Defect-Detection Technologies for Low-Observability Aircraft Skin Coatings

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Abstract

This report is a survey of the open literature on technologies for detection (finding) and characterization (area measurement and labeling of nature) of defects in low-observability (LO), or "stealth" coatings on aircraft. The focus is primarily on computer vision algorithms operating on images captured by conventional visible-light cameras, potentially with aids to detection such as specialized lighting schemes, stereoscopy, and other defect-depth characterization methods. A secondary focus is on alternative (and perhaps speculative) detection and characterization technologies, e.g., electromagnetic means outside the visible spectrum, ultrasonics, etc. Initial survey of open literature found no publications, patents, or supplier advertising except for several tablet-and-software based aids for alleviating the bookkeeping burden experienced by human visual inspectors. Our attention was therefore redirected toward the general field of computer-vision-based surface inspection, a field on which there is extensive literature addressing, e.g., in-process production of "web products" such as textiles, paper, and sheet metal.

However, the analogy of web-product manufacturing to defect detection and characterization of defects in LO coatings is weaker than one would like: in manufacturing, speed is more of an issue than comprehensive coverage, the focus is more on detection than on characterization, the total area that must be inspected has no upper bound, and each element of product area is typically seen only once. In contrast, there are only a few hundred LO airplanes in service, and each airplane is inspected frequently, at least after each flight and, after maintenance operations are completed, before the next flight.

This distinction in scenario suggests that a more fruitful path than one-shot detection and identification of defects might be a difference-based approach: how is the appearance of this surface patch different from its appearance upon the last inspection, and what is the meaning and importance of that difference? However, as an engineering problem vs. a computer-algorithm problem, success in difference-analysis will require precise spatial registration of images collected at different times, in turn requiring more precise knowledge of sensor package location in a coordinate system embedded in the aircraft surface than is required for one-shot web-product inspection.

We have collected, analyzed, and summarized in an annotated bibliography approximately 50 promising articles, patents, and manufacturer's brochures. This bibliography is meant to be read as part of the report.

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1 Introduction

The objective of this study is an evaluated survey of the open literature on currently practiced non-destructive inspection technologies for detection and characterization of damage and deterioration of low-observability aircraft skin coatings. The primary focus is on visible defects and deterioration that are detectable by commercial off-the-shelf cameras and illumination sources operating in the visible (and possibly also near-visible) light regime. A secondary focus is on other (not camera-based) currently practiced technologies (not camera-based), and promising technologies (camera-based or not) that are not currently practiced but that in our judgment could be implemented by adaptation of known science and technology to the low-observability damage and deterioration detection and characterization problem. In the visual detection part of the report we address both hardware -- human and/or camera plus illumination -- and software, i.e., defect- and damage-detection algorithms. Our emphasis with regard to alternative and potential future technologies is primarily on the proposed science and its (possibly speculative) technological implementations.

This is a general-purpose study that makes no assumptions regarding the materials, structures, or appearances of the intact low-observability aircraft skin coatings being inspected, nor about the nature or appearance of the damage and deterioration of interest. It is worthy of note that open literature regarding appearance—let alone visual or camera-based inspection techniques—of low-observability aircraft skin coatings is almost nonexistent. In this situation, currently, one of the best sources of specific information in context about actual practice consists of (otherwise unpublished) online documents like the on-the-job experience profiles listed in the resumes of military aircraft maintenance and inspection technicians, which enumerate the instruments and methods in which they are skilled, e.g., (Bailey n.d.); however, even these unconventional sources tell us nothing about the appearance or other distinguishing characteristics of actual defects, or of functionally irrelevant surface anomalies that might increase the false-positive detection rate of detection and classification hardware and software. Consequently much of this report's content, especially the part that is about visible-defect-detection algorithms, addresses the general area of camera-and-image-analysis algorithm-based inspection of surfaces in general, which may apply equally to paper and textile products, computer screen LCD display components and modules, and the like.

In the pre-radar and pre-sonar eras "low observability" meant making airplanes, ships, vehicles, equipment, and personnel difficult for human observers to see: it employed various kinds of camouflage that concealed the object by making it visually blend into the background sky, sea, or terrain, or by exploiting "bugs" in the human eye-brain system that blind us to shapes and patterns that we don't expect to see in the context in which they actually appear.

With the advent of sonar for detection and ranging of submarines, and soon thereafter the advent of radar for detection and ranging of aircraft and surface ships, concealment from visual detection by humans became secondary to concealment from these new echo-based technologies. Certainly by World War II, and probably even during World War I, submarines were coated with rubbery skins to suppress their hull's reflection of acoustic probe signals -- and also to some extent to attenuate the external intensity of internally-generated sounds as they pass through the hulls. Shortly after World War II, and with serious intensity by the mid-1970s, air forces became interested in analogously reducing the visibility of their aircraft to enemy radar probes. This involved, and still involves, two distinct classes of technology: first, replacing the aircraft skins' smoothly-curved surfaces, which scatter radar into more or less the entire 2π steradians back in the direction of the incoming radiation, with planar surfaces that scatter it specularly into directions where it is hoped the enemy has no receivers, and second, analogous to the early rubbery coatings on submarine hulls, to create skin materials, structures, or coatings that absorb rather than reflect incoming radar frequency energy.

