Manufacturing Strategy for the Treexalerator IMU Test Rig

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This technical report motivates the choice of a one-piece CNC machined aluminium 7075 body for the Treexalerator IMU–encoder test rig.

The PDF will be published in a public GitHub repository. Gemini 3.0 Pro was used for grammar integrity and proof reading.

Contents

1 Introduction

The Treexalerator project aims to build a precision test rig that rotates an inertial measurement unit (IMU) and compares its output against an absolute magnetic encoder. The encoder is an AksIM-2 MB064 readhead with an MRA064BC040 ring, which can reach sub-arcminute accuracy when mounted correctly. To make sure the rig measures the IMU and not just its own mechanical errors, the structure must hold tight geometric tolerances, on the order of 0.05 mm or better between key features.

At the same time, the part has to be manufactured only once or in very low volume, so the manufacturing process must be realistic for prototyping and small-batch production. Several options are possible: machining the main body from a single block, assembling it from smaller CNC parts, or using advanced 3D printing (additive manufacturing). This report compares these strategies and explains why a monolithic CNC machined body in aluminium 7075 is the best choice for this design.

The report also discusses different candidate materials—aluminium alloys (6061, 6082, 7075), titanium alloy Ti–6Al–4V, and carbon and stainless steels—with their strengths and drawbacks for this particular application.

2 Functional Requirements of the Treexalerator

2.1 Geometry and encoder performance

The Treexalerator's 3rd axis is essentially a short drum with two end plates and a central deck. One end couples to a CubeMars GL60 gimbal motor; the other carries the MRA064 magnetic ring. The MB064 readhead is bolted to the fixed structure and measures angle as the drum rotates.

According to typical AksIM-2 documentation, the following are important for the encoder [1, 2]:

- The air gap between ring and readhead must stay inside a narrow window (roughly 0.05 mm to 0.35 mm) and should not vary too much around the ring circumference.
- Tilt between the ring plane and the readhead plane is limited to about 0.2°, which corresponds to only about 0.11 mm height variation over a 64 mm diameter ring.
- Radial eccentricity between the ring and the encoder coordinate system should be small, otherwise a sinusoidal angular error is added.

From these points we can derive the key geometric requirements for the rig:

- Parallelism between the encoder-side plate and the motor-side reference plane better than 0.05 mm.
- Coaxiality of the shaft, motor seat, and ring seat better than roughly 0.03 mm.
- Stable distance between ring and readhead, ideally controlled to within about ± 0.1 mm.

If we do not reach those numbers, the mechanical error may be as large as or larger than the IMU error we want to measure.

2.2 Target manufacturing tolerance

Manufacturing handbooks list typical capabilities of different processes. Groover reports that conventional machining processes like milling and turning typically hold tolerances in the range of ±(0.02–0.1) mm depending on the operation, and that fine finishing like grinding can reach even ±(0.005–0.01) mm [1]. Kalpakjian and Schmid give similar ranges in their table of process capabilities [2].

CNC job-shop guides confirm this: standard CNC milling is often quoted with ±0.05 mm or better when requested, and precision machining can reach ±0.01 mm on critical features [3, 4, 5]. In this project I target ±0.05 mm for key datums and parallelism, which is demanding but not exotic for 3-axis CNC.

Additive manufacturing technologies like SLM/DMLS, SLS or MJF have much worse guaranteed dimensional accuracy. Industrial sources usually quote tolerances around ±0.1 mm to ±0.2 mm for metal powder-bed fusion, and similar or worse for polymer systems [6, 7, 8, 9]. This is already larger than the total tolerance budget available for the ring–readhead gap and the plate parallelism, so it is a critical limitation.

3 Overview of Manufacturing Options

3.1 Option 1: One-piece CNC machining from a solid block

In this strategy the whole body of the Treexalerator—both end plates and the central deck—is machined from a single billet of metal. The part is roughly 147 mm long and 100 mm in diameter, so it fits easily on a medium-size 3-axis or 5-axis machine. Most surfaces can be milled, with some drilling and boring for the central shaft and the encoder mounting patterns.

