The use of remotely sensed imagery and GIS analysis for the automated detection of water infiltration in residential structures.

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ABSTRACT: *The potential for application of GIScience techniques and technologies is increasingly being realized by a multitude of diverse domains. This paper reports on one such application in the domain of building diagnostics, a subfield of the broader economic sector of building construction. A pressing issue in building diagnostics is the detection of water infiltration, a condition that can cause significant damage to the structure of the home and the health of its inhabitants. One source of water infiltration stems from the failure of the home's chimney pan, a flashing used externally on the chimney for the purpose of diverting rain water away from the chimney flue while allowing smoke to escape from the fireplace. The possibility of remotely detecting chimney pan failure as a proxy for water infiltration in residential structures is discussed. A model with multiple variants is offered that uses a combination of remote sensing and GIS methods to detect and extract the locations of failed chimney pans. The feasibility of implementing this model is then addressed, describing both technical and ethical impediments to successful remote monitoring of chimney pan failure. Of the variants, remote detection of chimney pan reflectance using high-resolution aerial photography in a suburban context appears to be the most promising possibility.*

Keywords: *remote sensing, GIS applications, residential construction, building diagnostics, water infiltration, water damage, home dampness, epidemiology, chimney pan proxy*

1. INTRODUCTION

GIScience is the theoretical, technical, and applied study of geographically registered data and the associated computer systems that store, manipulate, analyze, and represent this geographic data (Longley et al. 2005). The field of GIScience is currently expanding into new application domains with tools and techniques of increasing sophistication and utility. In 2004, GIScience and its related technologies were identified by the reputable scholarly journal *Nature* as "one of the three most important emerging and evolving fields, along with nanotechnology and biotechnology" (Gewin 2004, 376). Due in part to accessible technologies like NASA World Wind and Google Earth, there is a growing awareness in a broad range of public and private institutions for the potential application of geographical information systems (GIS) and remote sensing (RS), two important and overlapping subcategories of GIScience. Techniques and technologies associated with GIS and RS can be applied to assist in solving any problem with a fundamental geographic component.

This research reports on the application of GIScience in the domain of building diagnostics, a subfield of the broader economic sector of building construction. The *construction sector* is defined as the erection, maintenance, and removal of residential, commercial, and industrial structures, while *building diagnostics* refers specifically to the maintenance component of construction (Pierce 2006). GIS and RS have been applied to building diagnostics in the past, focusing mostly on the feasibility of remotely detecting heat loss due to failure of the roof's insulation (Bowman and Jack 1979; Brown et al. 1979; Brown et al. 1981;Balaras and Argiriou 2001; Lillesand et al. 2004). The aim of this practice, termed *infrared thermography of buildings* (IRTB), is to detect failures in the insulation of the home, either planimetrically (from above) or obliquely (from the side), with the goal of preventing energy waste. Key to this detection is that it is done remotely, in an unobtrusive manner (Balaras and Argirious 2001).

I will discuss the possibility and feasibility of applying remote sensing and GIS methods to an equally pressing issue in building diagnostics: water infiltration. The infiltration of water past the exterior barrier can be fatally damaging to the home and its inhabitants. The paper begins by describing water infiltration in residential homes and the subsequent damage that it causes. Next, the chimney pan is introduced as a proxy for remotely detecting the potential presence of water damage. A model is then offered detailing several ways in which chimney pan failure can be automatically detected using remotely sensed imagery and GIS analysis. Finally, I enumerate several potential setbacks to automated detection that may decrease the feasibility of remote detection of water infiltration via the chimney pan proxy.

2. THE PROBLEM: WATER INFILTRATION

The infiltration of water into building materials, along with the nutrients and chemicals the water contains, is a primary cause of a house's deterioration (Küntz and Lavallée 2001). While the most violent cause of water infiltration is flash flooding, slower, yet equally damaging sources of water infiltration include failure of the roofing materials (e.g., shingles, gutters, chimney pans), improper sealing of joints between dissimilar external materials (e.g., at windows and doors, at the foundation/siding joint), basement flooding (seepage through cracks in the foundation, sump pump failure), and leakage of internal piping (e.g., central plumbing, water heaters, washing machine or dishwasher connections), among others (Small 2003). Such water infiltration softens the underlying wood, turning the studs to pulp and jeopardizing the structural integrity of the wall (French 1991). The high moisture content and the soft wood provide an ideal habitat for unwelcome organisms, including rodents and insects. The presence of such organisms amplifies the destruction of the house's innards, chewing it apart from the inside-out in the case of termites and related species.