This background, at this level of general principles, is easy enough to learn from the open literature. And achieving low-observability based on suitably oriented specularly reflecting surfaces is easy enough to achieve, provided only that once the designers have achieved a geometrical design with sufficiently low radar cross section, their airplane will actually fly.

The second set of technologies, the technologies of low observability based on low reflectivity via high absorption or attenuation aircraft coatings, is much more complicated. To the limited extent that it is discussed in the open literature, it seems speculative and sometimes even contradictory. The inspection of these radar-return-signal-reducing coatings, primarily but not exclusively by machine vision and image processing, is the main topic of this report.

The focus of this paper is primarily on finding and characterizing low-radar-observability aircraft skin coating damage and degradation using a narrow range of all the instrumentation that one might imagine bringing to bear on this task: off-the-shelf visible light cameras and illumination systems. It is hard to see something, and it is harder to understand what you are seeing, when you don't know what it is supposed to look like[1]. The difficulty posed by not knowing what you are looking for is exacerbated when the looking is being done by a camera and an image-understanding program vs. a human's eye-brain system: whereas defects in and damage to surfaces of known visual appearance can be found more rapidly and more reliably by state-of-the-art instruments than by human inspectors, in general[2] the advantage is with the human inspector when anomalies are of unknown a priori appearance. In contrast, anomalies that can be characterized in advance are usually straightforward to program into both the hardware and the software components of the inspection protocol. While it is universally acknowledged that the various low observability coatings that are employed on different aircraft types and models are all fragile in one way or another, and that they thus require a large ratio of maintenance hours to operational hours, the exact nature of their fragility, how they look undamaged and damaged, whether there are kinds of functional damage that are not visible, and whether there are kinds of appearance defects that can be ignored because they are not functional detriments, represent information that is generally unavailable publicly. The difficulty of generalization is exacerbated by the fact that (as indicated by hints in certain online discussions) the more effective coatings that have been developed for later model aircraft are sometimes retroactively applied to some but not all units in an older model fleet, meaning that nominally identical aircraft might in fact require different inspection set-ups.

2 Types of damage and methods of detection

2.1 Structural impact damage

What we mean by structural impact damage should be obvious: in automobile collision parlance, dings and dents to the aircraft skin's substrate -- not just to its LO coating – caused by collisions with tools, stray nuts and bolts, pebbles and birds on the runways, etc. In the commercial aircraft sector this is called FOD—foreign object damage. To these dings and dents add the crushing injuries caused by collisions with, e.g., gantries, robots, other aircraft, ground vehicles, hangar doors, etc.

These sorts of damage are mostly not germane to the present report: the initiating event is usually known, the damage is usually visible to the naked eye of even an untrained observer, and the repair protocol is the same as for any non-LO aircraft, presumably save for initially

[1] In fact, presenting human observers with unexpected appearances ("razzle dazzle" camouflage) was used in the pre-radar era to confuse human observers. The technique seems to have reappeared -- in a somewhat muted form -- in modern naval vessel paint schemes like the Swedish navy's corvette *Helsingborg*.

[2] An important exception to this rule occurs when the undamaged surface has a pronounced and precisely periodic texture, e.g., wallpaper. Then finding any deviation from the expected pattern is easy. This is because what is expected is always present and easy to verify, so its absence -- the defect -- is easy to find.

removing the residual LO coating and finally renewing it.

An exception to this scenario might be impact damage to a composite vs. a metallic substrate: composites are well known to have a tendency to spring back, weakened beyond repair, so requiring replacement of the whole panel, but without any visible damage. However an impact of sufficient magnitude to damage the substrate—even invisibly—would almost certainly cause visible damage to the LO coating. This possibility means that inspection and maintenance protocols must specify emphatically that when the coating on a composite part is found to be damaged it is essential to inspect the substrate for loss-of-strength before renewing the LO coating.

2.2 Damage and deterioration visible to the naked eye

This is the topic of primary interest in this paper: due to mechanical trauma, water or other chemical trauma, natural or sunlight- or temperature-accelerated chemical breakdown, etc., an aircraft's low observability coating peels off the substrate, flakes, blisters, cracks, or otherwise undergoes changes in texture or color or both.

We can say with confidence that if you can see it, then an off-the-shelf camera and one or more off-the-shelf luminaires can capture an image of it, and an algorithm exists to find it in the image, characterize it, and, given the camera's stand-off distance, focal length, and pixel spacing, measure its size. The rub is that to do all of this—and not just report that there is an abnormal blob in the image—requires a library that contains an algorithm crafted for each kind of defect that you expect it is possible to find (Gunatilake et al. 1997). If you miss installing an algorithm for, say, blistering, then you wouldn't be able to characterize a defect as a blister. At best one would classify it as an abnormal area of such-and-such size located at such-and-such coordinates. At worst one would misclassify it as, e.g., a discoloration.

