Prabhu, and Drury, 1992). The design issues are similar for any information system:

- What information to present (issues of information sufficiency)
- When to present this information (temporal issues)
- How to present this information (information display issues) so that there are gains to be made by ensuing consistency across information sources. Hence this paper provides a framework for research in all areas of information design. In particular it combines concepts from the human factors knowledge base with specific needs of aircraft inspection. Specifically, it starts with the classification from Drury (1990) of aircraft inspection information into two sources: feedforward information and feedback information. Feedforward includes relatively general command information, and aircraft specific feedforward information.

2.0 A MODEL OF INFORMATION FLOW IN AIRCRAFT INSPECTION

The proposed model represents both the physical work flow as well as the information flow. It also highlights the cognitive aspects of the inspection task. It is a descriptive model in the sense that it represents the current state of the information flow in commercial aviation aircraft inspection. It is a general representation of how the aircraft inspector gathers, receives and uses information during the task and as such, is not specific to any particular aircraft operator's inspection system.

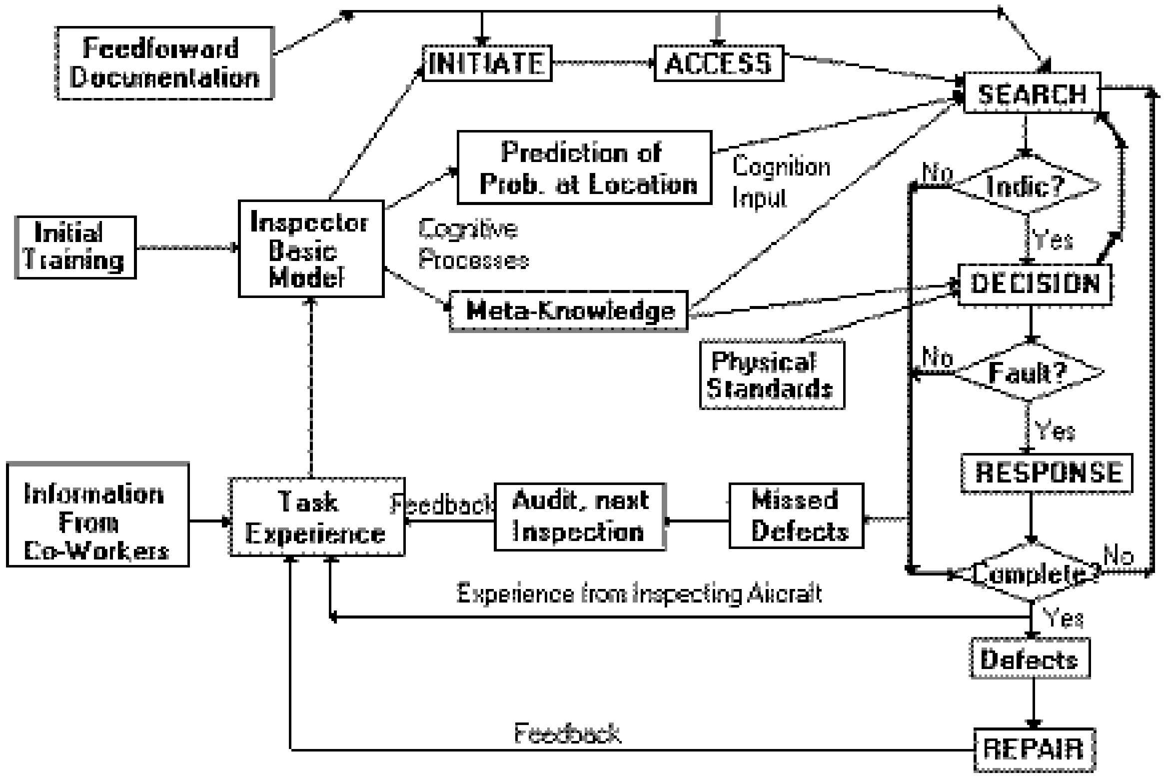

Figure 1 Model of Information Flow in Maintenance and Aircraft Inspection

2.1 FEEDFORWARD INFORMATION

From the model (Figure 1), feedforward information to the inspector is seen to come from the following sources:

1. Initial Training
2. Manufacturer/FAA/Airline Operator documents.
3. On-the-Job experience on a particular aircraft.
4. Information gathered from co-workers.
5. Command information in the form of standards.
6. Utilization of understanding about the fault causation mechanism in aircraft.

