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Rapid Communication

Availability of Feature-Oriented Scanning Probe Microscopy for Remote-Controlled Measurements on Board a Space Laboratory or Planet Exploration Rover

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Abstract

Prospects for a feature-oriented scanning (FOS) approach to investigations of sample surfaces, at the micrometer and nanometer scales, with the use of scanning probe microscopy under space laboratory or planet exploration rover conditions, are examined. The problems discussed include decreasing sensitivity of the onboard scanning probe microscope (SPM) to temperature variations, providing autonomous operation, implementing the capabilities for remote control, self-checking, self-adjustment, and self-calibration. A number of topical problems of SPM measurements in outer space or on board a planet exploration rover may be solved via the application of recently proposed FOS methods. Key Words: Feature-oriented scanning probe microscopy—Scanning tunneling microscope—Atomic force microscope—Nanotechnology—Space flight instruments—Planetary regolith—Bacteria—Biomolecules—Extraterrestrial life—Planetary mineralogy—Interplanetary medium—Meteoroids—Space debris—Cosmic dust. Astrobiology 9, 437–442.

1. Introduction

A scanning probe microscope mounted on board a spacecraft allows for the study of various surfaces at micrometer to nanometer scales. The scanning probe microscope (SPM) application in extraterrestrial research is rather promising in that it is a lightweight, compact, and reliable device that supports multiple measurement modes and has low power consumption and high spatial resolution (Pike *et al.*, 2000; Akiyama *et al.*, 2001; Gautsch *et al.*, 2001, 2002; Drobek *et al.*, 2004; Parrat *et al.*, 2005). Thus, scanning probe microscopy can be used for the study of regolith samples (Anderson *et al.*, 1999; Kempe *et al.*, 2004), rocks, minerals, space debris, and micrometeoroids, and can aid in the search for traces of extraterrestrial forms of life (Kempe *et al.*, 2002, 2005). It will also support investigations of the properties of materials, crystal growth, and biomolecular reactions, and help to implement nanotechnological operations in microgravity conditions.

2. Feature-Oriented Scanning

Recently, Lapshin (2004, 2007) suggested a feature-oriented scanning (FOS) method that may help to solve a number of problems connected with the use of an SPM on board a spacecraft. FOS is a method intended for the high-precision measurement of surface micro- to nanotopography as well as other surface properties and characteristics by way of scanning probe microscopy, where surface features (objects) are used as reference points for the microscope probe. The operation of the FOS method involves a determination of the relative distance between features and measurement of feature topographies called surface segments, while passing from one surface feature to another located nearby. This approach allows for the scanning of a particular area of a surface under investigation segment by segment, after which a complete image of the surface area is reconstructed from the obtained small-sized fragments, *i.e.*, the segments.

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A segment is a raster scan of a surface feature. The size of a segment is adjusted such that segments of neighboring features partially overlap. In this way, the topography of a measured surface can be reconstructed without any gaps.

A real-time recognition program performs a search for, and detection of, features and calculates the coordinates of feature positions. Any topographic element that resembles a hill or pit may be used as a surface feature. Examples of surface features include atoms, interstices, molecules, atom clusters, grains, nanoparticles, crystallites, quantum dots, nanoislets, pillars, pores, short nanowires, short nanorods, short nanotubes, elements of chains, bacteria, viruses, cells, organelles, and the like. The only restriction is the commensurability of a feature's lateral sizes. In other words, extensions of the features should be comparable in different lateral directions. Otherwise, the feature cannot be localized in a small-sized segment. "Unsuitable" surfaces, for instance, would be a defectless surface of a one-dimensional diffraction grating or a surface of an integrated circuit with a great number of long conducting wires.

It should be noted that surface features themselves are, as a rule, the subject of investigation. Strictly speaking, there are no absolutely smooth surfaces, as even atomically flat surfaces have finite corrugation. The critical issue is usually whether the features on a particular surface correspond to the measurement scale within which a researcher is engaged and whether the features display high contrast and they are stable enough to serve as reliable reference points.

Because of temperature variations and creep of scanner piezoceramics, the microscope probe drifts relative to the sample surface. One of the advantages of feature-oriented scanning probe microscopy is that the negative influence of drift is eliminated directly in the course of the measurement. As a result, it is possible to obtain surface scans undistorted by drift with no need to design a sophisticated microscope and thermostabilization subsystem.

