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Human Reliability in Civil Aircraft Inspection

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Abstract:

Inspection of structures, systems and engines is an important part of ensuring continued airworthiness of the civil aircraft fleet. This paper describes the airworthiness assurance system and considers applicable bodies of knowledge which help understand and predict aircraft inspection performance. Two examples of recent studies of aircraft inspectors are used to illustrate the extra depth and breadth of understanding available where such knowledge is applied to these tasks. It is concluded that perhaps we have two separate roles: to predict performance and to improve it. Quantitative prediction will never be complete, but better estimates of inspector variability help us set more realistic inspection intervals. However, for improving aircraft inspection tasks we should concentrate on broader contextual factors, despite our inability to quantify some of these effects.

Human Reliability Issues in Aircraft Inspection:

Civil Aviation is growing at over 3.34% per year, and the total annual passengers in many developed countries is comparable to the country's population. Flying is a relatively safe activity, but one whose failures are dramatic and highly publicized. Thus, the exposure to risk is seen by the population as high and increasing. As airline growth increases, the prediction (Boeing, 1997) is for increasing crashes, up to one per week in 2015 unless the current incident rate is decreased.

Of the most visible crashes, known as hull-loss accidents, the fraction with maintenance or inspection as a contributing factor has been about 20% historically (Boeing 1997), but the rate has been increasing in recent years. Thus, inspection and maintenance errors have been seen recently as a major airworthiness emphasis (e.g. Gore Commission Report, 1997).

This paper considers one aspect where human reliability plays a crucial role, that of inspection. The work reported here is the outgrowth of several initiatives by regulatory bodies, primarily the Federal Aviation Administration (FAA) in the USA, Transport Canada and the UK's Civil Aviation Administration (CAA). These range from reliability measurement of inspection tasks to the use of Crew Resource Management (CRM) techniques in maintenance and inspection activities. The aim of this paper is to consider the findings of these initiatives and other applicable human factors knowledge in the domain of aviation maintenance. What can each contribute to improving system reliability? What are lessons for other highly-regulated safety-critical systems which have an inspection component? To do this, we first present an overview of the system for inspecting and maintaining aircraft, and then summarize the findings from contributing fields.

The System:

Airworthiness of civil aircraft depends upon a process by which a team composed of aircraft manufacturers, regulators and one or more airlines predict possible system failures. This process, Maintenance Steering Group 3 or MSG-3, considers possible failure pathways (for example in structures, controls, avionics) and for each pathway determines a recovery strategy. For structural failure, this may be replacement after a fixed service life, regular inspection to assure detection, or an indication to crew of the malfunction. In this paper the concern is with the reliability of the primary failure recovery system for aircraft structural inspection: regular inspection to assure detection.

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Failure modes of aircraft structures can be cracks, corrosion, fastner/bonding failure or deformation beyond the plastic limit. Inspection systems are designed to detect all of these in a timely manner, i.e. before the failure has a catastrophic effect as structural integrity. For example, crack growth rates can be predicted probabilitistically from material properties and applied stresses, so that the MSG-3 process can schedule inspections before a potential crack becomes dangerous. However, the detection system has certain limits on size crack that can be detected, so that MSG-3 typically schedules several inspections between the time the crack becomes detectable and the time it becomes dangerous. If too many inspections are scheduled, the costs are driven up in a highly-competitive industry, and the risk of collateral damage is increased due to the inspection process itself. Conversely, if too few inspections are scheduled, the probabilistic rate of the crack growth prediction process may combine with the probabilistic nature of the detection process to cause dangerous cracks to remain undetected. Spectacular failures of this inspection process have occurred both for aircraft structures (Aloha incident, Hawaii 1988) and engine components (Pensacola incident, Florida 1997).

The MSG-3 process thus requires quantitative data on inspection reliability to function correctly. In addition, no rule-based prediction system can foresee all possible malfunctions, so that once an aircraft is in service, regular detailed inspections are made of the whole structure to discover any unexpected cracks. When such "new" cracks are found, the information is typically shared between manufacturers, operators and regulators in the form of supplementary inspections. Similar considerations apply to other failure modes such as corrosion.