Specific algorithms or classes of algorithms that have been demonstrated to be effective for specific defect geometries, textures, and shapes, are catalogued in the annotated bibliography, including (Elbehiery et al. 2007), and those developed by Tsai and his students and collaborators over the course of more than a decade in which they systematically addressed a sequence of increasingly difficulty shapes and textures (Tsai & Hsieh 1999; Tsai & Hsiao 2001; Tsai & Huang 2003; Tsai & Chiang 2003; Tsai et al. 2006; Tsai & Lai 2008; Chao & Tsai 2008; Chao & Tsai 2010; Tseng & Tsai 2010), as well as the convenient and comprehensive summary assembled by Xie (Xie 2008). These are only the most obviously useful references; additional examples can be found in the annotated bibliography.

2.3 Damage and deterioration not visible to the naked eye

If you can't see it, can a camera see it? It depends why you can't see it. If it is too small for you to see, then macrophotography with appropriate illumination might be able to magnify it enough; most likely a coating flaw too small to be seen this way is too small to interfere with the low-observability functionality of the coating. But then the field-of-view of the camera would be only a small area of the aircraft skin, so it would take a long time to cover the inspection area, as the camera would have to be moved very slowly.

Could it be too big for you to see? Yes, because the human visual system is not good at seeing low spatial frequencies that are not also time-varying, so a subtle gradient would probably be invisible to a human inspector. However if we knew it was important to find a small gradient over a large distance, several algorithms designed to find low-contrast features are available (Lin 2007; Chao & Tsai 2010; Tseng & Tsai 2010; Tsai et al. 2006).

Could it be visible in a spectral regime that you cannot see? Yes, some damage, and (perhaps more likely) some kinds of deterioration, could be easily visible in the ultraviolet or the infrared. Off-the-shelf camera lenses generally block ultraviolet wavelengths, but ultraviolet illumination often stimulates visible fluorescence, which is easily photographed and processed by the same algorithms discussed above and throughout the bibliography. Off-the-shelf camera lenses generally transmit infrared out to beyond the long-wavelength sensitivity limit of silicon image sensors, but the sensors generally are covered by infrared blocking filters to prevent their rendition of color from being distorted by the presence of infrared. However, cameras can be purchased without blocking filters, or, with care, most blocking filters can be removed. High intensity infrared LEDs provide excellent illumination for infrared photography.

2.4 Stereoscopic techniques

Stereoscopic image pairs, from which distances in the direction of the camera's optical axis can be computed, are typically captured by camera pairs. With this technique (range from stereo) it is possible to measure, e.g., the depth of gouges or the height of blisters. If an apparatus scans the surface with a moving camera, it is unnecessary to use two cameras: it is sufficient to analyze two images taken with a single camera in two different positions along the scan line. The utility of stereoscopically-derived depth information in inspection scenarios is discussed in the literature (Pernkopf & O'Leary 2003).

2.5 Non-visual inspection

As noted already, it may seem a bit strange to be focusing on the visible and near-visible light appearance of low-observability coatings when the essential issue is how visible they are to the radar to which they are intended to be invisible. This strongly suggests that some effort ought to be devoted to inspecting the integrity and performance of these coatings at much lower than optical frequencies, e.g., at the radar frequencies per se, or at even lower frequencies at which electrical parameter measurements, e.g., by eddy-current sensing (Siegel et al. 1998), can detect flaws, such as micro-cracks and debonding between layers, that might be invisible to the eye or the camera.

Some LO coatings are reportedly semiconducting polymer materials. These could be heated by a microwave burst and observed in their subsequent infrared emission. The image structure might reveal cracks, inclusions, etc., that are not visible in visible light illumination, and the temporal decay of the temperature could reveal disbonding that would otherwise be difficult or impossible to detect.

Some LO coatings are reported made by suspending micro-sized iron, ferrite, or other ferromagnetic materials in epoxy paint. These too could be heated with microwave bursts and the temperature pattern and decay rate observed via infrared photography. Magneto-optic imaging would presumably also provide valuable diagnostic information.

As reported in the Olsen legal case (Boyd et al. 2009), the LO coating of the Lockheed Martin F-22 Raptor consists of three layers: a primer to level the substrate and provide a strong bond, a conductive layer loaded with metallic silver flakes, and "third is the topcoat, which has other metallic materials and infrared properties to reduce heat and thus RADAR detection". Both straightforward reflectivity measurement at the radar frequencies of interest and eddy-current probing seem plausible inspection technologies for the functionality and structural integrity of this coating.

3 Summary and conclusion

Based on this literature survey one can say with confidence that if a human visual inspector can find a defect, characterize it, and specify where it is and how big it is, then one can build machine vision hardware and software that will find it, characterize it, and specify where it is and how big it is. Via a variety of visible and near-visible light and lighting techniques, and by making some rather simple lighting changes and camera variants, we can extend our inspection capability beyond what human observers can accomplish, assuming that one knows what one is looking for.

