STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with government support under Cooperative Agreement No. RITARS-11-H-UAF awarded by the Department of Transportation, Research and Innovative Technology Association. The government has certain rights in the invention.

[0002] The subject disclosure may be understood more readily by reference to the following detailed description of exemplary embodiments of the subject disclosure, to the Figures and their description herein, and to Appendix A which describes various features and aspect of the disclosure and is an integral part thereof.

[0003] Before the present articles, devices, and/or methods are disclosed and described, it is to be understood that the subject disclosure is not limited to specific systems and methods for monitoring of solid surfaces via close-range synthetic aperture radar (SAR). It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting.

[0004] As used in the specification and the appended claims, the singular forms “a,” “an” and “the” include plural referents unless the context clearly dictates otherwise.

[0005] Ranges may be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another embodiment. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

[0006] In the subject specification and in the claims which follow, reference may be made to a number of terms which shall be defined to have the following meanings:

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where said event or circumstance occurs and instances where it does not.

[0007] As employed in this specification and annexed drawings, the terms “unit,” “component,” “interface,” “system,” “platform,” and the like are intended to include a
computer-related entity or an entity related to an operational apparatus with one or more specific functionalities, wherein the computer-related entity or the entity related to the operational apparatus can be either hardware, a combination of hardware and software, software, or software in execution. One or more of such entities are also referred to as “functional elements.” As an example, a unit may be, but is not limited to being, a process running on a processor, a processor, an object, an executable computer program, a thread of execution, a program, a memory (e.g., a hard disc drive), and/or a computer. As another example, a unit can be an apparatus with specific functionality provided by mechanical parts operated by electric or electronic circuitry which is operated by a software or a firmware application executed by a processor, wherein the processor can be internal or external to the apparatus and executes at least a part of the software or firmware application. In addition or in the alternative, a unit can provide specific functionality based on physical structure or specific arrangement of hardware elements. As yet another example, a unit can be an apparatus that provides specific functionality through electronic functional elements without mechanical parts, the electronic functional elements can include a processor therein to execute software or firmware that provides at least in part the functionality of the electronic functional elements. An illustration of such apparatus can be control circuitry, such as a programmable logic controller. The foregoing example and related illustrations are but a few examples and are not intended to be limiting. Moreover, while such illustrations are presented for a unit, the foregoing examples also apply to a component, a system, a platform, and the like. It is noted that in certain embodiments, or in connection with certain aspects or features thereof, the terms “unit,” “component,” “system,” “interface,” “platform” can be utilized interchangeably.

Throughout the description and claims of this specification, the word “comprise” and variations of the word, such as “comprising” and “comprises,” means “including but not limited to,” and is not intended to exclude, for example, other additives, components, integers or steps. “Exemplary” means “an example of” and is not intended to convey an indication of a preferred or ideal embodiment. “Such as” is not used in a restrictive sense, but for explanatory purposes.

Reference will now be made in detail to the various embodiment(s), aspects, and features of the subject disclosure, example(s) of which are illustrated in the accompanying drawings. Aspects, features, or advantages of the subject disclosure will be set forth in part in the description which follows, and in part will be obvious from the
description, or may be learned by practice of the subject disclosure. The advantages of the
subject disclosure will be realized and attained by means of the elements and combinations
particularly pointed out in the appended claims. It is to be understood that both the
description herein is exemplary and explanatory only and are not restrictive of the
disclosure.

[0010] Conventional visual inspection of pavement requires a trained pavement
engineer to visually inspect every frame of video imagery to detect and then analyze pavement
cracking and surface conditions. As described in greater detail below, the subject disclosure
relates to monitoring and inspection of solid surfaces with remote sensing technologies
integrated with position sensors to geolocate (e.g., to associate a data record with a location
record) imagery and laser digital data sets. The remote sensing technologies can comprise
one or more of laser profilers, radar units, optical cameras combined with laser profilers,
radar units combined with laser profilers. The solid surfaces can comprise road pavement.
One or more digital data sets indicative of at least one image of a probed surface can be
output to a computer device (e.g., user equipment) for analysis, such as maintenance
planning and the like.

[0011] Radar as employed in the disclosure can be utilized to image and characterize
road and bridge pavement, for example, to assess and monitor pavement condition,
cracking, and/or roughness. In one aspect, radar imaging of a solid surface, as described
herein, can provide suitable imagery for locating and characterizing the condition and degree
of cracking of the solid surface (e.g., pavement). In another aspect, the disclosed radar
imaging can augment traditional camera imaging of solid surfaces, such as pavement. In yet
another aspect, the disclosed radar imaging, when used in conjunction with video imaging
techniques, for example, can permit automated detection of pavement cracking and
conditions speeding the manual inspection and analysis of video imagery. In certain
implementations, the disclosure can be utilized by pavement engineers, pavement imaging
companies, city and county engineers, and state and federal departments of transportation.

[0012] Exemplary salient features or aspect of the disclosure can comprise the
following: (1) Radar can collect data at night, day, and through fog, unlike optical systems
employing cameras and/or lidar; (2) radar can automatically pavement joints and cracking
orthogonal to the radar imaging angle being an effective tool to automatically geolocate
joints and cracking and further, geolocate data collected from other pavement imaging
systems such as cameras and lidar; (3) three dimensional models of the feature/asset can be
assembled from the SAR measurements; (4) Temporal measurements are also enabled, particularly through interferometry, allowing the automated change detection of the feature/asset, with centimeter accuracy; (5) small-scale (or minute) pavement features, including pavement cracking, are readily discernable with SAR; and/or (6) Surface roughness is more easily quantified.

[0013] In one embodiment, a miniaturized radar sensor can permit collecting backscattered radiation off a monitored surface, and computer-executable instructions can permit data processing and related feature extraction. In one aspect, experimental results indicate that the radar hardware has made considerable advances in miniaturization and imaging performance. In another aspect, software can be configured (e.g., programmed) to discriminate signal from noise and generate imaging data indicative of imagery of a monitored solid surface.