Water infiltration also poses a serious, sometimes fatal health risk to the home's inhabitants. When water infiltrates the exterior barrier of the home, it increases the amount of water vapor in the air, producing a condition known as *home dampness*. The increase in humidity promotes the growth of molds that circulate airborne spores. Numerous studies in epidemiology have found correlations between home dampness and lower respiratory disease (e.g., Dales et al. 1991, Brunekreef 1992, Verhoeff et al. 1995, Bornehag et al. 2001). The connection between home dampness and the development of childhood asthma has been proven to be especially strong (Belanger et al. 2003, Wickman et al. 2003, Jaakkola et al. 2005). However, it is less clear if the main determinant is an increase in humidity, the presence of mold, or a synergy between the two. A species of mold commonly found in homes with water infiltration is *Stachybotrys chartarum*, a black mold that causes fatal respiratory health problems (Leino et al. 2003). Severe outbreaks of *Stachybotrys chartarum* require that the building be demolished to the foundation.

Despite the deleterious effects of water infiltration to both property and health, most homeowners practice just-in-time maintenance with water infiltration (Small 2003). *Just-in-time maintenance* (JIT) is an approach to building diagnostics where an inspector of appropriate specialty is called to the house only after a significant symptom of the problem is reported by the homeowner (Wood 2003). JIT is the opposite of *planned preventative maintenance* (PPM), where regular inspections are scheduled, usually on a cycle of several years. While JIT can be cost effective for inexpensive and easily monitored household appliances and equipment, it is not recommended for the house itself, as the costs of structural damage and health care far outweigh the cost of scheduled preventative maintenance (Small 2003).

3. THE CHIMNEY PAN PROXY

Many of the point sources of water infiltration listed in the previous section can be monitored using *in situ* methods. *In situ* detection, in contrast to remote detection, requires that the inspector come into physical contact with the entity being monitored and often yields more accurate and reliable measurements (Jensen 1983). However, *in situ* detection is a more costly, time-consuming, and invasive process compared to remote detection. Many of the point sources of water infiltration cannot be detected remotely, including those that are underground (e.g., seepage through the foundation) or inside the home (e.g., leaking pipes). Other point sources have the potential of remote detection, but only obliquely (e.g., improper sealing of joints between dissimilar materials along the house's outer walls). Oblique remote sensing is often not cost effective, as a structure requires a unique image for each of its sides. Only sources of water infiltration on the roof of a home have potential for planimetric remote detection, where a single remotely sensed image can capture hundreds, even thousands of houses at once. Planimetric remote detection of rooftop water infiltration sources is particularly conducive to a suburban context, as the densely packed distribution of primarily residential buildings can be captured in a small number of remotely sensed images. This paper addresses only one of the sources of water infiltration on the top of the home, the chimney pan, although it can be assumed that other rooftop sources such as failed shingles or improperly functioning gutters could also be detected remotely.

The presence of a fireplace necessitates an opening in the home's exterior barrier. Smoke and other debris are funneled away from the fireplace by the *chimney flue*, a special vent that extends from the top of the fireplace, through the home, and out the external portion of the chimney, called the *chimney chase* or smoke stack. An uncovered chimney chase allows precipitation to enter the house through the chimney flue, infiltrating the substrate through untreated interior joints. The *chimney pan*, sometimes called the chimney cap, is a flashing used externally on all residential homes with chimney chases for the purpose of diverting rain water away from the chimney flue while still allowing smoke to escape. Chimney chases are typically covered by a chimney pan with dimensions of 36x60 to 84x120 inches. Although chimney pans can be made from cement or brick, the majority of residential pans on recently built homes are manufactured using galvanized metal (Waddell 2004). Figure 1 shows the most common chimney pan designs. Three of the four most common designs have a flat, smooth surface, allowing for planimetric detection with remote sensing instrumentation.

