

# DESIGN OF PRECISION MANIPULATORS USING BINARY ACTUATION AND DIFFERENTIAL COMPLIANT MECHANISMS

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## 1. INTRODUCTION

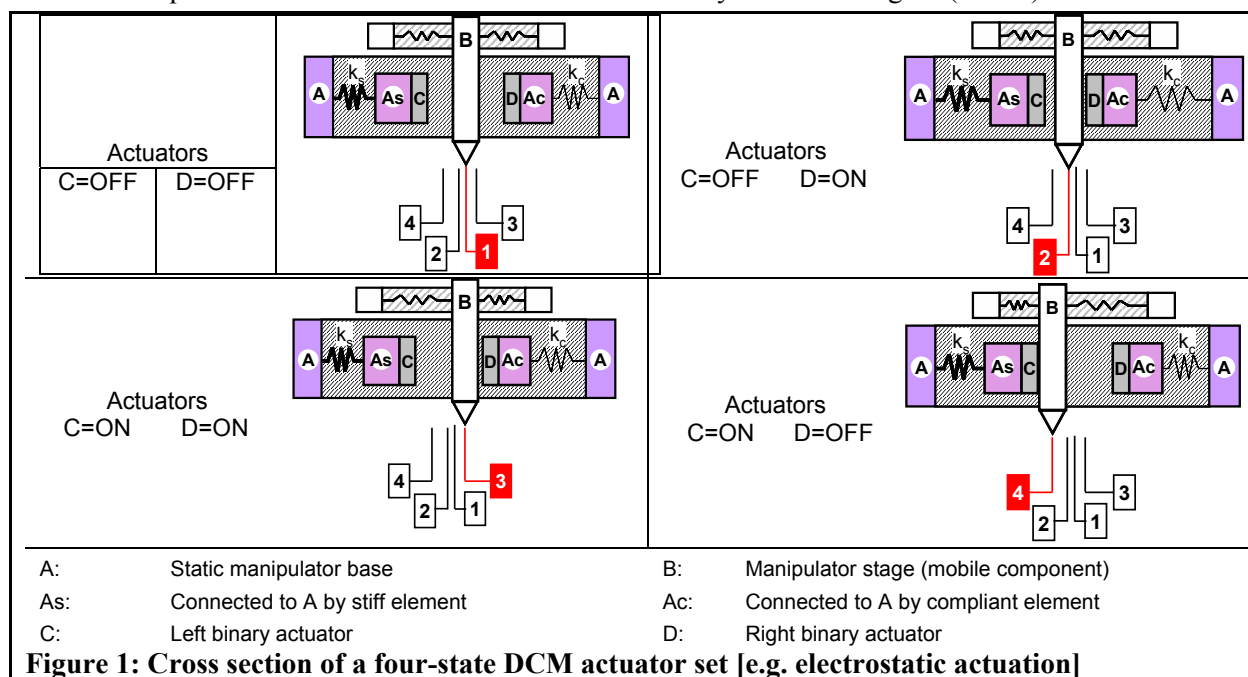
The quality of fixturing, testing/inspection, material handling and other manipulation processes for micro and nano-scale devices depends on the performance of positioning equipment. Many “next generation” positioning technologies are enhanced versions of decades old hexapods, stacked linear stages or flexure stages. Forcing these macro-scale concepts to provide sub-micron performance yields expensive manipulators. These equipment costs are then reflected in micro and nano-scale products, often making up as much as 50% of packaging cost. As a result, many scientists and engineers are now convinced that small-scale products which require manipulation/alignment or assembly can not be commercially viable.

Discrete Nano-Actuation Technology (DNAT) may change this perception. We propose a novel, low-cost manipulator which uses teams of opposed, binary actuators in series with compliant elements to attain many repeatable, discrete positions in a given workspace. The purpose of this paper is to demonstrate the technology via a case study on a macro-scale Cartesian manipulator. The end goal of this research is to miniaturize this concept to a micro-scale manipulator for manipulation of small-scale components (e.g. on-chip Nanomanipulation).