Because all critical features (motor seat, ring seat, readhead pad and IMU deck) are produced in the same setup or at least in a small number of controlled setups, the relative tolerances between them can be very good. Modern CNC mills can hold ±0.05 mm or even ±0.02 mm position and flatness on such dimensions with proper fixturing and inspection [3, 4, 5]. By defining careful GD&T datums the shop can inspect parallelism, runout and position to verify that the part meets the requirements.

This approach gives a rigid, monolithic structure with no joints in the load paths between motor, encoder and IMU. Long-term stability is high, because there are no interfaces that can slip, creep or loosen over time. The main disadvantages are:

- Higher material waste, since most of the billet is removed.
- Slightly higher up-front cost for setup, especially in western countries.

For this specific part, quotes from online services for CNC machining in aluminium are around 150–250 USD from Chinese vendors and around 500–800 GBP from a UK provider, depending on lead time and surface finish. These services offer ISO 2768 medium tolerances to ISO 286 grade 6 and allow specifying a tightest tolerance of about ±0.05 mm on critical dimensions. From the functional requirements this is enough and leaves some margin.

3.2 Option 2: Assembly from multiple smaller sub-parts

A tempting idea for cost saving is to split the large part into several simpler parts: for example, two separate plates and a separate deck, plus small blocks for holding the readhead. These could be joined using bolts, dovetail joints, press fits or adhesives.

However, mechanical design texts and tolerance stack-up guides warn that such multi-part assemblies suffer from accumulated dimensional variation. Each interface has its own tolerances for flatness, location, and hole patterns. The final misalignment between the ring and the readhead is then the combination of all errors in the stack [10, 11]. If each part has even a modest tolerance of ± 0.05 mm, combining three or four parts can easily lead to $\pm(0.15–0.2)$ mm relative displacement in worst case, which is already on the level of the whole allowed encoder gap. That would mean the rig might work only with careful manual shimming and still be less stable.

In addition to stack-up, joints introduce:

- **Reduced stiffness.** Bolted and dovetail joints have compliance; the effective stiffness of a structure with joints is lower than a solid monolithic body. Under cyclic loads they can experience micro-slip and fretting, slowly changing alignment [11].
- **Assembly variability.** The exact clamping order, torque on screws, interference in press fits and adhesive layer thickness are hard to control tightly without production tooling. Two rigs built "the same" may end up with different actual geometries.
- **More complex inspection.** Instead of inspecting one part, each sub-part and the complete assembly must be checked. Achieving a verified ± 0.05 mm parallelism between plates across several joints is not trivial at all.

For a precision metrology fixture these issues are critical. Saving perhaps 50 USD on machining at the cost of worse stiffness and long-term drift does not make engineering sense.

3.3 Option 3: Additive manufacturing (3D printing)

Advanced metal 3D printing processes like selective laser melting (SLM) or direct metal laser sintering (DMLS) can build complex geometries in materials such as aluminium and titanium. In theory they could build the Treexalerator body in one piece.

However, several facts make this a poor option here:

- The guaranteed dimensional accuracy of SLM/DMLS is typically around ± 0.1 mm to ± 0.2 mm, depending on machine and material [6, 7, 8, 9]. This is at least 2–4 times worse than the ± 0.05 mm required between key features.
- Process-specific distortion, residual stresses and surface roughness make flatness and parallelism hard to control. Most design guides recommend post-machining precision surfaces after printing, especially for bearing seats and sealing faces.
- The price is high. A rough quotation for printing the part in Ti–6Al–4V using SLM is about 550 USD, still with a tolerance of about ± 0.2 mm. To reach better tolerance one would need to add CNC finishing anyway, increasing cost further.

Polymer or resin 3D printing technologies, which are cheaper, have even worse tolerances and much lower stiffness, so they are not appropriate for a rigid encoder mount.

For these reasons no currently available additive manufacturing option can meet the ~ 0.05 mm tolerance budget of the Treexalerator without heavy secondary machining. At that point it is simpler and cheaper to machine from solid directly.