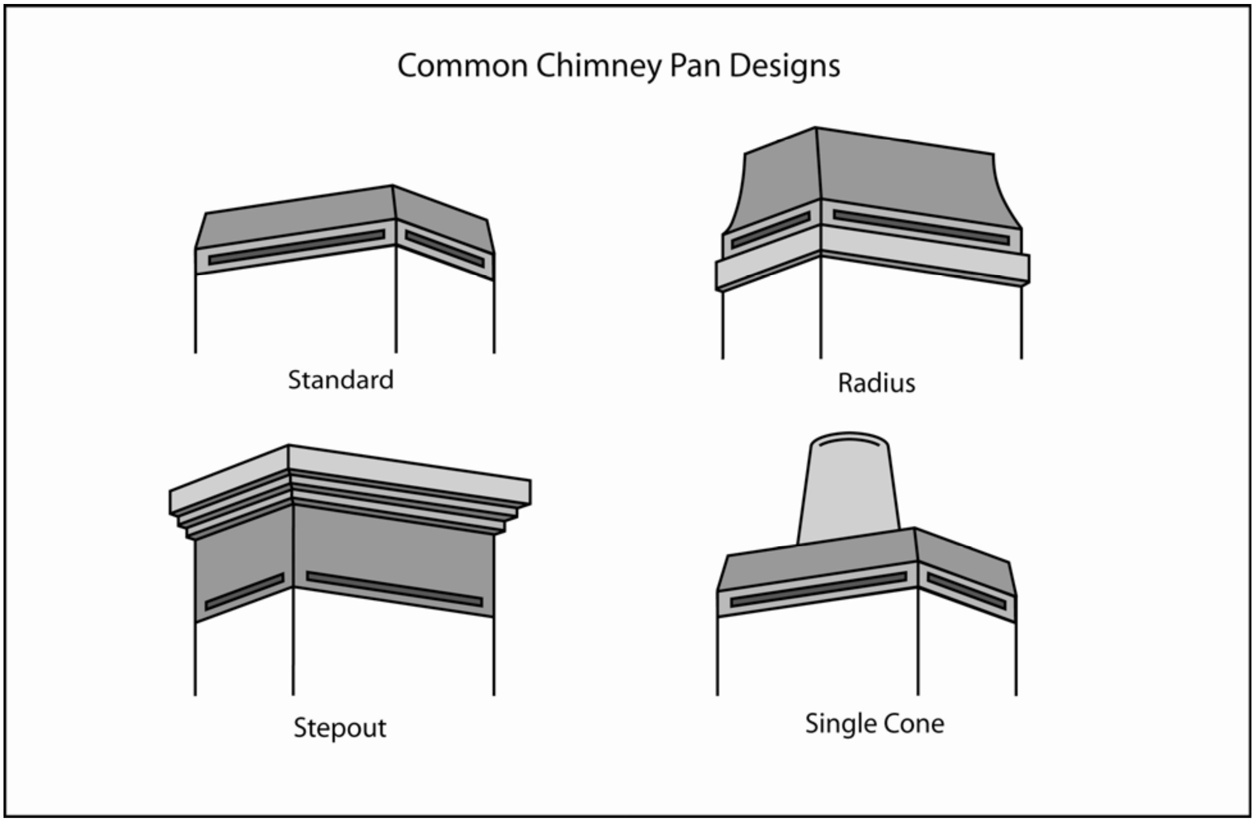

Figure 1: Illustrations of the most common chimney pan designs modeled after the Waddell (2004). Please note that the categories *standard*, *radius*, and *stepout* have a flat surface when viewed planimetrically.

Although the galvanization of the metal helps to hinder the corrosion of the pan, it is common knowledge that the functional life of a chimney pan is only 7-10 years before rusting. A rusted, or *failed*, chimney pan no longer protects the exposed flue from precipitation, allowing for the infiltration of water into the substrate. A failed chimney pan is visually easy to distinguish, as it exhibits a remarkably different color and texture than a functioning chimney pan on the exterior surface. Because of the chimney's pans awkward position atop the home and the typical approach of JIT maintenance by the homeowner, there is great utility in developing an application of remote detection for monitoring chimney pan failure. It is important to note that the chimney pan can only be used as a proxy for home water infiltration; failure of a chimney pan does not necessarily mean there is a damaging amount of water infiltration, although it can be assumed that water damage will eventually follow, and the presence of a functional pan certainty does not rule out water infiltration from other sources.

4. ASSESSING POSSIBILITY: REMOTE DETECTION OF CHIMNEY PAN FAILURE

4.1. Remote Sensing as a Data Collection Tool

The first step in modeling the detection of chimney pan failure is to determine how RS can be used as a data collection tool. When remotely sensed images are taken planimetrically, they can be geometrically corrected to remove sensor and relief distortions, producing orthographically-rectified photographs, called *orthophotography*, that have a constant scale across the image (Lillesand et al. 2004). It is possible to remotely detect the presence of chimney pan failure using orthophotography in two ways: 1) by characterizing the spectral reflectance of a failed versus functional chimney pan and 2) by identifying the spectral radiance of a failed versus functional chimney pan.

4.1.1 Spectral reflectance

A large portion of remote sensing instrumentation using analog or digital film measures the *spectral reflectance* of sunlight, defined as the degree that entities on the earth's surface reflect, rather than absorb or transmit, incident energy (Lillesand et al. 2004). The sun radiates energy that has dominate wavelengths in the visible (red 0.4-0.5µm, green 0.5-0.6µm, and blue 0.6-0.7µm) and near-visible (near-infrared 0.7-1.3 µm) bands of the electromagnetic spectrum (Jensen 2005). When incident energy from the sun strikes an entity on the earth's surface, this energy can be absorbed by the entity (raising the entity's internal temperature), transmitted by the entity (acting as a conductor of energy), or reflected by the entity. It is the energy that is reflected in the visible wavelengths, rather than absorbed or transmitted, that gives the entity its 'color' when viewed remotely. By formalizing the degree to which an entity reflects sunlight in the visible and near-visible wavelengths, features can be identified and mapped (Lillesand et al. 2004).