## 2. DESCRIPTION OF DNAT TECHNOLOGY

### 2.1. Fundamentals of DNAT manipulation

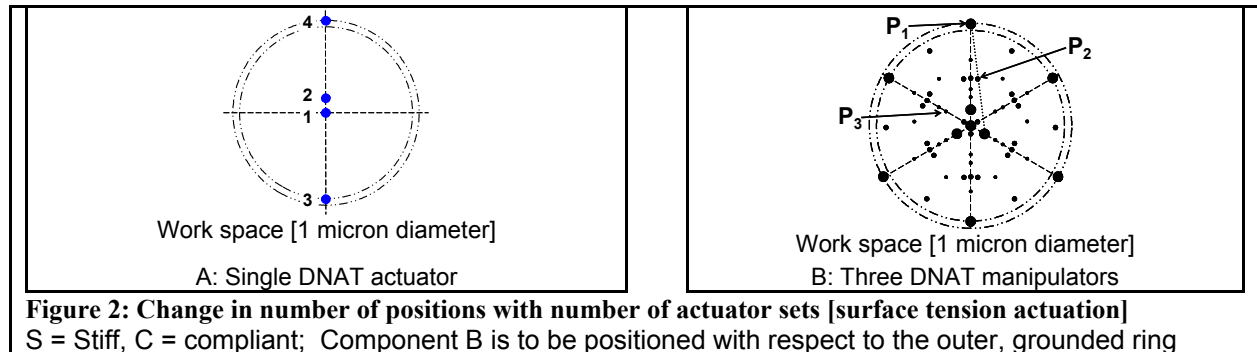
Figure 1 shows the basic building block of DNAT manipulators, a single, linear DNAT set. We wish to position B (e.g. wave guide or carbon nano-tube) with respect to A using this set. Opposed compliant elements of different stiffness ( $k_s$  and  $k_c$ ) permit sub-components of part A,  $A_c$  and  $A_s$ , to move relative to A due to compliant connections. This is achieved with easily controlled digital (on-off) actuation.



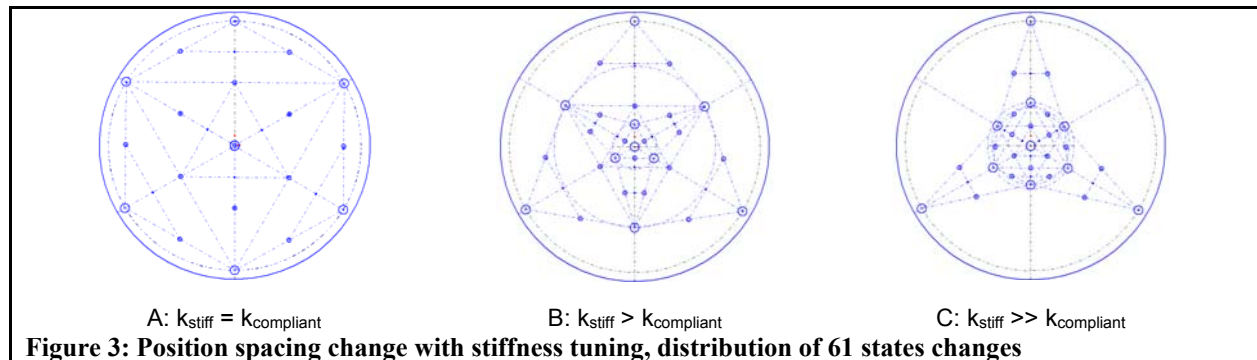
Actuators C and D, are energized as indicated to produce four positions. It is important to note the range/spacing of states for a set may be set by changing the difference in stiffness between  $k_s$  and  $k_c$ .

## 2.2. Practical application of DNAT actuators

The displacements from several sets of DNAT actuators may be superimposed to form a Cartesian (x-y) manipulator. Figure 2 provides a comparison between a single set (4 states) and 3 sets (61 states). The difference in stiffness of each DNAT actuator and the compliance of the manipulator enables one to superimpose different digital actuation combinations to obtain many of the positions within a given work space. Without the difference in stiffness (differential stiffness), attaining many of the states shown in Figure 2 would be impossible. They are combinations of states obtained via differential compliance.



DNAT devices are used to position at discrete points that achieve an acceptable aligned position. For example, one may move from  $P_1$  to  $P_2$  or to  $P_3$  if this provides an improved state of alignment. By saturating the work space with more points (i.e. adding actuator sets), the performance of DNAT devices approaches that of analog alignment systems. This is easily accomplished as the number of discrete positions scales with:  $2^{(2 \times \# \text{ of actuators})}$ . Six DNAT sets provide over 4000 positions in a given work space. This yields repeatable positions spaced an average of 15 nm. Smaller or larger spacing may be achieved by changing the difference in stiffness between the opposed compliant elements. The effect of varying the stiffness is shown in Figure 3.