The insusceptibility to drift makes it possible to average a large number of measurements of distances between features and topographies in the segments, which notably increases scanning precision. The number of averagings may reach up to hundreds of thousands or even some millions. Theoretically, the number of averagings is unlimited. In practice, however, the number of averagings is mainly restricted by a long-term stability of the microscope as a whole, the investigated surface, and the experimental environment.

Another distinctive feature of the FOS method is the ability to reconstruct surface topography when the details of interest are smaller than those detectable by conventional scanning methods. Moreover, by means of a computer-controlled distributed calibration (Lapshin, 2004, 2006), it is possible to correct, in one procedure, all spatial distortions caused by nonlinearity, nonorthogonality, and parasitic cross couplings of the X, Y, Z piezomanipulators of the microscope scanner.

The distributed calibration is a kind of FOS method. A crystal surface with an *a priori* known lattice constant is used as a standard. During the distributed calibration, local calibration coefficients are determined for each point of the scanner movement space. These coefficients are then used to correct both subsequent conventional scans and scans obtained by the FOS method.

The new performance capabilities of the FOS method are available as a result of the use of the following combination of techniques (Lapshin, 2004, 2007): localization of the measurements, operation with separate surface features, movement by short distances from one feature to another located nearby, relative nature of the measurements and multiple measurement iterations, consecutive probe attachments to surface features, continuous monitoring of drift velocity, and use of hierarchically organized counter displacements of the probe.

The proposed feature-oriented approach allows for precise movement of the probe, in principle, within an arbitrarily large scan area of a fine positioner (a microscope scanner). The method also allows, by attaching the probe to reference surface features, for precise location of the scan area of the fine positioner, in principle, within an arbitrarily large movement field of a coarse positioner (Lapshin, 2004). The feature-oriented probe positioning enables "delicate" manipulations with separate nanoparticles, molecules, or even atoms at room temperature. The ability of the microscope to move the probe autonomously across the sample surface from one feature to another in a given direction can be used for automatic acquisition of feature statistics (surface characterization) or to search for specific features (Lapshin, 2004).

The FOS method may be used with any instrument of the scanning probe microscopy family: a scanning tunneling microscope, an atomic force microscope, a magnetic force microscope, a near-field scanning optical microscope, etc. The FOS method can also be applied to a scanning electron microscope. Generally speaking, the FOS method may be used with any device that has a probe (mechanical tip, focused light beam, focused electron beam, focused ion beam, etc.), a scanning system (a scanner), and a unit that registers probe interaction with the measured surface (a detector).

The general rule for FOS is as follows: the greater the dynamic distortions (*e.g.*, creeps, thermodrifts, noises, and scan failures) the longer the scanning time. To reach a preset precision, the FOS algorithm, by assessing the amount of distortion, indicates whether to rescan the apertures (an aperture is a raster scan that includes the current feature and several neighboring features) and segments or insert additional attachments and skippings (a skipping is a basic measurement operation in FOS) (Lapshin, 2004). By using an optimized connection trajectory, aperture-wise scanning (Lapshin, 2007), and closed-loop systems equipped with position sensors, the productivity of the FOS method proposed may be improved. It should be noted that any FOS method will always be slower than conventional scanning because of the redundancy inherent in it.

A surface scan obtained by the FOS method is shown in Fig. 1. The surface under investigation is a plasma-deposited carbon film (Alekhin *et al.,* 2004; Lapshin, 2004). The FOS method is able to operate on surfaces of any kind—ordered, partially ordered, or completely disordered. The surface in Fig. 1 is related to the most common case, *i.e.*, a completely disordered surface. During the feature-oriented scan, both carbon clusters (hills) and intercluster hollows (pits) were used as surface features.

