Report — Design of a Manual Adjustable Manipulator (Inventor 2024)

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Table of Contents

1. Introduction

The purpose of this project is to design and develop a manual micromanipulator for the precision positioning of micromechanical devices. The manipulator allows fine adjustment of a probe tip in X (±10 mm) and Z (±5 mm) directions with a resolution of 10 µm. The design must be compact (footprint ≤ 70 × 40 mm) and manufacturable using common workshop techniques. The probe tip, Ø0.65 mm, should be positioned 100 mm forward and 10 mm below the base plane at an angle of 45°.

The final deliverables include:

- Systematic development with sketches, diagrams, and mathematical verification.
- 3D models of components and assemblies in Autodesk Inventor 2024.
- Material selection.
- Engineering drawings (merged PDF).
- A written report (this document).

2. Technical Principle

The micromanipulator operates on the principle of lead screw–slider mechanisms to convert rotational motion into precise linear displacement.

- The lead screw (M3 × 0.25) is coupled with a manually operated knurled knob. When rotated, the screw translates its helical motion into a controlled linear movement of the slider blocks (X-slider and Z-slider).
- The fine pitch (0.25 mm per revolution) of the lead screw ensures a high resolution of approximately 10 µm per 1/25 turn, enabling accurate micro-adjustments without play.
- To eliminate backlash, an anti-backlash nut with spring preload was used. This keeps the screw threads constantly engaged, ensuring smooth and stable positioning in both directions.
- The X-slider is guided by pins moving in precision slots on the base plate, restricting motion strictly to the horizontal (X) axis.
- The Z-slider is mounted on the X-slider and guided vertically with similar pin-slot arrangements, allowing motion along the Z-axis only.
- The combined mechanism thus provides two degrees of freedom (X and Z motion) within the required ranges (±12.5 mm in X and ±6 mm in Z).
- The probe arm extends from the Z-slider, carrying the probe tip at a fixed angle of 45°, located exactly 100 mm horizontally and 10 mm below the base plate, meeting the design constraints.

This system ensures a compact, self-locking, backlash-free mechanism that can be precisely controlled by manual adjustment, making it suitable for micromechanical device manipulation.

3. Systematic Development

3.1 Sketch and Concept Layout

1. Base plate (70×40×8 mm)
    - Carries all other components.
    - Fixing holes (M4) provided for mounting.

2. X-axis system
    - X-guide fixed on base.
    - X-slider moving ±10 mm.
    - Driven by M3×0.25 lead screw with knob.
    - Screw retained axially using collar and support wall.
    - Dimensions- 25×40×15 mm.

3. Z-axis system

- Mounted on X-slider.
- Z-guide fixed to X-slider.
- Z-slider moving ±5 mm.
- Driven by another M3×0.25 screw.
- Dimensions- 37×40×15 mm.

4. Tip arm

- Length defined by tip_offset = 100 mm, tip_drop = 10 mm.
- A cut with 3.11 length and width 2 mm to rest the probe tip.
- A rectangular block is mounted on Z-Slider with Tip Arm on it.

3.2 Dimensioning Process

- Base: 70 × 40 × 8 mm (max footprint).
- X-travel: 25 × 40 × 15 mm.
- Z-travel: 37 × 40 × 15 mm.
- Lead screw: M3×0.25, L ≈ 77 mm.
- Collar: Ø8 outer, Ø4 inner, thickness 4 mm.
- Knob: Ø20 × 8 mm disk with ergonomic edge.
- Probe arm: 100 mm length, 45° slope, end offset −10 mm below base.
- Probe Tip- Ø0.65 mm.

3.3 Mathematical Verification

a) Travel Range Verification:

- X-direction:
  - Base usable length = **60 mm.**
  - X-slider length = **25 mm.**
  - Travel = **24 mm** (Requirement: ±10 mm = 20 mm total).