Not all entities reflect incident energy in a similar fashion, a characteristic that can be very useful for the detection of failed chimney pans. Smooth surfaces (metals and calm water) are termed *specular reflectors*, while rough surfaces (vegetation, concrete, and in this case, rust) are termed *diffuse* or *Lambertian reflectors* (Lo 1986). When incident energy strikes an ideal specular reflector, the entirety of the energy is reflected at a symmetric angle away from the sun. Because the camera is held at nadir and the sun is not at nadir for the mid-latitudes, the camera is at the exact symmetrical angle of the incident energy for only a small portion of the image, if any portion at all. This phenomenon is termed *bidirectional reflectance* (Lillesand et al. 2004). Because all the energy is reflected away from the instrument, the feature has a reflectance reading of zero and looks black on a panchromatic image. Conversely, ideal diffuse or Lambertian reflectors will redistribute the reflected incident energy in all directions equally. With a diffuse reflector, regardless of the position of the camera in relation to the sun angle, there should be some reading, producing a value of gray on a panchromatic image.

The understanding of incident reflection can be applied in practice to the detection of failed chimney pans. The majority of the functional chimney pans are black rectangles within the roof footprint because the galvanized metal is a near perfect specular reflector. Conversely, failed chimney pans have a rough surface, causing diffuse or Lambertian reflection and producing an intermediate value of gray on panchromatic imagery. The actual gray value would fluctuate in the panchromatic band depending on the amount of incident energy at a given time, the season, the cloud cover, and the degree to which the pan has rusted. Figure 2 illustrates this difference between specular and diffuse reflectors for chimney pan detection.

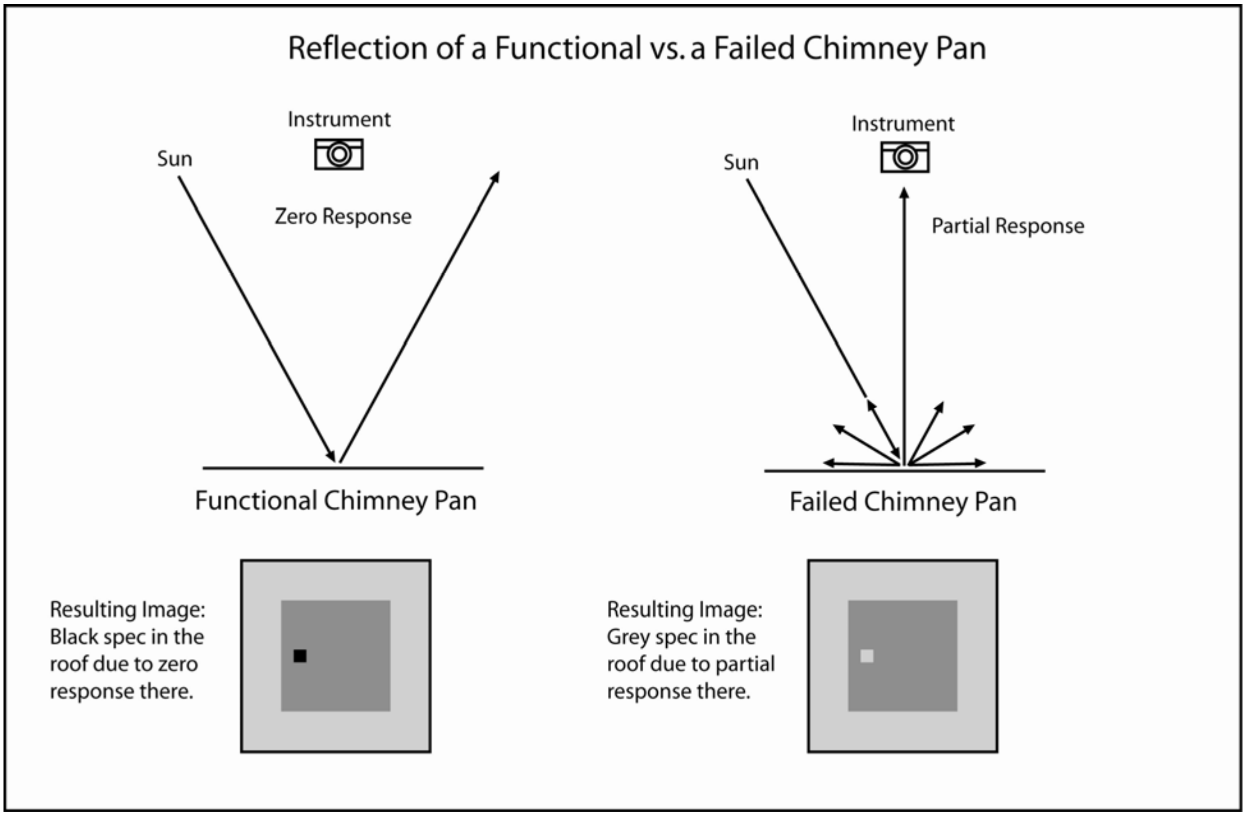

Figure 2: An illustration showing the different reflectance signals produced from a functional chimney pan (a specular reflector) versus a failed chimney pan (a diffuse or Lambertian reflector).