Initial Training. Taylor (1990) found that the current hangar maintenance organization has a bi-modal experience distribution of 30 plus years and three or fewer years. The inspection group is expected to have a similar distribution with three to five years added to the lower value. No formal inspection training programs were observed or reported at any of the airlines. Typically, inspectors hold an A and P license and have maintenance experience. Most of the training is on the job where an experienced inspector puts the novice through his paces and shows him the various aspects of inspection.

Documentation. There is an immense amount of potentially useful information available both in paper (hard copies) and paperless (computer, microfiches) form. The documents are generated by a triad consisting of the Federal Aviation Administration (FAA), aircraft manufacturers and aircraft operators. There is a complex, multi-dimensional interaction in the flow of data between these three.

Experience on a Specific Aircraft Type. Aircraft at a maintenance facility are serviced over various lengths of time depending on the type of service. The transfer of an aircraft to a different facility (other than the one it normally goes to) is very rare and occurs in case of contingencies or in case of heavy workload at the regular facility. Similarly, movement of personnel between different facilities is very low. Thus, most maintenance and inspection personnel accumulate experience on a particular type of aircraft. The effect of such job specialization on the occasional inspection of a different aircraft type has not been studied. Knowledge about the aircraft is accumulated over a period of time through on-the-job work. Experienced inspectors gradually develop an understanding of the cause-effect relationship of defects and also know what to look for and where.

Information from Co-Workers. Airline inspectors typically work independently and occasionally in teams of two. The frequency of formal meetings amongst inspectors varies from airline to airline. Drury, Prabhu, and Gramopadhye, (1990) during the task analysis of inspection in the airline industry found few formal meetings of mechanics or inspectors despite frequent informal contact among inspectors, and less frequent contact between inspectors and mechanics. The mechanics and inspectors contact each other for buy-back or for the approval of a repair. Mechanics finding faults during scheduled maintenance tell inspectors about this. This contact for advice/instruction is at times the only formal information exchange between the inspector and the mechanic.

Comparative Standards. There seems to be almost no standards that are accessible to inspectors at the worksite for defects like corrosion, cracks, dished/pouched rivets, wear, component play, etc. A small subset of standards does exist with the manufacturer, FAA, etc. but these have not been organized into a scheme for utilizing comparative standards on the job. The closest inspectors come to a standard in visual inspection is to use adjacent areas to make a comparison, which is not a reliable method (Drury, 1990).

Understanding Fault Causation Mechanisms in Aircraft. Inspection of aircraft is largely composed of pure search activities followed by decision-making tasks whose output is of the form of "acceptable/non-acceptable." However, some areas of inspection involve utilization of cues, knowledge of how faults are caused, and knowledge of how the behavior of one particular aircraft component indicates behavior of related components. Examples are: dirt streaks around a rivet on the fuselage indicate a loose rivet, bulging of the paint on the aircraft skin indicates underlying corrosion, scraped paint at the fairings indicates underlying fairings are rubbing, play at the flap vanes points to worn out bearings or tracks, etc. Use of such indirect evidence is a powerful technique to enhance detection and discovery of a fault, particularly where faults are not directly accessible to pure visual/auditory/tactile search.

2.2 FEEDBACK INFORMATION

From the model, it is seen that feedback can be either on the job or in training. Use of feedback on the job has been found to reduce the number of false alarms as well as reduce missed defects. Training schemes implementing feedback have been used to improve learning rates, to develop schemes, and for the efficient transfer of training skills to on-the-job performance.

On-The-Job Feedback. There seems to be no systematic and obvious system in place that provides feedback to the inspector. Feedback in search/decision making comes when the inspector talks to a supervisor or a fellow inspector to confirm a borderline case, although this occurs rarely. Also rare is the feedback that could come from the repairer or the buy-back inspector who both have potential data on the fault. There is very little feedback on any defect that the inspector misses. This feedback can only occur through audits and quality control inspections, but these systems do not ensure a consistent feedback to all inspectors on a regular basis.

