SubArc: An Inexpensive, High Resolution, Open Source, Absolute Magnetic Rotary Encoder

Problem

- **Precision machinery is vital in semiconductor manufacturing, astronomy, medicine, aerospace, defense, and more**
- **High resolution rotary encoders make machinery precise** by measuring angular position when mounted on joints/axes
- **Current high resolution encoders cost $100s - $1,000s** each for precision machines, driving up their cost
- High encoder costs, and a consequently increased cost of precision machinery, **prevents precision machinery from being accessible and impedes scientific progress**

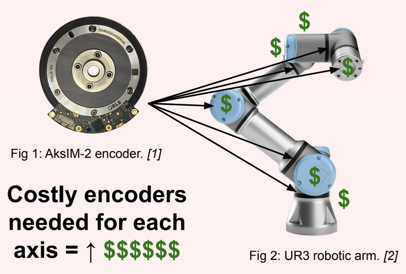

Fig 1: AksIM-2 encoder. [1] Fig 2: UR3 robotic arm. [2]

Engineering Goal

Solution: Develop a low cost, high resolution encoder to lower the cost of nearly all precision machinery and instrumentation

< $40 Cost
More than 10x cheaper than one of the least costly 20 bit encoders, the AksIM-2, and aligns with bare minimum cost of electronics for design goals

Resolution
1.23 arcseconds/ 0.000343° / **20 bit resolution**

Accuracy
0.0417° or **150 arcseconds**

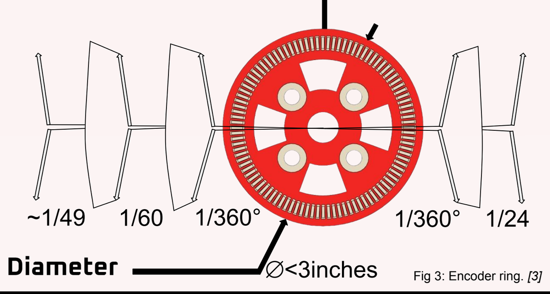

Fig 3: Encoder ring. [3]

Customizable
Easily change diameter, ring count, and sensors to meet exact resolution needs; 20+ bit resolution potential

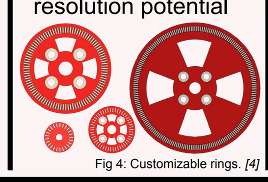
Fig 4: Customizable rings. [4]

Environment Fluctuation Compensation
Temperature Fluctuations:
Mounting/Peak Calibration:
External Magnetic Field:

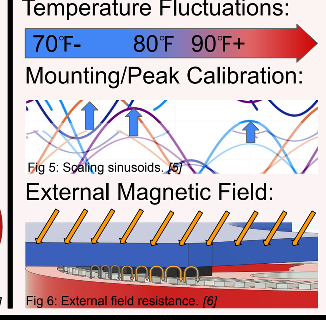

Fig 5: Sensing sinusoids. [5] Fig 6: External field resistance. [6]

Current Technology Comparison

Diameter: 80mm	*Diameter: 55mm*
Resolution: 20 bit	*Resolution: 20 bit*
Environmentally Robust: Yes	*Environmentally Robust: Yes*
Cost: $415	***Cost: <$40***

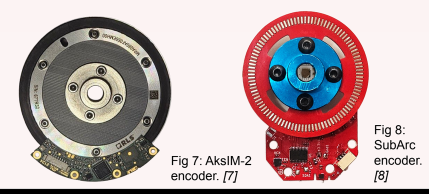
Fig 7: AksIM-2 encoder. [7] Fig 8: SubArc encoder. [8]

Design Constraints/Variables

- **Magnetic encoder:** Unlike optical encoders, resistant to stray dust particles and fluids, less fragile, and more environmentally robust
- **Novel configuration, construction, & information processing techniques:** Allows for decreased manufacturing costs and a more compact design
- **PCB design:** Reduces cost, easily configure micro-hall sensor placement & magnetic ring configuration, customizable
- **Calibration station:** Duplicates parent encoder resolution to unique calibration file, lowering cost

Background Information

- **Two main types of encoders:** Optical and magnetic
- **Encoder modes:** | *Absolute* → angular position always saved | *incremental* → position resets to zero when reset |
- **Optical encoders:** Patterned disk, changes in light intensity increment angular position, high resolution, costly, fragile, dust-sensitive
- **Magnetic encoders:** Use bipolar magnet or multipole magnet disks, changes in magnetic field increment angular position

Material Cost Breakdown

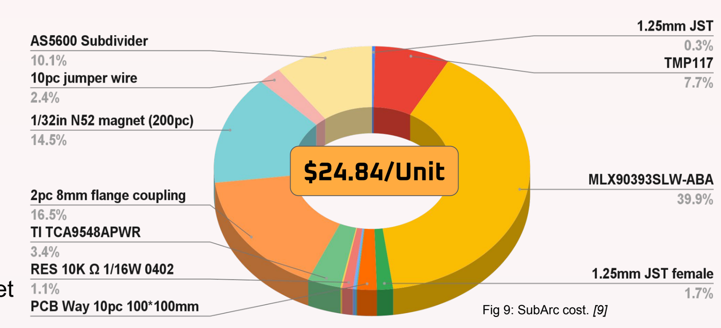

Fig 9: SubArc cost. [9]

Method/Design Theory

Absolute Multipole Magnetic Encoder (AMPME)

- **Outer multipole magnet (MPM):** Equally spaced ultra-thin neodymium magnets Increase $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ → increases resolution
- **Central bipolar magnet (BPM):** Subdivides finer yet repeated field fluctuation periods into absolute position

