# Driving a Femtosecond Machined Tactile Scanning Probe Stage in the 100 µm Range

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## Abstract

We propose a novel meso-sized electromagnetic actuator design for driving a femtosecond machined tactile scanning probe stage in the 100 µm range. The final design uses a static flat single-turn coil with heat fins, with which thermal limitations usually faced in high precision actuation are overcome. High current densities up to $10^8$ A/m$^2$ can be reached. On a PCB, we easily manufacture a first prototype, with which we predict to achieve a (constant) 5 mN force over a 200 µm range.

## 1 Introduction

Systems built for actuation on the micro-scale are of high interest in the field of optics and high precision 3D metrology systems. Due to complex interplay of the different scaling laws at the meso-scale, such actuators are usually micro- or macro-sized [1]. Continuing on the research of Bousteen et al [2], we investigate the effects of scaling laws on the performance limits of high force (1 mN), high stroke (100 µm) meso-sized (0.5 – 2 mm$^3$) actuators, i.e. electrostatic, electromagnetic and piezoelectric actuators. The best performing actuation method is selected, optimized and fabricated for the actuation of a 3 degree-of-freedom (3DOF) stage, suitable for ultra precision 3D tactile scanning probes.

## 2 Selection of Actuation Principle

The choice of actuation principle for a certain application is usually based on databases and determined by interpolating (using scaling laws) between performance characteristics of documented (commercial) actuators. Such interpolation procedures and the few available meso-sized actuators however, serve as poor guidelines for establishing the performance limits of these types of actuators.

A better approach would be to investigate the maximum achievable work density of representative designs for each physical principle. We write the work density as a function of geometrical design variables limited by a set of constraints (e.g. physical properties and/or physical thresholds), which must all be satisfied.

Using optimization algorithms, we compared electrostatic (ES), electromagnetic (EM) and piezoelectric (PE) actuators. Highest work densities are found in EM and PE actuators. Even so, in the case of ES and PE actuators, there is an inevitable need for amplification mechanisms to reach the desired stroke. On this scale this leads to the use of flexures: a lot of the available work is lost in the movement of these flexures, resulting in poor dynamic behaviour. Overall, in terms of dynamic behaviour, complexity of fabrication and maximum work density, EM actuators show to be the most suitable actuation scheme in the meso-domain.

## 3 Implementation

The major limitation of Lorentz actuators is their thermal weakness [3]. To address this, as well as dealing with practicality and fabrication reasons, different configurations were devised and simulated for implementation in a 3DOF stage. The three free degrees of freedom needed are $z$, $\theta_x$ and $\theta_y$. As we use a planar base plate, an out-of-plane actuator is desired (Figure 1A).

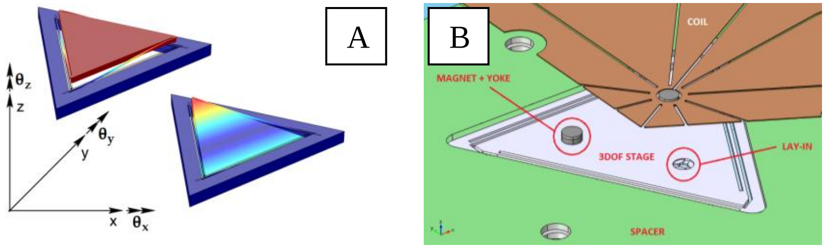

Figure 1 – A: Simple 3DOF stage with the corresponding coordinate system. B: Semi-assembled CAD model of the final design.

The final design (Figure 1B) consists of a cylindrical Nd-magnet (∅1.5 mm, h 0.5 mm, $B_r$ 1.38 T) with on top an iron yoke (∅1.5 mm, h 0.25 mm) to compress the magnetic field and guide it outwards. Around the yoke, a flat single-turn copper coil is located (Figure 2A), embodying the most magnetic flux in its initial position ($\varnothing_i$ 1.9 mm).

