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

Background and Problem

Precision machinery is critical in nearly all scientific and consumer domains: astronomy, medicine, aerospace, integrated circuits, energy, defense, robotics, optics, and more.

- High resolution encoders give many precision machines their high precision measuring ability
- Current high resolution encoders cost $100s—$1,000s for the 20—22+ bit resolutions required for many precision machines
- ↑ precision machinery cost → prevents many from developing or utilizing vital precision machinery

Costly encoders needed for each axis = ↑ $$$$$$

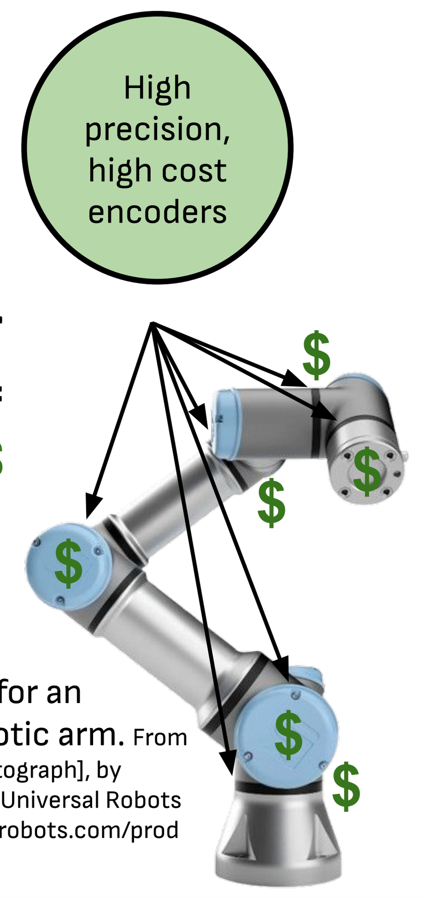

Fig 1: UR3e used for an example of a robotic arm. From UR3e Robotic Arm [Photograph], by Universal Robots, (n.d.), Universal Robots (https://www.universal-robots.com/products/ur3e/)

Solution and Engineering Goal

Solution → Create SubArc: An inexpensive, high resolution, open source, absolute magnetic rotary encoder

<$40 accessible cost **20 bit resolution** **<150 arcsecond average accuracy**

Environmental robustness:

- External magnetic field compensation
- Mounting Calibration
- Temperature Compensation

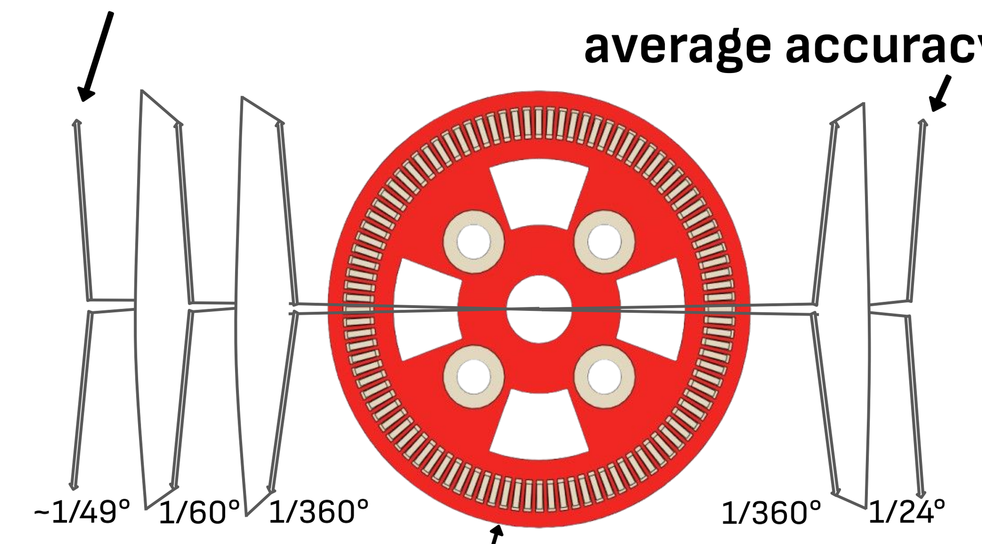

Fig 2: SubArc encoder ring. Image made by finalist with Fusion 360 and Google Slides, 2025.