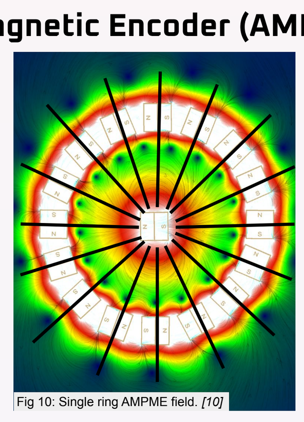
Fig 10: Single ring AMPME field. [10]

- **New dual-ring magnetic field compression (MFC):** Compresses same-pole fields to produce greater $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ in select regions, MFC factor determines increase in resolution, and is largely dependant on Δx and most importantly ring proximity
- **MFC increases $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ without increasing diameter:** More compact design, decreases cost as less magnets needed, and implementation in current state-of-the-art magnetic encoder designs to further boost their resolution

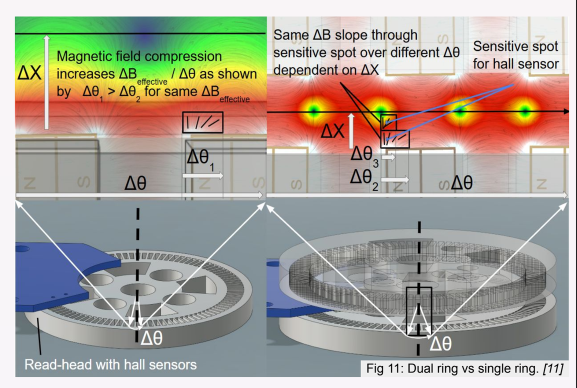

Fig 11: Dual ring vs single ring. [11]

Magnetic Field Imperfections and High Tolerances

- **High tolerance manufacturing:** PCB readhead and magnetic ring are designed for manufacturability and tolerance-aware, but focus on low-cost first, resulting in magnetic field imperfections with higher tolerances than typical precision encoders
- **Outer multi-pole magnet (MPM):** Uses the smallest, mass-produced neodymium magnets to maximize pole count & surface field strength, increasing resolution, and also minimizing the cost of the ring.
- **Magnetic field compression (MFC):** Produces higher $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ in select regions, lower $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ in other regions = uneven magnetic field distribution

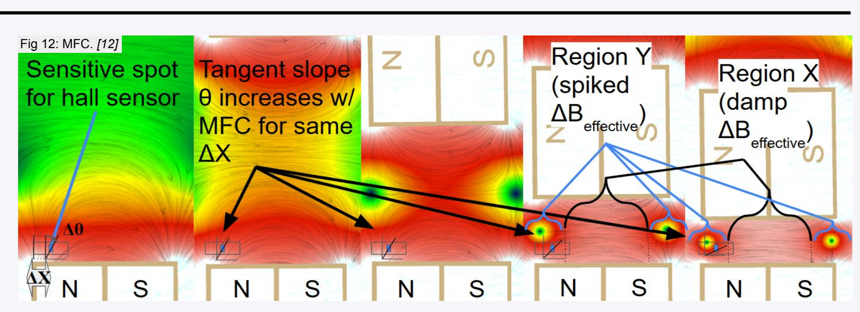

Fig 12: MFC. [12]

Signal Processing, Calibration, and Compensation

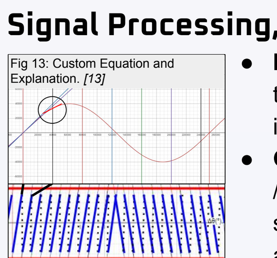
Fig 13: Custom Equation and Explanation. [13]

- **Imperfections:** Field imperfections from cost-cutting, higher tolerances, and non-sinusoidal $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ from MFC → impossible to resolve angular position with traditional algorithms
- **Greatest change method:** Ensures constant high $\Delta B_{hall\ sensors}/\Delta\theta_{smallest\ increment}$ > hall sensors' repeatability, matches the BPM hall sensor's and hall array's field readings with the calibration encoder's angle for each of many increments, generating a calibration file

$$\text{minimum slope value of } d/d\theta(\text{periodic function}) \times 2\pi\,(\text{period}) \times |\text{maximum field strength}| \times \text{MFC factor} \times \#\text{ of magnet poles} \div \text{repeatability range of hall sensor} = \text{CPR or resolution}$$

Derived equation: Determines SubArc design parameters

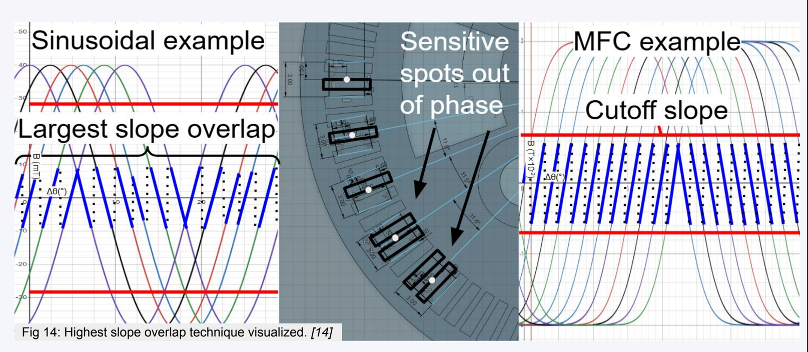

Fig 14: Highest slope overlap technique visualized. [14]