4 Material Selection

4.1 Candidate materials

Several materials were considered for the body of the Treexalerator:

- Aluminium 6061-T6 and 6082-T6

- Aluminium 7075-T6
- Titanium alloy Ti–6Al–4V (Grade 5)
- Mild carbon steel (e.g. AISI 1018)
- Austenitic stainless steels (304 and 316L)

Below we summarise their key mechanical properties and discuss pros and cons for this application.

4.2 Aluminium 6061-T6 / 6082-T6

Alloy 6061-T6 is one of the most common structural aluminiums. Typical yield strength is about 240 MPa to 280 MPa and ultimate tensile strength around 290 MPa to 330 MPa, with density about 2.7 g/cm^3 and modulus of elasticity about 69 GPa [12, 13]. 6082-T6 is similar, with slightly higher yield strength around 260 MPa and good extrudability [12]. Both alloys have very good machinability and weldability, and excellent corrosion resistance in normal environments.

For the Treexalerator, 6061 or 6082 would provide enough strength and stiffness. The main disadvantages compared to 7075 are lower yield strength (so the structure must be slightly thicker for the same rigidity) and slightly lower hardness. But honestly, they are still very good candidates.

4.3 Aluminium 7075-T6

Aluminium 7075-T6 is a high-strength aerospace alloy. Typical yield strength is about 430 MPa to 503 MPa and tensile strength up to about 540 MPa, with density around 2.8 g/cm^3 [14, 15]. Its modulus of elasticity is about 72 GPa, very close to other aluminium alloys. It also has good fatigue strength and fairly high hardness [14].

Advantages for this project:

- Much higher strength than 6061/6082 (about 1.7–2.0 times the yield strength), so the structure is very stiff with a good safety factor even under aggressive spinning and handling.
- Still lightweight; density is only a little higher than 6061.
- Machinability is acceptable; although slightly worse than 6061, it is widely used in aerospace CNC parts.

Disadvantages:

- Poorer corrosion resistance than 6000-series alloys, especially in salt environments [14]. For an indoor lab fixture this is not a big issue.
- Material cost is higher than 6061, but for one part the difference is maybe a few tens of dollars.

Because stiffness and dimensional stability are more important than corrosion resistance here, aluminium 7075-T6 is a very good compromise.

4.4 Titanium alloy Ti–6Al–4V (Grade 5)

Ti–6Al–4V is the most widely used high-strength titanium alloy, with yield strength around 880 MPa to over 1100 MPa depending on heat treatment and tensile strength around 900 MPa to 1170 MPa, at a density of about 4.43 g/cm^3 [16, 17, 18]. Its modulus of elasticity is about 110 GPa, roughly half that of steel but higher than aluminium. The combination of high specific strength and excellent corrosion resistance makes it ideal for aerospace and medical parts.

For the Treexalerator, titanium would give:

- Very high strength and good stiffness.
- Lower mass than steel, though still heavier than aluminium.
- Great corrosion resistance.

But it also has significant downsides:

- Much higher raw material cost and much more expensive machining (tool wear, low cutting speeds) [1].
- The SLM titanium option evaluated costs around 550 USD with only ±0.2 mm tolerance.
- The CNC cost is 1700 GBP via Xometry UK wit ISO 286 Grade 6 standart.

The rig does not need such extreme strength or corrosion resistance, so titanium would just make it more expensive and harder to manufacture without real benefit.

4.5 Carbon steel (AISI 1018)

Low-carbon steel such as AISI 1018 has yield strength around 370 MPa, tensile strength around 440 MPa, density about 7.87 g/cm^3, and modulus of elasticity about 205 GPa [19, 20]. It machines well, is cheap and available everywhere.

Pros for the Treexalerator:

- High stiffness because $E \approx 200$ GPa, almost three times aluminium.
- Reasonably high strength and good machinability.

Cons:

- Very heavy: density almost three times aluminium, so the rotating mass and inertia are large.
- Requires surface treatment (paint, plating) to avoid rust; any coating adds small dimensional changes.

A heavy steel rig could still work, but the extra inertia would demand more torque from the motor and may make handling and mounting more difficult.