Customizable and open source:

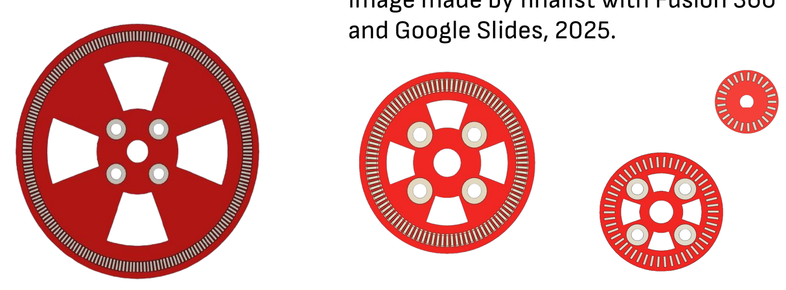

Fig 3: SubArc encoder ring customization example. Image made by finalist with Fusion 360 and Google Slides, 2025.

New Signal Processing Technique

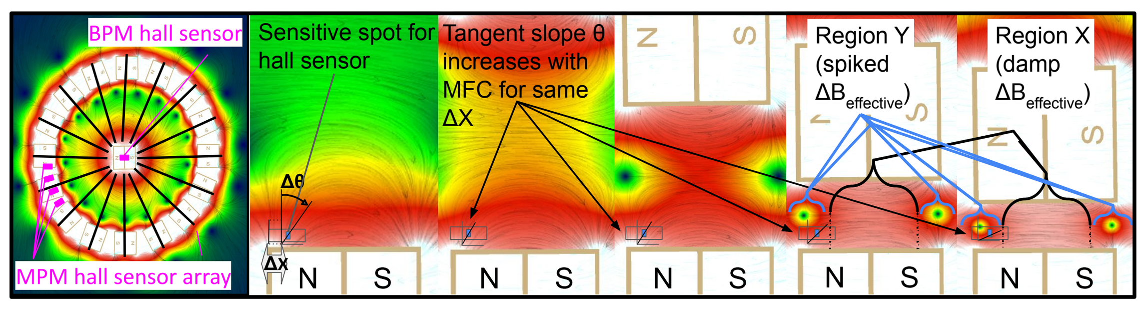

Fig 4: The configuration SubArc used to boost resolution and the theoretical dual ring field compression to further boost resolution. Image made by finalist with open source DEVRECi MagSim and Google Slides, 2025.

Signal process matches SubArc magnetic ring and bipolar magnet readings with expensive 20 bit calibration encoder position → generates unique calibration file → enables higher tolerance production

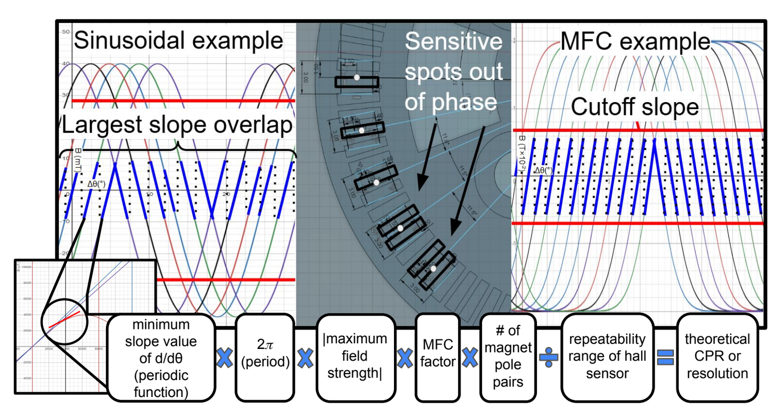

Fig 5: SubArc resolution equation and example of how calibration data would be like from calibration stand with different ring configurations. Image photographed created by finalist using Google Slides, Fusion 360, and Desmos, 2025.

