Ergonomics for the Invisible

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Introduction

Nanotechnology represents a major area for research and development and has already led to the introduction of hundreds of products that incorporate nanotechnology-based materials, components, or methods. It is an area of significant investment and economic development globally. NanoInk, Inc. designs and develops instrument systems used for nanotechnology research, education, and manufacturing. Our initial product was built to support sophisticated research programs in academic and government labs. It was based on a complex instrument that was difficult to learn and use: the atomic force microscope (AFM). In order to make our technology accessible and useful to a broader range of potential customers and markets, NanoInk developed a new instrument platform, NLP 2000, that is simpler to learn and operate by users who are not university-trained PhDs. This article will discuss several of the challenges, design goals, and approaches taken in developing this instrument platform.

Dip Pen Nanolithography

NanoInk designs and builds desktop nanofabrication platforms for patterning a variety of materials using the technique of Dip Pen Nanolithography® (DPN®). DPN was initially developed using AFMs [1, 2].

The simplest way to visualize DPN is to imagine an old-fashioned quill pen touching the paper and leaving ink behind. A modified AFM tip or array of tips is used as a pen. The head of the tip is coated with ink. When the tip touches the substrate, the molecules of the ink are deposited onto the surface through a solvent meniscus (Figure 1) that forms between the head of the tip and the substrate. As for the ink, many materials can be used including biological molecules, nanoparticles, and small molecules such as self-assembled, monolayer-forming thiols. You can think of this as the world's smallest quill pen because the pen is only several micrometers across at the base. Structures that are written by these pens are too small to be seen by even the most powerful light microscopes. Hence, we sometimes say we work at the level of invisibility with this technology. In short, DPN is a direct-write, tip-based lithography technique. It has evolved directly from AFM and initially was performed primarily on AFM hardware. We designed the NLP 2000 System, the first non-AFM-based platform for DPN, with dual goals: (a) to overcome limitations of AFMs and (b) to create an easy and intuitive DPN experience for users without specialized AFM skills.

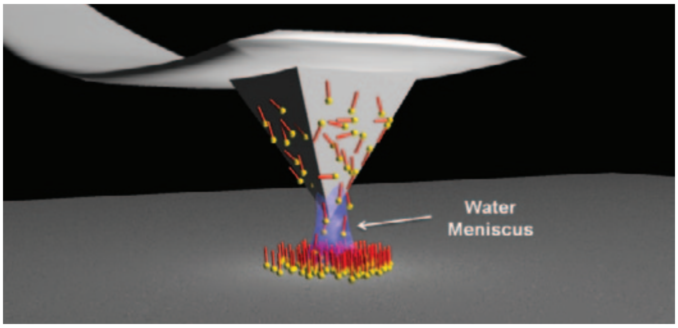


Figure 1: Nanoparticles from an AFM tip deposited on a surface through a solvent meniscus.

The Invisible World of Nanotechnology

The NLP 2000 is capable of writing features smaller than 100 nanometers on a variety of substrates. One of the most common is a standard glass microscope slide (75 × 25 mm). The scale factor of a 100 nm dot to the width of a glass slide (25 mm) is approximately the same as the thickness of the sheet of paper to the width of football field. To put it another way, it is the size of a car to the size of the United States of America.

Taking this scale factor into consideration, the NLP 2000 can be viewed as an ink delivery system that bridges the gap between the macro world of human fingers, tweezers, and pipettes and a nano world of molecules. Ink is delivered in a three-step process with the help of a micro fluidic device called an inkwell. The inkwell is a silicon chip (10 × 10 mm) that has been precisely etched and treated for an exact combination of hydrophilic/hydrophobic properties. Figure 2A shows a top view of a typical inkwell with six reservoirs. Each reservoir has a diameter of 2 mm and a depth of 85 μm. The reservoirs are linked to the 20 μm diameter microwells via 40 μm wide channels that lead into 6 μm wide microchannels (Figure 2B).

