Unification of satellite and medical scan methods

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***Abstract*—Remote sensing from an aerial platform has many similarities to medical imaging. Line, whiskbroom, and pushbroom scanning techniques are compared with scan patterns from medical imaging. Satellite imaging uses a scan mirror or sensor array to achieve across track imagery and uses its procession in orbit to achieve along track movement. Medical imaging technologies, like confocal microscopy and optical coherence tomography, use similar scanning mechanisms for across track imagery, but are not in orbit and must introduce the along track movement with a second galvanometer scan mirror or linear stage. Square, triangle, sinusoidal, and sawtooth waveform inputs to the galvanometer provide the actuation signal to control sweeping patterns across a sample. A tissue handling system for medical applications is introduced for discussion and simulation of scan mechanism implementation. The scan system uses a galvanometer and linear stage combination to provide control over light delivery and sample positioning. The synchronization requirements and efficacy of various scan patterns are examined.**

I. Introduction

Remotely obtained images provide new insight and perspective to everyday scenes. The many benefits of scanning from an aerial platform include obtaining a larger ground swath and achieving efficient coverage of geographically complex and sprawling areas. In contrast, medical imaging occurs in close proximity to a sample, over a small area, with the objective of mapping tissue histology. In non-geosynchronous aerial applications, the movement of the ground beneath the sensor provides a unique perspective for collecting data; in medical imaging there often exists full two axis control. In all remote imaging applications there are penalties associated with capturing distorted images or missing target swaths. The penalty is often computational, however, in medical imaging the penalties can be life threatening if an abnormal feature is missed. Further, long lead times during image acquisition and analysis lead to stress and increased risk that a patient's condition may deteriorate.

The scope of this paper is limited to the most prevalent satellite scan systems and due to their similarity, scan systems used in confocal microscopy (CM) and optical coherence tomography (OCT). By optimizing scanning methodologies while ensuring the same or better quality of scan, there will be increased image throughput and risk identification.

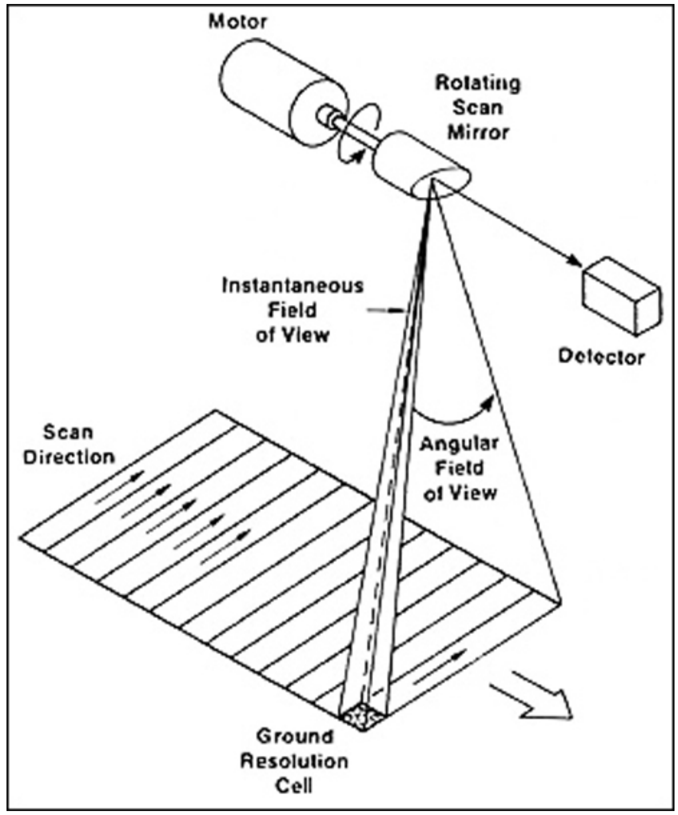

Fig. 1. A line scanner generates an image one pixel at a time, line by line (image from [2])

II. Satellite scan methodologies

A. Line scanners

Line scanners feature a rotating mirror, as illustrated in Fig 1. Earth radiation enters the satellite, reflects against the scanning mirror and is sent to a sensor. The across-track image is created one pixel at a time, line by line. The along-track procession occurs as the satellite moves through its orbit. Since there is movement in both the along-track and across-track directions, the dwell time is low and noise is prevalent. Operationally, line scan systems feature specifications like 1 km spatial resolution and 2400 km field of view (from the Advanced Very High Resolution Radiometer (AVHRR) satellite system[1]).