New Encoder Design and Programming

New encoder design features:

- Low cost manufacturing of new PCB-based magnet ring and PCB readhead
- Calibration stand to test and produce unique calibration file for new encoder
- Environmental compensation techniques

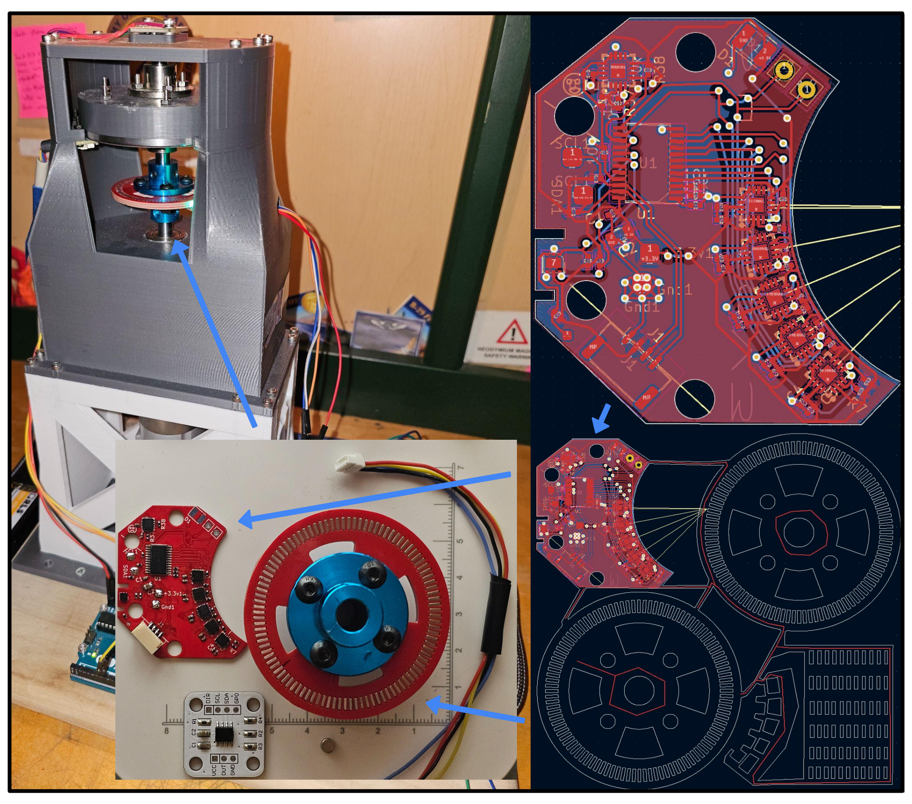

Fig 6: SubArc encoder PCB, components, and testing stand. Image photographed created by finalist using Google Slides and KiCAD, 2025.

Prior Iteration and Design

Created iterations to confirm the theory and scale the idea:

V1: Verifies bipolar magnet (BPM) can subdivide multi-pole magnet (MPM) into a higher resolution absolute position

V1.5: Verifies smaller hall sensor and N52 magnets for next SubArc design iteration

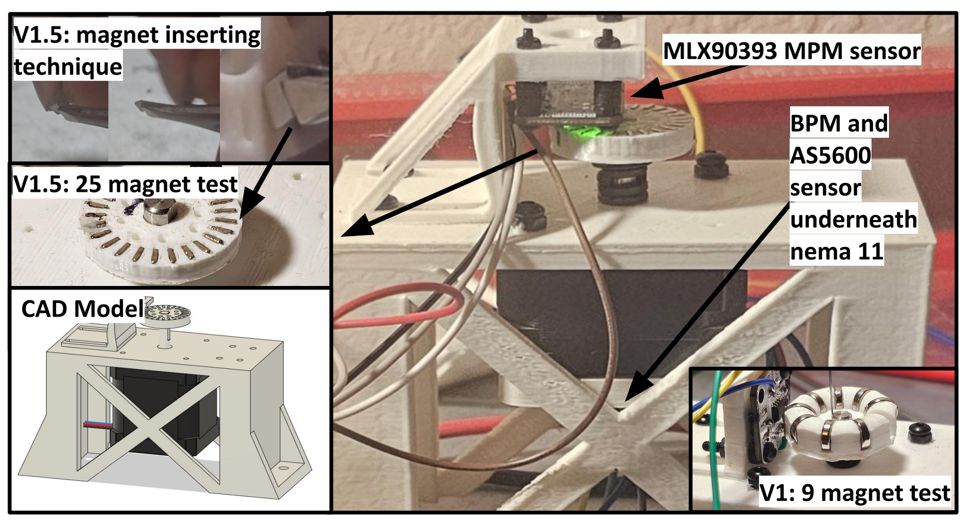

Fig 7: Testing stand V1, MPM V1/V1.5, and MPM ring building process. Image photographed and made by finalist with Fusion and Google Slides, 2025.