The first step takes place in the macro world. Using a standard lab micropipette, a small droplet of ink is deposited into the reservoir. Any person with reasonable dexterity and minimal training can accomplish the task. From the reservoir,

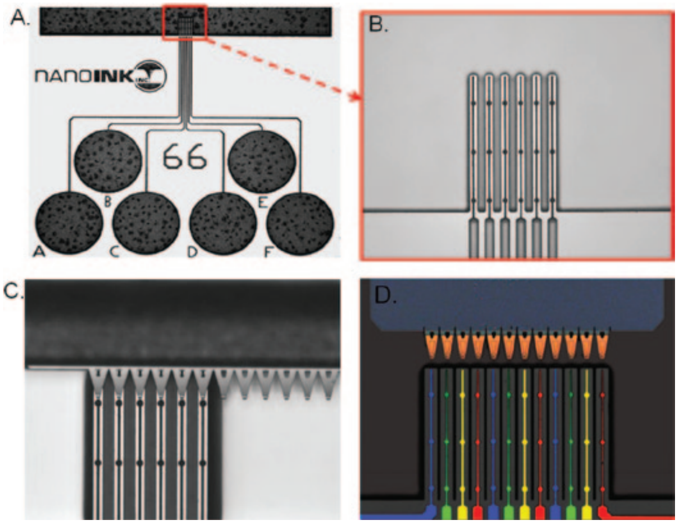


Figure 2: Inkwell and inked tips. (A) Top view of six ink reservoirs, (B) microchannels for ink distribution, (C) alignment of tips with microwells, and (D) multiple reservoirs for different inks.

ink is distributed to the microwells by capillary wicking in micron-sized conduits, or "microchannels."

The second step takes place in the micro world. Through the use of its 5-axis nanopositioning stage and high-magnification light microscope, the NLP 2000 makes it possible to precisely align a tip or array of tips with the microwells (Figure 2C) and then dip them into the ink. Figure 2D shows multiple reservoirs for different inks.

The third and final step is a transfer of the ink from the tip to the substrate. Results of this step may or may not be visible through the light microscope regardless of the microscope's magnification level. The limits for light microscopy are generally considered to be about a half wavelength of visible light, which is between 400 and 700 nm. A dot that is 100 nm in diameter, for example, will not be visible through the light microscope and will require other, more sophisticated means of detection. So the process of nanofabrication facilitated by the NLP 2000, inkwells, and tips allows a user to take macro scale materials and create essentially invisible structures at the nanoscale [3]. The challenges of designing a system for this purpose stem from this transition in scale.

Bridging the Gap

Well-designed devices perform as expected. When expectations are not fulfilled, humans become increasingly cautious. This is the natural result of uncertainty in human–machine interaction. However, what if human limitations are the cause of uncertainty? In the world of micrometers, let alone nanometers, people are clumsy. Even the person with the finest motor skills will have difficulty operating tiny objects with sufficient precision. When a glass slide needs to be oriented parallel to the inkwell, how can we ensure they are parallel? Imprecise placement of the parts can greatly affect the results of nanolithography. There is also an emotional aspect of positioning uncertainty, which often translates into a perception of the instrument not behaving "as expected."

In order to mitigate a tactile ambiguity, we deployed a variety of intermediate devices. Their purpose is to overcome physical limitations of human extremities. First and most widely known is the micropositioner. The NLP 2000 uses these devices to move tip arrays under the light microscope. For the optimum user experience, we optimized all micropositioners for high linear resolution, smoothness, and minimal hysteresis.

The second intermediary device is commonly known as a kinematic coupling. The kinematic coupling (or mount) is a system that enforces kinematic determinacy between two parts in contact. An example of a kinematic mount consists of three balls in one part that mate with three radial V-grooves in another. There are two basic concepts for kinematic systems (Figure 3), known as Maxwell and Kelvin mounts. Although there has been much debate over whether the Maxwell or the Kelvin kinematic coupling is more accurate, the preference in NLP 2000 design was given to the Maxwell type system, as more thermally stable.