- **Calibration file:** Each SubArc encoder system possesses a unique calibration file to resolve for absolute position during operation after its I2C values are calibrated
- **Calibration includes:** Parent high-resolution calibration encoder, SubArc's hall array, central BPM sub-divisional encoder, and environment sensing to correct field values

Cal_Encoder θ(°)	Sensor 1		Sensor 2		Sensor 3		Central encoder θ(°)	Temp (°F)
-------------------------	X_Axis	Z_Axis	X_Axis	Z_Axis	X_Axis	Z_Axis	----------------	----------------
0.0005	-770uT	390uT	-370uT	820uT	-1210uT	140uT	0	72.1
0.0006	-780uT	440uT	-390uT	830uT	-1210uT	160uT	0	72.1

Fig 15: Example theoretical data. [15]

Iteration & Theory Confirmation

Test Stand V1

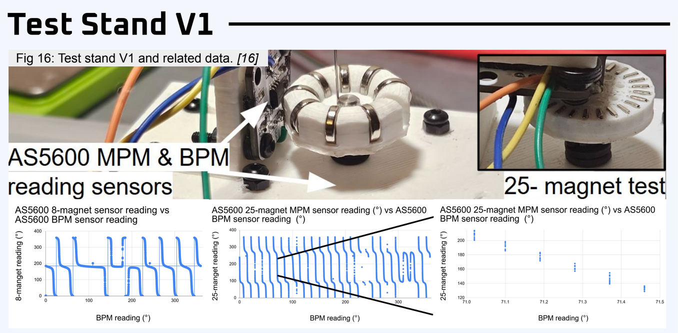

Fig 16: Test stand V1 and related data. [16]

- **9-magnet MPM & sub-dividing central BPM testing:** Proved finer MPM field periods can be subdivided by low-res absolute BPM encoder and converted to absolute position
- **3-axis hall sensor needed:** AS5600 fine data displays non-sinusoidal graph, sin-cos components needed, 3-axis hall sensor considerations: cost, field range, resolution, repeatability, smallest thickness, and lowest field range

Test Stand V1.5

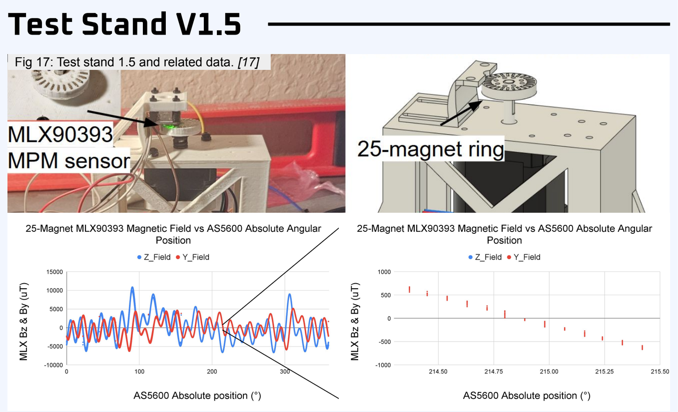

Fig 17: Test stand 1.5 and related data. [17]

- **Magnet & hall sensor selection:** after hall sensor trials, testings stand V1.5 proved 0.8mm N52 magnets where strong enough with MLX90393 hall sensor
- **Refinement:** Proves AS5600 sub-division BPM encoder could separate MLX90393 readings & sin-cos components be used for greatest $\Delta B_{hall\ sensor}/\Delta\theta_{rotation}$ method

Test Stand V2 & V2.5

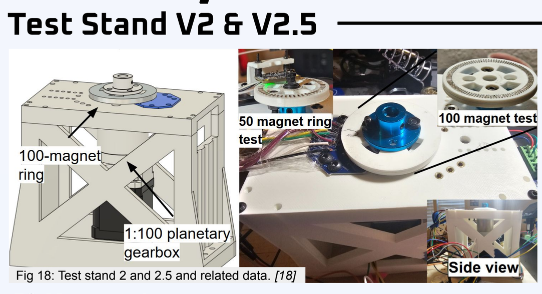

Fig 18: Test stand 2 and 2.5 and related data. [18]

50 Magnet ring:
- **Perfect polarity:** 50 periods/revolution, no distortion in sinusoidal components from incorrectly oriented magnets
- **Repeatable in revolutions:** 500 arcsecond revolution period difference due to 60 arcminute backlash in gearbox and due to temperature fluctuations

100 Magnet ring:
- **Primitive PCB hall sensor array tested:** Produces 4 x 25 cos-sin pairs, greatest change method produces >+-10μT changes/20 bit smallest increment → pre-confirms 20 bit resolution possibility

Testing stand:
- **More uniform fields:** Increased hall sensor proximity, uniform sinusoids mostly have >40mT peaks produced
- **Improved microstep ability:** New gearbox and new stepper driver allow for up to 2,560,000 counts per revolution

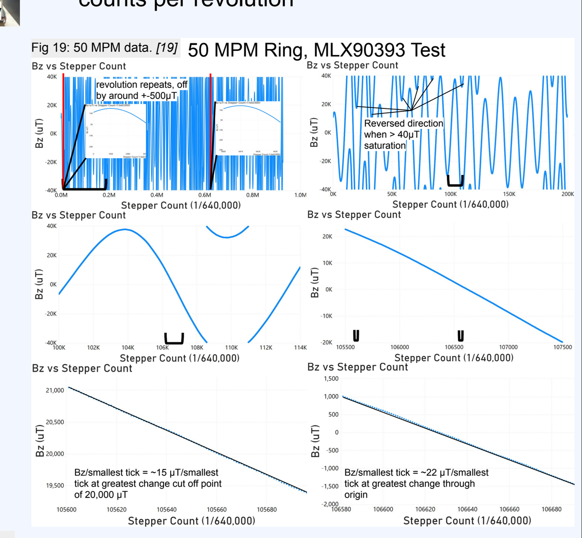

Fig 19: 50 MPM data. [19]