Since low-observability aircraft skin coatings have engineered electromagnetic properties that may be damaged even if the coatings are visually intact, and conversely, that may be electromagnetically intact even if the coatings are visually damaged, we feel strongly that if it is desired to localize all functional flaws then comprehensive local radar-frequency inspection of coatings is a necessary integral component of the inspection process. If on the other hand it is felt that global radar cross-section (RCS) testing is adequate, and the intent of visual inspection is secondary, e.g., its function is to localize the source or sources of RCS test failure, then visual inspection alone might be adequate. The efficiency -- but not the effectiveness -- of such a strategy would depend in large part on the extent to which the RCS test apparatus is able to provide at least some localization.

Further details are found in the annotations to the items in the following bibliography, and in the references themselves. Especially recommended is the sequence of papers by Tsai and his collaborators, who over more than a decade systematically investigated and developed algorithms for defect-detection tasks.

4 Annotated bibliography

Annotations in this bibliography describe relevance and applicability to the tasks of LO defect detection, classification, and characterization, or to background material that supports implementation of those methods. Note that many of the references below are not cited elsewhere in this article.

Anon, 2013. *Stealth Aircraft: the Complete Guide*. Available at: en.wikipedia.org/wiki/Book:Stealth_aircraft.
Included for reference: a book-length Wikipedia entry on stealth aircraft and LO technology. Heavily illustrated and referenced, this might well be the best open-literature source of information on the topic.

Associated Press, 2004. Stealth bomber to get faster coating. Topeka Capital-Journal. Available at: cjonline.com/stories/071104/pag_stealth.shtml#.WQtwE9y1u70.
Northrop's new formula and automated application system to improve LO performance and cut down maintenance time: “minutes instead of days.”

Astral Technologies Unltd., Low observable materials. Available at: www.astraltechnology.com/low_observables.html.
Describes substrates, coatings, films, engineered-structure materials, materials characterization services.

Bailey, C., (LinkedIn resume). Available at: www.linkedin.com/in/christopher-bailey-24090093.
Indication of materials, processes, and skills required to maintain LO coatings in service.

Biswas, D., 2014. Is it possible to make a stealth aircraft by using organic polymers? Available at: www.researchgate.net/post/Is_it_possible_to_make_a_stealth_aircraft_by_using_organic_polymers.
Speculative discussion, about polypyrrole specifically and alternatives generally, proposed for LO aircraft coatings.

Bourzac, K., 2011. Nano paint could make airplanes invisible to radar. *MIT Technology Review*. Available at: www.technologyreview.com/s/426276/nano-paint-could-make-airplanes-invisible-to-radar/.
“Forest of nanotubes” known to be extremely black in the visible regime, claimed to be black in the radar-frequency regime, speculatively applicable to radar as well as visual LO.

Boyd, S.L., Warren, D.R. & Benson, P.E., 2009. United States of America, Ex rel. Darrol Olsen, Darrol Olsen, individually, Plaintiff vs. Lockheed Martin Corporation, Defendant. Case No. CV-07-06385 R (CWx),
A legal brief in which former long-time Lockheed Martin and Northrop employee Olsen alleges on behalf of the government that

Lockheed Martin knowingly applied defective LO coatings to F-22 Raptor aircraft. The document is a qualitative but deeply detailed textbook of LO coating theory and practice, including details of application and repair processes, and what can go wrong with them.

Caleb-Solly, P. & Smith, J.E., 2007. Adaptive surface inspection via interactive evolution. *Image and Vision Computing*, 25(7), pp. 1058–1072.
Describes a man-in-the-loop iterative system for tuning the parameters of a machine-vision-based defect-detection system; the man in the loop needs to understand what is and what is not a defect, but not the internal details of the machine-vision system.

Ceno Technologies. Cenospheres - Low observable technology. Available at: cenotechnologies.com/low_observable_technology.php.
Hollow ceramic microspheres, waste-product of coal-fired power plants, incorporated in F-22 and possibly other LO aircraft coatings. Functionality is not completely clear: it seems that the microspheres' function is twofold: to decrease the IR reflectivity of the aircraft, and to scatter the radar-frequency radiation within the RF-dissipating material to enhance its effectiveness.

Chao, S.M. & Tsai, D.M., 2008. An anisotropic diffusion-based defect detection for low-contrast glass substrates. *Image and Vision Computing*, 26(2), pp. 187–200.
This annotated bibliography contains multiple references to papers published over more than a decade by Tsai and collaborators. Tsai is usually the first author, with apparently a graduate student as second author, though in this paper Chao is first author. During an era when US and European vision researchers had already begun to focus their attention on open-ended computer vision topics related to, e.g., outdoor scene understanding, Tsai and his colleagues in Taiwan were still focused on the kinds of industrial machine-vision problems that occupied Western researchers 10 or 20 years earlier. With contemporaneous improvements in cameras, algorithms, and computers over those years, Tsai was able to generate a paper approximately every two years, each covering a new aspect of machine vision for defect detection in constrained industrial production environments. This paper (the seventh of the nine Tsai papers cited here, in chronological order) specifically addresses the authors' algorithmic approach to detecting subtle low-contrast defect areas in the glass substrates of TFT-LCD display panels. This approach may be valuable for finding and characterizing low-contrast splotchy areas in LO coatings resulting from uneven initial application, rework and repair, water damage, etc.