Feature-oriented scanning of the carbon film was carried out with an atomic force microscope (Solver™ P4, NT-MDT Co.) in tapping mode at ambient conditions. After assem-

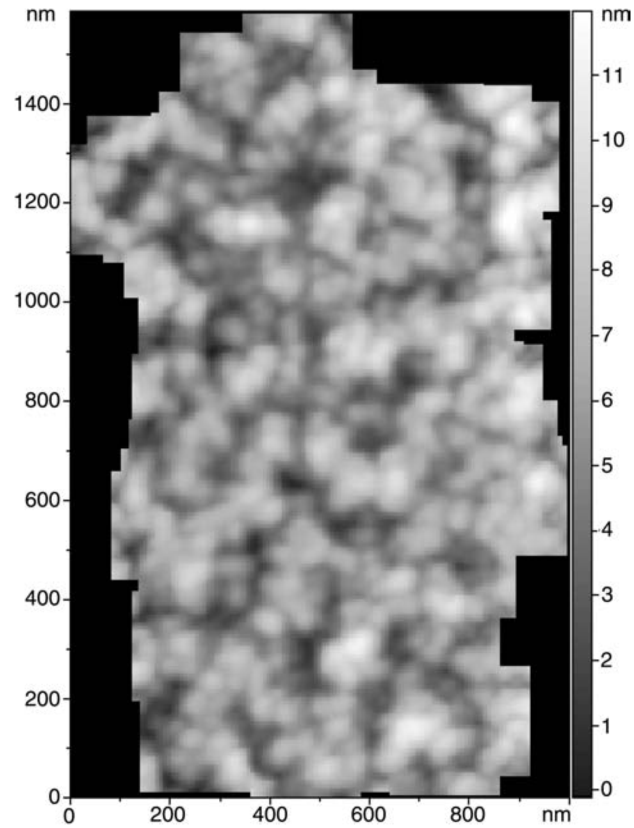

FIG. 1. Atomic force microscope topography of the surface of a plasma-deposited carbon film obtained by the FOS method. The jagged edges of the image indicate that it consists of separate surface fragments also known as segments. The surface is completely disordered. Both hills (carbon clusters) and pits (intercluster hollows) were used as features. Reproduced with permission from Lapshin (2004), © 2004 IOP Publishing, Ltd.

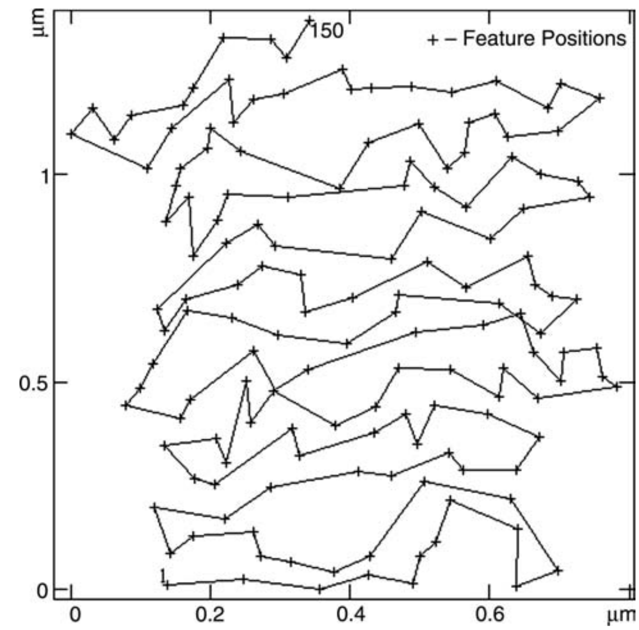

FIG. 2. "Skeleton" of the carbon film surface image—a chain of positions of surface features used as reference points. The number of features in the chain is 150 (95 hills, 55 pits). The rasterlike structure of the chain is obvious. Reproduced with permission from Lapshin (2004), © 2004 IOP Publishing, Ltd.

blage, no image smoothing was applied. The segment structure of the image is only noticeable as "torn" edges. Afterward, the torn edges may be cut out so that the obtained image looks like a conventional one. The absence of any segment-related artifacts in the reconstructed image means, in particular, that the image is not distorted by drift.

In the course of FOS, a sequence called a chain (see Fig. 2) is formed of those features used as reference points. The chain is a sort of a framework or skeleton to which the surface segments are fixed during the assemblage. It can be easily seen in the figure that the chain structure is in the form of a system of feature "lines." The feature lines allow for scanning a surface area of practically any size. It should be noted that the movements from one feature to another in adjacent lines are made in opposite directions, which helps to slow down the creep from the scanner that moves the probe along these lines.