[0014] The software can be configured according to one or more various methods of the disclosure. Such methods can be grouped into two broad categories: Discrimination and then classification. The discrimination process broadly encompasses the logging, compression, decimation and preliminary filtering of the radar signal to remove obvious signal noise, signal multipath, signal over-saturation, and ranging blunders. These preprocessing steps may occur in real-time or near-real-time, before the remaining data is saved to our computer data logging system, however the raw radar measurements with the geocoding information may be completely retained for later processing and analysis. The saved radar data with its geocoding information will be subjected to further discrimination and filtering before it is processed by classification algorithms. Classification algorithms will evaluate the radar data for three broad categories of data including surface texture, surface cracking, and other features on the surface that are not intrinsically part of the surface. Surface texture includes roughness, grooving, and texture and this aspect is important because it is important to understand how the surface of road pavement creates friction with the tire rubber in contact with road for safety purposes. The surface cracking is broadly defined as the joints found in pavement intentionally placed to permit the expansion and contraction of pavement surfaces as well as the undesirable cracking of pavement that occurs due to wear and tear of traffic and weather. Cracking takes on a multitude of forms because the damage occurs in many different ways. The third category of classification will include features on the surface of pavement that are not part of the pavement structure and this includes stray items that are lost from passing traffic, blown
onto road surfaces from weather, and other unexpected items. Both the discrimination and classification methods will be based on mathematical and statistical filters derived from machine learning and expert rules.

[0015] In one implementation, the radar/sensor technology of the disclosure can augment traditional optical and laser sensors. Available data indicates that morphological features (e.g., joints and cracking in pavement) can be detected. One or more embodiments of the disclosure can discriminate—e.g., output data that can permit identification of specific features—concrete pavement from asphalt pavement. In one aspect, the joints and cracks in pavement being identified are smaller than the theoretical resolution of the radar imaging sensors. In one aspect, two types of theoretical resolution can be contemplated. The first includes the real resolution of the radar sensor determined by the antenna size and frequency at which it operates, i.e. L-band, X-band, Ku-band. The second form of resolution is smaller than the frequency and antenna size and makes use of the peculiar ways that microwave energy is collected, concentrated and reflected, creating very strong signals easily detected and recorded by the radar and these features can be on the order of 10 to 100 times smaller than the resolution of the sensor. Thus a frequency of 16 cm (L-band) can detect features much smaller, even sub-millimeter in size.

[0016] Similar to laser profilers that characterize pavement, radar is an active remote sensing technology. Similar to the light emissions from a laser profiler, radar emits microwave energy, albeit at a longer wavelength. Both sensors can operate as a radiation source and thereby illuminate a target surface, the sensor can detect reflected radiation, or energy flux thereof, and data indicative of strength of the radiation, or amount of energy flux sensed, can be recorded. In one aspect, at least one feature of the collected data can serve as a fingerprint, or can be indicative, of a specific morphological feature (e.g., a crack or a boundary, such as joint) of the monitored surface. Such fingerprint provided by the data indicative of the reflected energy can be utilized to characterize its signal and to create an image.

[0017] Laser profilers and radar imagers are also similar in that they emit many pulses of energy per second to create an image. In certain embodiments, pulses can be transmitted at rates of the order of KHz. In both cases high-precision clocks on the sensors record the time it takes for each pulse of energy to return. Such information can be employed to calculate a distance or range. Accordingly, these technologies are referred to in manners that include the term “ranging”: Light Detection and Ranging (LiDAR) and Radio Detection
and Ranging (RADAR).

[0018] Close-range synthetic aperture radar (SAR) of the disclosure can yield imaging data resulting from excitation of a solid surface with X-band and K_{\mu}-band radiation produced and detected by a radar unit (e.g., radar sensor and radar source). For example, the radar unit can be manufactured by ImSAR. In certain implementations, probed solid surfaces comprised asphalt pavement and concrete pavement in a variety of conditions of such surfaces. In one aspect, the K_{\mu}-band provide higher resolution imaging than the X-band and, as described herein, with side-looking SAR imaging performing better than the forward/backward-looking radar at producing images readily suitable for analysis and/or interpretation.

[0019] Besides the ranging data, the strength of the returned radiation (e.g., visible radiation, microwave radiation) signal can be recorded. Certain surfaces reflect laser and microwave energy very well, whereas other surfaces can scatter such energy thus reducing a returned signal. In general, when laser or microwave energy impinges onto a smooth surface at an angle, the energy can be reflected away, whereas a rough surface diffusively scatter the energy in various directions, returning a portion of the incident energy back to a radar sensor that is part or functionally coupled to a radar unit. The radar unit also can comprise or be functionally coupled to a radar source (e.g., a source of radio waves, such as electromagnetic radiation having wavelengths ranging from about 1 mm to about 1 km).

[0020] Energy scattered away from the sensor typically results in less returned energy and, thus, signals with lower strength. In one aspect, a low-strength signal can be represented as dark feature in an image. Accordingly, a rougher surface can scatter microwaves and, thus, can create a region of gray in the image. In another aspect, the brightest features in an image of a probed surface can occur in a scenario in which radiation, and associated energy, incident in the probed surface is reflected directly back to the sensor. Thus, in such scenario, roughness of the probed surface can be recorded as various shades of gray in an image.

[0021] Features made of different materials interact differently with radar microwaves and infrared laser energy. Metal reflects microwaves very well, which is why radar is good for imaging aircraft. The high dielectric-metal skin makes excellent reflections, while the wings and tail at right angles focus microwave bounces directly back to the radar. Water will appear black in an image created with both microwave radar and infrared laser energy. Concrete is highly reflective of both microwaves and laser energy. In one aspect, asphalt
tends to absorb a portion of both microwave and laser energy while asphalt’s coarse surface can scatter the energy of both sensors.