As an example of how we deploy kinematic mounts throughout NLP 2000, consider how substrates are prepared for nanolithography. Early on it became clear that loading small parts directly onto the instrument is tricky. A preferred approach is to have a detachable part, a "substrate table," which we can take to the workbench, load with inkwells and substrates, and then return to the instrument (Figure 4A).

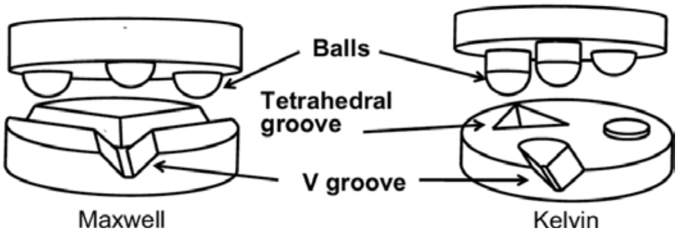


Figure 3: Kinematic couplings (MIT Precision Engineering Research Group).

This preferred approach is derived from our observations of routine lab practices. It also makes common sense. It is not too difficult to pick up a small piece of silicon with tweezers and move it an inch or two to the substrate table, which is sitting on the same workbench (same elevation). Moving the same piece of silicon several feet away, to a different elevation, and possibly reorienting it in the process is more difficult and

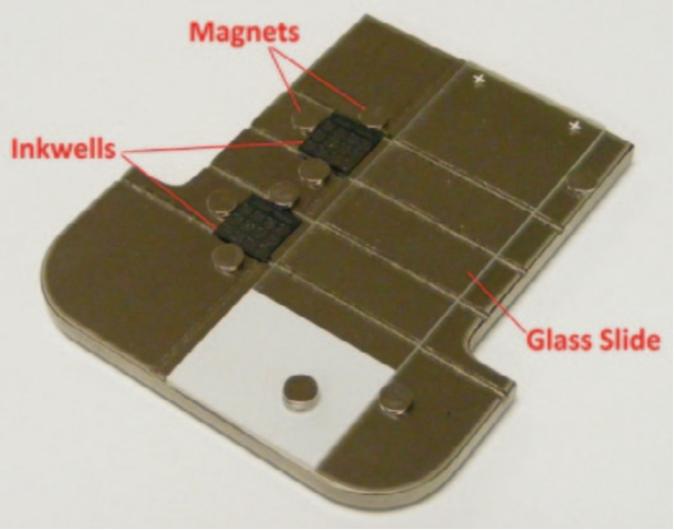


Figure 4A: Detachable substrate table with glass slide and two inkwells.

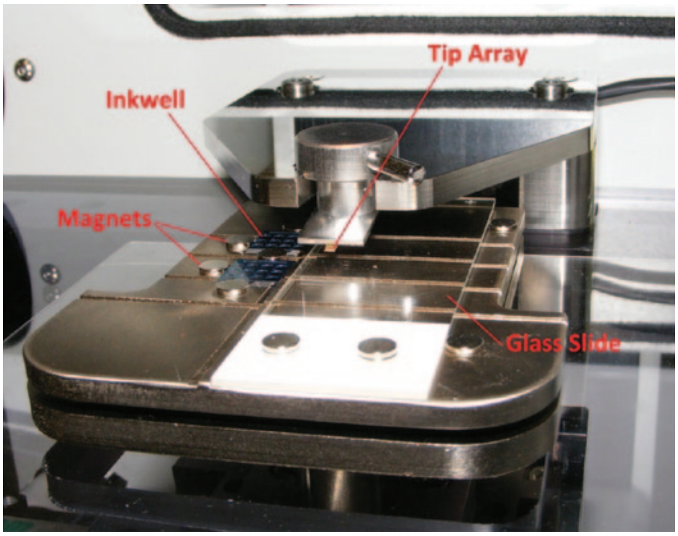


Figure 4B: Detachable substrate table on the instrument.

has a substantially lower success rate. Why is that? We have no difficulty moving larger parts with our bare hands and orienting them as needed. Why can't we do it with tweezers? The answer is in the lack of tactile feedback. The piece of silicon is too light for the human hand. We can feel neither the weight of the piece nor the inertia of it when we move it. Moreover, holding the piece with tweezers heavily distorts the sense of pressure we apply.