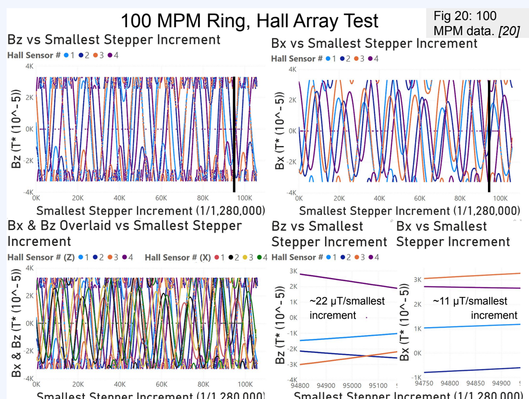

Fig 20: 100 MPM data. [20]

- **Temperature compensation confirmed:** 100 magnet & hall array demonstrated better +-60μT field ranges for temperatures, range was further reduced by averaging field values for each temperature increment

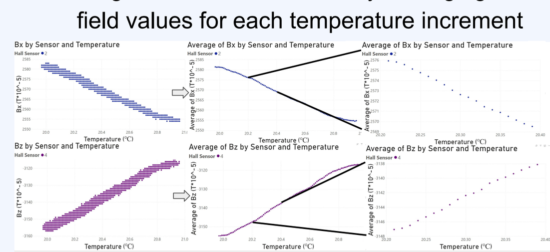
Fig 21: Temperature compensation data. [21]

Final Design Mechanical

Calibration Stand

- **AksIM-2 parent calibration encoder:** 20 bit resolution RLS AksIM-2 calibration encoder with an accuracy of ~15 to 227 arcseconds depending upon mounting eccentricity. In production, an optical encoder with negligible accuracy deviation would be used for better calibration accuracy
- **DM542T stepper driver & 100:1 gearbox:** 25,000 pulses per revolution (PPR) geared with 1:100 gearbox for a maximum of 2,500,000 counts per revolution (CPR) to increment the smallest angle, at 21 bit resolution – 1 bit over calibration resolution goal
- **AS5600 sub-divisional BPM absolute encoder:** Considering its tested repeatability, it provides around 2000 guaranteed absolute positional subdivisions, enough to subdivide the 100 N-S magnet pole periods into their own distinguishable absolute position
- **Low tolerances:** Double flanged bearing alignment, h7 tolerance on the shaft, rigid flanged couplings, stepper motor mounting on top and bottom

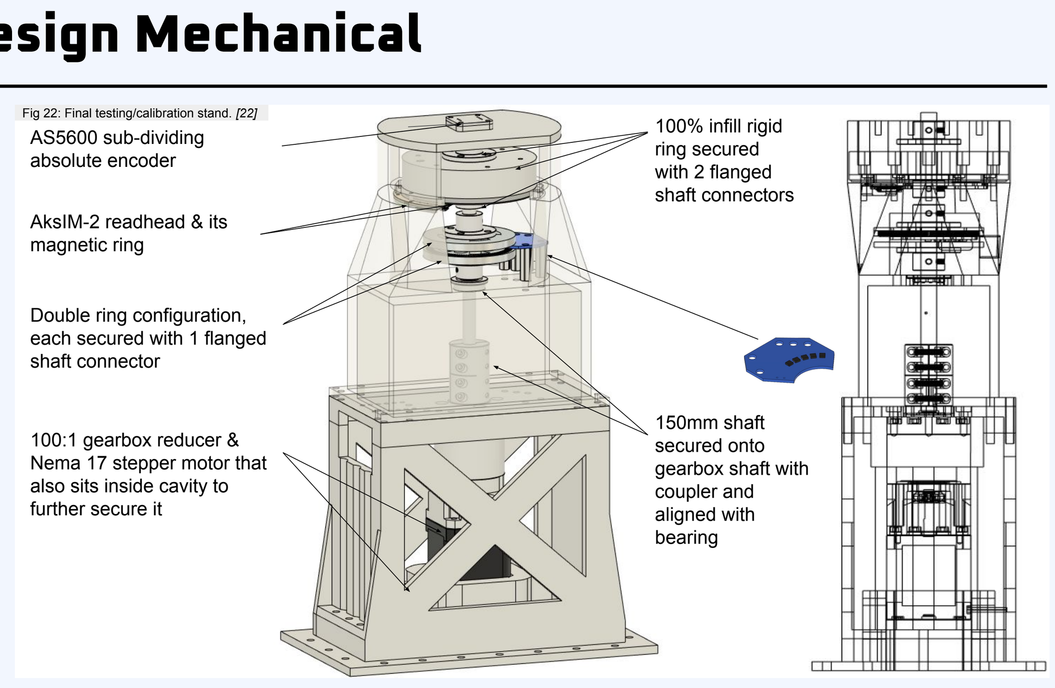

Fig 22: Final testing/calibration stand. [22]

Encoder Rings

- **Press fit 3D-printed ring design:** Easy 3D printing prototyping, impact damages magnets' uniformity, high thermal expansion
- **FR-4 final ring design:** Lower thermal expansion (<18ppm/°C) than most aluminium alloys, lower cost, more uniform magnet alignment, easier manufacturing, lower tolerances