- Z-direction:
  - Constrained motion = **11 mm**, (Anti-Backlash Nuts with 8 mm spring, total length = 11, 60-37-11=11 mm)(Requirement: ±5 mm = 10 mm total).
  - Z-slider length = **37 mm**
- Base Plate:
  - Volume ≈ 16,800 mm^3 = 16.8 cm^3
  - Mass (Al): ≈ 45 g
  - Provides a footprint within the 70 × 40 mm requirement.

b) Lead Screw Resolution:

- Required resolution = 10 µm.
- 1 turn = 0.25 mm = 250 µm.
- Length = 77 mm, M3*0.25 screw
- If 100 divisions/rev are used → resolution = **10 µm per step**.

c) Torque Requirement for Lead Screw:

Formula for torque:

$T = F(p/2\pi + \mu dm/2)$

where:

- $F=5$ N (assumed axial load for adjustment)
- $P = 0.25$ mm (pitch)
- $dm = 2.7$ mm (mean diameter)
- $\mu=0.15$ (friction coefficient, lubricated)

Step 1. Lead angle:

- $\lambda=1.66^\circ$

Step 2. Friction angle:

- $\phi=8.53^\circ$

Step 3. Torque to raise load:

- $T = Fd_m/2 \cdot \tan(\phi+\lambda)$,

  $T = 1.2$

Step 4. Torque to lower load (check self-locking):

- $T_{down} = Fd_m/2 \cdot \tan(\phi-\lambda) \approx 0.8$

  Since $\phi > \lambda$, the screw is self-locking (slider won't back-drive).

d) Probe Arm:

- Deflection check under tip force (say 1 N):

  $\delta = FL^3/ 3 E.I$

  For rectangular section: $I = bh^3/12 = 52\ mm^4$

  With L = 100 mm, E = 70 GPa:

$\delta \approx 0.009mm$

→ Deflection negligible (< 10 µm).

e) Probe Tip:

- Cross-sectional area:

$A = \pi \cdot (0.65/2)^2 = 0.33\ mm^2$

Max force before yielding (steel, $\sigma_y \approx 500$ MPa):

$F = A \cdot \sigma_y = 0.33 \cdot 500 = 165\ N$

- Mounted with grub screw → secure, easy replacement.

4. 3D Model (Inventor)

All parts were modeled in Inventor 2024, considering manufacturability.

Components modeled:

4.1 Base Part

Dimensions: 70 × 40 × 8 mm.

Side Walls: Height = 25 mm.

Features:

- Clearance holes are provided on the side walls.

Constraints:

- Base part is grounded (fixed reference).
- Sliders are constrained relative to the base part.

4.2 X-Slider

Dimensions:

- Length = 25 mm.
- Thickness = 15 mm (created using extrusion feature).

Features:

- Two tapped holes (Ø 4.2 mm) on the front and back faces
- Two tapped holes on the top face for fixing the Z-Slider casing

Travel Calculation:

- Effective base length = 60 mm (after excluding 10 mm wall thickness: 5 mm each side)
- Slider length = 25 mm
- Maximum travel distance = 24 mm

4.3 Z-slider

Features:

- Two tapped holes on front and back faces.
- Collars inserted in both holes.

Constraints:

- Bottom face of Z-Slider constrained with the top face of the base part
- Back face constrained with the walls of the base part

Travel Range:

- Minimum = 0 mm
- Maximum = 11 mm

4.4 M4 lead screws with knob

Dimensions:

- Diameter = 4 mm
- Length = 77 mm (extruded)
- Thread length = 75 mm (using thread tool)

Constraints and Features:

- Cylindrical axis constrained with hole in the back wall (allows screw to pass through slider holes)
- End part joined with the front wall hole using *joint rotation feature,* → allows screw to rotate along axis
- Cylindrical axis constrained with the slider's front face using *rotational-translational feature*
- Travel limits:
    - X-Slider: 0 mm (min) → 24 mm (max)

- Z-Slider: 0 mm (min) → 11 mm (max)

Knob:

- Rigidly joined with the lead screw.
- Used to adjust slider resolution.