The advantages to using line scanners include simple optics, large fields of view, and inherent registration for multispectral scans. Multispectral scans diffract the incoming beam into the

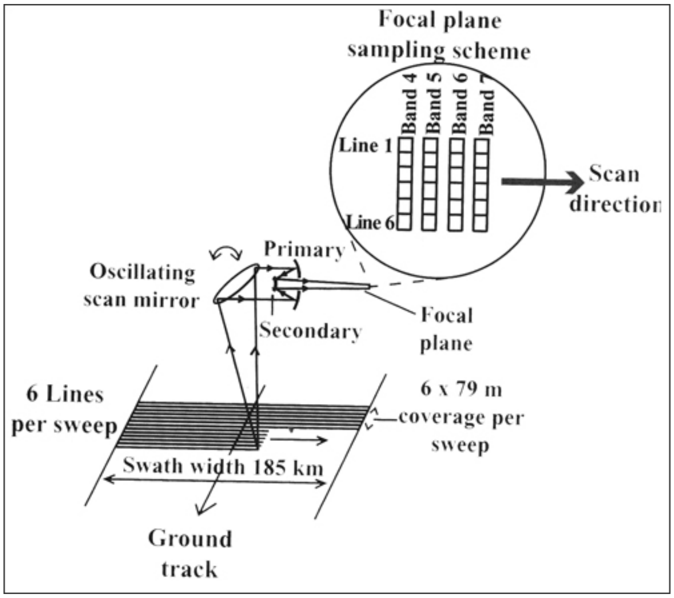

Fig. 2. A whiskbroom scanner covers ground more efficiently than a line scanner since it collects multiple lines at once (image from [1])

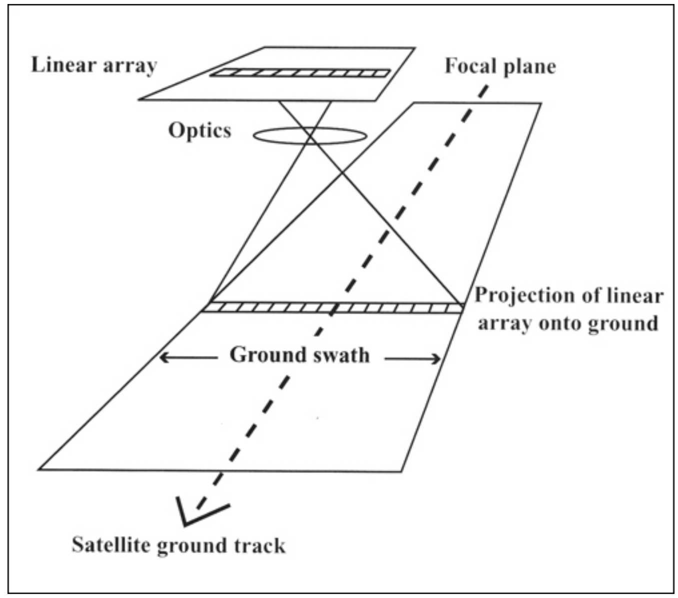

Fig. 3. A pushbroom scanner collects a full line of imagery simultaneously. The scanner has a high dwell time, but often a limited field of view (image adapted from [1])

constituent wavelengths and each frequency is focussed to one pixel in a linear array. The major disadvantage of line scanning is the wasted scan time when the mirror faces away from the Earth.

B. Whiskbroom scanners

Whiskbroom scanning satellites tend to be passive systems in which the scanner sweeps across-track and receives a line of information for each pixel in a line detector, as illustrated in Fig. 2 [1], [3]. Since several lines of data may be received simultaneously, it takes the spacecraft less time to achieve the same coverage as a line scanner. Movement in both the along- and across-track directions necessitates short sensor integration time and the signal to noise ratio may be decreased. Early whiskbroom scanners used rotating mirrors and wasted much of their scan time facing away from Earth. Recent crafts, e.g., the Moderate Resolution Imaging Spectroradiometer satellite [1], use a rotating mirror with reflective coating on both sides to increase usable scan time.