Feedback in Training. As explained in the earlier section, the feedback in aircraft inspection is relatively scarce and on the occasions that the inspector gets it (e.g., audit) it is delayed in time. Delayed feedback makes learning by practice alone difficult (Woods, 1989). The current state of training is that much emphasis is placed on both the procedural aspects of the task (e.g., how to set up for an X-ray inspection of an aileron), and on the diagnosis of the causes of problems from symptoms (e.g., troubleshooting an elevator control circuit). However, the inspectors we have studied in our task analysis work have been less well trained in the cognitive aspects of visual inspection itself. How do you search an array of rivets -- by columns, by rows, by blocks? How do you judge whether corrosion is severe enough to be reported?

3.0 ANALYSIS OF INFORMATION REQUIREMENTS: AN S-R-K BASED APPROACH

For effective use of feedforward and feedback information, the information requirements of human inspection have to be identified for both the expert and novice whose needs may be very different. Thus, we can posit that studying the behavior of the human inspector interacting with the system (while performing the inspection) will help identify possible information support points as well as providing guidance to the type of information (either feedforward or feedback) that is needed at these points. The skill-rule-knowledge based hierarchy of Rasmussen (1983) affords us a robust framework within which this analysis can be carried out, and will be mapped onto both visual inspection and NDI.

3.1 VISUAL INSPECTION

Search and decision making form the critical components of visual inspection. The search component can be further decomposed into pre-attentive search, and a detailed search consisting of foveal (pure search or search plus decision making) and extra-foveal processes. Identification of the behaviors associated with each of these subtasks results in a many to many mapping as seen in Table 1. These mappings have been identified for an expert inspector. An interesting aspect of these mappings is the existence of relatively few knowledge-based behaviors exhibited by the expert inspector. This seems logical since there is less problem-solving or active reasoning in aircraft inspection and more detection, identification and classification.

Table 1 Mapping a Visual Inspection Task to Cognitive Behavior for Expert Inspector

Visual Inspection Processes	Behavior Categories		
	Skill-Based	**Rule-Based**	**Knowledge-Based**
Pre-Attentive Search	Scan and Detect		
Foveal (Pure Search)	Fixate and Detect		
Foveal Decision		Identify and Classify	
Extra-Foveal Search	Trigger move to next area		
Decision-Making (Outside of Search)		Move to next area, Rules of what to look for	Reason and Decide

The SRK framework aids understanding of how behavior will be qualitatively modified as the inspector goes from a novice to an expert. Thus, although both the novice and the expert exhibit, say, rule-based behavior, the behavior of the expert will be qualitatively different from the novice (Sanderson and Harwood, 1988). In Table 2 we have mapped a specific visual inspection task (inspection of rivets) to the SRK framework, to represent the performance of an expert inspector. We can expect that some of the defects identified at the skill-based and rule-based levels by the expert will be identified at the rule-based and knowledge-based levels by the novice, indicating a rightward shift on Table 2 corresponding to an upward movement on the SRK hierarchy. Thus, this analysis points to the need for different levels of information support for the expert and the novice inspector. It can also provide guidelines to define training requirements for novice inspectors based on identifying expert inspector behaviors.

Table 2 Visual Inspection of Rivets: Cognitive Behaviors for Different Defect Types

1. Missing Rivets **4. Cracks** **7. Pooched or Dished Rivet**

2. Hole in Skin **5. Ripples in Skin** **8. Wear**

3. Dents **6. Loose Rivets** **9. Corrosion**

VISUAL INSPECTION PROCESSES	BEHAVIOR CATEGORIES		
	SKILL-BASED	RULE-BASED	KNOWLEDGE-BASED
PRE-ATTENTIVE SEARCH	* Missing rivet * Hole in skin		
FOVEAL (PURE SEARCH)	* Missing rivet * Hole in skin * Deep dents * Large cracks * Prominent corrosion		
FOVEAL DECISION		* Borderline corrosion * Slight wear * Dished rivets * Ripples in skin * Small cracks	
EXTRA-FOVEAL SEARCH	* Chipped paint in periphery leads to next fixation		
DECISION-MAKING (OUTSIDE OF SEARCH)		* Streaks around rivets trigger inspection for loose rivets * Powdery contamination triggers search for corrosion * Borderline defects	* Defect type not listed * Use of meta-knowledge