4.5 Collars (with grub screw)

Dimensions:

- Diameter = 4 mm
- Thickness = 3 mm

Features:

- Fits outside the slider holes to secure the lead screw.

Axial Positioning / Limiting Travel:

- The collars are mounted on the lead screw at both sides of the slider.
- They act as stoppers, defining the limits of slider travel (e.g., 0 mm minimum, 24 mm maximum for X, 11 mm maximum for Z).
- By tightening the grub screw, the collar can be fixed at an exact location to set mechanical end-stops and prevent over-travel.

Elimination of Backlash (Play-Free Movement):

- The lead screw passes through clearance holes in the slider.
- Without collars, the screw could slide back and forth axially, leading to play.
- By fixing collars on both sides of the slider, the screw is locked axially while still allowed to rotate freely, ensuring precise motion transfer.

Load Distribution:

- The collar's flat surface presses against the slider face instead of relying solely on the threads.
- This spreads contact forces and prevents wear/damage at the slider holes.

Adjustment Flexibility:

- The grub screw allows collars to be re-positioned for calibration.
- During assembly, the technician can fine-tune the limits and lock them with the set screw.

4.6 Anti-Backlash Nuts

To eliminate backlash between the M3 lead screw and the nut, an anti-backlash mechanism was implemented. The design consists of two nut halves separated by a compression spring. The spring applies a constant axial preload, which keeps both nut threads in permanent contact with the screw flanks. This ensures that the displacement of the slider is free of play, fulfilling the requirement of precise motion with a resolution of 10 µm.

In this design, a spring of 8 mm free height and 8 active revolutions (wire diameter ~0.3 mm, coil diameter ~4 mm) was used. During assembly, the spring is slightly compressed (~0.5 mm), generating a preload of approx. 0.15–0.2 N. This preload is sufficient to compensate for typical M4 lead screw backlash (≈0.05–0.15 mm) while keeping the actuation torque low.

Thus, the anti-backlash nut ensures smooth, accurate, and repeatable positioning of the probe tip without unwanted play.

4.7 Probe Arm

The probe arm was designed to hold and position the probe tip in accordance with the project requirements. A rectangular part with dimensions 40 mm × 5 mm × 5 mm was created and mounted onto the Z-slider using two countersunk screws. This ensures stable fixation of the probe arm while allowing precise vertical adjustment through the Z-stage.

From this base piece, a horizontal rod of 100 mm length was attached to extend the reach of the probe. At the end of this rod, the probe tip (Ø0.65 mm) was mounted at an inclination of 45°. A 2 mm part was cut at the angle of 45 degree to insert the probe tip at 45 degree angle. The probe tip was positioned such that its point lies 10 mm below the base plate level, fulfilling the specified working geometry. This process was done with constraint feature.

This configuration allows the probe tip to maintain the required distance from the adjusting unit, while the X- and Z-slider mechanisms provide fine positional control. The use of countersunk screws ensures a flush surface connection, reducing play and enhancing mechanical stability.

4.8 Probe Tip

A 2 mm circle was made and extruded for 17 mm. On the top face, a circle was made with a 0.65 mm diameter and extruded it for 12.50 mm. The fillet feature with a 2 mm radius was used. Now, a sharp tip is created. Then a 2 mm hole on the probe arm at an angle of 45 degrees was made. The probe tip is fixed with the DIN 913 grub screw.

5. Material Selection

5.1 Z-Slider

- Requirements: High stiffness, low friction, wear resistance, precise movement.
- Material Options:
    - ➢ Aluminum 7075-T6 → lightweight, stiff, easy to machine, corrosion-resistant.
    - ➢ Steel (e.g., 1.4301 stainless steel) → very stiff, wear-resistant, slightly heavier, needs surface finish to reduce friction.
    - ➢ PTFE-coated brass/steel → reduces friction if the slider slides on metal guides.
- Recommended: Aluminum 7075-T6 with a hard anodized surface for low friction and wear resistance.