V2: Proves 19 bit resolution potential and resolution equation scalability

V2.5: Proves 20 bit resolution is possible and dual MPM-based MFC isn't needed to achieve the engineering goal

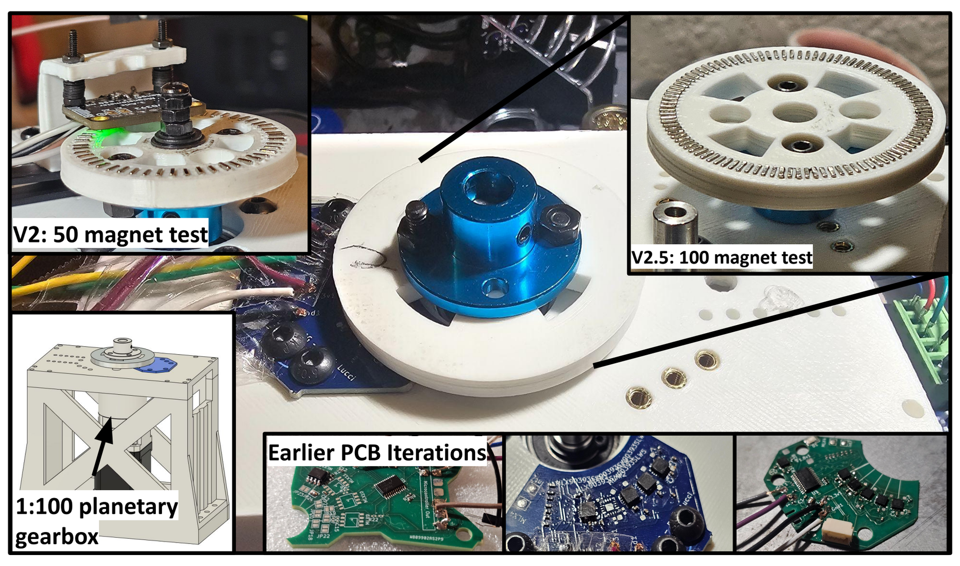

Fig 8: Testing stand V2, MPM V2/V2.5, PCBs V1/V2/V3, and MPM ring building process. Image photographed and made by finalist with Fusion and Google Slides, 2025.

Final SubArc Full Testing and Data Analysis

Resolution: Calibrated over a full 20 bit rotation (~1 million counts per rotation), checked calibration file for repeatability of hall sensor < ΔB /ΔΘ for all 20 bit increments

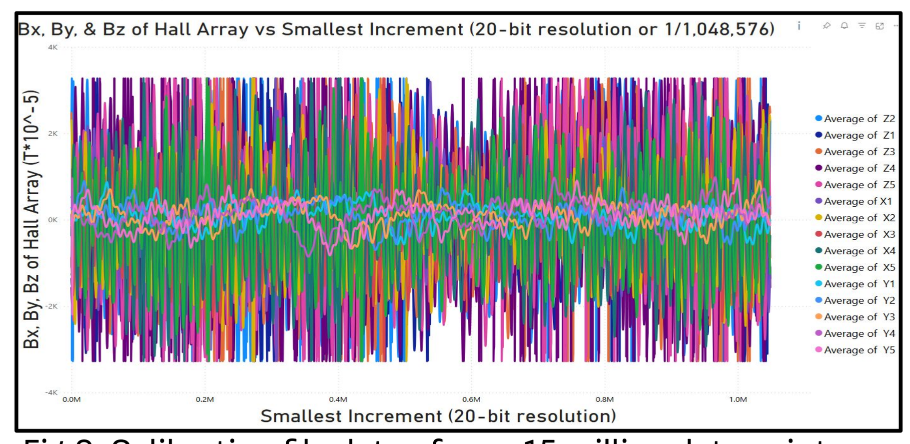

Fig 9: Calibration file data of over 15 million data points. Image made by finalist with Microsoft Power BI and Google Slides, 2025.