Table 1 and Table 2 also indicate the large role that skill-based and rule-based behaviors play in visual inspection. The visual search part of visual inspection is seen to be entirely skill and rule-based for the expert inspector (or after training to criteria). The skill-based behavior can be associated to the scanning, fixating and detection activities (see Table 1). Since skill-based performance is essentially unconscious and feedforward controlled, we can conclude that the information aid for this part of the visual search should be something that does not require active conscious use by the inspector. This points to visual environment changes (better lighting, improved contrast), and improving human detection capabilities (increasing visual lobe, increasing target conspicuity). At the same time, this also indicates training as a critical need to attain satisfactory sensory performance.

Table 1 and Table 2 also highlight rule-based behavior as a significant mode of visual inspection, resulting in the identification and classification of defects. Thus, finding corrosion, wear, small cracks and similar difficult defects takes place due to rule-based behavior. It is pertinent to note at this point that the work card system used in the aircraft industry to control aircraft maintenance and inspection relies heavily on a linear procedural approach (Drury, 1991; Drury, Prabhu and Gramopadhye, 1990). Rule-based behavior also accounts for search strategy based on past experience and work card instructions. Thus, we reach the conclusion that it is very important to develop procedural knowledge (workcard design), checklists and comparison standards to support this behavior.

Knowledge-based behavior is often a slow and error prone process, besides creating cognitive workload for the human. Often in such circumstances the human will try to minimize cognitive strain by using shortcuts in the reasoning and decision making process, which can lead to suboptimal performance. Thus, we should try to design the system and the information environment to minimize the need to indulge in knowledge-based behavior. Knowledge-based behavior in visual inspection will be more evident in a novice inspector, providing a strong impetus to the design of adequate training programs to bring the novice to expert levels and thus minimize knowledge-based behavior. Once a certain level of expertise is attained the knowledge-based behavior will be needed only in case of unfamiliar work situations. This can, for example, happen if an inspector who normally works only a specific part of the aircraft (e.g., the wing section) is asked to inspect a cargo door. Thus, it becomes important that the workcard (feedforward environment) be designed for usability as well as have the information needed to make a smooth transition to an unfamiliar task. Feedback information from a buddy system, and efficient communication lines with the supervisor also has to be considered. Also important is the development of the knowledge about the spatial and functional aspects of the aircraft, which is partly built through the years of prior experience of the inspector as an aviation mechanic. This is normally five years, but is decreasing due to a shortage of inspectors, with some inspectors having as little as three years of maintenance experience. There are cognitive error implications in too rapid a promotion system.

3.2 NON-DESTRUCTIVE INSPECTION

NDI can be decomposed into three broad stages -- calibration, probe movement, and display interpretation (Table 3). Skill-based behavior is indulged in while using the probe and is a sensorimotor, feedback-controlled movement. This indicates the need for manual control training on tracking tasks (e.g., circle drawing, tracking) which transfer to this movement control task. Similarly, thought should be given to providing tracing paths (e.g., circles around rivets) which provide adequate feedback information. Templates can be and are being used (although some inspectors do not like to use them due to handling difficulties) and the improved design and use of such aids should be encouraged. The rule-based behavior component of calibration points to the necessity of developing adequate and well designed checklists along with procedural knowledge for reliable performance. Swain and Weston (1988) point out that during the calibration procedures, powerplant technicians who very often have followed written steps, rely on memory and this increases the probability of omissions. This points to calibration process design that is capable of providing cues to the next step on the display screen as well as detecting wrong inputs by the operator. Where calibration can be rigidly defined, the checklist is the obvious cognitive aid, already extensively used in aviation. Those calibration tasks which have some flexibility must be clearly delineated for separate treatment.