[0022] In one aspect, the angle at which the radar sensor images a surface also can determine how the energy is scattered and reflected back (or backscattered) and, thus, how a resulting image can be formed. For radiation in the microwave portion of the electromagnetic spectrum, the resulting image can be referred to as a microwave image. In one embodiment, radar’s microwave energy obliquely striking the surface (e.g., a paved surface) can have the microwave energy reflected back to the radar sensor by the cracks in such surface, thus making one or more of the cracks detectable in both the microwave return signal and the microwave image.

[0023] In one embodiment, a radar sensor mounted in the bed of a truck, pointed backwards, and oriented at a 45 degree angle towards the pavement. Such configuration referred to as the “real aperture radar” because the “aperture” is the size of the radar antenna which creates a footprint on the ground that is determined by diffraction theory.

[0024] In another embodiment, the radar sensor points down to the side of the vehicle, wherein the radar is oriented perpendicular to its direction of travel. Such configuration, which he referred to as “side-looking configuration” or “side-looking SAR” can permit utilization of the vehicle’s movement to collect sequential radar returns of a probed solid surface. These sequential images can then be synthesized into a single image that achieves the high resolution (e.g., cm-range) associated with a very large “synthesized” aperture. This is where the term synthetic aperture is derived.

[0025] In one aspect, the side-looking SAR can detect minute cracking oriented orthogonal to the SAR side-look angle. The theoretical resolution of the K‚-band (e.g., from about 12 GHz to about 18 GHz) SAR can be coarser than the cracks detected and such cracks can be clearly visible in imagery produced from collected imaging data (e.g., strength of backscattered radiation). In one embodiment, a radar sensor employed in such configuration can operate from an aircraft flown at, for example, 1,000 feet above ground level, a feat not possible with existing pavement imaging technology. In another embodiment, imaging data for SAR imagery also can be collected with detection system (e.g., see Figure 1A) on a truck, wherein imaging data so collected can yield better results having less noise (also referred to as image clutter) than SAR imagery produced from imaging data collected from an airborne detection system.

[0026] In one embodiment, the forward/backward-looking radar configuration can
detect linear cracking that can be oriented orthogonal to the radar angle of view. In one aspect, the forward/backward-looking radar configuration is intended and designed to detect cracks as a vehicle carrying the detection equipment moves over a solid surface (e.g., pavement) being probed. In one aspect, the radar sensor can detect cracks. Yet, the image created via the close-range SAR of the disclosure is not an image like one obtained from an optical camera. Rather, the image obtained via close-range SAR is an image of pavement data continuously moving, thus the crack appears as a smear through time, with the image having time on one axis and the crack “signature” on the other axis. See, e.g., Figure 2. In one aspect, crack "signature" is a blip of microwave energy that has bounced back. It should be appreciated that such novel imagery is not an imagery that pavement engineers, for example, are familiar with. In one aspect, Global Positioning System (GPS) coordinates can be associated, or linked, to these blips, and, as a result, geocoding of the crack signatures can be attained.

In certain embodiments, geocoding the radar imaging data, such as data indicative of the signal strength of backscattered radiation, with other sensor data (data acquired by a video camera, data generated by a lidar profiler, etc.) can include at least seven parameters. For example, in one aspect, a first set of three parameters of the seven parameters can be the xyz coordinate calculated from the global positioning system. These xyz coordinates can be transformed from the native earth-centered-earth-fixed spherical coordinate system that GPS utilizes into local plane coordinates used by local mapping systems. Another set of three parameters comprises orientation parameters from the inertial reference system, which can provide the orientation of the radar within the coordinate space; see, e.g., Appendix A. The orientation parameters are a set of three-dimensional orientation angles describing the look angle of the radar system; see, e.g., Appendix A. Yet another parameter of the seven parameters can be a time stamp (e.g., a time record) obtained, for example, from the GPS. The time stamp can be applied to all other data sets, including the video imagery and lidar profiler, thereby allowing the integration of the complete pavement imaging solution.

The forward/backward-looking radar configuration can yield a substantive amount of data. For example, amounts of the order of a few gigabytes per minute can be common. In one aspect, such data is rich and complex, particularly, yet not exclusively, because a portion of the data can be associated with roughness of a probed surface (e.g., pavement) that do no present cracking or other morphological anomaly or feature that is
intended to be detected. In certain implementations, one or more methods can be implemented to analyze the collected data, identifying and/or removing contributions to the data arising from such roughness (referred to as “roughness data”), and yielding information associated directly with cracking. Imaging data collected in the forward/backward-looking radar configuration can be utilized to detect surface roughness.

[0029] In certain embodiments, SAR imaging data collected in the forward/backward-looking radar configuration can permit integrating crack detection with conventional pavement imaging technology, such as line cameras and LiDAR, to indicate presence of cracks in data sets obtained via such conventional techniques. Such integration of forward/backward-looking radar is that can provide a very useful sensor in an integrated pavement management system, the sensor reducing manual inspection time, and other human intervention time, since the cracks can be pre-detected automatically.

[0030] In one embodiment, the radar is small, weighting 3.5 pounds and its antenna is seven inches long. Such radar can consume several Watts to operate. Other radar units having less weight than 3.5 pounds also can be utilized. For example, radar units embodied on one or more integrated circuits that include antenna(s) can be utilized. The radar in Figure 1A can be mounted in the bed of a truck on a wooden scaffold about five feet above the ground. The antenna can be pointed at a 45 degree angle towards the pavement to create an oblique view from the back of the vehicle.
Figure 1A. The entire radar system with the antenna (A), processor (B) and data communications (C), all mounted on the tailgate of the truck.

[0031] The exemplary system of Figure 1A can be mounted on a wheeled-terrestrial vehicle, this technology could be integrated on aircraft, including unmanned aerial systems. Applications are not limited to road pavement, but may also include bridges, aircraft runways, building roofs, parking lots, etc.