As the mass of the magnet and yoke is sufficiently small, we find that it is more convenient to make the coil the stator, meaning it can be fabricated on a fixed substrate. This, together with the low resistance of the single-turn coil, addresses the thermal limitation mentioned above, as we can now easily add cooling fins to the coil. Furthermore, using PCB fabrication methods, we can easily manufacture a first prototype with high enough precision. Using this method however, we are limited in the height of the coil for the first prototype. For typical thicknesses of 35 - 70 µm, the motor-constant is shown in Figure 2B. An optimum is found at a width of 0.4 mm.

For the proposed system, according to FEM simulations in *COMSOL Multiphysics 4.2a*, a 1 A current at 293.15 K, leads to a temperature increase of about 1 K. Furthermore, temperature gradients are almost absent. This is confirmed by an infrared measurement (Figure 3A): when subjected to a current of 0.8 A, the coils remain at room temperature. Moreover, when a 1 A current is applied a current density of $10^8$ A/m$^2$ is to be expected. When properly guided, this results in a stroke of over 200 µm with an almost constant force of 5 mN. So not only is the motor-constant almost independent on the stroke (and temperature), but this also means we can use relatively simple amplifiers/circuit boards for actuation.

The yokes are cut from a 0.25 mm soft iron plate by wire-EDM. The 3DOF stage is fabricated by exposing a 0.5 mm thick amorphous silica wafer to femtosecond laser pulses. This induces structural modifications at the laser focal spot, due to nonlinear absorption. Due to preferential etching, the modified regions are etched away in a hydrofluoric (2.5%) etching agent, after which we are left with the desired stage. Lay-ins for the magnets ensure proper individual axial alignment (Figure 3B).

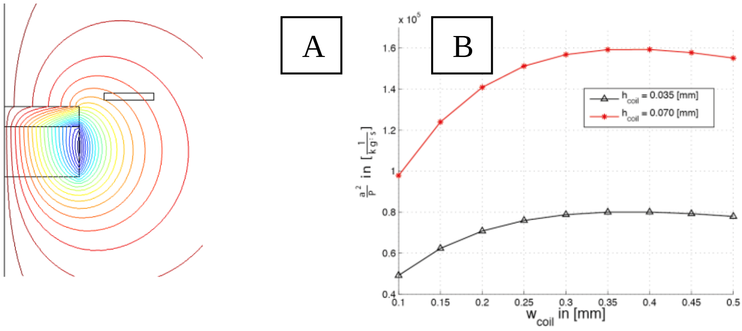

Figure 2 – A: 2D rotationally symmetric simulation of the final design. B: Motor constant for the suggested system as a function of width for two different coil thicknesses (35 and 70 µm).

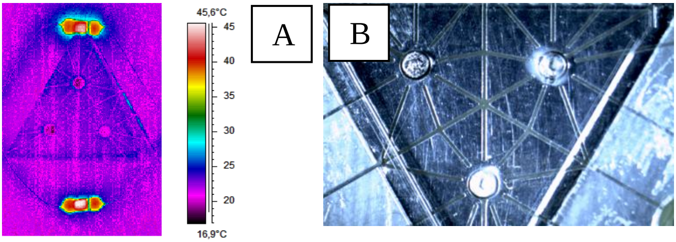

Figure 3 – A: Infrared image of the system. When the coils and a similar resistor (0.5 Ω) are subjected to *I = 0.8 A*, the coils stay at room temperature, while the resistor's temperature increases significantly. B: Assembled system with the magnets glued into the lay-ins of the 3D machined, transparent silica 3DOF stage.

## 4 Outlook

Future work includes the testing of the final prototype. Typically, in 3DOF tactile stages, strain gauges are used for measuring the angular deflection of the stage [4]. However, using an autocollimator, we will optically investigate the angular deflection that the actuators can generate as a function of operating frequency. By characterizing the stage (force-displacement relation) beforehand, we have a reference for the force delivered by the actuators.

## References:

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[4] Gannen XP, XPRESS Precision Engineering, http://www.xpresspe.com/