The degree of distortions caused by the drift that occurs during SPM measurements is shown in Fig. 3. Here, the absolute coordinates of the probe movement trajectory are superimposed on the relative coordinates of the feature chain shown in Fig. 2 (probe movements while scanning segments

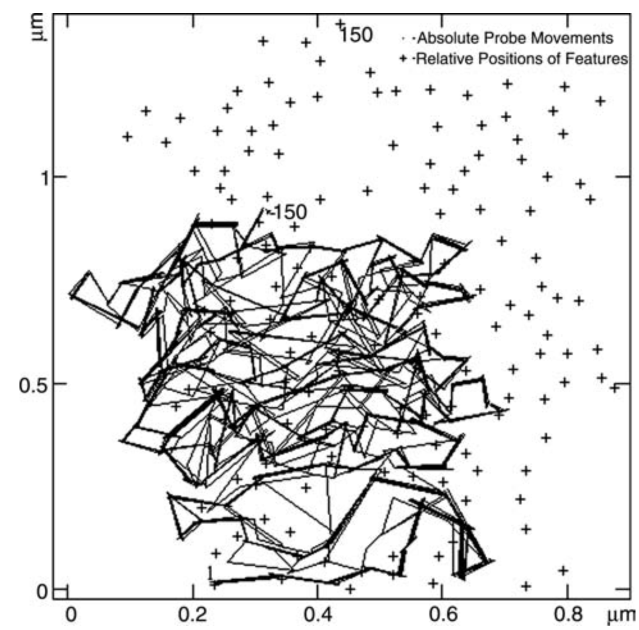

FIG. 3. Absolute positions of the microscope probe trajectory superimposed on relative positions of the chain of features used for probe attachment. Movements in apertures and segments are not shown. The rapid increasing difference between the absolute and relative positions of the same features points out strong distortions induced by microscope drift during scanning. Reproduced with permission from Lapshin (2004), © 2004 IOP Publishing, Ltd.

and apertures are not shown). The superimposition is carried out by matching the positions that correspond to the first feature (designated by the digit 1) in which the absolute and the relative coordinates coincide. As shown in Fig. 3, the absolute probe movement and the relative feature positions in the chain diverge quickly due to drift.

The surface presented in Fig. 1 is biocompatible; it is used for investigations of cell attachment and protein adsorption. Thus, both this surface and the feature-oriented scanning probe microscopy method may prove to be useful for *in vitro* study of vital cell activity and protein properties under cosmic radiation and microgravity conditions.

3. Prospects of Application of Feature-Oriented Scanning to Space and Planet Research

Scanning probe microscope measurements taken on board a spacecraft or a planet rover should be performed autonomously with minimal control intervention from an Earth command center, since a critical time delay may exist between the issue of operator command and its actual execution (Gautsch *et al*., 2001). Even when using an SPM on board a manned space station, it is desirable to have the microscope operate in an unattended mode, since experienced microscopists are not typically available among the station crew. Thus, the astronaut should only perform simple manipulations, like changing the sample, replacing the probe, replacing a defective microscope module, etc. A high degree of SPM measurement automation in the proposed method is achieved due to the fact that real-time feature recognition and probe scanning are closely connected with each other.

Since all the relative positions of the features, as well as the set of characteristics (geometrical, physical, or chemical) of these features, are determined during FOS, it is possible to apply complex control scripts. Moreover, these scripts may not only define a sequence of measurement operations and check its execution but also apply modifying actions. Part of those scripts may be created and tested on Earth before the space mission; another part may be uploaded after the mission has begun, depending on online flight circumstances.

The following new feature-oriented scanning probe microscopy capabilities, which may be used in nanotechnological operations (nanofabrication) in space, are of importance (Lapshin, 2004):

(1) Automatic probe return into the operational zone after sample dismounting-mounting;
(2) Automatic probe movement between different operational zones;
(3) Automatic determination of the exact relative position of the analytical and technological probes in multiprobe instruments;
(4) Automatic successive application of the whole set of probes to the same surface object or to an area located in the object's vicinity;
(5) Simple data exchange between the SPM and a computer-aided molecular design system.

Nanofabrication is considered to be a sequence of operations performed at the nanoscale that lead to the construction of a nanostructure(s). An SPM provides a tool for nanofabrication, *i.e*., for surface measuring, surface influencing, and manipulating matter on the surface.