We designed the substrate table for NLP 2000 to produce affirmative tactile feedback for the user. The table has a form factor compatible with the size of the human hand. It has a weight to it that is just right (not too heavy and not too light). It can also hold a variety of substrates and inkwells. The table features a number of grooves and ridges against which the user can press the substrate (glass slide) and inkwell(s) to enforce desired parallelism. The table is detachable, so the user can remove it from the instrument. When the glass slide and inkwell(s) are in position, the user secures their relative positions with small magnets. Now the table can be returned to the NLP. The bottom side of the table is equipped with three balls. Each of the balls will mate with its respective kinematic mount V-groove when the table is returned to the NLP (Figure 4B).

Strictly speaking, there should be a reasonable expectation that when the human hand releases the substrate table at the instrument, the table must find its stable and repeatable position without any additional human interaction. This is known as self-positioning. As the user's hand releases the table, gravity takes over; the table "sinks" into V-grooves until it has nowhere to go. Moreover, the user should be able to say with certainty that the table has actually "sunk" into the mount. The haptic feedback of the coupled kinematic mount is unmistakable and further reinforces the notion of "as expected" instrument behavior.

The third intermediary device is a magnet. We like magnets and use them liberally throughout NLP 2000. In some instances magnets serve a structural purpose, such as holding together two parts against the forces of gravity, thermal expansion, or air pressure. In other cases we deployed magnets for the sole purpose of reinforced tactile feedback. If the part is light, the added feeling of suction the magnet creates, articulates the completion of the placement.

Camera-Centric Design

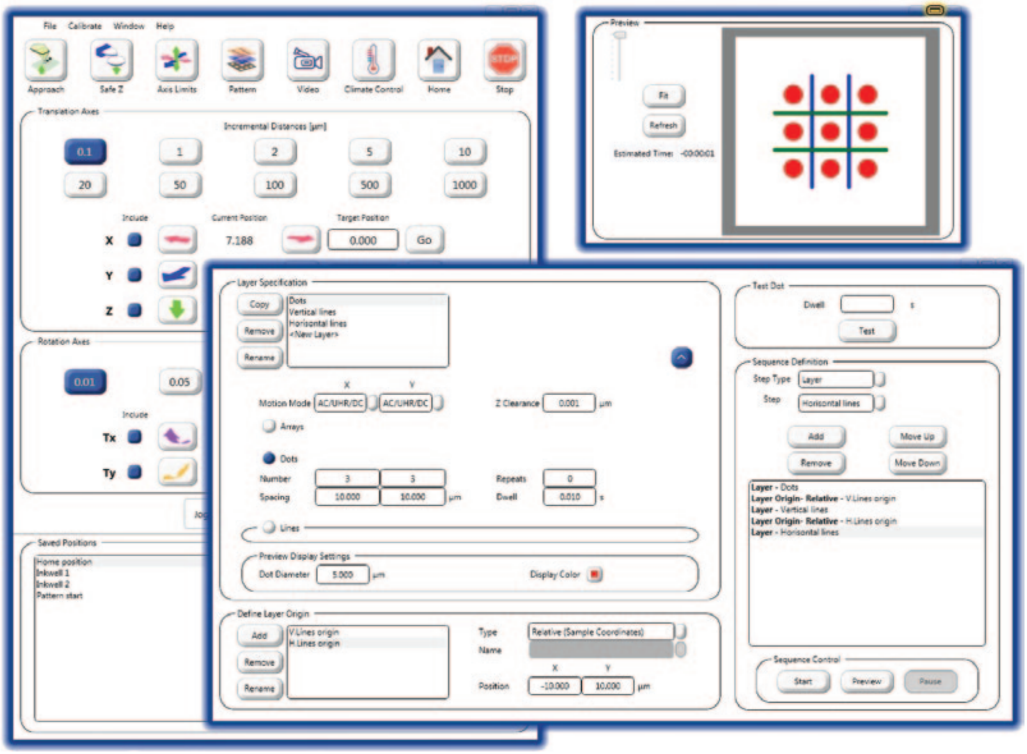
The visual feedback of the NLP 2000 system is realized through the use of a light microscope and high-resolution camera delivering a live feed of the tip and substrate area to the computer screen. From the user's point of view, the camera on NLP 2000 is stationary. Everything the user observes on the computer screen corresponds to movements in a real 3-D environment. For example, when the user moves the tip from left to right using the manual micropositioner, the image of the tip also moves from left to right on the computer screen. Similarly, when the user moves the substrate against the tip using the 5-axis nanopositioning stage, the corresponding movement on the computer screen reflects proper direction.