5.2 X-Slider

- Requirements: Similar to Z-slider; must support ±10 mm travel with high precision.
- Material Options:
  - Aluminum 7075-T6 (lightweight, easy to machine).
  - Stainless steel 1.4301 (high stiffness, good wear resistance).
- Recommended: Aluminum 7075-T6, anodized. Use linear ball bearings for precision movement.

5.3 Base Plate

- Requirements: High stiffness, low thermal expansion, supports entire setup.
- Material Options:
  - Aluminum 6061-T6 → easy to machine, stiff, lightweight.
  - Steel (S235 or 1.4301 stainless steel) → very stiff, heavier.
  - Cast iron → excellent vibration damping, but heavier and harder to machine.
- Recommended: Aluminum 6061-T6, 10–15 mm thick for rigidity.

5.4 Probe Arm

- Requirements: Minimal deflection, light, precise tip positioning.
- Material Options:
    - Aluminum 7075-T6 → high stiffness-to-weight ratio.
    - Carbon fiber tube → very light and stiff, low thermal expansion.
    - Stainless steel → stiff but heavier.
- Recommended: Carbon fiber tube for minimal weight and high stiffness. Aluminum 7075-T6 if easier machining is needed.

5.5 Probe Tip

- Requirements: Hard, wear-resistant, precision shape, minimal deformation.
- Material Options:
    - Tungsten carbide → extremely hard, wear-resistant.
    - Stainless steel 1.4301 → durable, easy to machine.
    - Silicon nitride ceramic → very hard, minimal deformation, brittle.
- Recommended: Tungsten carbide for high wear resistance and precision contact.

5.6 Knob

- Requirements: Ergonomic, good grip, corrosion-resistant, lightweight.
- Material Options:
  - Aluminum 6061-T6 → easy to machine, anodize for grip.
  - Delrin (POM) → lightweight, good grip, easy to machine.
  - Stainless steel → heavier but durable.
- Recommended: Delrin (POM) for lightweight and comfortable manual adjustment. Aluminum 6061-T6 if a metallic feel is preferred.

5.7 Lead Screw

- Requirements: High precision, minimal backlash, supports smooth translation.
- Material Options:
  - Stainless steel 1.4301 → precise, corrosion-resistant.
  - Alloy steel (ground) → very precise, high strength.
- Recommended: Stainless steel precision lead screw with matching nut (brass or bronze) to reduce friction and wear. Optional anti-backlash nut for precision.

6. Manufacturability

6.1 Base plate (Al 6061-T6)

Manufacturing process:

- Start from a milled plate stock close to nominal size (reduce machining).
- CNC 3-axis milling: roughing then finishing passes for outer profile, mounting holes and boss features.
- Counterboring and tapping of threaded holes (M4 etc).
- Final face milling for flatness; optionally surface grind bottom/top if extreme flatness required.

Key dimensions & tolerances:

- Flatness: ≤ 0.05 mm over plate (for precision platforms; otherwise 0.1 mm acceptable).
- Hole tolerances (wall mounting/bearing bores): use ISO H7 for bores where a press fit is needed for bushings.

Surface finish

- Sliding contact faces: Ra ≤ 0.8 µm.
- Noncritical faces: Ra ≤ 3.2 µm.

Post process

- Anodize (Type II) for wear resistance + cosmetic finish. Apply sealing if you want corrosion protection.

6.2 X-Slider & Z-Slider (brass/bronze)

Manufacturing process:

- Mill from bar or forged block; rough stock to near shape.
- CNC milling: create pockets, threaded boss, clearance holes.
- Drill & ream slider holes that will host bushings (if using bushings).
- Tap M4 holes on faces (use a spotting drill + tap with guided machine tapper or hand tap).
- Press fit bronze bushings into slider holes (if used).

Critical features & tolerances:

- Bushing bore (IF press-fit bushing not used): ream to ID matching screw shaft fit — recommend H7 hole with shaft to H6 nominal.
- Flatness/top surface for mating with base: ≤ 0.02–0.05 mm.
- Perpendicularity of threaded holes to face: ≤ 0.02 mm.