4.6 Stainless steels 304 and 316L

Austenitic stainless steel 304 has density about 8.0 g/cm^3, yield strength around 190 MPa to 205 MPa, ultimate tensile strength $\sim$ 500 MPa, and modulus of elasticity about 193 GPa [21, 22, 23]. Grade 316L has similar mechanical properties but better corrosion resistance due to molybdenum [24, 25, 26]. Both alloys are stiff and tough, and highly corrosion resistant.

For this rig the problems are:

- Very high density and mass, worse than carbon steel.
- More difficult machining compared to aluminium, especially for deep pockets.
- Material and machining cost are significantly higher, as also visible in the online quotes.

So stainless steels are overkill in both corrosion resistance and cost.

4.7 Summary and material choice

Table 1 summarises approximate properties of the candidate materials.

Table 1: Approximate material properties for candidate body materials (room temperature, typical values).

Material	Density [g/cm^3]	Yield strength [MPa]	E [GPa]	Notes
Al 6061-T6	2.7	240–280	69	Good corrosion, easy machining [12, 13]
Al 7075-T6	2.8	430–500	72	Very high strength, fair corrosion [14, 15]
Ti–6Al–4V	4.4	880–1100	110	Very high strength, expensive [16, 17]
AISI 1018	7.9	370	205	Cheap, rusts, heavy [19, 20]
SS 304	8.0	190–205	193	Corrosion resistant, heavy [21, 22]
SS 316L	8.0	170–200	193	Better corrosion, even heavier [24, 25]

Taking into account strength-to-weight ratio, machinability and cost, aluminium 7075-T6 is chosen for the Treexalerator body. It provides stiffness and strength comparable to many steels at one third the density [14], and it is easily machined to the target tolerances.

5 Cost and Process Comparison

During the design phase, quotes were obtained from several online manufacturing services:

- CNC machining in aluminium 7075 from a Chinese service (JLCNC): approximately 160–230 USD for one part, depending on lead time and bead-blast + anodised finish, with ISO 2768 medium and a tightest tolerance option of ± 0.05 mm.
- CNC machining in aluminium 6082 or 7075 from a UK service (Xometry): around 500–800 GBP for one part, again with ISO 286 Grade 8 and ± 0.03 mm allowed on selected dimensions.
- CNC machining in Bakelite or other plastics: around 110–120 USD, but the stiffness and dimensional stability are far too low for the encoder mount.
- SLM metal 3D printing in titanium alloy: around 550 USD with a quoted tolerance about ± 0.2 mm; still requiring machining for functional surfaces.
- PCBWay gave a preliminary web estimate around 280 USD for the aluminium part, but in practice their engineers often increase this by about 30 %, which would lead to $\sim$ 360 USD.

From these numbers it is clear that:

- A one-piece CNC aluminium part is *not* dramatically more expensive than multi-piece or 3D printed solutions once realistic tolerances are included.
- For titanium in particular, the material and process cost becomes several times higher while still not meeting the required tolerances without extra machining.

Because CNC machining is one of the few processes that can directly deliver the required ±0.05 mm tolerances, using a reputable third-party CNC manufacturer is the most economical way to obtain a metrology-grade part.

6 Conclusions

The Treexalerator IMU test rig needs a rigid, geometrically accurate body to support an AksIM-2 magnetic encoder and a gimbal motor. Analysis of the encoder requirements and of process capabilities shows that:

- The relative positions of motor seat, ring seat and readhead must be controlled to roughly ±0.05 mm, with tight parallelism and runout limits.
- Standard CNC machining can reliably reach these tolerances; they fall well inside the typical range of modern machining centres [1, 2, 3, 5].
- Additive manufacturing processes, even advanced metal ones like SLM and DMLS, typically offer dimensional accuracies no better than ±0.1 mm to ±0.2 mm unless followed by extensive machining [6, 7, 8].
- Assembling the body from several smaller parts would make tolerance stack-up, joint compliance and assembly variability dominate the error budget [10, 11].

Considering also material properties and costs, aluminium 7075-T6 emerges as the most suitable material. It offers strength comparable to many steels at much lower weight [14, 15], machines reasonably well, and is available from many CNC suppliers. Ti–6Al–4V and stainless steels are technically possible but add cost and mass without real benefit for this lab environment.