Early generation whiskbroom scanners collected data in only one across-track direction; six lines during each scan using six detectors. Each successive mirror sweep was timed so that each set of six lines were adjacent to the previous six, thereby providing continuous coverage. Current generation scanners make use of both directions and are called bowtie scanners since the ground swath created resembles a bowtie [1]. The advantages of whiskbroom scanning include faster speeds, higher sampling density, large ground swaths, and maturity in technology [4]. Notable drawbacks are increased complexity reconstructing and registering data, and decreased reliability due to additional moving parts.

C. Pushbroom scanners

Pushbroom scanners [3], [4], [5] take advantage of increasingly large sensor sizes. These instruments acquire one across-track swath of data simultaneously for every position in the along track, as illustrated in Fig. 3. As a result of moving in solely the along-track direction, the sensor is able to dwell longer for each pixel providing increased integration time.

Modern pushbroom satellites feature pointing mirrors to look across-track at significant angles [5]. This reduces the revisit period of the satellite since a desired ground swath can be targeted. The Satellite Pour l'Observation de la Terre (SPOT) can look up to +/- 31 degrees from the downlooking direction [1].

The advantages of a pushbroom scanner are simple optical configuration, reduced revisit time, inherent registration, and easy installation aboard aircraft. Without a scan mirror, pushbroom scanners have no moving parts, low wear and power consumption, simple control schemes, and increased dwell time. The disadvantages of pushbroom scanners include the necessity for large detectors, narrow fields of view (the field of view of SPOT is only 60 km compared to 2400 km for AVHRR [1]), and large datasets produced simultaneously which need to be stored and transmitted. Multispectral pushbroom scanning is enabled by placing a diffraction grating before a 2D detector. One dimension of the detector is used to provide the line of scan data, while the other dimension receives the spectrum. Registration of various channels is inherent since the spectra pixels are tied to spatial location. The cost of large 2D detectors is high, but as prices decrease, more sensing systems will employ pushbroom technology.

III. Medical scanners and methodologies

The highest resolution medical imaging systems are OCT and CM. OCT uses interferometric techniques to obtain an image and is discussed below, while CM directly images a sample. Many of the scan methodologies [6] apply to both CM and OCT and so focus will be given solely to OCT. OCT is

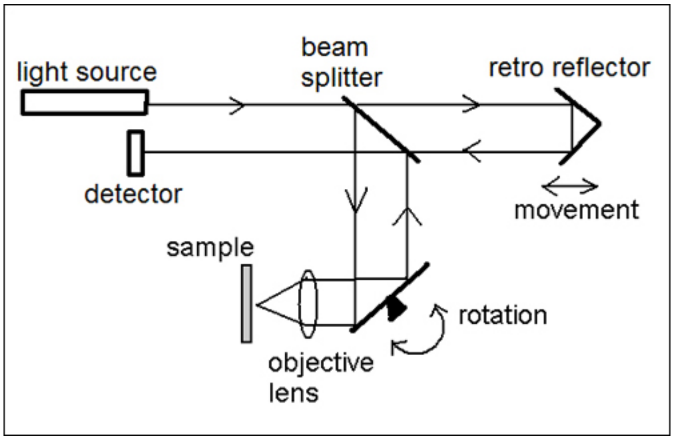

Fig. 4. A time domain OCT system uses interferometric techniques to generate imagery. The path length in the reference arm is varied to change the interference pattern and obtain a depth profile

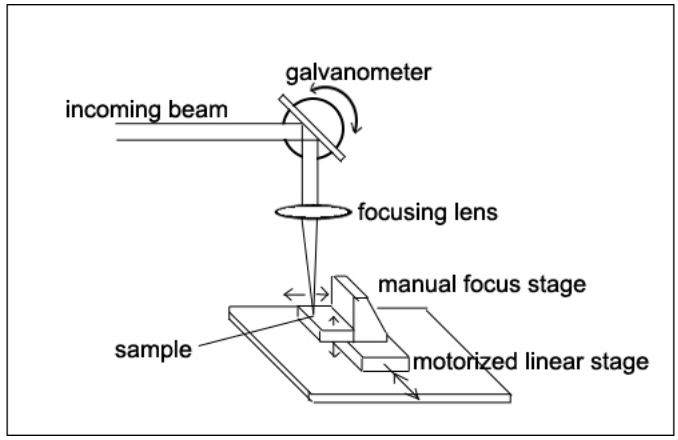

Fig. 5. Architecture of the sample delivery system for OCT. The scan pattern is dependent on how the light beam moves across the sample and how the sample is delivered to the light beam