[0032] In one embodiment (e.g., Figure 1A), a radar imaging system of the disclosure can comprise various units. For example, a first unit can be a radar unit (also referred to as radar), having a radar sensor and a radar source pointed at an angle to a solid surface (e.g., pavement) that is being probed or inspected. A radar imaging unit can be part of or be functionally coupled to the radar. A second unit can be a video camera pointed at the solid surface (e.g., pavement) that can collect optical imaging data of the solid surface. A third unit can be a laser profiler (or lidar profiler) pointed at the solid surface (e.g., pavement) that can permit characterizing the morphology of the solid surface. A fourth unit can be a vehicle on which the radar imaging system is mounted. A fifth unit can be, for example, a geolocation system comprised of a GPS for xyz coordinate geolocation augmented with an inertial reference system (IRS) that can provides xyz coordinate information when a GPS
fix is unavailable. Imaging data obtained with the radar imaging system of the disclosure can be output to a user device, e.g., a device of a pavement engineer, for analysis of imagery associated with the imaging data generated through inspection of pavement via the close-range SAR of the disclosure.

[0033] In one aspect, the radar can be pointed ahead, behind, or to the side of the vehicle so as to form an angle allowing the radar microwave energy to concentrate in the solid surface and morphological features thereof, such as pavement cracks, and be reflected back (or back scattered) to an antenna in the radar unit (referred to as the radar antenna). In one aspect, the video camera can be pointed down towards the solid surface (e.g., the pavement) and so can the lidar profiler. The fifth unit, e.g., the GPS augmented with IRS, can provide the data to geolocate all or a portion of the collected imaging data, and to synchronize, using time and coordinate stamps, for example, one or more data sets having such data.

[0034] In one embodiment, the radar is mounted on the front or back of the vehicle, oriented at an angle down towards the solid surface (e.g., pavement). As the vehicle moves, the radar can emit microwave pulses, for example, that are scattered and reflected back to the radar. Because of the way the radar microwaves are concentrated and reflected back to the sensor, such stronger returns can be indicative of the location of a specific morphology feature (e.g., a crack) of the solid surface. Information associated with signal strength of the returned radar pulses can form a fingerprint indicative of roughness of the solid surface (e.g., pavement). Knowledge or access to the location of the morphology feature (e.g., the crack) from the radar pulse, the speed of the vehicle and spatial coordinates thereof, the radar imaging system can geolocate the crack location and surface roughness with the other data being collected, which includes the video imagery and lidar profile data. In one aspect, the radar can provide a triggering mechanism that indicates the presence of a crack or anomaly in the pavement, flagging the integrated GPS/IRS, video imagery, and lidar profile data for follow up investigation by the pavement engineer.

[0035] One exemplary operation of the disclosure can comprise the radar performing a first inspection of the solid surface (e.g., a road) and flagging video imagery obtained with the video camera and lidar-based imaging data. Such flagging step, or identification step, can simplify inspection and interpretation of conditions of the surface, such as pavement, by a field engineer (e.g., a pavement engineer).

[0036] In one implementation a conventional survey vehicle suitable (e.g., designed) for
pavement imaging and profiling can be configured or fitted with the radar imaging system of the disclosure; see Figure 1B, by adding, for example, the radar and the related radar imaging unit, in either a forward or backward looking direction, in a manner that at least a portion of the solid surface (e.g., a lane of pavement) in which the survey vehicle moves also is being imaged with the radar and other components of the disclosure.

Figure 1B. Exemplary radar imaging system in accordance with one or more aspects of the disclosure.

[0037] In this configuration, the microwave energy from the radar can strike the pavement about 10 feet behind the truck in a footprint about 3-foot wide. This spotlight behind the truck (or vehicle transporting the radar) can be where the strongest radar signal returns from cracks, or other morphology features, are recorded. Pavement further away can reflect unwanted radar energy away in order to reduce radar signal noise.

[0038] In certain implementations, a return signal can appear as a blip on an oscilloscope, with a bigger blip being a bigger crack.
In such implementation, the truck can move past two well-defined metallic features. In Figure 2, the background color (blue) is the random noise of the pavement and the speckled pattern is caused by the roughness of the pavement. The lighter tones of grey (or, as illustrated, green and yellow colors) indicate returned signals: one for each of the metal features. Such type of graph is called a “waterfall” because it tracks the signal through time and over distance. The first return begins at location “1” and the second return begins at location “2”.

Returns of these strength and well-formed definition can be easily detected with automated signal processing software. In one embodiment, methods for analyzing the imaging data can utilize a matched filter approach to extract the signal from the clutter (or noise). These return signals can be easily geo-referenced, or geocodes, by linking coordinate information from the global positioning system and a back-up inertial navigation system. Thus cracks can be geo-referenced, or geocoded.

In another implementation, a concrete sidewalk with well-defined joints can be probed or monitored. Driving the truck over the sidewalk provides imaging data conveying clear returns in the waterfall plot.

Figure 2. Waterfall plot showing the received signal from the radar with distance traveled in the y axis and time traveled on the x axis.
Figure 3. Sidewalk imaged by real aperture radar.

Figure 4. Concrete sidewalk cracks can be clearly observed in the above waterfall plot as a succession of lines at the lower range scale (e.g., less than 30).

[0042] Collected data and associated analysis demonstrate that real aperture detection can be accomplished at close range.

[0043] In one aspect, detection of the joints and cracking on concrete roadways can detect perpendicular line of sight where the radar antenna is oriented. In another aspect, alternative antennae configuration(s) and/or orientation(s) can detect cracking in other perpendicular directions. For instance, steering the antenna beam in various directions can permit the radar beam to sweep pavement at continuously or nearly continuously changing angles as the vehicle drives through the pavement. In one embodiment, switched-beam
electronically scanned arrays on monolithic microwave integrated circuits can be or can comprise a radar sensor configured to operate with antenna sweeping.

[0044] The results of the asphalt imaging test can be best characterized by comparing two scenes: one for a pristine asphalt road with no discernible cracks and one for a road with a maze of “spider” cracks. This comparison is shown in **Figure 5**.