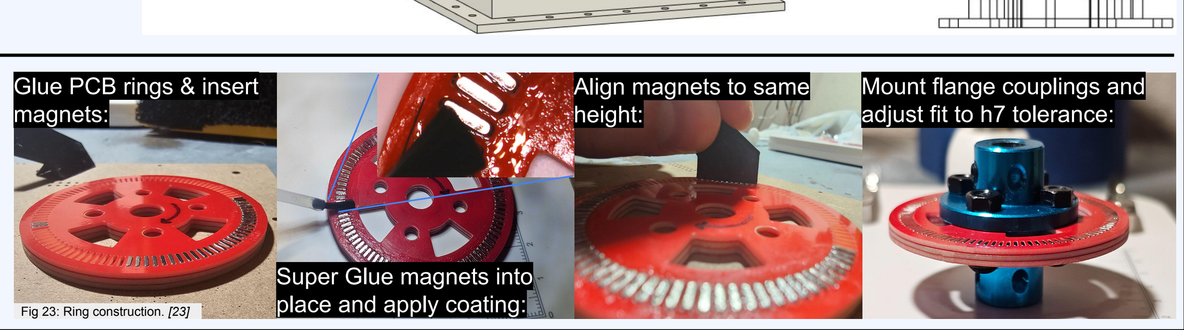

Fig 23: Ring construction. [23]

Final Design Electrical

PCB Development

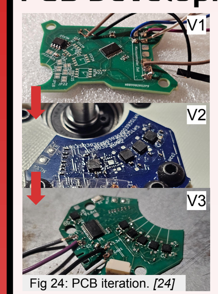

Fig 24: PCB iteration. [24]

- **Hall sensor trials:** 1D to 3D hall sensors, SOIC-8 packaged MLX90395 hall sensors to QFN packaged MLX90393 hall sensors for a more compact and repeatable hall sensor
- **Environmental compensation:** MLX90393 temperature sensors only sufficient to account for MLX90393's expected field readings, added external TMP117 to account for shift in physical magnetism of the N52 magnets
- **Rerouting:** Organized routing layout over iterations remove routing errors, misalignments, inconveniences, and make the readhead smaller

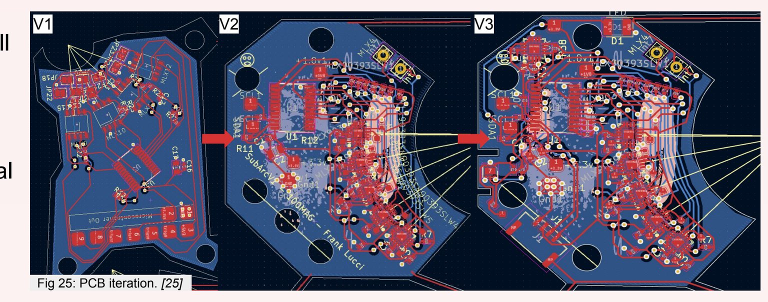

Fig 25: PCB iteration. [25]

Final Design

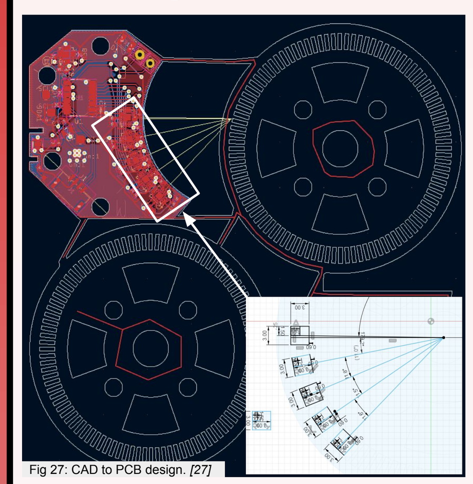
Fig 27: CAD to PCB design. [27]

- **6x I2C MLX90393 hall sensors:** Has a +-10μT repeatability determined from derived equation
- **Pull up resistors & decoupling capacitors:** 0.1uF and 10uF dec-caps. 10k Ω pull-up resistors
- **TCA9548A I2C multiplexer:** Communicates with same I2C address hall sensors, allows for a maximum of 64 encoders/microcontroller
- **TMP117 temperature sensor:** Temperature compensation sensor with -20°C to 50°C range
- **Grounding plane & voltage plane:** More direct I2C signal path to reduce signal noise
- **Panelized PCB:** Costs reduced with alignment tool, readhead, and precise MPM ring all in one
- **CAD to PCB:** Allows for $\pi/20$ phase shift

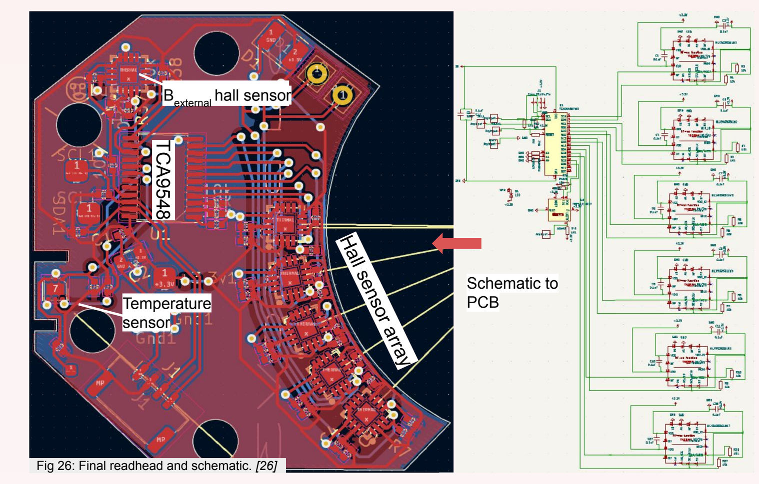

Fig 26: Final readhead and schematic. [26]