Therefore, the recommended manufacturing strategy is:

- Machine the entire Treexalerator body from a single block of aluminium 7075-T6 on a professional 3-axis or 5-axis CNC mill.
- Specify ISO 2768 medium as general tolerance and add explicit ±0.05 mm and GD&T callouts (parallelism, position, runout) on encoder-critical datums.
- Use a third-party CNC manufacturer that can certify these tolerances and, ideally, provide inspection results.

This approach minimises geometric error sources, simplifies assembly, and gives a robust test rig whose limitations are very likely dominated by the sensors under test rather than by the mechanics.

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7 Too Long Didn't Read

Table 2: Pugh-style decision matrix for manufacturing methods for the Treexalerator body.

Method	Typical tolerance	Stiffness / stability	Assembly effort	Indicative cost (1 pc)	Main pros / cons
One-piece CNC machining (Al 7075)	±0.02–0.05 mm	Very high (monolithic)	None (no joints)	150–250 USD (China); 500–800 GBP (UK)	**Pros:** Meets 0.05 mm requirement, excellent rigidity, simple inspection and assembly. **Cons:** More material waste, needs access to professional CNC shop.
Multi-part CNC assembly (Al alloys)	Each part: ±0.05 mm, but stack-up $\approx$ ±0.15–0.20 mm	Medium (joint compliance)	High (alignment, shimming, fasteners)	Slightly cheaper per part, but more total parts	**Pros:** Smaller parts, easier to machine individually. **Cons:** Tolerance stack-up, joint slip, long-term drift; hard to guarantee encoder gap and parallelism.
Metal additive manufacturing (SLM Ti–6Al–4V or Al)	±0.10–0.20 mm (before machining)	Medium (porosity, residual stress)	Medium (support removal + machining)	~550 USD for Ti SLM, plus machining	**Pros:** Complex shapes possible, good for lattices. **Cons:** Accuracy too poor for 0.05 mm requirement, surface rough, expensive; still needs CNC finishing on critical faces.
Polymer / resin 3D printing	±0.15–0.30 mm (typical)	Low (low E, creep)	Low	100–150 USD range	**Pros:** Cheap prototypes, quick iterations. **Cons:** Insufficient tolerance and stiffness for precision encoder mount; large thermal and long-term deformation.

Table 3: Pugh-style decision matrix for candidate body materials.

Material	Density [g/cm^3]	Yield strength [MPa]	Machinability	Relative cost	Main pros / cons
Al 6061-T6 / 6082-T6	≈ 2.7	240–280	Excellent	Low	**Pros:** Cheap, easy to machine, good corrosion resistance; widely used for fixtures. **Cons:** Lower strength than 7075, slightly less stiffness for same geometry.
Al 7075-T6 (chosen)	≈ 2.8	430–500	Very good	Medium	**Pros:** Very high strength-to-weight, good fatigue and stiffness; ideal for a light but rigid rotating body. **Cons:** Worse corrosion than 6000-series, a bit more expensive and slightly trickier to machine.
Ti–6Al–4V Grade 5	≈ 4.4	880–1100	Difficult	Very high	**Pros:** Extremely high specific strength, excellent corrosion resistance. **Cons:** Expensive material and machining, SLM print quoted ~550 USD with only ± 0.2 mm tolerance; unnecessary strength for a lab rig.
Mild steel (AISI 1018)	≈ 7.9	~370	Good	Low	**Pros:** High stiffness ($E \approx$ 205 GPa), cheap, easy to machine. **Cons:** Very heavy, rusts without coating; coating can change critical dimensions slightly.
Stainless steel 304 / 316L	≈ 8.0	170–205	Moderate / poor	High	**Pros:** Excellent corrosion resistance, stiff and tough. **Cons:** Very heavy, harder to machine, high cost; overkill for an indoor metrology fixture.
Engineering plastics (e.g. Bakelite, POM)	1.2–1.5	50–100 (very approximate)	Easy	Low	**Pros:** Cheap, easy to machine or mould; good for non-structural covers. **Cons:** Low stiffness and creep, poor dimensional stability over time; cannot hold encoder alignment at 0.05 mm level.