**Figure 5.** Waterfall images for asphalt pavement in case of heavily cracked (upper) and new condition (lower)

[0045] Unlike the cracking detected in concrete surfaces, differences between imaging data for the “good” and “bad” asphalt shown in Figure 5 are subtle. In one aspect, without intending to be limited by theory, simulation, and/or modeling, subtle differences (e.g., specific pattern of signal strength embedded in a noisy background signal) can be attributed to the radar unit (e.g., radar sensor, radar source, or both) producing a significant amount of “back scatter” signal.

[0046] In one aspect, cracks of about 2 centimeters and larger were identifiable. The substantive volume of data from the radar sensor can be processed according to methodology(ies) described herein (see, e.g., ¶[0013]). Such techniques can be suitably modified to efficiently so that real-time processing of the radar signal returns can be classified and then geocode the crack information in real time with the other data sets from the imagery and lidar sensors. Such an approach can utilize statistical filters and artificial neural networks to classify cracks based on their morphology and importance for later examination by pavement engineers. In another aspect, as described herein, detected cracks
are oriented orthogonally to the direction of the platform’s movement and radar antenna orientation.

[0047] As radar data processing software improves, the technology and approach will improve as will the ability to automatically detect cracks. The future application for this approach with real aperture radar would be in conjunction with other technology, where the radar sensor would automatically detect the presence and characteristics of the pavement cracking, and then integrate this information with other sensors such as camera and laser pavement imaging/profiling systems.

[0048] Such integrated approach can provide (e.g., output) data that can assist pavement engineers in their visual inspection of camera imagery. In one aspect, the data can comprise data and/or metadata indicative of images requiring inspection based on the detected cracks. For instance, the data and/or metadata can indicate (e.g., flag) such images. This improvement in efficiency, in one aspect, renders the disclosed imaging technology advantageous over conventional solutions.

[0049] Another test comprised synthetic aperture radar (SAR). A system configured on a small aircraft, a Cessna 172, can be employed to collect data. Theoretically, the operation of the SAR from an aircraft can yield the same imaging results as from a truck. In addition to waterfall plots, richer high-resolution images can be produced from the data collected airborne.

[0050] In one aspect, better imaging results were obtained for the concrete features. As in the case of the real-aperture radar, SAR can easily see sidewalk cracks in concrete but the orientation of the cracks and joints can be orthogonal to the radar antenna orientation.

[0051] In one implementation, the SAR image was flown in a left/right direction. In such implementation, cracks that run parallel to the flight line can be easily observed, whereas those sidewalk cracks running perpendicular to the flight direction may be undetectable.
Figure 6. Google Earth image (left) and SAR image (right) of roads and sidewalks. Cracks running left/right (the same direction as the flight direction) are readily seen. One exemplary result from this experiment is that the SAR, side-look imaging can detect small cracks and joints from a low-flying aircraft, using an airborne platform.

[0052] In the real aperture radar test, cracking was detected as radar return signals when passing over concrete cracks. Such approach includes data processing method(s) for removing signal noise that can mask fingerprint(s) of cracks.

[0053] In one aspect, real aperture radar detection does not generate a conventional image. Rather, in one embodiment, real aperture radar detection can yield signal that can be traced through time and distance on a waterfall plot. In another aspect, SAR can generate a real image that appears similar to an air photograph. Such forms of detection can be georeferenced to permit integration of other pavement imaging technologies with real aperture and synthetic aperture technologies.

[0054] Detecting and imaging cracks in concrete is easier than in asphalt. Without intending to be limited by theory, modeling, and/or simulation, it is believed that greater roughness of the asphalt compared to concrete surfaces can result in lower signal-to-noise ratio for the data obtained from experiments in asphalt.

[0055] Pavement cracks and joints were best detected when their orientation is perpendicular to the antenna orientation. A solution to this issue is potentially a method of sweeping the pavement being imaged by shifting the look angle of the radar antenna. In certain implementations, beam-switched radar technique can be employed to accomplish such shifting. Accordingly, the radar unit of the disclosure can be or can comprise a beam-switched radar system which can exploit phased-array radar that uses, for example, a horn-antenna array to move the radar beam in multiple directions. In one aspect, such radar unit
can permit operation with fields of view as wide as 49 degrees from a single sensor. Thus a 360 degree field of view with a continuously sweeping radar beam is possible with no moving antenna utilizing 8 of these radar sensors. Ultra-high frequencies in the Q, V, and W-bands of the radar spectrum also can be employed.

[0056] One or more methods for analyzing imaging data obtained according to aspects of the disclosure can process (e.g., manage, operate, and/or the like) the substantive size of the datasets, decimate data, filter/reduce/eliminate noise from signal, classify signal as false positive and true positive, extract true positive, and then attempt to classify true positive signals.

[0057] Airborne SAR experiments of the disclosure demonstrate that pavement inspection may not be performed exclusively from a terrestrial vehicle. The miniaturized SAR also can be operated from unmanned aerial systems flying at lower altitudes. It should be appreciated that conventional airborne SAR can be performed on platforms in deep space (e.g., satellites) and high flying jets, for example. In conventional systems, such high altitude is needed because of the baseline necessary in terms of distance flown to create the synthetic aperture. Such high altitudes in conventional systems also are needed to give the emitted radiation time to travel the ground and then return on the bounce, even though it is travelling at the speed of light. In contrast to such conventional features, the close-range SAR of the disclosure, and related embodiments of system and methods, can synthesize the aperture at very short distances, low altitudes, and sill travel enough distance on the platform to so synthesize the aperture.
Figure 7. Exemplary operating embodiment in accordance with one or more aspects of the disclosure.

[0058] Figure 7 illustrates a block diagram of an exemplary operating environment 700 having a computing device 701 that enables various features of the disclosure and performance of the various methods disclosed herein. Computing device 701 can embody a data processing unit that can be part of the radar or can be functionally coupled thereto. This exemplary operating environment 700 is only an example of an operating environment and is not intended to suggest any limitation as to the scope of use or functionality of operating environment architecture. Neither should the exemplary operating environment 700 be interpreted as having any dependency or requirement relating to any one or combination of functional elements (e.g., units, components, adapters, or the like) illustrated in such exemplary operating environment.
The various embodiments of the disclosure can be operational with numerous other general purpose or special purpose computing system environments or configurations. Examples of well known computing systems, environments, and/or configurations that can be suitable for use with the systems and methods of the disclosure comprise personal computers, server computers, laptop devices or handheld devices, and multiprocessor systems. Additional examples comprise mobile devices, programmable consumer electronics, network PCs, minicomputers, mainframe computers, distributed computing environments that comprise any of the above systems or devices, and the like.