Final Design Construction

Encoder Readhead & Ring Construction


Fig 28: Build pt.1. [28]


Fig 29: Build pt.2. [29]

- Pop readhead, tin and heat solder all capacitors, resistors
- MLX90393 copper tinned, excess removed, first sensor heat-soldered, alignment tool placed, rest soldered


Fig 30: Build pt.3. [30]

- Confirm sensor connections and functionality, TCA9548A copper tinned, multiplexer soldered


Fig 31: Build pt.4. [31]

- Solder TMP117, 1.25mm female JST, and final components

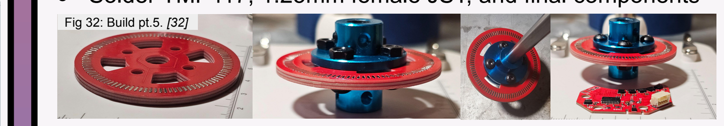
Fig 32: Build pt.5. [32]

- Assemble ring, attach couplers, & check tolerances

Calibration Stand

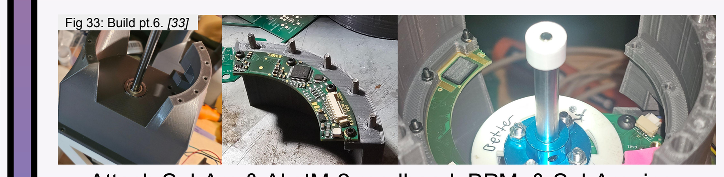
Fig 33: Build pt.6. [33]

- Attach SubArc & AksIM-2 readhead, BPM, & SubArc ring


Fig 34: Build pt.7. [34]

- Attach AksIM-2 ring, decrease eccentricity, wire AS5600

Final Design Programming

Calibration Process Visualization

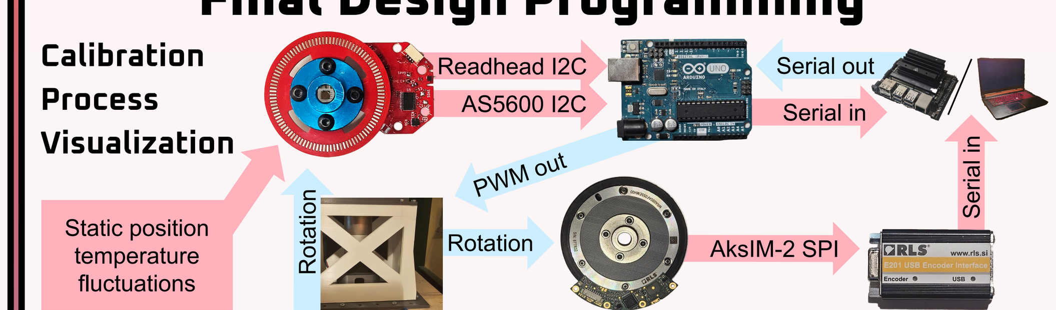

Fig 35: Calibration process signal flow diagram. [35]

Microcontroller Programming

1) Reads I2C data, cancels $B_{external}$ from SubArc hall sensor array readings, and transmits I2C data through serial bus to computer

Position Calibration & Data Refinement

1) Logs AksIM-2 absolute position with SubArc data for each smallest increment and saves data to unique calibration file
2) Increments stepper motor for >1,048,576 (20 bits) a revolution

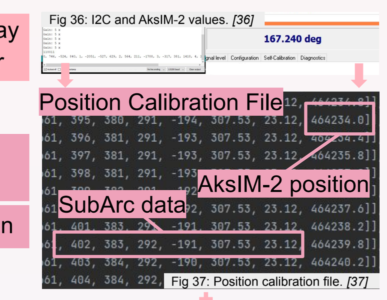

Fig 36: I2C and AksIM-2 values. [36] Fig 37: Position calibration file. [37]

Temperature Compensation

1) Temp is fluctuated, encoder position is held static, logs hall array readings vs temp in a separate unique calibration file
2) Uses position calibration temp vs live temp to find ratios between the two to scale the live hall array readings accordingly

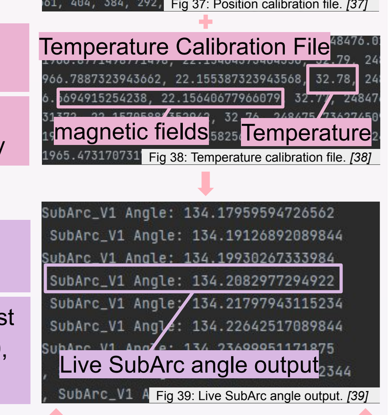

Fig 38: Temperature calibration file. [38] Fig 39: Live SubArc angle output. [39]

Live Angle Positioning

1) Reads SubArc field values, factors in live temperature and mounting calibration ratios to scale magnetic field values
2) Searches position calibration file for the angle with the nearest net field values in the specific period determined by the AS5600, returns that angular position, and adds static offset value

Mounting Calibration

1) Measures SubArc position, finds values of nearest peak and trough in sinusoid for all fields in position calibration data
2) Increments and finds current, actual nearest peak and trough fields, and returns ratios between expected and actual values

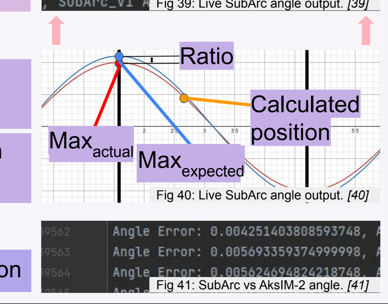

Fig 40: Live SubArc angle position. [40] Fig 41: SubArc vs AksIM-2 angle. [41]

Average Angle Deviation

1) Finds difference & logs deviation, finds average & std deviation

Calibration/Testing

Calibration Data

Position calibration procedure:
1) While keeping temperature as constant as possible, set stepper motor to 12800 pulses per revolution.
2) Calibrate SubArc position using AksIM-2 position and increment for entire revolution, save data file.