Chao, S.M. & Tsai, D.M., 2010. Anisotropic diffusion with generalized diffusion coefficient function for defect detection in low-contrast surface images, *Pattern Recognition*, 43(5), pp. 1917–1931.
This is the eighth (in chronological order) of the nine papers by Tsai and his colleagues. This paper extends the approach of Chao & Tsai (2008) by presenting a generalized diffusion model intended to provide enhancement of defects and faster convergence compared to the 2008 paper.

Chin, R.T. & Harlow, C.A., 1982. Automated visual inspection: a survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 4(6), pp. 557–573.
A survey with 288 categorized references of the state-of-the-art of computer vision for inspection—mostly surface inspection—in 1982. Considers both the hardware and the software sides, including camera, illumination, differencing, etc. Recommended as a starting point to provide the background needed to understand the signification of more recent papers that assume the reader is familiar with the history it encapsulates.

Despain, R.R. et al., 1996. RF imaging of low observable coatings using a wire-over-ground-plane transmission line. U.S. Patent 5,483,169.

Test method for detecting flaws in RAM (radar absorbing materials) coatings that might not be accompanied by any visible indication.

Echols, A., 2013. LO: how the F-22 gets its stealth. Tyndall Air Force Base News. Available at: www.tyndall.af.mil/News/Features/Display/tabid/6651/Article/669883/lo-how-the-f-22-gets-its-stealth.aspx.
LO coating application, inspection, and maintenance from the perspective of an airman whose job is to do it.

Elbehiery, H., Hefnawy, A. & Elewa, M., 2007. Surface defects detection for ceramic tiles using image processing and morphological techniques. *International Journal of Computer, Electrical, Automation, Control and Information Engineering*, 1(5), pp. 158–162.
Flaws in ceramic tile production are identified as 1. chips (edges and corners), 2. cracks, 3. scratches, 4. glaze faults, 5. holes and pitting, and 6. lumps. Most if not all of these are likely to have counterparts in LO coatings. Simple machine-vision hardware and algorithmic approaches to their detection are described and illustrated with real-world examples.

Federal Aviation Administration, 2013. Development of a nondestructive inspection program/organization. Advisory Circular AC 25-29, Available at: www.faa.gov/documentLibrary/media/Advisory_Circular/AC_25-29.pdf.
Included for reference: US-DoT-FAA guidelines for visual inspection, including summary of lighting and optical aids for visual inspectors. Focuses primarily on cracks and corrosion.

Federal Aviation Administration, 1997. Visual inspection for aircraft. Advisory Circular 43-204, Available at: www.faa.gov/documentLibrary/media/Advisory_Circular/43-204.pdf.
Included for reference: Primarily US-DoT-FAA guidelines for creating and operating a commercial aircraft NDI inspection facility, but provides useful summaries of the most common inspection technologies in use: visual inspection, dye penetrant (exposing small cracks), magnetic particle (similar to dye penetrant, for ferromagnetic structural components), eddy current inspection (changes in complex impedance due to presence of cracks, metal thickness, delamination, etc., so could be relevant to some LO defect detection), ultrasonic inspection, radiographic (penetrating x-ray) inspection.

Fitzpatrick, G.L. et al., 1996. Nondestructive inspection of tagged composites using real-time magneto-optic imaging. In Proc. SPIE. Nondestructive Evaluation of Materials and Composites, 2944, pp. 217–230.
Review of magneto-optic imaging (MOI), which might prove a useful technique for detecting and characterizing defects in LO coatings that contain, e.g., iron particles in general, or preferentially oriented magnetic domains specifically.

Gunatilake, P. et al., 1997. Image understanding algorithms for remote visual inspection of aircraft surfaces. In Proc. SPIE. Machine Vision Applications in Industrial Inspection V, 3029, pp. 2–13.
The primary author of this paper was a graduate student supervised by the paper's second author, who is the first author of this report. The paper summarizes work done in this author's lab during the mid-1990's toward vision-based robotically-deployed inspection of aging commercial aircraft subject to cracking and corrosion. Algorithms developed and described for both types of defect are potentially applicable to LO surface images, cracks corresponding to cracks, and corrosion corresponding to defects such as mottling.

Hess, D.W., 2008. Introduction to RCS measurements. In Proc. Loughborough Antennas and Propagation Conference, pp. 37–44.
A review of radar cross section (RCS) measurements, relevant for background.

Iivarinen, J. et al., 2000. A defect detection scheme for web surface inspection. *International Journal of Pattern Recognition and Artificial Intelligence*, 14(6), pp. 735–755.