This whole reliability assurance process thus rests upon an inspection system which checks both points where malfunctions are expected and points where they are not expected, for a variety of malfunctions. For good reasons, human inspectors are part of this inspection system, so that human inspection reliability is an essential element in ensuring structural integrity, and hence airworthiness. The rest of this paper considers bodies of knowledge and data from three sources which should be applicable to human inspection reliability. Parts of this material have been reviewed previously (Drury and Spencer, 1997) to which the reader is referred for further details and references.

The Inspection Task:

The inspection task implied above combines two goals: detection of expected malfunctions and detection of unexpected malfunctions. Neither detection is particularly easy or particularly rapid, so that inspection can be a difficult and time-consuming task. In some ways inspection can be classified as an ill-structured task (Wenner, 1999) because there is no simple step-by-step procedure which will ensure success, and because there is usually no knowledge of task success available during the task. Finding (n) malfunctions in a structure still leaves an unknown number (hopefully zero) potentially undetected.

In addition, inspection is typically scheduled at the beginning of an aircraft's maintenance visit so that malfunctions can be detected early and their repair scheduled to overlap in time with other maintenance activities. As airlines streamline their parts inventory to reduce holding costs, the lead time for replacement components can increase, again pressuring the inspection system to ensure early detection. Aircraft typically arrive following scheduled service, i.e. after the last flight of the day. Following opening up and cleaning processes, maximum inspection resources are committed to the initial inspection. In practice this means inspectors working overtime, even double shifts, starting with a night shift, under some implied pressure for early detection. Human inspection reliability may not be optimal under these conditions.

The inspection task itself is classified in aviation as either Visual Inspection or non-destructive inspection. Regulatory bodies have issued formal descriptions of both of these tasks (e.g. Bobo (1989) for the FAA), and both have somewhat different characteristics in aviation

Non-destructive inspection (NDI) comprises a set of techniques to enhance the ability to detect small and/or hidden malfunctions. One set of NDI techniques are those which enhance what is essentially still a visual inspection task, for example X-ray, fluorescent particle, magnetic particle or D-sight. They show cracks which are very small (fluorescent particle) or hidden within other structures (X-ray). Apart from the steps necessary to ensure a good image, they have many of the human interface characteristics of visual inspection. The other

set of NDI techniques are focused on specific malfunctions in specific locations, e.g. eddy current, ultrasound. For this reason, they are only useful for detection of malfunctions already predicted to exist. In practice, such NDI techniques are much more proceduralized than visual inspection or NDI techniques which contain a human visual inspection component.

Visual inspection is much more common, comprising 80% of all inspection Goranson and Rogers (1983). It consists of using the inspector's eyes, often aided by magnifying lenses and supplementary lighting, as the detection device. Inspectors must visually scan the whole structure of interest, typically using portable mirrors to examine areas not directly visible. Whether the task is categorized as Visual Inspection or NDI, its aim is to detect flaws (indications) before they become hazardous. Next we consider the bodies of knowledge potentially applicable to aircraft inspection reliability. This section is adapted from Drury and Spencer (1997).

Applicable Knowledge 1. NDI Reliability:

Over the past two decades there have been several studies of human reliability in aircraft structural inspection (Rummel, Hardy and Cooper, 1989; Spencer and Schurman, 1995; Murgatroyd, Worrall and Waites, 1994). All of these to date have examined the reliability of Non-Destructive Inspection (NDI) techniques, such as eddy-current or ultrasonic technologies.

From NDI reliability studies have come human/ machine system detection performance data, typically expressed as a Probability of Detection (PoD) curve, e.g. Spencer and Schurman (1995). This curve expresses reliability of the detection process (PoD) as a function of a variable of structural interest, e.g. crack length, providing in effect a psychophysical curve as a function of a single parameter. Sophisticated statistical methods (e.g. Hovey and Berens, 1988) have been developed to derive usable PoD curves from relatively sparse data. Because NDI techniques are designed specifically for a single fault type (e.g. cracks), and much of the variance in PoD can be described by just crack length, the PoD is a realistic reliability measure. It also provides the planning process with exactly the data required, as remaining structural integrity is largely a function of crack length.

Both the FAA (*National Aging Aircraft Research Program Plan*, 1993, p. 26, p. 35) and the Air Transport Association (ATA) have recognized the need for equivalent studies of the reliability of visual inspection as a research priority.