The processing effected in the disclosed systems and methods can be performed by software components. In one aspect, the disclosed systems and methods can be described in the general context of computer-executable instructions, such as program modules, being executed by one or more computers, such as computing device 701, or other computing devices. Generally, program modules comprise computer code, routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. The disclosed methods also can be practiced in grid-based and distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules can be located in both local and remote computer storage media including memory storage devices.

Further, one skilled in the art will appreciate that the systems and methods disclosed herein can be implemented via a general-purpose computing device in the form of a computing device 701. The components of the computer 701 can comprise, but are not limited to, one or more processors 703, or processing units 703, a system memory 712, and a system bus 713 that couples various system components including the processor 703 to the system memory 712. In the case of multiple processing units 703, the system can utilize parallel computing.

In general, a processor 703 or a processing unit 703 refers to any computing processing unit or processing device comprising, but not limited to, single-core processors; single-processors with software multithread execution capability; multi-core processors; multi-core processors with software multithread execution capability; multi-core processors with hardware multithread technology; parallel platforms; and parallel platforms with distributed shared memory. Additionally or alternatively, a processor 703 or processing unit 703 can refer to an integrated circuit, an application specific integrated circuit (ASIC),
a digital signal processor (DSP), a field programmable gate array (FPGA), a programmable logic controller (PLC), a complex programmable logic device (CPLD), a discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. Processors or processing units referred to herein can exploit nano-scale architectures such as, molecular and quantum-dot based transistors, switches and gates, in order to optimize space usage or enhance performance of the computing devices that can implement the various aspects of the subject disclosure. Processor 703 or processing unit 703 also can be implemented as a combination of computing processing units.

[0063] The system bus 713 represents one or more of several possible types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port, and a processor or local bus using any of a variety of bus architectures. By way of example, such architectures can comprise an Industry Standard Architecture (ISA) bus, a Micro Channel Architecture (MCA) bus, an Enhanced ISA (EISA) bus, a Video Electronics Standards Association (VESA) local bus, an Accelerated Graphics Port (AGP) bus, and a Peripheral Component Interconnects (PCI), a PCI-Express bus, a Personal Computer Memory Card Industry Association (PCMCIA), Universal Serial Bus (USB) and the like. The bus 713, and all buses specified in this specification and annexed drawings also can be implemented over a wired or wireless network connection and each of the subsystems, including the processor 703, a mass storage device 704, an operating system 705, SAR analysis software 706, SAR data storage 707, a network adapter 708, system memory 712, an Input/Output Interface 710, a display adapter 709, a display device 711, and a human machine interface 702, can be contained within one or more remote computing devices 714a,b,c at physically separate locations, functionally coupled (e.g., communicatively coupled) through buses of this form, in effect implementing a fully distributed system.

[0064] SAR analysis software 706 can configure the computing device 701, or a processor thereof, to perform one or more of imaging data collection, analysis of at least a portion of such data for feature extraction associated with morphological features of a probed solid surface, and geocoding of at least a portion of the imaging data and location data in accordance with aspects of the disclosure. SAR analysis software 706 can be retained in a memory as a group of computer-accessible instructions, e.g., computer-readable instructions, computer-executable instructions, or computer-readable computer-
executable instructions. In one aspect, the group of computer-accessible instructions can encode one or more methods of the disclosure. In another aspect, the group of computer-accessible instructions can encode various formalisms for feature extraction, such as wavelet analysis, autonomous classification, or the like. Certain implementations of SAR analysis software 706 can include a compiled instance of such computer-accessible instructions, a linked instance of such computer-accessible instructions, a compiled and linked instance of such computer-executable instructions, or an otherwise executable instance of the group of computer-accessible instructions.

SAR data storage 707 can comprise various types of data that can permit implementation (e.g., compilation, linking, execution, and combinations thereof) of the SAR analysis software 706. In one aspect, SAR data storage 707 can comprise imaging data described herein, such as data available for waterfall plots, and data structures containing information associated with imaging data, location data, and geocoding.

The computing device 701 typically comprises a variety of computer readable media. Exemplary readable media can be any available media that is accessible by the computer 701 and comprises, for example and not meant to be limiting, both volatile and non-volatile media, removable and non-removable media. The system memory 712 comprises computer readable media in the form of volatile memory, such as random access memory (RAM), and/or non-volatile memory, such as read only memory (ROM). The system memory 712 typically contains data (such as a group of tokens employed for code buffers) and/or program modules such as operating system 705 and SAR analysis software 706 that are immediately accessible to and/or are presently operated on by the processing unit 703. Operating system 705 can comprise OSs such as Windows operating system, Unix, Linux, Symbian, Android, iOS, Chromium, and substantially any operating system for wireless computing devices or tethered computing devices.

In another aspect, computing device 701 can comprise other removable/non-removable, volatile/non-volatile computer storage media. As illustrated, computing device 701 comprises a mass storage device 704 which can provide non-volatile storage of computer code (e.g., computer-executable instructions), computer-readable instructions, data structures, program modules, and other data for the computing device 701. For instance, a mass storage device 704 can be a hard disk, a removable magnetic disk, a removable optical disk, magnetic cassettes or other magnetic storage devices, flash memory cards, CD-ROM, digital versatile disks (DVD) or other optical storage, random access
memories (RAM), read only memories (ROM), electrically erasable programmable read-only memory (EEPROM), and the like.