Aimed primarily at web-produced product manufacture, e.g., paper, textiles, plywood, sheet metal, etc., where speed is of the essence. Cited primarily because there may be circumstances when it is advantageous to rapidly inspect the complete surface of an LO aircraft with a low detection threshold (high false-positive rate), then go back and inspect, characterize, quantify, and if necessary repair each of the initially detected potential flaws.

Jia, H. et al., 1997. An intelligent real-time vision system for surface defect detection. In Proc. International Conference on Pattern Recognition, pp. 239–242.

Like Iivarinen et al. (2000), this paper addresses a web-produced product, rolled steel. Its importance is that it describes a neural-network algorithm (support-vector machine (SVM)) that learns to recognize defects in response to a teaching process in which it is shown examples of good and flawed regions. Learning approaches are particularly valuable if the nature of the defects are difficult to describe in words ("semantically"), but distinguishing bad from good can be learned from numerous examples of both.

Kassim, A.A., Mannan, M.A. & Mian, Z., 2007. Texture analysis methods for tool condition monitoring. *Image and Vision Computing*, 25(7), pp. 1080–1090.

This paper discusses texture capture and analysis primarily in the tool-wear domain. Because tool-wear texture patterns are scrape-like, it seems likely relevant to LO coating defect detection and characterization when the damage is due to a scraping or scuffing injury caused, e.g., by a mechanic's tool or shoe.

Kauppinen, H., Rautio, H. & Silven, O., 1999. In Proc SPIE. Nonsegmenting defect detection and SOM-based classification for surface inspection using color vision, polarization and Color Techniques in Industrial Inspection, 3826, pp. 270–280.

Segmentation is the process of dividing an image into regions based on a measure of similarity among nearby image pixels, e.g., grey-level or color. The authors identify an issue with segmentation: how to decide on what parameter to segment. The compare it to a statistically-based learning algorithm—similar to principal component analysis—that they identify as a self-organizing-mapping (SOM). They demonstrate SOM's advantage specifically in a sawn-wood classification application, which might have some similarities to characterizing mottled LO coatings.

Latif-Amet, A., Ertüzün, A. & Erçil, A., 2000. Efficient method for texture defect detection: Sub-band domain co-occurrence matrices. *Image and Vision Computing*, 18(6), pp. 543–553.

A wavelet-based approach (compare with Gunatilake et al. (1997) for corrosion detection) for defect detection in textiles. As noted in Footnote 2, this approach would be particularly relevant if there are LO coatings or coating regions that should have a pronounced periodic structure, like a wire mesh, as it would be particularly sensitive to flaws in the pattern.

Lin, H.-D., 2007. Computer-aided visual inspection of surface defects in ceramic capacitor chips. *Journal of Materials Processing Technology*, 189(1), pp. 19–25.

Another wavelet-based technique particularly adapted to detecting "ripple defects"—subtle low-contrast periodic wave-like non-uniformities in surface appearance, e.g., of the sort we might expect in a LO coating that set-up before brush-marks had leveled out.

Newman, J.W., 2008. Aerospace NDT with advanced laser shearography. In Proc. 17th World Conference on Nondestructive Testing, pp. 1–6. Available at: www.ndt.net/article/wcndt2008/papers/534.pdf.

This is a review article and tutorial about laser shearography, a large-area interferometric technique for revealing structural damage under apparently intact skin, e.g., disbonding of layered materials such as those LO coatings disclosed in Boyd et al. (2009).

Newman, T.S. & Jain, A.K., 1995. A Survey of Automated Visual Inspection. *Computer Vision and Image Understanding*, 61(2), pp. 231–262.

This is another survey article, following Chin & Harlow (1982) by 13 years, with 272 references, focusing only on the previous five years. We include it in this bibliography to provide a rough measure of hardware and algorithmic approach evolution in roughly the decade following the former. A major change that the authors identify in the preceding decade is the rapid transition from traditional draftsman's drawings to CAD design, and the consequent ability to compare “as designed” to “as seen”—an essential ability that by now has evolved to the point where commercial systems are available for semi-automatically recording detected or suspected flaws directly on an aircraft's CAD drawing, e.g., US Patent 8983172 B2, “visual inspection system includes a database storing a wireframe model of an object and a portable electronic device equipped with an imaging device and a display….” Also see Warnica (2014).

Nichani, S. & Scola, J., 1999. Semiconductor device image inspection utilizing image subtraction and threshold imaging. U.S. Patent 5,949,901.

Included here primarily as an illustration of the value of examining the difference-images when lighting is varied, e.g., normal vs. grazing-angle illumination, inasmuch as this technique often makes the undamaged regions disappear and the damaged regions stand out starkly. Commercial aircraft visual inspectors routinely use dynamic lighting to distinguish, e.g., scratches from cracks: they are generally indistinguishable under static lighting, but behave distinctly differently under dynamic illumination.