Peak calibration:
1) Enable peak calibration script, auto-increment and finds ratios, enter ratios to live angle positioning. Tested for functionality, used if out of tune over time.

Temperature compensation:
1) While collecting data from SubArc, power off motor, slowly raise and lower temperature to the maximum operating range necessary. To prove functionality, a range of 60°F - 90°F was collected and tested.

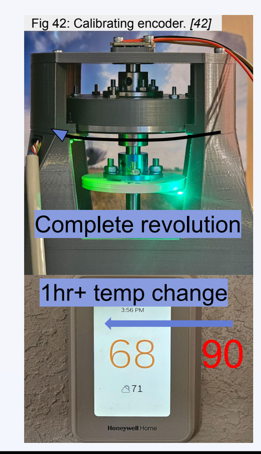

Fig 42: Calibrating encoder. [42]

Resolution & Accuracy

Resolution testing:
1) To confirm 20 bit resolution, there should be at least a +-10μT change for more than 1,048,576 (20 bits) increments of the full calibration revolution.
2) To further ensure 20 bit, the angle should not fluctuate when held still while reading the live angle.

Accuracy testing:
1) Combine the average angle deviation script with the live angle positioning script. Over a slow, 5 hr+, full revolution where temperature changes, the average angle deviation shouldn't exceed 150 arcseconds (0.04167°).
2) Reboot system, scramble position, and repeat accuracy testing thrice over 4 days to reduce experimental uncertainty.

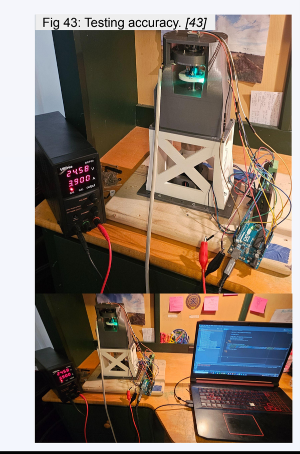
Fig 43: Testing accuracy. [43]

Data Analysis

Position Calibration & Resolution

- **Calibration:** Over one full 20 bit AksIM-2 calibration rotation, over 15 million identifying field data points were matched, with at least **a detectable & repeatable +-10μT change for >1,048,576 increments confirming 20 bit resolution.** The AS5600 successfully split periods; values unique for periods

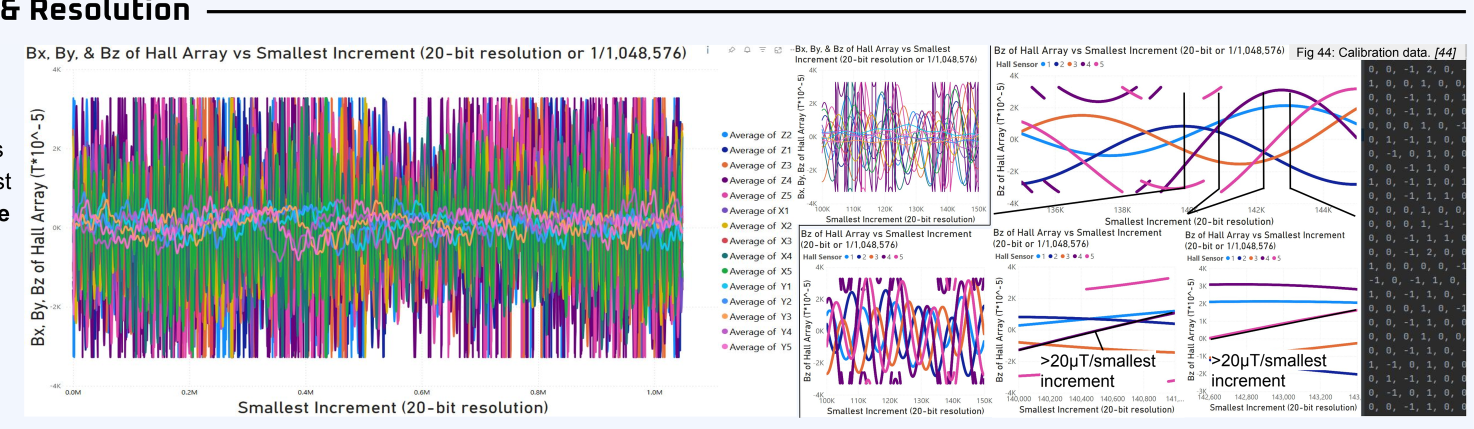

Fig 44: Calibration data. [44]

- **Position holding:** When position calibration data was used for live angle positioning and the rotor was kept still, a **constant, non-fluctuating angle was output**
- **Data set analysis:** To confirm graphical insights, a script marking the greatest change confirmed +-10μT changes across >1,048,576 increments (20 bit resolution)