Optionally, any number of program modules can be stored on the mass storage device 704, including by way of example, an operating system 705, and tracking software 706. Each of the operating system 705 and SAR analysis software 706 (or some combination thereof) can comprise elements of the programming and the tracking software 706. Data and code (e.g., computer-executable instruction(s)) can be retained as part of SAR analysis software 706 and can be stored on the mass storage device 704. Tracking software 706, and related data and code, can be stored in any of one or more databases known in the art. Examples of such databases comprise, DB2®, Microsoft® Access, Microsoft® SQL Server, Oracle®, mySQL, PostgreSQL, and the like. Further examples include membase databases and flat file databases. The databases can be centralized or distributed across multiple systems.

In another aspect, a user can enter commands and information into the computing device 701 via an input device (not shown). Examples of such input devices comprise, but are not limited to, a camera; a keyboard; a pointing device (e.g., a “mouse”); a microphone; a joystick; a scanner (e.g., barcode scanner); a reader device such as a radiofrequency identification (RFID) readers or magnetic stripe readers; gesture-based input devices such as tactile input devices (e.g., touch screens, gloves and other body coverings or wearable devices), speech recognition devices, or natural interfaces; and the like. These and other input devices can be connected to the processing unit 703 via a human machine interface 702 that is coupled to the system bus 713, but can be connected by other interface and bus structures, such as a parallel port, game port, an IEEE 1394 Port (also known as a Firewire port), a serial port, or a universal serial bus (USB).

In yet another aspect, a display device 711 also can be functionally coupled to the system bus 713 via an interface, such as a display adapter 709. It is contemplated that the computer 701 can have more than one display adapter 709 and the computer 701 can have more than one display device 711. For example, a display device can be a monitor, an LCD (Liquid Crystal Display), or a projector. In addition to the display device 711, other output peripheral devices can comprise components such as speakers (not shown) and a printer (not shown) which can be connected to the computer 701 via Input/Output Interface 710. Any step and/or result of the methods can be output in any form to an output device. Such output can be any form of visual representation, including, but not limited to, textual,
graphical, animation, audio, tactile, and the like.

As illustrated, one or more sensor(s) 718 can be functionally coupled to the system bus 713 through an I/O interface of the one or more I/O interface(s) 710. The sensor(s) can comprise LiDAR an RADAR (also referred to as “radar”, without capital letters). Through the functional coupling through such I/O interface, the one or more camera(s) can be functionally coupled to other functional elements of the computing device. In one embodiment, the I/O interface, at least a portion of the system bus 113, and system memory 712 can embody a data collection unit that can permit receiving imaging data acquired by at least one of the one or more sensor(s) 718. Such data collection unit can be an analog unit or a unit for collection of digital data, or a combination thereof. In case of an analog unit, processor 703 can provide analog-to-digital functionality and decoder functionality, and the I/O interface can include circuitry to collect the analog signal received from at least one sensor of the one or more sensor(s) 718.

The computing device 701 can operate in a networked environment (e.g., an industrial environment) using logical connections to one or more remote computing devices 714a,b,c, and equipment 716. By way of example, a remote computing device can be a personal computer, portable computer, a mobile telephone, a server, a router, a network computer, a peer device or other common network node, and so on. Logical connections between the computer 701 and a remote computing device 714a,b,c can be made via a local area network (LAN) and a general wide area network (WAN). Such network connections can be implemented through a network adapter 708. A network adapter 708 can be implemented in both wired and wireless environments. Such networking environments can be conventional and commonplace in offices, enterprise-wide computer networks, intranets. The networking environments generally can be embodied in wireline networks or wireless networks (e.g., cellular networks, such as Third Generation (3G) and Fourth Generation (4G) cellular networks, facility-based networks (femtocell, picocell, Wi-Fi networks, etc.). A group of one or more network(s) 715 can provide such networking environments. In one scenario, the remote computing devices 614a,b,c can embody additional sensor(s), such as inertial guidance system(s). In another scenario, equipment 716 can comprise various part of the exemplary system illustrated in Figure 1. In yet another scenario(s), equipment 716 also can comprise an inertial guidance system.

As an illustration, application programs and other executable program components such as the operating system 705 are illustrated herein as discrete blocks,
although it is recognized that such programs and components reside at various times in different storage components of the computing device 701, and are executed by the data processor(s) of the computer. An implementation of SAR analysis software 706 can be stored on or transmitted across some form of computer readable media. Any of the disclosed methods can be performed by computer readable instructions embodied on computer readable media. Computer readable media can be any available media that can be accessed by a computer. By way of example and not meant to be limiting, computer-readable media can comprise “computer storage media,” or “computer-readable storage media,” and “communications media.” “Computer storage media” comprise volatile and non-volatile, removable and non-removable media implemented in any methods or technology for storage of information such as computer readable instructions, data structures, program modules, or other data. Exemplary computer storage media comprises, but is not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by a computer.
In view of the aspects described hereinbefore, at least one exemplary method that can be implemented in accordance with the disclosed subject matter can be better appreciated with reference to the flowchart in Figure 8. For purposes of simplicity of explanation, the exemplary method disclosed herein is presented and described as a series of acts; however, it is to be understood and appreciated that the claimed subject matter is not limited by the order of acts, as some acts may occur in different orders and/or concurrently with other acts from that shown and described herein. For example, the various methods or processes of the subject disclosure can alternatively be represented as a series of interrelated states or events, such as in a state diagram. Furthermore, not all illustrated acts may be required to implement a method in accordance with the subject disclosure. Further yet, two or more of the disclosed methods or processes can be implemented in combination with
each other, to accomplish one or more features or advantages herein described.

[0075] It should be further appreciated that the exemplary methods disclosed throughout the subject specification can be stored on an article of manufacture, or computer-readable medium, to facilitate transporting and transferring such methods to a computing device (e.g., a desktop computer, a mobile computer, a mobile telephone, a blade computer, a programmable logic controller, and the like) for execution, and thus implementation, by a processor of the computing device or for storage in a memory thereof.