User Interface

To facilitate intuitive interaction, the user interface was specifically designed to avoid a steep initial learning curve. It is simple and self-explanatory for straightforward interactions. As familiarity with the instrument grows, the user may start accessing an increasingly complex variety of tools. This progressive disclosure of complexity and functionality extends all the way to the ultimate flexibility of a scripting language that is built into the product.

Figure 5 shows the Pattern Design window. In the arsenal of NLP 2000 tools, this one is of medium complexity. The user designs a lithography pattern as a sequence of operations or steps. Each step, in its simplified form, is either a layer or a repositioning move. Each layer is an uncomplicated pattern of dots or lines. The preview window provides an immediate visual feedback for the design pattern.

The "tic-tac-toe" pattern (Figure 5), for example, consists of three layers: dots, vertical lines, and horizontal lines. The user can assign different colors to distinguish the layers. Real-life patterns, however, are substantially more complex



X Current Position: 7.188
Target Position: 0.000

Saved Positions:
Home position
Inkwell 1
Inkwell 2
Pattern start

Estimated Time: ~00:00:01

Layers:
Dots
Vertical lines
Horisontal lines
<New Layer>

Motion Mode X: AC/UHR/DC Y: AC/UHR/DC
Z Clearance: 0.001 µm
Number: 3 3
Spacing: 10.000 10.000 µm
Repeats: 0
Dwell: 0.010 s
Dot Diameter: 5.000 µm

Layer origins:
V.Lines origin
H.Lines origin

Type: Relative (Sample Coordinates)
Position X: -10.000 Y: 10.000 µm

Step Type: Layer
Step: Horisontal lines

Layer - Dots
Layer Origin- Relative - V.Lines origin
Layer - Vertical lines
Layer Origin- Relative - H.Lines origin
Layer - Horisontal lines

Figure 5: User interface: main control panel and pattern design tool.

and multilayered. To accommodate the user's need for visual feedback during design, the preview window offers full zoom and resize. When the user selects "Start," the patterning sequence is executed, and the tips write the pattern displayed. Because the resulting physical pattern may be too small to visualize in the optical system of the NLP 2000, the graphical preview is critical for the user to visualize what will be printed by the system.

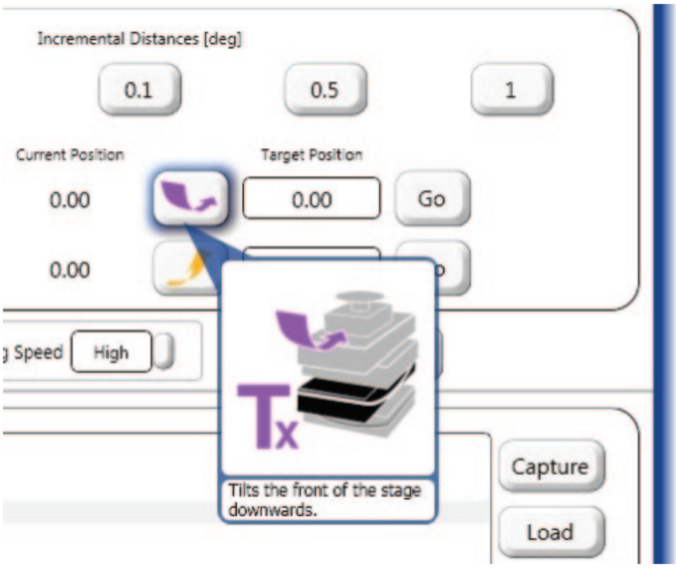
Special attention was paid to design of icons and the information displayed by tool tips. If in doubt, the user can hover the mouse pointer over the control in question and see the tooltip. All of them contain both text and graphics, illustrating the specifics of the message (Figure 6).

