Interface specification for synthetic dry adhesive materials for a wall-climbing robot

Mark R. Cutkosky, Alan T. Asbeck, Matthew Spenko -- Stanford University

The interface description contained herein contains Physical, Functional, Behavioral and Organizational requirements for collaboration with Stanford University regarding the fabrication of dry adhesive feet for a climbing robot.

Physical and behavioral requirements

The most important requirements are functional, however the specimens need to meet the following physical and behavioral requirements in order to be considered legitimately as nanofiber dry adhesives. It is not Stanford's intent to design synthetic dry adhesives. The estimates regarding dimensions, physical properties and behavioral requirements are drawn from the existing literature and represent an educated guess.

Specimen patches should preferably have dimensions of at least 2mm x 2mm to facilitate assembly onto the foot suspension systems. If specimens of this size cannot satisfy the Functional requirements, it may be possible to use smaller specimens with alternative fabrication methods, such as bonding a row of specimens onto a row of suspension elements and dicing them afterward. This will take longer to develop and has implications for the Organizational Requirements below.

The specimens are composed of nanofibers and a substrate. The nanofibers are approximately cylindrical shapes with maximum diameters of 2μm or less and lengths of at least 20μm, although the exact dimensions depend on achieving adequate contact with moderately smooth surfaces as discussed under Functional Requirements.

Definitions of Terms

Requirements – can be physical, functional, behavioral or organizational:

- *Physical requirements* - pertaining to dimensions, chemical compounds, and physical properties such as density, and thermal and electrical conductivity.
- *Functional requirements* - What the specimens must do or accomplish in order to fulfill their mission. Functional requirements are fulfilled subject to constraints.
- *Behavioral requirements* - pertaining to physical, electrical and chemical behavior of the materials. Examples include hardness as measured by Rockwell or Shore hardness procedures, compliance, fatigue life and other properties established through a prescribed testing procedure.
- *Organizational requirements* - procedural requirements to assure successful collaboration – including agreements to respond to requests for information within a specified time period, agreement to provide requested volumes of samples at a specified frequency and treatment of intellectual property.

Nanofibers - flexible, approximately cylindrical entities with average diameters of 2 micrometers or less and length/diameter aspect ratios of 10/1 or greater.

Substrate - A flexible material to which the nano-fibers are anchored and which is attached to the foot suspension system.

Specimens – small patches of 2mm x 2mm or greater, consisting of nanofibers bonded to a substrate and satisfying the physical and functional requirements.

Foot suspension system – a compliant suspension provided by Stanford to achieve conformability to surfaces at length scales of 0.5mm and greater. The suspension system is attached to the underside of the foot and supports one or more Specimens.

The nanofibers do not require a round cross section; however they should not be so flexible in any direction or have a surface energy such that they clump together. The nanofibers can be tapered from base to tip and they can have distal features such as the spatulae seen on gecko hairs. The density of nanofibers will probably need to be at least 10,000/mm^2 to achieve adequate functional levels of adhesion.

The substrate for the specimens should be no more than 100μm thick and should be thin enough to be attached to curved surfaces with a radius of curvature of r = 5mm or less.

Quality: When looking at a specimen in the microscope, it should be seen that approximately 75% or better of the nanofibers meet the physical requirements listed above.

It should be possible to cut or dice the specimens into smaller patches as part of the manufacturing process for integrating them with feet. It may be possible to encapsulate the substrate and nano-fibers in a sacrificial material while this is done to prevent damage.

It should be possible to bond the substrate, using adhesives, to the suspension elements being designed at Stanford.

Functional Requirements

When specimens are pressed against a moderately smooth surface, they must provide adequate levels of adhesion and shear traction. For purposes of testing, a good example of a "moderately smooth" surface is machined granite tile, for which a surface profile is given in Figs. 1 and 2.

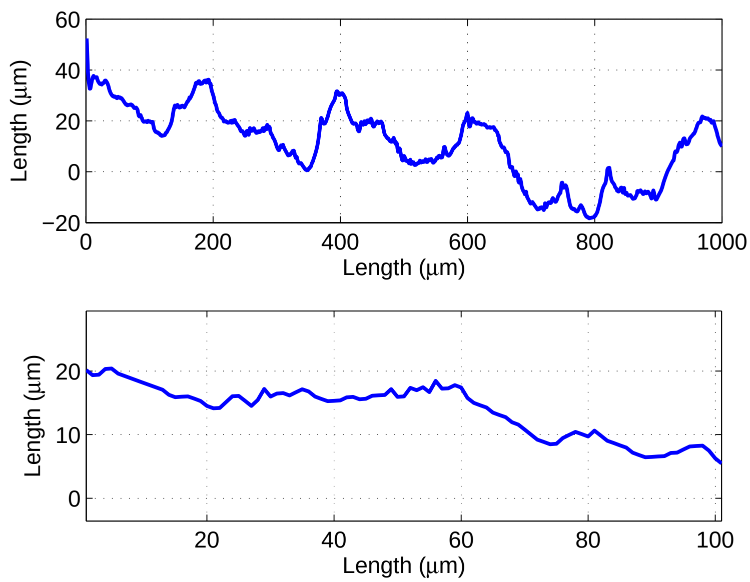

Figure 1: Surface profile for a machined granite tile (top) and same surface magnified such that the axis length scales match (bottom). The surface is qualitatively smooth to the touch, but not polished.