4.1.2. Spectral radiance

Special remote sensing instruments, called *multi-spectral sensors*, are designed to measure the amount of energy emitted by an entity, called its *spectral radiance*, over the entire electromagnetic spectrum to produce a specific *spectral signature*, sometimes referred to as an entity's spectral fingerprint (Lillesand et al. 2004). All entities that have an internal temperature above absolute zero radiate energy. A spectral band is a range of wavelengths, measured in meters and micrometers; the band in which an entity radiates the most energy is called its dominant wavelength (Lo 1986). Absorbed energy gives non-radioactive or non-living entities their internal heat, or kinetic temperature (Jensen 2005). Therefore, spectral radiance can be used as a proxy for remote detection of the degree of incident energy absorption by inanimate, non-radioactive entities.

A *spectral radiometer* is used to determine the spectral radiance of an entity over the entire electromagnetic spectrum, plotting the spectral signature as a curve relating radiance to wavelength (Lillesand et al. 2004). The height and width of the curve on the electromagnetic spectrum are determined by the mass of the entity and its *emissivity* (emitting ability), a term that describes the percentage of incident energy that will be absorbed and then radiated at a given spectral band (Lo 1986). Smoothed metals have a low emissivity reading because they allow a large percentage of the energy incident upon them to be specularly reflected or transmitted (the property that allows them to be such great conductors of energy) (Lillesand et al. 2004). Conversely, the chemical change of metal that occurs during corrosion gives rust a higher emissivity reading, as only a small amount of incident energy is transmitted and a degree of the incident energy is reflected back upon its surface for possible re-absorption. Therefore, the spectral signature is narrow and rounded for the functional, metallic pan but broad and peaked for the failed pan. Figure 3 illustrates the expected spectral signatures of a failed versus functional chimney pan.

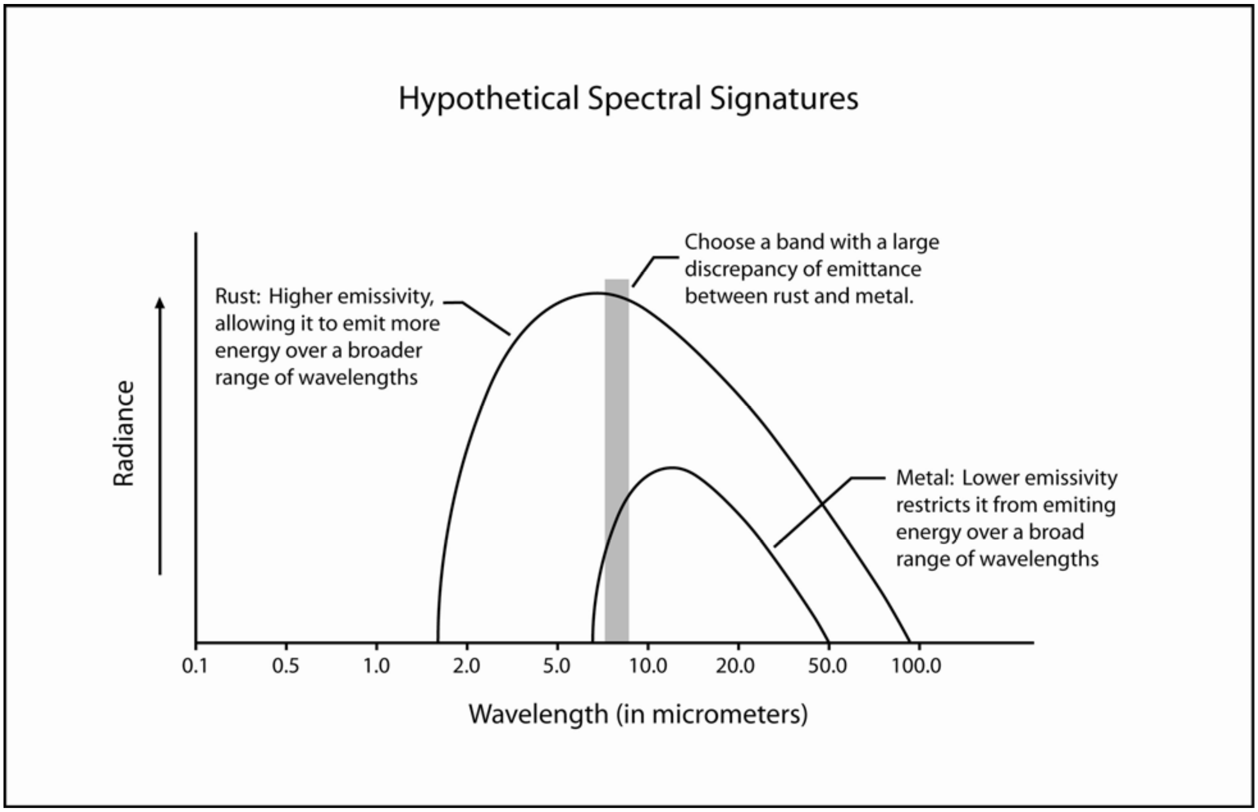

Figure 3: An illustration showing the expected spectral signatures of a metallic, functional chimney pan and a rusted, failed chimney pan.