Applicable Knowledge 2. Industrial Inspection:

Human factors analyses of inspection tasks have been published since the 1050's and 1960's with a steady evolution of approaches. Early studies (e.g. Thomas and Seaborne, 1961) tended to be rich and holistic descriptions of inspection tasks. They focused on some of the unique perceptual cues used by experienced inspectors. These showed for example that inspectors organize their perspectives so as to enhance subtle task relevant visual or auditory cues and surpress what a novice would perceive as salient cues. This tradition of description has occasionally resurfaced (Biederman and Shiffar, 1987; Dalton, 1991) but has been largely replaced by more quantitative studies.

The next wave of work measured human performance in a variety of inspection tasks, typically in terms of the two possible errors: missed defects and false alarms. Reviews of this work are readily available (Drury, 1992; Megaw, Alexander and Richardson, 1979). Table 1 classifies some of the factors found to affect inspection performance, using ICAO's SHELL model (ICAO, 1989). Following such studies, and indeed overlapping them, were model-oriented studies treating inspection as either a signal detection task (Harris, 1969; Drury and Addison, 1973) or a visual search task (Kundel; 1975; Drury, 1990). The advantage of such approaches is that they can use the underlying models to predict which variables are most and least likely to affect inspection performance. They also allow succinct descriptions of tasks and task performance, potentially leading to quantitative models. For example, NDI studies of aircraft inspection often provide Relative Operating Characteristic (ROC) curves relating miss rate to false alarm rate for a given defect type.

An inspection model combining search and decision (Drury, 1975) can also be helpful in understanding the inspector's tasks in inspection. This model, summarized in Figure 1, shows an inspector searching an item by repeated fixations of small areas. If an indication (potential defect) is found, a decision task takes place to determine whether the indication should be classed as a reject. If not, or if the fixation found no indications, search continues. The inspection task stops (or moves to the next item) when there is no further time left for inspection, either because of the inspector's stopping policy or external pacing of inspection. This model allows us to specify the variables affecting each stage. Thus, peripheral visual acuity should affect fixation area and thus, search performance (Courtney, 1984). Conversely, the decision stage should be affected by cost and probabilities of the decision outcomes (Chi and Drury, 1998). Overall, this model has been useful in interpreting the speed/ accuracy tradeoff in inspection (Drury, 1994).

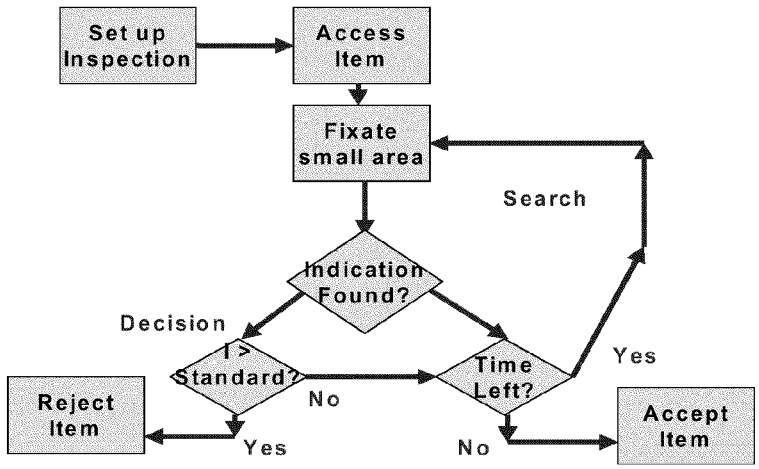

Figure 1: Model of inspection performance incorporating search and decision

Knowledge of how people perform inspection tasks in both manufacturing industries and medical diagnosis has been reviewed many times (e.g. Drury, 1997). It has also been interpreted in an aviation context following the Aloha incident (Drury, 1989; Wiener, 1989). Briefly, inspection is composed of several functions or processes, the most error-prone of which are search and decision. In search, the inspectors' eyes (or probe for NDI) move around the area to be inspected, stopping when some indication is found. In decision, this indication is compared to known (available or remembered) standards to determine whether or not a reportable fault condition exists.

A flavor of the findings of this tradition can best be given through ICAO's model of human factors in aviation: SHELL (ICAO, 1989), each element of which represents a key component of the human/ machine system. How each component interfaces with the individual considered (pilot, air traffic controller, AMT, inspector) determines the sources of both successful human performances and human errors. Table 1 summaries industrial inspection findings using this aviation-based model of human factors.