based upon a Michelson interferometer. In time domain OCT one of the interference [7] arms is replaced with a sample and the other arm, the reference arm, reflects from a mirror. A typical time domain OCT system featuring a beam of light incident on a sample is illustrated in Fig. 4. A broadband, low coherence light source such as a super-luminescent diode is used to illuminate the scan location. During the process of light propagation in the sample, data about the sample's structure is stored. Light back-reflected from the sample is recombined with the reference beam to allow reconstruction of the sample's structure. By placing the reference arm at different positions, structure information may be obtained over the depth of the sample.

In frequency domain OCT a diffraction grating allows for all frequencies of the broadband light to be collected simultaneously. Each frequency hits a different pixel of the detector. Examining all of the frequencies simultaneously negates the need to change the reference arm's path length and allows for all points in the depth profile to be collected simultaneously [8]. In OCT there is specific terminology used to differentiate scan directions: the depth dimension is termed an 'A'-Scan and a group of A-scans next to each other in the across-track direction is called a 'B'-scan.

A. Light delivery and sample positioning system

A scan system was designed for use in an OCT system. The system architecture, illustrated in Fig. 5, includes a single axis galvanometer, driven by a class 1 servo amplifier.

The servo amplifier receives an analogue signal and based upon the frequency and amplitude of the analogue signal, generates a rotational movement in the galvanometer. There is a linear relationship between the input voltage and the output angle of the galvanometer where +/- 10 V input produces +/-20 degrees optical tilt. The inertia of the scan mirror introduces a maximum frequency at which the galvanometer can sustain oscillations. A sinusoidal input on the order of 50 Hz is within the performance envelope of this system. A linear stage provides the second dimension of sample placement control. The stage moves along-track, perpendicular to the B-scan direction. The stage uses an encoder and microcontroller to provide closed loop feedback control over the position of the stage. Testing shows the stage is able settle to a specified position with accuracy as high as 50 nm. The linear stage has a translation stroke of 5 cm.

Broadband light centred at 850 nm, 100 nm bandpass, enters the sample delivery system. The light reflects from the galvanometer mirror and is sent through a focusing lens mounted beneath the galvanometer. The lens focal length is 100 mm and the sample is placed upon the linear stage at the focus. A Z-axis manual stage was placed atop the motorized linear stage to finely control the vertical position of the sample. To maximize the intensity of the returned light and ensure proper interferograms are generated, the top of the sample was placed at the focal point of the focusing lens. Back-scattered light moves back through the sample delivery system into the OCT spectrometer where it will pass through a diffraction grating and be captured on a line-scan detector.

B. Synchronization

Synchronization in this system is provided by matching all movements to clock trigger pulses. For each trigger the galvanometer moves one position step, the camera takes an exposure, and the linear stage checks if the galvanometer is at the end of its motion range. If the galvanometer is at the edge of its range, the stage moves one step forward. This continues until the stage has moved a desired amount. The current scan pattern implementation scans laterally across to produce a B-scan and then while the stage increments in position, the galvanometer is moved back to the initial position. Thus, only one B-scan direction is used and movements are done in a stepwise fashion; in other words, a sawtooth pattern actuates the galvanometer. This system has been implemented in a lab setting and performs well, however, there are optimizations that can be made with respect to the scan pattern used.

IV. Discussion of Scan Pattens

Scan patterns using the light delivery system introduced above were simulated in MatLAB (The Mathworks Company).