Temperature Compensation & Peak Calibration

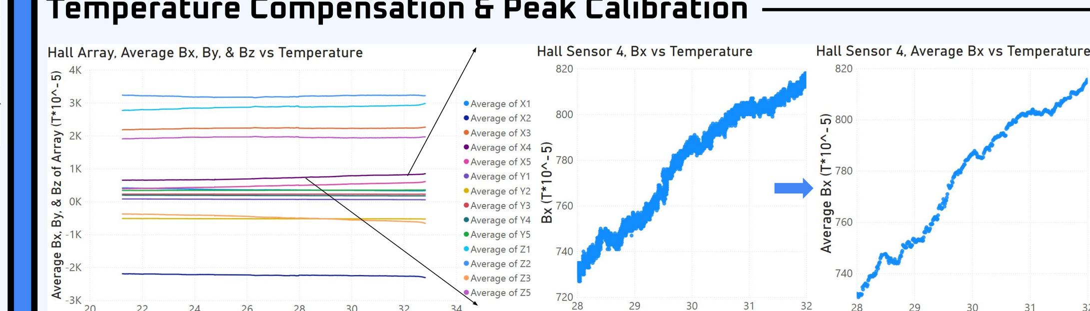

Fig 45: Temperature compensation data. [45]

- **Temperature compensation:** After calibrating from 70°F to 90°F, field values were averaged to refine compensation data, returning <+-50μT ranges. This error range made for highly effective temperature compensation ratios. **The temperature compensation algorithm was successfully implemented** in live positioning, using the calibrated average data table.
- **Peak calibration:** **The algorithm worked,** successfully identifying theoretical and real amplitudes and **scaling the live real values by the ratio**

Accuracy

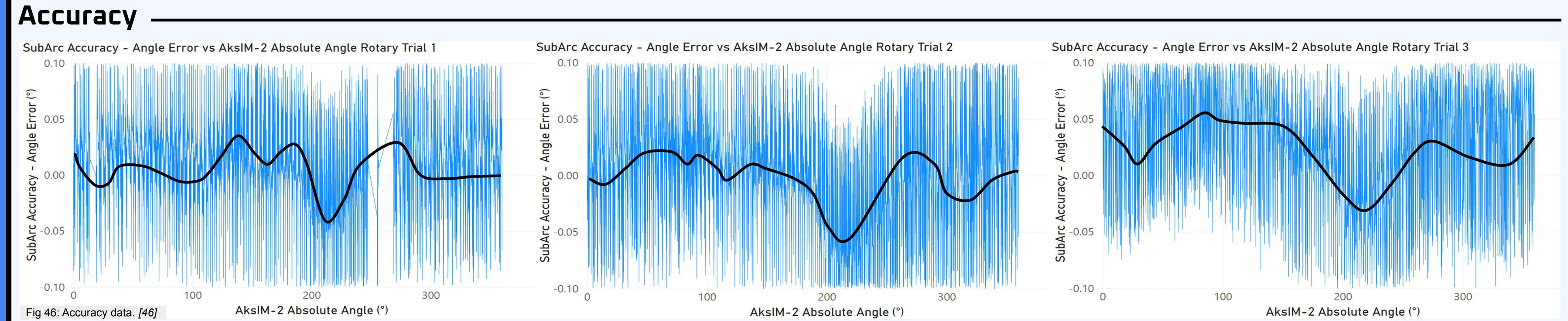

Fig 46: Accuracy data. [46]

- **Individual averages:** By tuning each rotation by an unchanging offset value, their average accuracies were 0.0336° for trial 1, 0.0385° for trial 2, and 0.0390° for trial 3
- **Individual standard deviations:** For the individual trials, the standard deviations of their accuracies were 0.0264° for trial 1, 0.0315° for trial 2, and 0.0319° for trial 3
- **Combined avg acc & std dev:** By using overall unchanging offset value for all trials, the overall average accuracy was 0.0384° with a **standard deviation of 0.0308°**. Therefore, **the average accuracy was successfully under 150 arcseconds (0.0417°) at 138 arc seconds (0.0384°)**

Double Ring to Single Ring

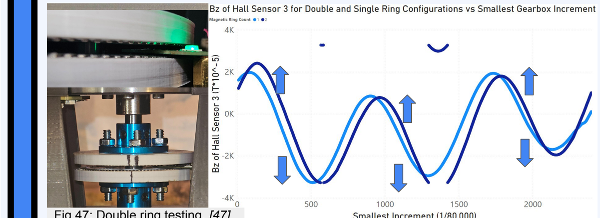
Fig 47: Double ring testing. [47]

Transition: Single ring had enough ΔB /smallest increment of 20 bit CPR **Trade-off:** Smaller multiplier than expected, can be used to slightly boost current encoders without increasing diameter

Scale Cost Analysis & Publication

Open Source →
Encoder size: ring & readhead size & calibration encoder can be customized to alter resolution & accuracy to fit application
Industry: SubArc can be manufactured for individual use cases or mass produced to lower overall encoder cost

Cost Analysis →
Calibration stand: **$896** (Most cost from the AksIM-2)
<100 Units: $24.84 (current cost)
100 Units: $20.05/Unit
1000 Units: $18.09/Unit
10000 Units: $17.16/Unit

Conclusion

Performance:
- **20 bit resolution (0.000343°)** ✔
- **138 arcseconds (0.0384°) = < 150 arcsecond average accuracy** ✔
- **$24.84/unit = < $40** ✔
- **2.17in (55mm) Ø = < 3in Ø** ✔
- **Temperature, external magnetic field & mounting/peak compensation = environmentally robust** ✔
- **Open source customizable design** ✔

Impact:
- **High precision robotics, machinery, and instrumentation can drop in price, become accessible, and billions of dollars can be saved in an ever-growing automated world**

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