Table 1: Summary of inspection findings using ICAO's SHELL Model

SHELL System Component	Typical Findings from Inspection Studies
S: Software e.g. procedures, instructions, workcards, feedback	Instructions given to the inspector have a great effect on both p (detect) and p (false alarm). In addition, feedback information to the inspector has large positive influences on performance (Gramopadhye et al, 1997).
H: Hardware e.g. job aids, enhanced vision systems, magnifiers	Equipment such as semi-automated visual inspection systems improve performance when well-integrated with human functions (Hou et al, 1993). Enhanced vision systems, such as magnification or lighting aids sometimes help, sometimes do not. Providing visible comparison standards improves decision.
E: Environment e.g. lighting, thermal, noise	Some effects, but only at relatively extreme values and with long exposure times.
L: Liveware (Individual) e.g. individual inspector characteristics	Some general characteristics of "good" inspectors, such as field independence and peripheral visual acuity. Often each inspection task shows performance correlations with different individual characteristics.
L: Liveware/Liveware e.g. interactions with other people in system	Job design is important. Inspectors tend to feel their jobs isolate them from others. Expectations of others can have large effects on what gets reported as fault.

Applicable Knowledge 3. Human Factors in Aviation Operations:

There is a long tradition of human factors analysis of both the tasks involved in flying/guiding aircraft, and the accidents arising from these tasks. Indeed, one of the earliest human factors studies (Fitts and Jones, 1947) analyzed 460 "pilot error" accidents and found that many were induced by poor design or placement of controls and displays in the cockpits of the time. Over the succeeding years, these studies have led to great improvements in the design of cockpits, selection procedures and pilot training programs (Wiener and Nagel, 1988).

In recent years the interest, both on the flight deck and in air traffic control, has focused on the two issues of automation and interpersonal interactions. Automation studies, again both of how tasks should be performed and the accidents arising when they are performed incorrectly, have led to changes in automation systems (e.g. Phillips, 1998).

Interpersonal relations on the flight deck have also been studied both analytically and through accident analysis. From this, work has emerged a body of theory and practice known generally as Resource Management. Crew Resource Management (CRM) is now a regular, and potentially ICAO mandated, component of flight training and retraining programs (e.g. Heimreich, Foushee, Benson, and Russini, 1986; Foushee and Helmreich, 1988). Pilots (and others) learn techniques for working together more effectively from flight planning through to handling of unplanned incidents. Such results have found rational applicability in the aviation maintenance domain, now becoming known as Maintenance Resource Management (MRM). Taylor (1991) has taken a socio-technical systems approach to analysis of inter-personal activities in maintenance. This has led to training programs (e.g. Robertson, 1996; Komarniski, Russell and Johnson, 1996) which have been successful in changing attitudes and behaviors of maintenance personnel.

Using Applicable Knowledge:

Aircraft inspection has already benefited from some of these knowledge areas. Thus the ECRIRE program (Spencer and Schurman, 1995) examined one NDI technique, eddy-current inspection, incorporating human factors variables. They were able to test one-person versus two person teams (no consistent effects) and gross body posture (a small decrease in detection performance when the inspector had to work at about knee height). A FAA program on human factors in aviation maintenance and inspection (e.g. Drury, Shepherd and Johnson, 1997) has had some success in improving documentation design, lighting and communications. This program expanded the search-plus-decision model following industrial inspection findings to include five generic inspection functions (Drury, 1992):

Initiate	inspection, e.g. calibration, documentation
Access	area to be inspected, e.g. by removing access hatches
Search	area by successive fixations or probe movements
Decision	on whether indication exceeds standard
Response	by signing inspection as complete or recording defect.

Such a task description invites task analysis, which would lead naturally to human reliability analysis (HRA). Indeed, perhaps the earliest work in this field applied HRA techniques to construct fault trees for aircraft structural inspection (Lock and Strutt, 1985). The HRA tradition lists task steps, such as expanded versions of the generic functions above, lists possible errors for each step, then compiles performance shaping factors for each error. Such an approach was tried early in the FAA's human factors initiative (Drury, Prabhu and Gramopadhye, 1990), but was ultimately seen as difficult to use because of the sheer number of possible errors and PSF's. It is occasionally revised, e.g. in the current FRANCIE project (Haney, 1999) using a much expanded framework that incorporates inspection as one of a number of possible maintenance tasks. Other attempts have been made to apply some of the richer human error models (e.g. Reason, 1990; Hollnagel, 1997; Rouse, 1985) to inspection activities (Latorella and Drury, 1992; Prabhu and Drury, 1992; Latorella and Prabhu, 1998) to inspection tasks. These have given a broader understanding of the possible errors, but have not helped better define the PoD curve needed to ensure continuing airworthiness of the civil air fleet.