4.2. Automating Extraction of Failed Chimney Pan Locations

The next step in the detection process is extraction of failed chimney pans locations from the image. The rectified orthophoto is represented in GIS software using a raster data model and each pixel is given a digital number (0-255 with an 8-bit radiometric resolution) that represents the reflectance or radiance captured by the instrument (Burrough and McDonnell 1998). Once the relationship between digital number and reflectance/radiance is established, the selection of pixels with targeted digital numbers is used to extract the locations of failed chimney pans. One of three selection processes can be used to extract the failed pans from the remotely sensed image: (1) visual interpretation of the image, (2) implementation of a supervised classification, and (3) implementation of an unsupervised classification.

Manual visual interpretation is the most labor-intensive digital image processing technique, although it may be the most exhaustive approach as each chimney pan will be considered by the technician in context to the house. It is important that the GIS analyst has expertise in remotely sensed image interpretation (i.e., technical expertise) and knowledge of the nature of the chimney pan proxy (i.e., domain expertise) when visually interpreting the image (Luttrell et al. 1988). Although some degree of manual adjustment is typically required either preceding or following any automated analysis, completely manual approaches to extraction do not take advantage of the automated capabilities of GIS and RS software.

A second approach that combines visual interpretation with automation is the use of a supervised classification. *Image classification* describes a category of digital image processing techniques that groups pixels based on their digital numbers (Lo 1986). A *supervised classification* is a particular type in which an expert delineates training sets that are known to be uniform ground truths of the desired classified group (Lillesand et al. 2004). An RS program then takes the digital numbers included in the training sets and extends the classification to all other pixels that have similar values. In applying the supervised classification to failed chimney pan detection, it is important that the expert chooses wavelengths that exhibit large distinctions between the functional and failed chimney pan signals. As a percentage of pixels are always misclassified, manual post-processing validation and ground-truthing is necessary to increase the accuracy of location extraction. This may be aided by the use of edge detection algorithms to identify the location of structures in the image for filtering of pixels that are not within the bounds of a structure (Jensen 2005).

The final approach to extraction is the unsupervised classification, the closest procedure to complete automation of image interpretation (Muller 1988). With *unsupervised classification*, the digital numbers are automatically divided into significant groupings in statistical space (Lillesand et al. 2004). The expert is only involved at the end, where he or she identifies the particular grouping that represents the desired feature. In the analysis of failed chimney pans, the constructed spectral signatures are used to match a cluster to failed and functional chimney pans. Post-processing similar to that described for supervised classification is also necessary for unsupervised classification.

Regardless of the extraction approach taken, the output is a raster list of spatially referenced pixels that can be converted to vector point locations. The key to making this application usable, and potentially profitable for private firms, is the incorporation of land parcel data. Using the point-in-polygon technique, land parcels are identified that contain failed chimney pans, producing a prospective parcel data layer (Longley et al. 2005). Depending on the robustness of the parcel information, addresses and owner identification information can be extracted from the attribute database. If such information is not available, each parcel can be geocoded to get an address estimate. Figure 4 summarizes multiple variants of a conceptual model for detecting and extracting the locations of failed chimney pans.

