Fundamental Electromagnetics and HHC knowledge:
https://shura.shu.ac.uk/24854/1/TAES-201800546R_manuscript_doublecolumn.pdf
https://apps.dtic.mil/sti/tr/pdf/ADA557488.pdf
B-dot detumbling algorithm: Development, Integrated Investigation, Laboratory and In-flight Testing of Chibis-M Microsatellite ADCS (2014)
Testing of Attitude Control Algorithms for Microsatellite 'Chibis-M' at Laboratory Facility (2012)
GWSAT Satellite Test-Bed (2025)
CaNOP CubeSat Cage (2018)
UC CubeCats Helmholtz Cage (code for the HHC):
https://github.com/uccubecats/Helmholtz-Cage

Items to further research:

- Testing & Validation Methods
    - Uniformity characterization procedures: How to measure and validate field uniformity across the test volume - what are acceptable tolerances? Where exactly do they measure (Helmholtz Cage Design and Validation for Nanosatellites HWIL Testing is good starting point)?
    - Calibration procedures: How often do cages need recalibration? What causes drift? How to calibrate magnetometers inside the cage?
    - Ambient field cancellation strategies: Active vs passive shielding, measurement techniques, how to null Earth's field effectively
    - Error sources and mitigation: Temperature effects on coil resistance, magnetic interference from power supplies
- Control System Design
    - Transfer function characterization: Voltage to magnetic field (V→|B|), system dynamics, inductance effects, time constants
    - Control law comparison: PID vs other approaches, tuning methods (Ziegler-Nichols), feedforward compensation
    - Sampling rates and latency requirements: For different test scenarios (passive calibration vs active detumbling), communication bottlenecks
    - Closed-loop stability analysis: How to ensure stable field control, handling sensor noise in feedback
    - Investigate HWIL, and get an understanding of how they built their feedback system (Helmholtz Cage Design and Validation for Nanosatellites HWIL Testing is a starting point)
    - What kinds of scenarios will our Helmholtz cage need to be able to simulate, and testing procedures. What are the measures of success?
        - From that, we can figure out how quickly our cage needs to be able to switch polarities.
- Mechanical/Physical Design
    - Coil geometry trade-offs: Square vs circular coils (square uses $\gamma=0.5445$), nested arrangement optimization, spacing constraints
    - Thermal management: Power dissipation in coils, cooling requirements, temperature effects on field accuracy

- Structural materials: Why aluminum vs other materials, magnetic vs non-magnetic considerations, frame rigidity requirements (less important, standard seems to be aluminum)
    - Wire gauge selection rationale: Why AFIT used 12 AWG, how to calculate required wire size, current density limits
    - Investigate how square rounded corners might impact calculations (Helmholtz Cage Design and Validation for Nanosatellites HWIL Testing)
- Electrical Architecture
    - Power supply specifications: Why specific voltages (60V vs 20V), current ratings, ripple requirements, unipolar vs bipolar supplies
    - H-bridge design considerations: Current ratings, switching frequency capabilities, protection circuits, heat sinking
    - Relay specification: Contact ratings, switching speed, lifetime expectations, bounce characteristics (understand the context in which a relay is used)
    - Grounding and noise: How to minimize electromagnetic interference (EMI) , proper grounding schemes, shielding requirements
    - Figure out necessity of H-bridges (typically for how quickly we need to switch polarities), type of wire, power supplies, etc.
- Software & Integration
    - Communication protocols: GPIB (mentioned in AFIT), RS-232, Ethernet - latency comparison
    - Real-time operating system requirements: For HWIL, what determines if you need RTOS, and do we need it?
    - Orbital propagation integration: How STK or other tools interface with cage control, coordinate frame transformations
    - Data logging and analysis: What parameters to record, sampling rates, post-processing methods
- Cost Analysis
    - Component cost breakdown: Coils/wire, power supplies, control hardware, sensors, frame materials
    - Budget vs capability trade-offs: What you lose going from $50k cage to $5k cage
    - Commercial vs DIY approaches: When to buy vs build components
- Scaling Considerations
    - Size vs uniformity trade-offs: Larger cages (AFIT 8'×8'×8' vs typical 2m), how size affects design
    - CubeSat size accommodation: 1U, 3U, 6U testing - does cage size need to scale (this will also be determined at the end with the cost analysis)
    - Field strength requirements: Why some projects need ±200 μT vs ±50 μT, and re-check our requirement in the ADCS testing requirements document
- Specific Scenario Testing Details
    - Detumbling scenario parameters: Initial tumble rates, convergence criteria, typical test duration
    - Orbit simulation fidelity: LEO, polar vs equatorial, update rates needed for realism

    - Sun acquisition testing: How to simulate sun sensors in conjunction with magnetic field
    - Nadir pointing validation: Testing requirements, accuracy metrics
- Safety & Practical Considerations
    - High current safety: Fusing, interlocks, emergency shutoff procedures
    - Magnetic field exposure limits: For operators working near cage, safety (no jewelery, etc.)
    - Failure mode analysis: What happens if power supply fails, relay sticks, sensor malfunctions?
- Literature Gaps to Fill
    - Comparative studies: Papers that directly compare different cage designs/approaches
    - Lessons learned papers: Post-mortem analyses of what worked/didn't work
    - Frequency response testing: Dynamic characterization methods
- From Past Research - Specific Follow-ups
    - Why University of Brasilia Y-axis was limited: Power supply voltage issue - generalize this lesson
    - Relay vs H-bridge decision matrix: Create concrete decision criteria based on application requirements
    - What determines acceptable update rates?
    - Cross-coupling rejection in closed-loop systems: How feedback suppresses induction effects