The profile in Figure 1 can be approximated with a two-term Fourier series to obtain a Reference Surface:

$$Height(x,y) = 2\cos\left(\frac{2\pi}{60x}\right)\cos\left(\frac{2\pi}{60y}\right) + \frac{3}{2}\cos\left(\frac{2\pi}{6x}\right)\cos\left(\frac{2\pi}{6y}\right)$$

where x and y are linear dimensions parallel to the surface, measured in μm units. This surface lacks features at the finest length scales but presents a challenge for conformability at the scale of 1-2μm, which we believe to be the greatest unmet requirement for prototype nanofibers samples produced to date.

Other materials with similar surface properties include interior wall panels and ceramic tile. Glass is considerably smoother and is less useful as a surface for testing.

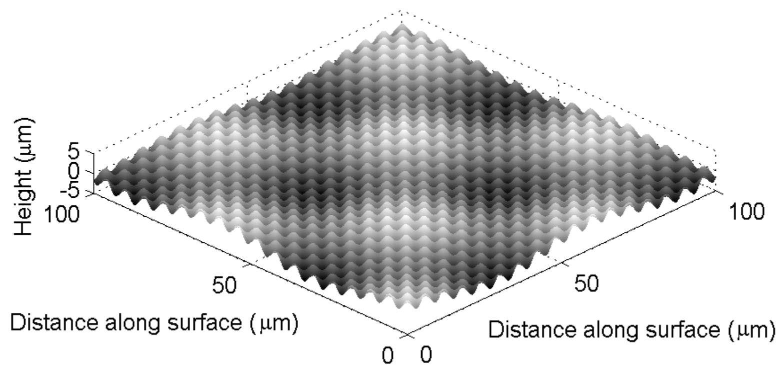

Figure 2: Reference surface

The essential requirement is that a sufficient number of nanofibers make contact with the reference surface to obtain useful levels of adhesion and shear force. For the purposes of this specification, minimum "useful" levels are:

- Adhesion $\geq 0.06 N/cm^2$ – For smaller patches, somewhat higher adhesive levels will be required, assuming that not all patches mate perfectly with the surface. For example, we anticipate needing $4x10^{-3}N$ per 2mm x 2mm square sample, as measured in a pure normal force pull-off test.
- Shear $\geq 0.5N/cm^2$ (i.e., at least 0.03N per 2mm x 2mm square sample, as measured in a pure shear force pull-off test, again assuming that not all patches mate perfectly).

These values are obtained assuming a small robot of 0.15 Kg mass with modest dynamic loading. For larger robot platforms, higher values of adhesion and shear stress will be needed for practical climbing, without enormous feet.

For rougher surfaces, it is assumed that the meso-scale suspension structures being designed at Stanford will provide the necessary conformability.

The above functional requirements for the specimens impose corresponding functional requirements for the nanofibers and the substrate. The fibers should not not detach from the substrate under imposed shear and tensile loads. The fibers and substrate should also not sustain permanent damage when larger shear forces (up to 10x the minimum values listed above) are applied in combination with positive normal forces of up to $1.0N/ cm^{2}$.

The specimens should also be able to undergo 1000 or more attach/detach cycles without significant reduction in their adhesive functionality.

Organizational Requirements

The quantify of specimens is such that we need to be able to populate up to 4 square centimeters per foot or 20 square centimeters per robot (x *N* robots). Thus, for example, if the specimens are 2mm x 2mm in size, we will require 25 specimens per square centimeter and as many as 100 per foot. We typically develop and test up to a dozen feet before releasing them to Carnegie Mellon and other partners for use on the RiSE platform. Therefore, if the specimens are less than one centimeter squared, we will require hundreds of them.

If hundreds of specimens cannot be provided that satisfy the Functional and Physical Requirements listed above then a collaborative effort will be required. For example, it may prove that adequate levels of adhesion are not obtained for specimens greater than 50μmx50μm in size. In this case, the supplier will need to collaborate with Stanford to develop a micro-suspension that bridges length scales between 50μm and 2mm. In this case:

- The partner must work with Stanford to define a joint manufacturing strategy that produces foot surfaces, populated with specimens in sufficient quantity and quality. Stanford can undertake the fabrication of micro- or meso-scale suspensions if the fabrication process itself does not require clean room facilities. Alternatively, Stanford personnel could be given access to the facilities of the supplier to help with the fabrication.
- Testing and fabrication will be take place over a period of several months to a year with incremental improvements each month. A smaller number of prototype foot surfaces will be produced every couple of months, requiring monthly shipments of prototype adhesive specimens in quantities of 20-100 samples for experimentation and testing.
- As useful levels of adhesion start to be achieved for specimens of 50μmx50μm or greater, it will be necessary for Stanford to produce a special lightweight (e.g. 0.15 Kg) robot platform specifically for the purposes of testing adhesives. Weekly teleconferences with the supplier will be required to monitor progress with the specimens and with their application to the robot platform and to establish functional and physical specifications that need further work.