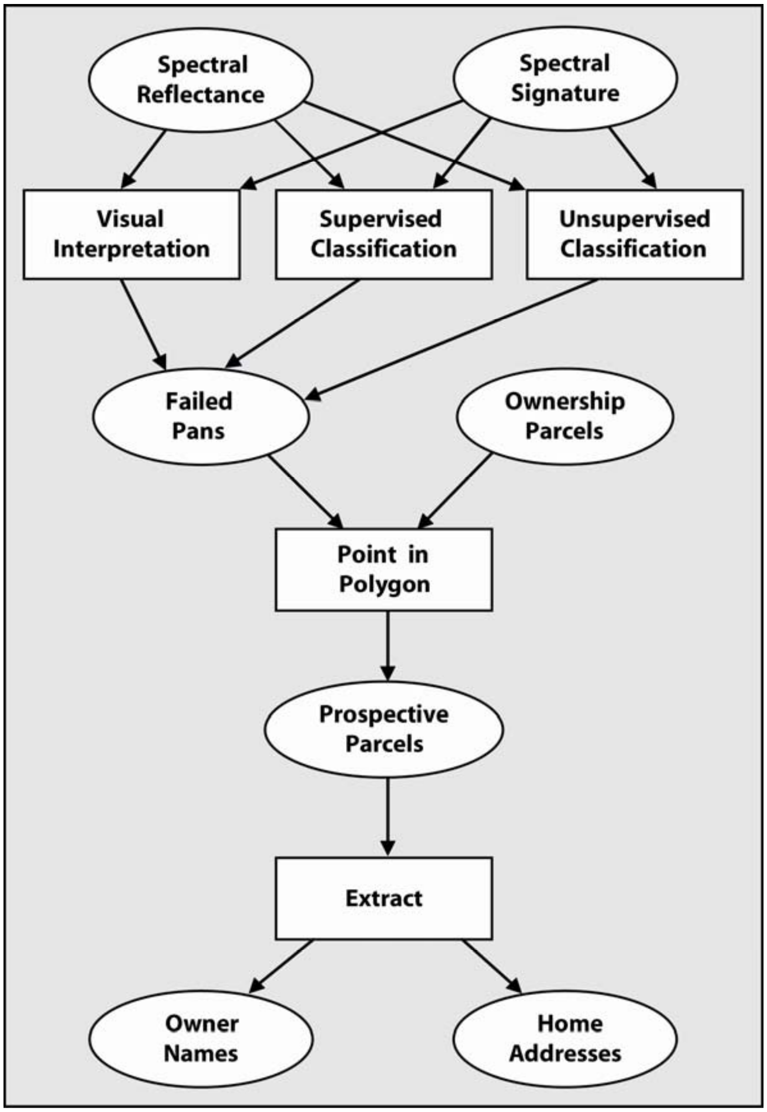

Figure 4: Multiple variants of a conceptual model for detecting and extracting the locations of failed chimney pans.

5. ASSESSING FEASIBILITY: CONCERNS WITH CHIMNEY PAN DETECTION

Despite the great potential for remote detection of water infiltration by proxy of chimney pan failure, there are several unresolved issues that influence the feasibility of such an application. These concerns fall into two broad categories: (1) technical and (2) ethical.

5.1 Technical Concerns

Technical concerns of detection feasibility are the issues relating to the quality of the analysis due to basic, perhaps too idealistic, assumptions in RS and the limits of available technical instrumentation used to collect the data. The major assumption in the above model is that there will be a standard, uniform response for a failed versus a functional chimney pan, not just from photo to photo, but also within an individual photo. While inter-photo variation was handled in the past in IRTB by calibrating each photo individually (Lillesand et al. 2004), intra-photo variation is a much more serious issue as it causes the cluster delineation of each classified category to elongate in statistical space, allowing for the possibility of ambiguity and overlap. This issue of ambiguous spectral response is a concern when measuring both spectral reflectance and spectral radiance.

In the case of spectral reflectance, intra-photo response ambiguity is caused by the incident energy source radiating non-uniformly upon the incident entity and then the reflected energy returning to the camera device in an equally non-uniform manner. The most basic type of non-uniformity occurs when the sun is at an extreme angle to the ground features; to ensure that the incident energy is most direct, it is important to collect data between the times of 10:00am – 2:00pm (Jensen 2005). This source of non-uniformity is typically only problematic in small-scale remotely sensed imagery that has too coarse of a resolution for chimney pan detection. Atmospheric effects are a more pressing cause of non-uniform incident energy for this application. The term *atmospheric effects* describe the influence that the atmosphere, as a medium through which energy passes, has on the energy itself (Song et al. 2001). Like any other entity, the atmosphere also reflects, transmits, or absorbs energy that is incident upon it. Although a large majority of the energy is transmitted by the atmosphere, a portion is reflected (producing Rayleigh scatter, Mie scatter, and nonselective scatter) and absorbed (creating atmospheric walls) (Lillesand et al. 2004). Atmospheric disturbance often generates a varying signal during data collection, particularly when measuring spectral reflectance. Song et al. (2001) describes a plethora of compensatory algorithms for atmospheric effects to help control for the condition of non-uniformity.

While atmospheric effects also generate intra-photo ambiguity in detection using the spectral radiation approach, a more likely cause of intra-photo ambiguity when using spectral radiation is attributed to variance in the spectral signature of a class of entities (Lillesand et al. 2004). This is particularly problematic with the detection of functional versus failed chimney pans, as metal is manufactured at different gauges and weights and rusting can occur on a chimney pan to different degrees. Both situations would cause a fuzzy boundary of possible spectral signatures rather than a crisp spectral signature delineation. Because of this, it is perhaps best to rely on the spectral reflectance property instead of the spectral signature or to couple change analysis with edge detection to find locations where the radiant signature changed significantly, rather than examining exact signatures at each point in time.

The feasibility of chimney pan failure detection is also restricted by sensor limitations. Every remote sensing instrument has a spectral, spatial, temporal, and radiometric resolution (Jensen 1983). Because of the relatively minute size of chimney pans, *spatial resolution*, or the smallest separation between two entities that can be resolved, is particularly important. Current commercially available panchromatic satellite imagery with the required resolution includes IKONOS, OrbView-1, and Quick Bird (Li 1998). It is important to note that the one-meter resolution offered in these sensors is only available over the visible spectrum and that no multi-spectral satellite imagery would be capable of monitoring chimney pans (Lillesand et al. 2004), excluding the possibility of detection using spectral radiance with satellite sensors. Satellite imagery with a panchromatic resolution of one-meter still runs the risk of capturing chimney pan information across multiple, mixed pixels. *Mixed pixels* occur when features in the pixel region are heterogeneous in nature, causing an instrument reading that is an average of the contained entities, obscuring the spectral signature of all entities within the pixel footprint (Lo 1986). Such mixed pixilation is less than ideal, making the aforementioned satellite sensors incapable of capturing the requisite detail. Because of this, aerial photography, which exhibits sub-meter panchromatic resolution, is the only current option for remote detection of chimney pan failure (Donnay et al. 2001).