Pernkopf, F. & O’Leary, P., 2003. Image acquisition techniques for automatic visual inspection of metallic surfaces. *NDT and E International*, 36(8), pp. 609–617.

Describes and compares three methods for inspection of metallic surfaces. Included here primarily because it might sometime be necessary to inspect the bare metallic surface of an aircraft before application of its LO coating to its metal skin areas to assure proper adhesion, insensitivity of LO characteristics to details of the underlying metal, etc. One of the techniques discussed is stereoscopic, a topic we discuss briefly in the main body of this report.

Prasanna, P. et al., 2012. Computer-vision based crack detection and analysis. In Proc. SPIE. Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems. 8345, p. 834542.

The article addresses crack detection on bridge surfaces, so on its surface is far removed from the LO flaw detection regime, but except for scale, crack patterns on bridge surfaces might not be significantly different from crack patterns in LO coatings. Compare with (Gunatilake et al. 1997) which describes a similar method for finding cracks in aging aircraft skins.

Ratwani, M., 2001. Inspection technologies. In Aging Aircraft Fleets: Structural and Other Subsystem Aspects. RTO Lecture Series. RTO-EN-015. Neuilly-sur-Seine, France: NATO Research and Technology Organization, pp. 14-1-14–17. Available at: www.dtic.mil/dtic/tr/fulltext/u2/a390841.pdf.

Included primarily for reference: this is a brief but relatively comprehensive background-level survey of nondestructive inspection (NDI) techniques used in the commercial aircraft domain.

Seegmiller, N.A., Bailiff, J.A. & Franks, R.K., 2010. Precision robotic coating application and thickness control optimization for F-35 final finishes. *SAE International Journal of Aerospace*, 2(1), p.284 (6 pp.).

Describes Lockheed-Martin's robotic equipment and process for spray-application of LO coating to the F-35, including some details of in-process sensing-for-control and post-process coating thickness verification.

Siegel, M., Gunatilake, P. & Podnar, G., 1998. Robotic assistants for aircraft inspectors. *IEEE Instrumentation and Measurement Magazine*, 1(1), pp. 16–30.

Compared with (Gunatilake, P. et al., 1997) above, this magazine-format article is broader in scope but easier to understand by readers who are not already expert in image processing. The sidebars in particular share many of the authors' insights developed during the creation of the robotic aircraft inspection field.

Sihvola, A.H., 2006, peculiarities in the dielectric response of negative-permittivity scatterers. *Progress in Electromagnetics Research*, 66(1), pp. 191–198.

Included in this report as an illustration of the potential for incorporating "engineered materials" in LO coatings. Compare with (Ceno Technologies), describing a natural material that is now used in LO coatings. The possibility of incorporating materials of similar geometry but not-found-in-nature radar-frequency electronic properties may create additional possibilities for LO functionality, but if so, will almost certainly create additional problems for LO integrity inspection and characterization.

Sotzing, G.A., 2006, polymeric compositions comprising thieno [3, 4-b] thiophene, method of making, and use thereof. U.S. Patent 7,125,479.

Included as an example of an exotic organic polymer that this patent mentions might be useful as a stealth coating, and that various web references, including other patents, suggest is used in that application. A key property appears to be the ability to dope it with p- or n-type impurities to control its conductivity and other electronic properties.

Sun, J. et al., 2007. Object surface recovery using a multi-light photometric stereo technique for non-Lambertian surfaces subject to shadows and specularities. *Image and Vision Computing*, 25(7), pp. 1050–1057.

Photometric stereo is a generalization of "shape from shading," a method for deducing the shape—the distribution of normal-vectors over a surface—from change in photographed brightness in response to controlled changes in lighting geometry. This paper analyses from first principles the minimum number of light-sources (six), etc., needed to fully characterize an object with a Lambertian (reflected-light-randomizing) surface and an everywhere-convex geometry, and discusses its extension to non-Lambertian (partly specular) surfaces.

Tomczak, L. et al., 2007. Image defect detection methods for visual inspection systems. In Proc. Int. Conf. Experience of Designing and Application of CAD Systems in Microelectronics, pp. 454–456.

Describes two statistics-based methods, one using principal component analysis, the other singular value decomposition, neither requiring training data ("learning"). Not entirely convincing in this brief format, but perhaps worth investigating in more depth.

Trimble, S., 2009. Ex-F-22 engineer to sue Lockheed for stealth design. FlightGlobal. Available at: www.flightglobal.com/news/articles/ex-f-22-engineer-to-sue-lockheed-for-stealth-design-329025/.

This article is discussed in an online discussion forum entry ("F-22 stealth maintenance problems?" (www.warfaresims.com/?p=755)), beginning with a synopsis of the legal case (Boyd et al. 2009), with some interesting back-and-forth among several discussants offering their own opinions on the technological issues in the case and somewhat beyond it.

Tsai, D.-M. & Lai, S.-C., 2008. Defect detection in periodically patterned surfaces using independent component analysis, p*attern Recognition*, 41(9), pp. 2812–2832.