## 2.3. Potential benefits of the technology over traditional precision manipulators

In comparing DNAT technology to traditional systems, one must consider the following:

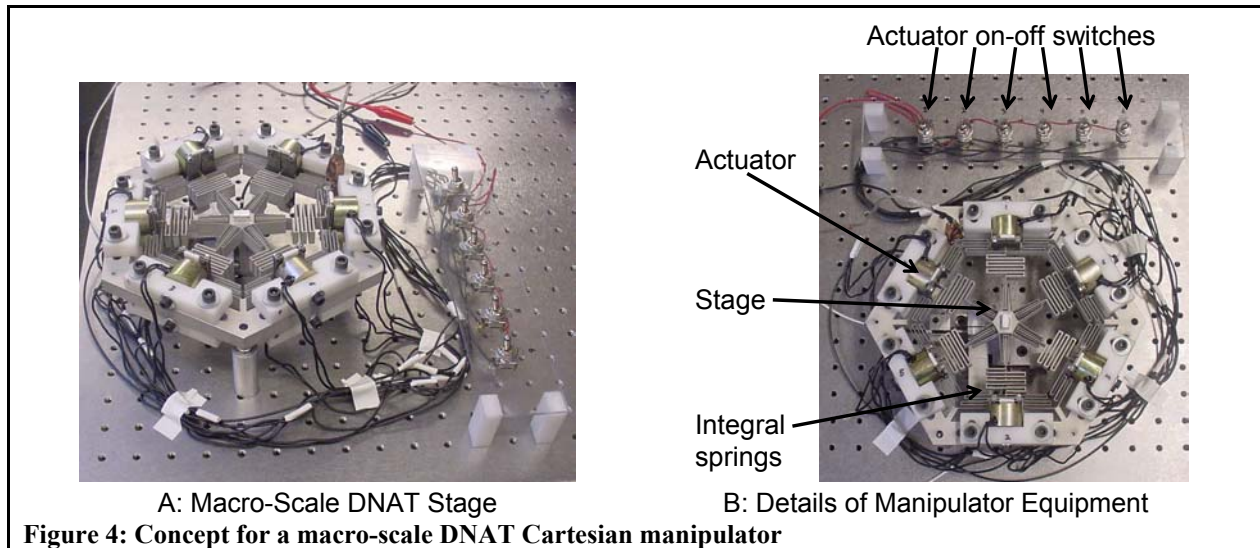
**Structure design and manufacture:** The manipulator is a monolithic compliant mechanism. Within the mechanism are flexible elements which passively work in teams to provide fine resolution position changes. These structures are easily defined/manufactured via DRIE and other micro-fabrication processes. As a result, integration into existing Microsystems should be possible.

**Actuation, sensing and control:** Binary actuators provide well-defined (i.e. repeatable) inputs to the manipulator that can be maintained with no power (off position) or low power (on position).

Repeatable binary actuation enables nanometer level repeatability (and accuracy if calibrated/mapped) without extensive sensing/feedback control.

### 3. EXPERIMENTAL SETUP AND PROCEDURE

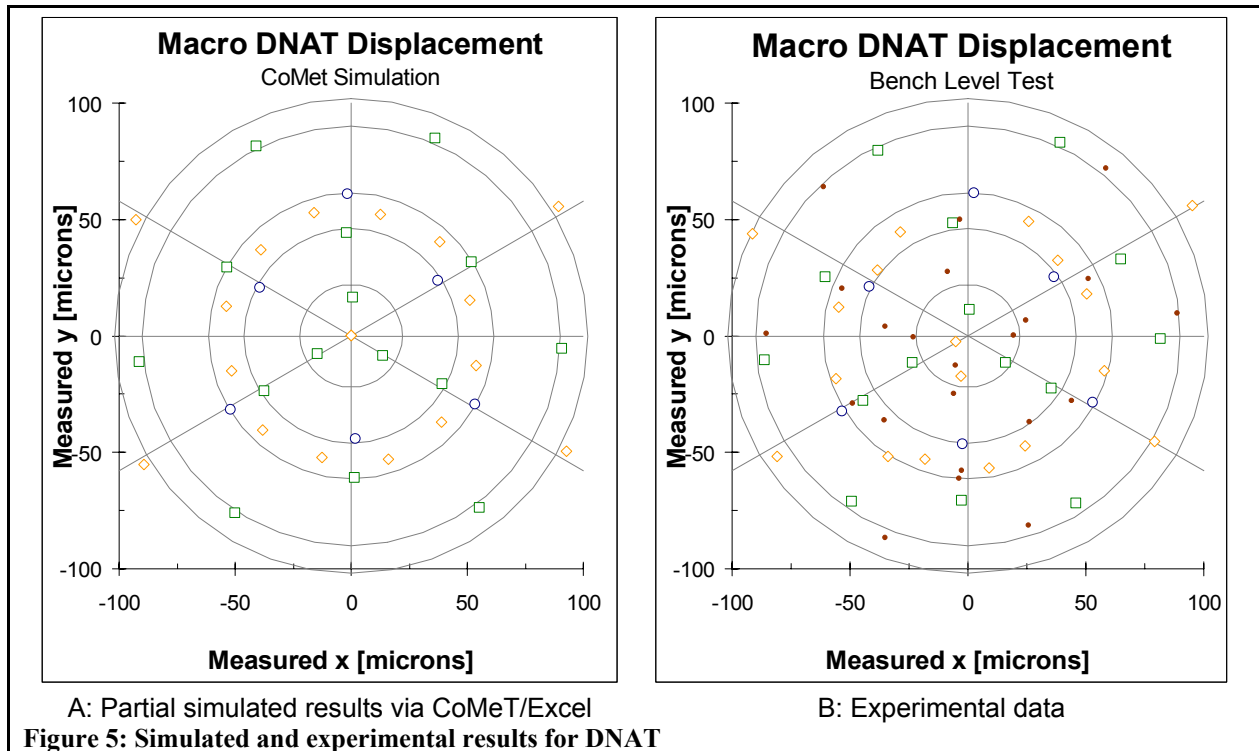
A macro-scale version of a three actuator DNAT manipulator was built to provide a means to characterize the performance of a manipulator concept. Figure 4 shows the macro-scale DNAT manipulator. The heart of the stage is a monolithic compliant mechanism which is cut from Aluminum sheet on an abrasive waterjet cutter. The mechanism is driven by sets of electromagnetic actuators which act in a binary mode (on-off). The electromagnets are thermally isolated from the compliant structure via polymer mounts and stand offs. When energized, they attract and cause a ferrous metal part on the manipulator to contact a hard stop. Thus a well-defined stroke is obtained for each binary actuator. Two capacitance probes are used to read the x and y displacement of the stage from its non-actuated (home) position.