5.2 Ethical Concerns

The second setback to remote detection of failed chimney pans is one of ethics concerning the remote monitoring of an individual's home. Privacy of the home in spatial data is directly related to the fourth amendment, which secures the right to protection against unreasonable searches of the home (Tuerkheimer 1972). This constitutional right to privacy was first declared in *Griswold v. Connecticut* in 1965, and was later legislated in the Privacy Act of 1974 (Boling 1996). Almost all remotely sensed information that is collected does not obtain consent from home or property owners, even when high-resolution sensors are employed that can collect fine, even intimate details about the home (Boothby and Dummer 2003). The increasingly common implementation of data mining in remote sensing is the attempt to collect this personal, individual-level information to the end of making meaningful assumptions about a potential target group (Gandy 2003). The unknowing detection of individuals, termed *surveillance*, has been identified as an ethically questionable approach to monitoring human activity in the landscape.

Former Chief Justice Louis Brandeis declared privacy as 'the right to be let alone' (Warren and Brandeis 1890). This definition has been used as precedence for defining the home as a place for private matters, where individuals should be left alone (Monmonier 2002). The use of high resolution imagery for data mining applications calls into question the nature of privacy and home, particularly when extended to the private sector. Mark Monmonier (2002, 176) goes as far as to state that such an ethical misuse of remotely sensed imagery and other data mining techniques by commercial firms could present "frightening and wholly plausible scenarios of GPS-based stalking and annoying sales pitches." Assessing feasibility of the application of failed chimney pan detection must move beyond the technical question of 'how do we implement this application?' to the ethical question of 'should we be implementing this application?' The last Supreme Court ruling on the legality of aerial photography was the 1986 case *Dow Chemical Company v. United States* (Monmonier 2002). The case questioned the ethicality of the U.S. government to invade the privacy of an industrial firm by use of remote sensing. Using SPOT satellite imagery, the government was monitoring violations of the Clean Air Act in order to better control industrial operations. The court ruling has been labeled the open field doctrine, stating that "whatever can be seen [planimetrically or obliquely] with commonly available technology is fair game for official or unofficial snooping" (Monmonier 2002, 174).

While the open field doctrine provides legal precedence for implementation of this application, several court cases have approached the issue of privacy and more invasive remote sensing technologies for residential surveillance. The use of forward-looking infrared (FLIR) sensors, the sensor necessary for IRTB, has been challenged as a violation of privacy when used to detect unusual amounts of waste heat in connection to indoor marijuana cultivation. FLIR is considered a more invasive remote sensing technology because it records heat levels from within the house, rather than simply capturing images of the home's exterior. While FLIR use was upheld in the 1991 Federal District Court case of *United States v. Penny-Feeney*, the Supreme Court ruled in a 5-4 decision that using FLIR for marijuana surveillance was a violation of privacy in the 2001 case of *Kyllo v. United States* (Monmonier 2002). Because legality does not confirm ethicality, it is important to continue to ask questions of ethical appropriateness when applying RS and GIS methods to extract individuals from the landscape that match a targeted profile.

6. CONCLUSIONS AND FINAL REMARKS

GIScience techniques and technologies are increasingly being applied to help solve real world problems. This paper discusses the potential application of these technologies in the construction sector, providing just one example in a broad range of possibilities. Specifically, remote detection of failed chimney pans is discussed as a proxy for the detection of residential water infiltration. Such a study falls into the tradition of IRTB in building diagnostics, where the development of cheap, unobtrusive, and labor-light detection of housing failures is desired. Despite several technical and ethical issues concerning the feasibility of implementing remote detection of failed chimney pans, such an application appears to be more than possible. Remote detection of chimney pan reflectance using high-resolution aerial photography in a suburban context appears to be the most promising possibility.

In practice, the feasibility of failed chimney pan detection is increased by what I term *the subdivision effect*. In many burgeoning metropolitan suburbs, large numbers of homes forming subdivisions are erected within the span of several months. Because of the spatial and temporal similarity, it is likely that the original chimney pans were installed at a similar time, are made from a similar material, and were put in place by a similar firm. These three factors typically produce homogenous failure at a subdivision scale, creating an effect that allows the detection of only several failed pans within a subdivision to act as a predictor for probable failure throughout the subdivision. Applying this spatiotemporal geographic relation at the scale of the subdivision to other topics studied by the field of building diagnostics may provide valuable predictive insight for the maintenance and prevention of residential structures and their causes of dilapidation.

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