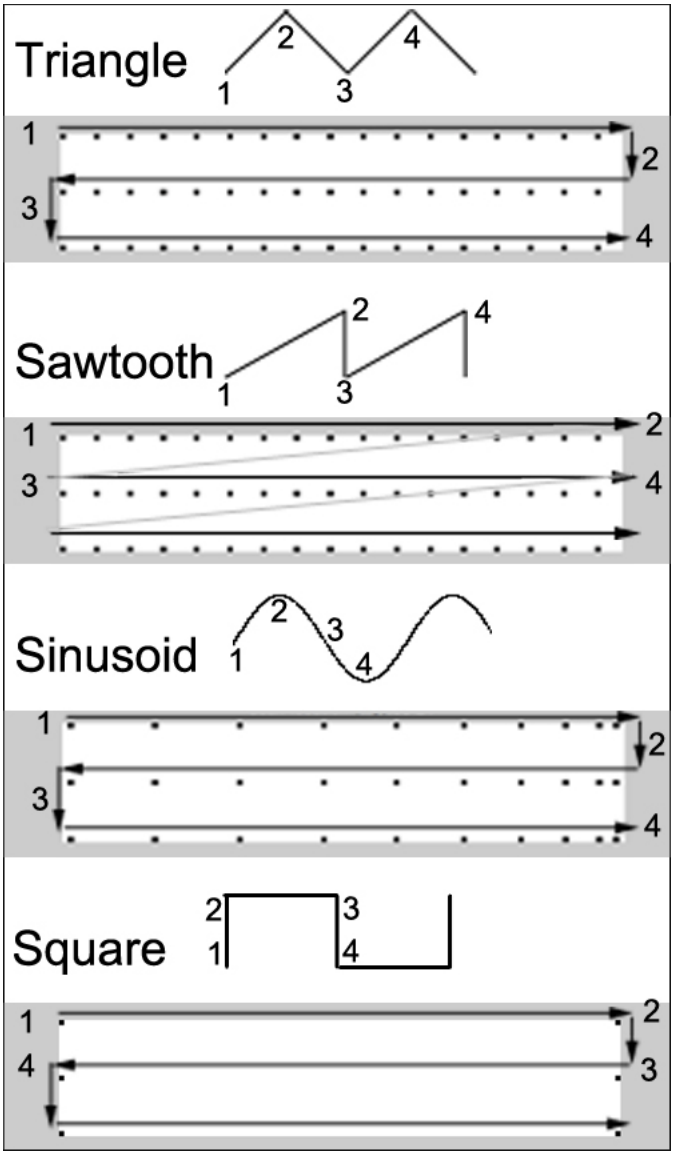

Fig. 6. Simulation results for galvanometer actuation by triangle wave, sawtooth wave, sinusoid, and square wave.

There are several key parameters that the system uses to generate the scan pattern. In order to minimize blurred pixels, the linear stage was moved in a stepwise fashion. Keeping the along-track dimension fixed in this way during B-scans increases the ability to collect good data. The galvanometer can be driven by any waveform. Continuous, or discrete signals with small step sizes work best to avoid large jumps in position. Square, triangular, sinusoidal, and sawtooth waveforms were simulated for actuating the galvanometer. In practice, the actuation waveform is a voltage signal input to the galvanometer to generate the corresponding movements. For simulation, each of the waveforms were discretized (stepped) to limit movement during camera capture. To visualize the effects of moving the galvanometer, consider the ground swath traced by the imaging beam. The results of the simulation are illustrated in Fig. 6.

In each of the results in Fig 6 the actuation signal is shown along with several numbered points. The numbered points correspond to the locations where the scan head injects the light into the sample at that time. The black dots represent the locations where images would be captured within each actuation signal.

The first result shows the ground swath generated by a triangular waveform input. A triangular wave causes a galvanometer to direct the light beam linearly across the scan area. This waveform acquires imagery in forward and backward B-scan directions for increased efficiency in imaging. Each period of the triangular wave represents one full scan forward and backward. After the B-scan is complete, the stage is given a signal to move forward in order to generate the adjacent B-scan. Other research [6] using triangular waveform actuation was shown to yield acceptable results despite sharp directional changes.

The sawtooth waveform is a combination of a triangle wave and a square wave. This waveform scans at a constant across-track direction and instead of scanning in reverse towards the initial position, the galvanometer is commanded to jump back. Quick jump behaviour is not appropriate for scanning and during empirical testing with hardware in a lab setting, the galvanometer jerk generates a ringing noise. According to the galvanometer manufacturer, this is not risking damage to the galvanometer, however, a violent move may cause unwanted vibration and additional settling time. Vibration is harmful to any optical system and may introduce slight alignment changes over time.

A sinusoidal waveform is undesirable since the distance between samples changes. Note in the Sinusoidal result of Fig. 6 that the distance between image locations decreases in the forward B-scan direction and then increases during the reverse scan. A benefit of sinusoidal scanning is the limited oscillation speed during direction changes. Direction changes can be completed quicker and are expected to generate less system vibration, which leads to reduced settling time in the mirror and more accurate positioning.