[0076] Figure 8 illustrates a flowchart of an exemplary method 800 for monitoring a solid surface via close-range SAR in accordance with one or more aspects of the disclosure. In one embodiment, the exemplary radar imaging system described in connection with Figure 1 can carry out the exemplary method 800. At block, backscattered radiation from a solid surface can be collected at a radar. Block 810 can be referred to as the collecting backscattered radiation step and can comprise delivering radiation onto the surface, at least a portion of the radiation yielding the backscattered radiation in response to interacting with the surface. In another aspect, the collecting backscattered radiation step can comprise generating a time series of data records associated with signal strength of the backscattered radiation.

[0077] At block 820, at least one feature associated with morphology of the solid surface can be extracted, by a computing device (e.g., computing device 701) from data yielded from the collected backscattered radiation. Block 820 can be referred to as an extracting step. In one aspect, the extracting step can comprise analyzing the time series and, in response, identifying a signal level above a threshold.

[0078] At block 830, optical imaging data associated with the solid surface can be collected at an optical detection device (a video camera, a CCD camera, a lidar unit, etc.). At block 840, the at least one feature can be associated, by the computing device, with at least a portion of the optical imaging data associated with the solid surface. At block 850, the at least one feature with location data can be geocoded, by the computing device. Block 850 can be referred to as the geocoding step. In one aspect, the geocoding step can comprise associating the at least one feature with location data, the location data comprising one or more of GPS-based data or IRS-based data.

[0079] In one embodiment, the exemplary method also can comprise associating, by the computing device, the at least one feature with at least a portion of the optical imaging data associated with the solid surface.
Various advantages or efficiencies emerge from the foregoing disclosure. In scenarios in which the solid surface is or comprises pavement, it should be appreciated that in conventional maintenance solutions, visual inspection of the pavement typically requires a trained pavement engineer to visually inspect one or more frames of video imagery to detect and then analyze pavement cracking and surface conditions. In contrast, the disclosed radar imaging, when used in conjunction with video imaging techniques, for example, can permit the automated detection of pavement cracking and conditions, thus mitigating or avoiding manual inspection or other human intervention, and analysis of video imagery.

As described herein, in certain implementation, the disclosure can be advantageous over conventional technologies to various service sectors associated with transportation. For example, pavement engineers, pavement imaging companies, city and county engineers, and state and federal departments of transportation can benefit from one or more of the aspects or features of the disclosure by achieving efficiencies not available through conventional technologies. The disclosure also can have other economic implications, such as better utilization of taxes resulting from reduced costs of pavement inspection and better pavement management strategies. Private sector and public sector organizations that utilize roads can benefit from the invention by being able to implement more adequate or efficient logistics with better pavement management systems.

In addition or in the alternative, it is noted that use of radar at substantively close ranges – closer than theoretical “range gates” that determine the minimum distance the sensor can be from the feature being imaged. It is also noted that conventional SAR solutions can be mounted on satellites and aircraft; in contrast, as described herein, the close-range SAR accomplishes radar imaging while mounted on a terrestrial vehicle, such as a trailer towed behind a truck. It is further noted that the disclosed radar imaging attained in a system mounted on a terrestrial vehicle can comprise mapping of radar imaging data to optical imaging data and/or time stamps.

In various embodiments, the systems and methods of the subject disclosure for management and recovery of a monetary instrument can employ artificial intelligence (AI) techniques such as machine learning and iterative learning. Examples of such techniques include, but are not limited to, expert systems, case based reasoning, Bayesian networks, behavior based AI, neural networks, fuzzy systems, evolutionary computation (e.g., genetic algorithms), swarm intelligence (e.g., ant algorithms), and hybrid intelligent systems (e.g., Expert inference rules generated through a neural network or production rules from
statistical learning).

[0084] While the systems, devices, apparatuses, protocols, processes, and methods have been described in connection with exemplary embodiments and specific illustrations, it is not intended that the scope be limited to the particular embodiments set forth, as the embodiments herein are intended in all respects to be illustrative rather than restrictive.

[0085] Unless otherwise expressly stated, it is in no way intended that any protocol, procedure, process, or method set forth herein be construed as requiring that its acts or steps be performed in a specific order. Accordingly, in the subject specification, where description of a process or method does not actually recite an order to be followed by its acts or steps or it is not otherwise specifically recited in the claims or descriptions of the subject disclosure that the steps are to be limited to a specific order, it is no way intended that an order be inferred, in any respect. This holds for any possible non-express basis for interpretation, including: matters of logic with respect to arrangement of steps or operational flow; plain meaning derived from grammatical organization or punctuation; the number or type of embodiments described in the specification or annexed drawings, or the like.

[0086] It will be apparent to those skilled in the art that various modifications and variations can be made in the subject disclosure without departing from the scope or spirit of the subject disclosure. Other embodiments of the subject disclosure will be apparent to those skilled in the art from consideration of the specification and practice of the subject disclosure as disclosed herein. It is intended that the specification and examples be considered as non-limiting illustrations only, with a true scope and spirit of the subject disclosure being indicated by the following claims.
CLAIMS

1. A method, comprising:
   collecting, at a radar, backscattered radiation from a solid surface;
   extracting, by a computing device, at least one feature associated with morphology of the solid surface from data yielded from the collected backscattered radiation;
   collecting, at an optical detection device, optical imaging data associated with the solid surface;
   associating, by the computing device, the at least one feature with at least a portion of the optical imaging data associated with the solid surface; and
   geocoding, by the computing device, the at least one feature with location data.

2. The method of claim 1, further comprising associating the at least one feature with at least a portion of the optical imaging data associated with the solid surface.

3. The method of claim 1, wherein the geocoding step comprises associating the at least one feature with the location data, the location data comprising one or more of GPS-based data or IRS-based data.

4. The method of claim 1, wherein the collecting backscattered radiation step comprises delivering radiation onto the surface, at least a portion of the radiation yielding the backscattered radiation in response to interacting with the surface.

5. The method of claim 1, wherein collecting backscattered radiation step comprises generating a time series of data records associated with signal strength of the backscattered radiation.

6. The method of claim 3, wherein the extracting step comprises analyzing the time series and, in response, identifying a signal level above a threshold.