Table 3 Mapping a NDI Process to Cognitive Behavior for Expert Instructor

NDI PROCESSES	BEHAVIOR CATEGORIES		
	SKILL-BASED	RULE-BASED	KNOWLEDGE-BASED
CALIBRATION	Probe Movement over test specimen	Calibration Procedures	
PROBE MOVEMENT	Tracking Along Desired Path	Supportive Mode Identifying Boundary Conditions	
DISPLAY INTERPRETATION		Interpreting Familiar Signal	Interpreting Unfamiliar, Unanticipated Signals

Display interpretation forms the critical portion part of NDI and as such can be either rule-based or knowledge-based or both. The information environment should thus support both these behaviors while trying to ensure through system design and training that the need for knowledge-based behavior is minimized. Since rule-based behavior is based on signs which trigger stored patterns which in turn control our choices, Rasmussen and Vicente (1989) suggest that the design of the display should be such as to provide action cues as signs which also have symbolic content, thus supporting both rule and knowledge- based performances. Display screens for NDI that allow comparisons of the current pattern (curve) with known defect curves for comparative decision making should be considered for viability utilizing the human's ability to compare complex patterns presented together. Also, the knowledge-based component found during display interpretation indicates the need to develop feedforward information (training and documentation) to provide technology knowledge, instrument knowledge, and aircraft defect history.

From the discussion above, it is evident that the mapping of the inspection processes to the SRK framework provides useful guidelines for, and a better understanding of, the type of information that has to be provided for aircraft inspection. This has been compiled in Table 4 where the information categories (feedforward and feedback) identified in the aircraft inspection information model (Figure 1) have been assigned to the various inspection subtasks based on the ty1 pe of behavior they would logically support.

Table 4 Information Requirements Identified from Mapping Inspection Processes to SRK Framework for Two Examples

INSPECTION PROCESSES	INFORMATION ENVIRONMENT	
	FEEDFORWARD	FEEDBACK
1. VISUAL (e.g. Rivet Inspection)		
o Pre-Attentive	o Training	
o Foveal Search	o Training	o Output Feedback
o Foveal Decision	o Training o Procedural Knowledge o Comparison Standards	o Cognitive Feedback o Buddy System
o Extra-Foveal	o Knowledge of Cues	o Feedback of Results
o Decision Making	o Co-Worker Information o Functional System Knowledge o Fault Causation Knowledge o Aircraft History (Defects)	o Communication Links o Buddy System o Cognitive Feedback
2. NDI (e.g. Eddy Current)		
o Calibration	o Checklists, Display Design	
o Probe Movement	o Training on Tracking and Accurate Movement Control	o Probing Aids (Templates or Markings Around Rivets)
o Display Interpretation	o Display Design o Functional System Knowledge o Technical Instrument Knowledge o Aircraft History	o Cognitive Feedback

4.0 SUMMARY

In the preceding sections we have presented a general descriptive model of information flow in aircraft inspection, and a methodology (using the S-R-K framework) to identify the information requirements of the aircraft inspector.

We need to develop training procedures for the search and decision making components of aircraft inspection using human factors techniques that include use of cueing, feedback, active training and progressive part training as suggested by Drury and Gramopadhye (1990). It has been found that off-line controlled training successfully transfers to the more complex on-the-job environment. We see that there is a great deal of research support to indicate that use of feedback in initial training is beneficial. From the airline inspection context this points to the necessity of developing a training methodology that incorporates performance feedback. Drury and Gramopadhye (1990) have demonstrated a training scheme for gamma ray inspection of a nozzle guide vane area of a JT9D engine.

We have to understand the problems created by the mismatches between the needs of the inspector (who is looking for information) and the design of the documents (that present data). There is a critical need for usable knowledge, which gets translated to utilized information, on the job. From a document design viewpoint we have to focus on creating usable documents. Information flow design and system design should ensure the availability of documents at the right place at the right time. The demonstration project on workcard design presented elsewhere in this proceedings is an example of applying such document design principles.