Two Recent Studies:

To help understand how human factors can contribute to the domain of aircraft inspection, two examples are given. The first pursues an analytical approach based on a task breakdown, while the second examines broader issues affecting human reliability.

The first study was the Visual Inspection Research Program (VIRP) undertaken for the FAA using a retired Boeing 737 test aircraft at Sandia National Laboratories (Drury and Spencer, 1997). Twelve experienced airline inspectors performed ten different inspection tasks, nine on the aircraft and one on a series of fuselage test panels containing known cracks. The total experiment lasted 1.5 to 2 days per inspector and was performed under highly realistic conditions in a flight hangar. Overall, performance was quite variable. Inspectors took from 7.5 to 12.3 hours of inspection time for the ten tasks. On a set of large cracks and corrosion defects which the manufacturers would expect inspectors to find, the probability of detection was also quite variable. PoD ranged from 0.5 to 1.0 on large cracks and from 0.3 to 0.6 on large corrosion areas. There was little evidence of a speed/accuracy tradeoff across inspectors. There were also low correlations between inspector performance on the 10 tasks, and also between pre-test measures and task performance. Individual differences were large and inconsistent.

A more detailed analysis of this data is possible by classifying errors into search errors and decision errors. Drury and Sinclair (1983) showed that this was possible in industrial inspection of aircraft bearings. For the panel inspection task, we used video tape records to classify the errors. It was possible to see from the video tape whether an inspector passed quickly over a crack defect (search error) or whether he paused to examine the defect more closely before either reporting it or moving on. This latter was a decision error, either a miss or as false alarm.

Figure 2 shows the individual differences between inspectors for search performance. Note that probability of search success is rather uniform and low. The mean was 0.5 and the coefficient of variation was 0.2. For decision performance, Figure 2 shows individual inspector results plotted on Relative Operating Characteristic space. The variability is readily apparent, with mean performance as follows:

p (correct hit): mean = 0.84 CV = 1.2
p (correct No): mean = 0.64 CV = 1.0

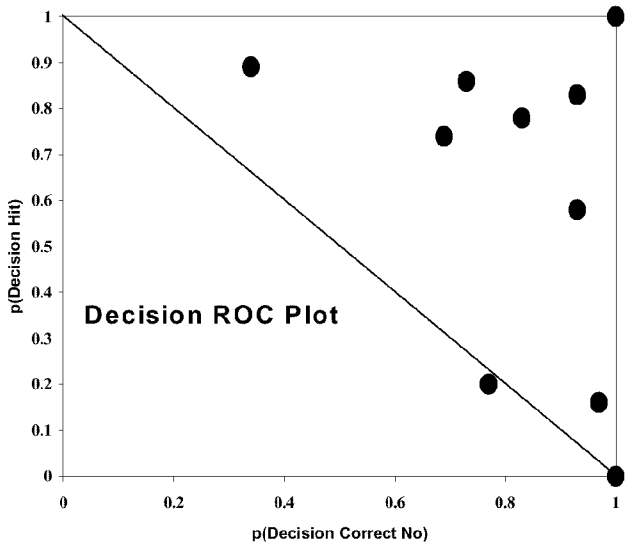

Figure 2: Relative Operating Characteristic (ROC) curve for decision component in aircraft structural inspection. Each point is from one inspector.

Thus, search performance could be characterized as consistently poor, whereas decision performance was better, but highly variable. Search and decision performance were statistically unrelated. Such findings allow us to focus interventions, for example by improving lighting and training to support search, while using training and feedback to reduce inter-inspector variability in decision (Gramopadhye, Drury and Prabhu, 1993).

The second experiment was similar to VIRP, but performed on a commuter aircraft (Fairchild Metro) using experienced regional airline inspectors. This study had inspectors perform seven inspection tasks, again over 1.5 to 2 days. Performance was again highly variable between inspectors and between tasks with almost no correlations between task performance or between task performance and pre-tests. However, in this experiment, the major concentration was on the subtleties of the inspection task and its context, detailed in Wenner and Drury (1997).

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