In addition to the real scanning mode, the suggested FOS algorithm supports a virtual scanning mode, which is usually used to acquire statistics about the features in surface images obtained by regular scanning. Moreover, the virtual mode enables modeling of the FOS process by introducing noises, instabilities, and vibrations; setting drift velocity components along three coordinate axes; and substituting dummy surfaces that have certain features, etc. Thus, the FOS method has a powerful built-in tool that allows all the scheduled SPM spacecraft onboard activities to be simulated, debugged, and checked under Earth laboratory conditions.

It should be noted that with the FOS method the trajectory of probe movement is not predefined; it is composed dynamically during the measurement. Only the general mode of behavior of the system responsible for the selection of the next surface feature is preset. In fact, FOS does not require any *a priori* information about surface morphology. This means that the FOS algorithm constantly makes autonomous decisions as to which feature within a nearby region could serve as a suitable reference point and which way to proceed. The described properties of the FOS method are somewhat similar to the behavior of a planet exploration rover when it decides in which direction it should proceed over a planetary surface so as to avoid obstacles and reach the destination point.

Before carrying out surface scans, the instrument would need to be configured and adjusted. In particular, it is necessary to choose the proper measurement mode, a suitable cantilever type, adjust the registration system, and set up certain scan parameters (such as set point, feedback loop gain, scan velocity, scan step, number of samples per point, etc). The mode selection and parameter adjustment can be done automatically during an iterative feature-oriented scan, based on the results of recognition and analysis of the surface features. Thus, a set of different test samples with known topographies and surface properties should be provided on board to enable SPM self-checking, self-calibration, and self-adjustment.

When investigating specific objects with an SPM, such as microfossils, the obtained results can only be adequately interpreted if it is known, at least approximately, to which part of the studied object the surface scan is related (Kempe *et al.,* 2002, 2005). To solve the problem of localization of the research spot within the objects, which, due to their large size, do not fit entirely in the "field of view" of the SPM, an optical or electron microscope and an XY-micropositioner should be used. Observing the object of interest and the SPM probe through the optical or electron microscope allows the operator to move the probe to the required location with the micropositioner.

The problem of localization of the research spot may also be solved with the use of feature-oriented scanning probe microscopy, which would require that the microscope be equipped with a walking-type XY-nanopositioner. The distinctive feature of a walking positioner is a theoretically unlimited range of movement. Lapshin (2004) showed that there is a positioning method by which a small field of the SPM scanner can be moved precisely within an arbitrarily large field of the walking nanopositioner. Thus, localization of the research spot in feature-oriented scanning probe microscopy can be implemented by the following operations: overview scanning of the studied object as a whole with a large step, choosing a place for high-resolution detailed scanning, and moving the scanner to the chosen place. The first and the last operations are carried out by the positioning method mentioned above; the overview scan represents a set of large scans that make up a single image of the surface.

4. Conclusions

High adaptability to continuously changing measurement conditions—in particular, temperature variations—should be reckoned among the advantages of the feature-oriented scanning probe microscopy method. The suggested FOS methodology possesses a complete set of components that allows for carrying out fully automatic SPM surface measurements and unmanned "bottom-up" nanofabrication with a microscope probe(s) as the tool. An operator at an Earth control center or an astronaut on board a near-Earth station would only formulate the task in general terms. The task would then be performed according to the principle "run and forget."

Weight, power consumption, and overall dimensions of an SPM to be applied on board a small space probe or a light planet rover are all constraining factors in terms of design and construction (Gautsch *et al.,* 2001; Drobek *et al.,* 2004; Parrat *et al.,* 2005). The significant progress recently achieved in microelectromechanical systems (Hafizovic *et al.,* 2004; Li *et al.,* 2007) is encouraging in this regard. The miniaturization also contributes to an increase in SPM performance (Lapshin and Obyedkov, 1993) and reliability, which is important for practical use of the FOS method. The fact is that both high measurement precision and new functionality in feature-oriented scanning probe microscopy are achieved at the cost of an abrupt decrease in scanning productivity. The drop in scanning productivity is caused by high data redundancy, additional probe movements, and a large number of averagings. Thus, the development of an SPM that consists of miniature units will help to produce a fast-acting, reliable, and stable instrument for extraterrestrial applications (Gautsch *et al.,* 2001; Drobek *et al.,* 2004; Parrat *et al.,* 2005). In this regard, the suggested FOS methodology represents a starting platform by which to formulate specifications for this miniature fast-acting SPM.

Acknowledgments

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Abbreviations

FOS, feature-oriented scanning; SPM, scanning probe microscope.

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