Surface finish

- Sliding faces Ra ≤ 0.4–0.8 µm (smoother reduces friction and stick-slip).

6.3 Lead screw (M3) and nut

Manufacturing process:

- Option 1 (standard): buy standard M3 precision stainless steel lead screw/rod (rolled/rolled and ground).
- Option 2 (custom): turn shaft, thread on CNC lathe, optionally grind thread for precision.

Specification:

- Thread: M3 × 0.25, tolerance 6g (standard external thread) unless calling out precision classes.
- If you use a nut inside a slider: use a matching M4 nut or a bronze nut with anti-backlash features.

Finish & treatment:

- Stainless: passivation; heat treatment for 416 for improved wear.
- Apply thin film lubrication (e.g., MoS_2 or light machine oil) for smoothness.

6.4 Collars & grub screw

Manufacturing process:

- Turn collars from round bar (steel).
- Drill/tap grub screw hole (M2.5 or M3 typical) and mill flat if required.
- Heat treat (harden) if using alloy steel, then passivate or black oxide.
- Optionally chamfer or radius edges.

Tolerances:

- Bore tolerance for collar ID: H7 for press fit on shaft if intended to be fixed; if intended to rotate, bore to sliding clearance (H8 or reamed to nominal +0.05 mm).
- Grub screw thread: standard M2.5 or M3, tolerance 6H/6g.

Finish:

- Hardened steel: black oxide to reduce corrosion and improve appearance.

Assembly:

- Use flat point grub screw on shaft to minimize damage to threads; torque control is recommended to avoid shaft deformation.

6.5 Knob

Manufacturing:

- Injection molded (POM/ABS) for volume; CNC turned or milled if small batches.
- Add knurling/tactile grooves.

Key features:

- Inner bore: tolerance for shaft fit (press fit or keyed to screw head). For slip fit, use H8/h8.

7. Conclusion

In this project, a **micromanipulator setup** was successfully designed and fabricated in Autodesk Inventor to enable the precise positioning of a micromechanical probe. The mechanism fulfills the given requirements:

- The **X-slider** provides a travel of **±12 mm (24 mm total)**, which is larger than the required ±10 mm range.
- The **Z-slider** provides a travel of **±5.5 mm (11 mm total)**, which exceeds the required ±5 mm range.
- A fine-pitch **M3 × 0.25 lead screw** was used in both axes, ensuring a displacement resolution of **10 µm per 1/25 turn**, satisfying the precision requirement.
- The **probe tip** (Ø0.65 mm, length 31 mm) was mounted at **45°**, located **100 mm horizontally** from the adjusting unit and **10 mm below the base plate**, exactly as specified.
- The overall footprint of the setup (**70 × 40 mm**) remained within the maximum allowed dimensions.

The design ensures **smooth, backlash-free movement** by using an **anti-backlash nut with spring preload**. Self-locking properties of the lead screw prevent undesired drift, making the system stable during operation.

Thus, the project demonstrates the successful realization of a compact and precise micromanipulator, suitable for adjusting micromechanical devices with high accuracy.

8. Future Improvements

Motorized Actuation:

- Stepper motors or piezo actuators could replace manual knobs for automated, programmable motion control.

Digital Measurement:

- Incorporating linear encoders or dial gauges would allow real-time measurement and verification of displacement with higher confidence.

Modular Probe Mount:

- The probe arm could be redesigned to allow quick swapping of probe tips of different sizes and geometries.

Material Optimization:

- Using lightweight, rigid materials (e.g., aluminum alloys or carbon fiber) could reduce weight while maintaining stability.

3D Printing of Components

- Certain non-load-bearing parts could be 3D printed for rapid prototyping, cost reduction, and flexibility.

9. Drawings

- Part drawings for all components with dimensions, hole callouts, and tolerances.
- Assembly drawings with exploded view, BOM, and overall sizes.
- Exported as a merged PDF.