A series of switches (see Figure 4B) were turned on/off to obtain different digital actuation combinations with corresponding unique position states. As indicated earlier, this radial design is capable of producing 61 unique states within a given work space.

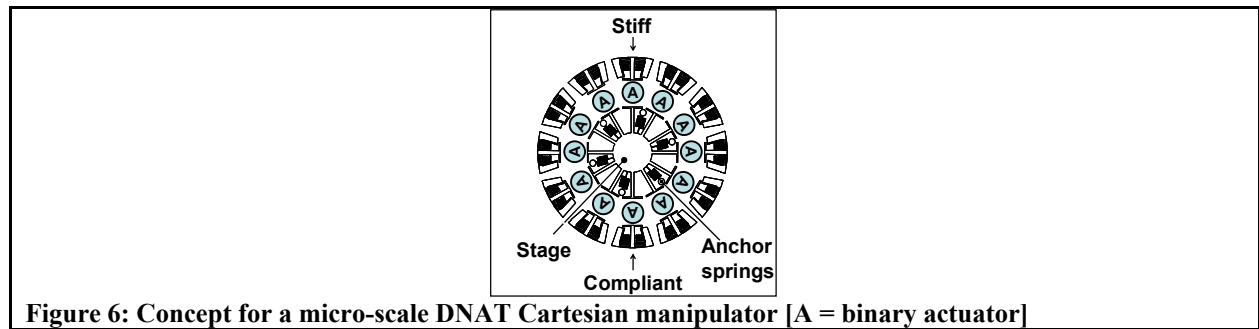
### 4. RESULTS

Figure 5 shows two plots which compare performance simulation with actual displacement of the DNAT manipulator. The digital actuation combinations and stage displacements were modeled using CoMeT and Microsoft Excel. Figure 5A shows a partial plot of simulated states (not all 61 are shown). Figure 5B shows a full plot of states obtained from an experiment. This comparison shows a reasonable agreement for a first-level prototype. From inspection, it can be seen that most displaced states vary by approximately 20% from their intended position. This is not surprising given the data was taken with no calibration and the fact that the stiffness of the compliant mechanism (local and global) differs from the model due to manufacturing errors (thickness variation and taper from the waterjet cut). Fortunately, the accuracy of this stage can be improved on the macro-scale by calibrating the space (~ 500 microns) between the hard stop and the ferrous target (e.g. shimming). However, on the micro-scale this promises to be more challenging as the final state of the fabricated device may be difficult to move/calibrate to achieve a desired behavior. The repeatability of obtaining a state with the macro-scale DNAT manipulator has been measured at better than 1% of the displaced value.



## 5. DISCUSSION

The results of the initial test are promising and warrant further study of the technology on the micro-scale. The next step in this research is to focus on building of a base of knowledge on the best way to apply this technology to micro-scale devices. At present, the concept in Figure 5 is being investigated for the first attempt at a micro-scale DNAT manipulator. The manipulator is equipped with on-off electrostatic actuators. Simulations predict this design will attain over 4000 discrete states within a  $1\mu\text{m}^2$  work area.



Additional efforts are underway to produce planar, spherical and spatial devices which utilize this digital actuation technology.

## 6. REFERENCES

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