It has been known for many years that if comparison standards are available at the work point, more accurate inspection will result. Yet in many cases such standards are not available to the aircraft inspector. If the maximum allowable depth of a wear mark is given as 0.010 inches, there is neither a convenient way to measure this, nor a readily available standard for comparison. Other examples are play in bearings and cable runs, areas of corrosion, or looseness of rivets. All are considered to be "judgement calls" by the inspector, but simple job aids, perhaps as part of the worksheet, or standard inspection tools, would remove a source of uncertainty. Leaving standards to unaided human memory may be expeditious, but it is also unreliable.

There is a necessity to gather the meta knowledge required for this indirect fault indication from experienced inspectors (through knowledge of engineering) who understand the utilization of such cues. There is also a need to identify the mappings between defects and fault causation mechanisms for a wide variety of such defects. The decision-making activity can then be converted to a rule-based, procedural type of task. Rules thus formed can be used in an effective training scheme to help inspectors increase the efficiency of the search and decision making process. This approach can be extended further to form an inspection data base which can be continually revised and updated to reflect the distributed knowledge that exists not only in a specific airline but across all airlines. Such a global knowledge-base would thus receive its input from experienced inspectors all over the aviation industry, thus consistently benefitting all users. It is also conceivable that an expert system could be developed that makes use of such a data base and supports decision-making tasks.

The information components identified in the model are connected to a particular task component using the methodology. In other words, task specific information needs are identified. We have to develop the information components identified by the model so that the cognitive behaviors that are needed for an inspection task are supported.

5.0 REFERENCES

Drury, C. G. (1991). Errors in aviation maintenance: taxonomy and control, In *Proceedings of the Human Factors Society 35th Annual Meeting,* San Francisco, California, 42-46.

Drury, C. G. (1990). The Information Environment in Aircraft Inspection. In *Final Report - Second Federal Aviation Administration Meeting on Human Factors Issues in Aircraft Maintenance and Inspection, Information Exchange and Communications,* 98-109.

Drury, C. G. and Gramopadhye, A. (1990). Training for Visual Inspection, In *Proceedings of the Third Federal Aviation Administration Meeting on Human Factors in Aircraft Maintenance and Inspection: Training Issues.* Atlantic City, New Jersey.

Drury, C.G., Prabhu, P. and Gramopadhye, A. (1990). Task Analysis of Aircraft Inspection Activities: Methods and Findings, In *Proceedings of the Human Factors Society 34th Annual Conference,* Santa Monica, California, 1181-1185.

Rasmussen, J. (1983). Skills, rules, knowledge: signals, signs and symbols and other distinctions in human performance models. *IEEE Transactions: Systems, Man and Cybernetics,* SMC-13, 257-267.

Rasmussen, J. and Vicente, K. J. (1989). Coping with human errors through system design: Implications for ecological interface design. *International Journal of Man Machine Studies, 31,* 517-534.

Sanderson, P. M. and Harwood, K. (1988). The skills, rules and knowledge classification: a discussion of its emergence and nature. In Goodstein, L. P., Andersen, H. B. and Olsen, S. (Eds.), *Tasks, Errors and Mental Models,* New York: Taylor and Francis, 21-34.

Shannon, C. E. and Weaver, W. (1949). The mathematical theory of communications. Urbana: University of Illinois Press.

Shepherd, W.T., Johnson, W.B., Drury, C.G., Taylor, J.C. & Berninger, D. (1991). *Human Factors in Aviation Maintenance Phase 1: Progress Report* (DOT/FAA/AM-91/16). Washington, DC: U.S. Department of Transportation, Federal Aviation Administration.

Swain, A. D. and Weston, L. M. (1988). An approach to the diagnosis and misdiagnosis of abnormal conditions in post-accident sequences in complex man-machine systems. In L. Goodstein, H. Andersen and S. Olsen (Eds.), *Tasks, Errors and Mental Models,* London: Taylor and Francis.

Taylor, J.C. (1990). Organizational context for aircraft maintenance and inspection. In *Proceedings of the Human Factors Society 34th Annual Meeting, Volume 2,* 1176-1180.

Woods, D. D. (1989). Coping with complexity: the psychology of human behavior in complex systems. In Goodstein, L. P., Andersen, H. B. and Olsen, S. E. (Eds.), *Tasks, Errors and Mental Models,* London: Taylor and Francis, 128-148.