(See introductory remarks under (Chao & Tsai 2008).) This sixth paper in the Tsai series explores defect detection in densely periodically patterned surfaces (vs. nearly featureless substrates with occasional defect features) using a similar convolution filter approach. It employs a clever trick to achieve high speed by examining the image one scan-line at a time rather than two-dimensionally. The trick is to compare the left and right halves of the scan line, registering the periodic part, and looking for any features that fail to register because they are not part of the periodic pattern.

Tsai, D. & Hsieh, C., 1999. Automated surface inspection for directional textures. *Image and Vision Computing*, 18, pp. 49–62.
(See introductory remarks under (Chao & Tsai 2008).) This first paper in the series explores detection of one- and two-dimensional directional surface textures employing primarily spatial Fourier analysis methods.

Tsai, D.M. & Chiang, C.H., 2003. Automatic band selection for wavelet reconstruction in the application of defect detection. *Image and Vision Computing*, 21(5), pp. 413–431.
(See introductory remarks under (Chao & Tsai 2008).) This fourth paper in the Tsai series explores also surface textures like those of sandpaper and leather, now using a wavelet vs. a spatial Fourier decomposition of the image.

Tsai, D.M. & Hsiao, B., 2001. Automatic surface inspection using wavelet reconstruction, p*attern Recognition*, 34(6), pp. 1285–1305.
(See introductory remarks under (Chao & Tsai (2008).) This second paper in the series explores detection of more complex more-or-less periodic textures using wavelet reconstruction methods.

Tsai, D.M. & Huang, T.Y., 2003. Automated surface inspection for statistical textures. *Image and Vision Computing*, 21(4), pp. 307–323.
This third paper in the Tsai series explores surface textures that are not periodic but still have characteristic scale-lengths, e.g., sandpaper or leather, based on statistical properties of the spatial Fourier spectrum.

Tsai, D.M., Lin, P.C. & Lu, C.J., 2006. An independent component analysis-based filter design for defect detection in low-contrast surface images, p*attern Recognition*, 39(9), pp. 1679–1694.
See introductory remarks for (Chao & Tsai 2008). This fifth paper in the series explores low contrast surface features, as does [CHAO-2008], but at an earlier stage of the work; it is included here for continuity with the other Tsai papers. It employs a convolution filtering scheme, which implies prior knowledge, or at least prior expectation of finding the textural features or patterns corresponding to the filters built and employed. The clever trick here seems to be building the filter to detect the normal defect-free background, and associate the absence of the normal background as defect.

Tseng, Y.H. & Tsai, D.M., 2010. Defect detection of uneven brightness in low-contrast images using basis image representation, *Pattern Recognition*, 43(3), pp. 1129–1141.
(See introductory remarks under (Chao & Tsai 2008).) This is the ninth (and last) paper in the Tsai series. The theme continues: low-contrast defect detection, such as we might expect in LO coatings that have been applied to uneven thickness, damaged by water, etc. The specific type of defect sought here is the "mura," a Japanese term of unknown etymology, used in the panel-display manufacturing industry, meaning luminance nonuniformity of a display device. Mura defects tend to be diffuse, i.e., lacking sharp edges, which might be characteristic of LO coatings in which some more-or-less circular regions received too much or too little coating. As in (Tsai et al. 2006), the trick is to look for the presence of the expected defect-free background, and associate its absence with a defect.

Warnica, R., 2014. How Vancouver's NGRAIN created a better stealth fighter inspection

system. *Canadian Business*. Available at: www.canadianbusiness.com/technology-news/how-vancouvers-ngrain-created-a-better-stealth-fighter-inspection-system/.
As discussed in general for Newman & Jain (1995), a tablet-and-“GPS”-based inspection data registration system that enters NDI measurements into a CAD drawing of the aircraft under inspection. "GPS" in quotes because, being used indoors, it is probably a local short-range GPS-like precision location system.

Wintersdorff, R.W. & Cota, G.R., 1977. Aircraft of low observability. U.S. Patent 4,019,699.
Included for reference and historical interest: a Teledyne patent, filed in 1975, for a B2-like "flying wing" emphasizing geometrically-based stealth, but mentioning the possibility of using radar absorbing coatings, especially on leading edges, ducts, etc.

Xie, X., 2008. A review of recent advances in surface defect detection using texture analysis techniques. *Electronic Letters on Computer Vision and Image Analysis*, 7(3), pp. 1–22.
A comprehensive summary of texture types and algorithmic approaches to their detection and characterization, including 155 references, many of them also in this list. Much more compact and readable than the Tsai series, but for actual implementation of any of these techniques it would probably be advisable to refer to the corresponding paper by Tsai for all the details.

Ysebaert, S.C. et al., 2011. An analytical approach to low observable maintenance practices using simulation and margin analysis. In Proc. Winter Simulation Conference, pp. 2525–2534.
A technical management document rather than a technology document, included as an illustration of the considerations that go into making resource allocation decisions in the LO aircraft maintenance arena, where it is necessary to trade off aircraft availability vs. the cost of that availability.