Environmental compensation: Tested ratio-based temperature compensation, $B_{external}$ minimization, & mounting calibration

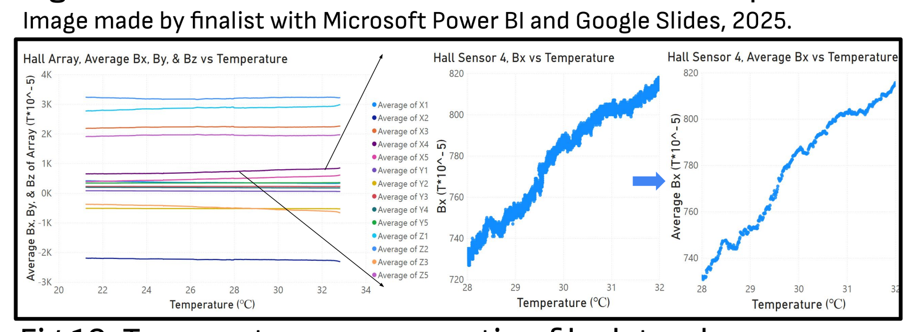

Fig 10: Temperature compensation file data, shows magnetism vs temperature from B_x of hall sensor 4. Image created by finalist using Microsoft Power BI and Google Slides, 2025.

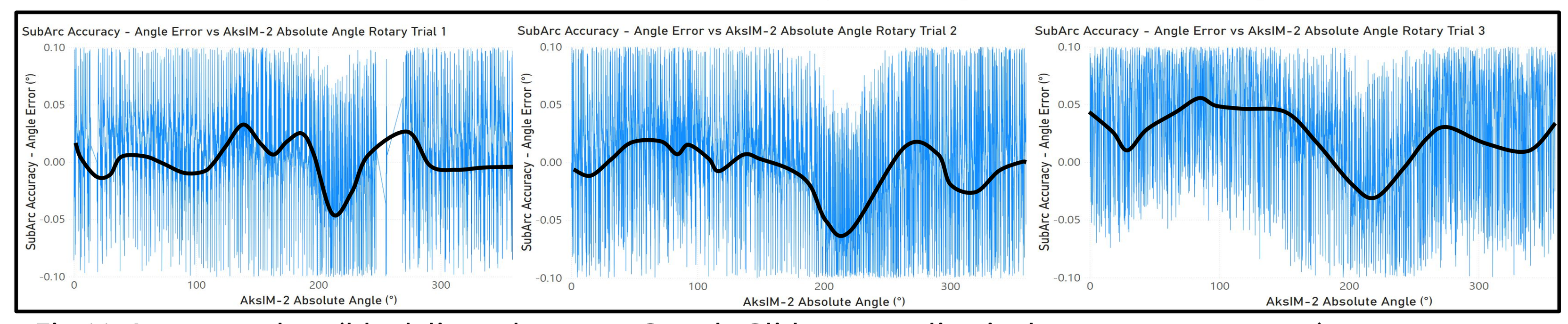

Fig 11: Accuracy data (black lines drawn on Google Slides to qualitatively represent average). Image created by finalist using Microsoft Power BI and Google Slides, 2025.

Accuracy: Trials tested over multiple days, taking average difference between AksIM-2 position & SubArc position with static offset value

Performance Conclusion

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

Overall Conclusion and Future Outlook

The SubArc encoder design met the engineering goals. The SubArc encoder is open source for anyone to continue research or use.

In the future, once the design has been refined, it may help to reduce the cost of precision machinery and make it more accessible in an ever-growing automated world

Important References: Principle and advantages of magnetic encoder. (n.d.). Asahi Kasei Microdevices. https://www.akm.com/global/en/products/rotation-angle-sensor/tutorial/magnetic-encoder/ ; AksIM-2™ Off-Axis Rotary Absolute Magnetic Encoder Module. (n.d.). RLS, A Renishaw Associate Company. https://www.rls.si/eng/aksim-2-off-axis-rotary-absolute-encoder ; Park, J. W., Nguyen, H. X., Tran, T. N.-C., & Jeon, J. W. (2021). A Linear Compensation Method for Improving the Accuracy of an Absolute Multipolar Magnetic Encoder. IEEE Access, 9, 19127–19138. doi: https://doi.org/10.1109/access.2021.3054362 ; MLX90393 Triaxis® Magnetic Node Datasheet. (2024). Melexis. https://www.melexis.com/-/media/files/documents/datasheets/mlx90393-datasheet-melexis.pdf ; Artos™ DHR Rotary and Linear Absolute Magnetic Encoder System. (n.d.). RLS, a Renishaw Associate Company. https://www.rls.si/eng/artos-dhr-rotary-absolute-magnetic-encoder-system

Frank Lucci