A square wave sends an impulse for the galvanometer to jump to the farthest angle. The ground swath starts at one end of the B-scan and as quickly as possible jumps to the other side. With the galvanometer changing tilt so quickly, there would be limited time to generate images across track and so images may only be taken at the extents. For similar reasons to the sawtooth waveform, this jump behaviour is undesirable.

A rounded triangle-wave, not simulated here, may be appropriate to permit a linear spacing and smooth transition from the forward to backward scan direction. Future work should investigate this in hardware implementation.

A. *Comparison of scanning technologies*

Remote sensing and medical imaging have many similarities. Both use multiple frequency bands to gather information about targets that are difficult to characterize otherwise. Frequency domain OCT is similar in hardware to a multispectral line scanner. Both collect information about a single point at a time and use diffraction gratings to separate incoming light into constituent frequencies. Each frequency reveals useful information about the nature of the target. The line scanner examines absorption and reflection in key bandwidth ranges to gather information about crops, water, and vegetation changes. In frequency domain OCT, the resulting interference pattern undergoes a Fourier Transform in order to identify which frequency components are present and essentially, which depths have structures. Interferometers may also be used in satellite remote sensing, however, time domain interferometers are challenging on spacecraft because the field of view must be fixed at a constant ground point while the reference arm is cycled through delay points [1].

To further illustrate the similarity between OCT light delivery systems and linescanner satellites, consider the imaging sequence: each point is imaged in progressively across track. This serves medical imaging well since a single beam is easily focussed to achieve a small spot size. With a small spot size, better resolution is achieved. In both multispectral line scanners and frequency domain OCT one point at a time is imaged and simultaneously resolves spectral information about that point. It is interesting to note that the spectral information has different purposes; OCT uses the information to determine structure, whereas satellite sensors use frequency attenuation to identify target constituents.

For peak sensor efficiency, many spaceborne sensors require cooling. Medical imaging sensors generally operate well in standard lab temperatures and cooling is not a requirement of sensor performance. However, thermal effects are noteworthy for particular types of optical alignment; variations of even a few degrees can misalign free-space optical components.

Remote sensing and medical imaging systems must take into account surface interactions and light propagation effects. The large distances present in satellite sensing require consideration of atmosphere effects. Atmospheric absorption and scattering attenuate energy that could be used to carry useful information and often, these absorption lines are of interest themselves. In OCT, the effects of air tend to be negligible, but light propagation through tissue or fluid is not. Light attenuation is governed by how much absorption and scattering occurs in the tissue sample. Tissue is a highly scattering medium and there is a limit to probing depth of approximately 2 mm [10]. During scans, geometric distortion may be introduced if the target moves. The rotation of the Earth or movement of the sample, and variance in mirror scan velocity induce these distortions. Additionally, scans taken far from the optical axis (off-nadir) result in larger physical areas per scan and the reconstructed image appears compressed. Modern galvanometers have tight tolerance over speed and are often rated to 99.9% linearity for movement [11]. Techniques like whiskbroom scanning have rarely been attempted in OCT due to the complexity and cost associated with multiple beams. A four beam approach [9] was successful in yielding 10μm transverse scanning resolution, yet with single beam OCT achieving as good as micron level resolution, continued development is necessary.

The same technological limitations that prohibit pushbroom adoption in aerial platforms —cost and low size of 2D sensors— makes it difficult to implement a pushbroom system in OCT. Additionally, achieving optics that would be able to focus an incident beam to a small spot size on the target would be a challenge since it would need to be done for each column of pixels.

V. Conclusion

Satellite imaging is a mature field that has many operational scan systems. The unique perspective aerial sensing offers has allowed areas to be examined with greater efficiency than ever before. Innovative scan systems and scan methodologies strive to gain further coverage of larger land swaths while decreasing the repetition period. Medical scan systems can take the knowledge accumulated from satellite imaging and put it into practice on a different scale. Medical scanners strive to complete fast scans with high resolution and increase patient throughput. Similar technology is already being developed in both fields like multi-beam OCT scanners that use mechanisms similar to whishbroom scanning. In the future, bridging the gap between satellite scan technology and medical imaging should lead to multi-use components and technology transfer.

Acknowledgment

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