Sticky Tape and Tip Positioning

The initial method of attaching tips to the tip holder used double-sided adhesive tape. The tools needed for such an operation are tape, tweezers, and a sharp blade (such as X-Acto knife). Once again, a human with reasonable dexterity and adequate training can accomplish this task with ease. Figure 7 shows the dimensions of a commonly used tip array. Merely placing the body of the tip on the adhesive tape and giving it a slight push with tweezers creates a sufficient bond for secure mount.

The surface area of the tip's body that is exposed to the adhesive tape is typically between 2 and 3 mm^2. The adhesion forces generated over such a large area are sufficiently strong for mounting. From a mechanical point of view, the tip mounting method is sufficiently rigid to support proper DPN operations.

Although initial internal company testing of the method indicated that it was useful and flexible, a wider general audience perceived it as inadequate. The two main comments were: (a) users noted a lack of tactile feedback during tip placement, and (b) the adhesive was viewed with a negative connotation (considered a "cheap," low-tech approach). To accommodate this user feedback, the tip holder was later redesigned to include a restrictive area for tip placement and spring-loaded clamp.



Tilts the front of the stage downwards.

Figure 6: User interface: tooltip.

Figure 8 shows features produced by the NLP 2000. This figure shows arrays of dots in a diamond pattern.

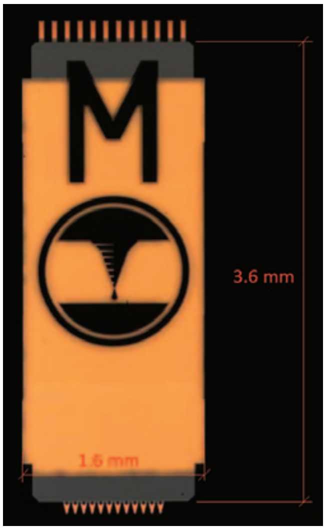


Figure 7: Typical tip array.

Applications

We believe that by achieving many of the design goals established for the NLP 2000 instrument system we have allowed the product to be successful in several significant new market areas and applications [4]. In addition, we have further customized elements of the system for specific customer segments. For example, one of the main applications for our technology is printing arrays of biomolecules on glass slides for DNA and/or protein assays [5]. Customers are primarily biologists or technologists working in biomedical labs. These are definitely not users who would be familiar with or capable of working with our original AFM-based tools. We have tailored the software, pens, inkwells, and slide holders specifically to the slide printing application. Furthermore, we have added additional automation for the entire slide layout and printing process, providing an almost turn-key system tailored to this specific user group.

One of the most promising new business areas for the NLP 2000 is our NanoProfessor^{TM} Nanoscience Education Program to prepare high school and university students for careers in nanotechnology. The NanoProfessor program includes an NLP 2000, along with several other instruments, a complete curriculum, labs, and student/teacher support materials. This demonstrates the value of developing a system with ease of learning and use because students as young as 14 years of age use this program. Figure 9 shows an NLP 2000

Figure 8: Light microscope image of arrays of dots in a diamond-shaped pattern created by the NLP 2000.

Figure 9: NLP 2000 installation at Dakota County Technical College.

at one of our NanoProfessor installations at Dakota County Technical College (DCTC).

Conclusion

Design considerations for interacting with nano-sized objects have been outlined. To produce components and devices with nanolithography, the user interface must be carefully thought out and even adjusted for particular user communities. An example of this type of ergonomic engineering is the NanoInk NLP 2000, an easy-to-use dip pen nanolithography system for research, manufacturing, and education.

Acknowledgments

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