ARIZONA STATE UNIVERSITY

HONORS THESIS

DIY Supercube

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A thesis submitted in fulfillment of the requirements for the degree of Honors Thesis in Software Engineering

in the

Fulton Schools of Engineering
Barrett, The Honors College

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Declaration of Authorship

I, Joseph HALE, declare that this thesis titled, "DIY Supercube" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

ARIZONA STATE UNIVERSITY

Abstract

Dr. Robert Heinrichs

Barrett, The Honors College

Honors Thesis in Software Engineering

DIY Supercube

by Joseph HALE

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor…

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List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($J\,s^{-1}$)
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 The Advent of Smart Cubes

Speedsolving, the sport of solving twisty puzzles like the Rubik's Cube as fast as possible, has seen a resurgence of popularity since the early 2000s. Over the past two decades many advances in cube technology have produced ever higher performing puzzles.

Recently, the speedcubing community has seen the entrance of smart cubes, special versions of a Rubik's Cube that can connect to a mobile device over Bluetooth. These smart cubes have sparked a wave of excitement with the vast opportunities they offer for automatic turn tracking, performance analysis, personalized improvement feedback, and networked competition.

1.2 Obstacles to Adoption

While a revolutionary idea, smart cubes still face several obstacles to widespread adoption.

- *Cost*: Smart cubes can cost up to eight times as much as a comparable non-smart speedcube. For example, one popular budget speedcube, the Moyu Weilong, costs only $5, while the cheapest smartcube, the Giiker Cube, starts at $40. [TODO sources!]. On the higher end, a premium speedcube, like the Gans 356 XS, retails for just over $60 while a premium smartcube, like the GoCube, retails for over $100. [TODO Make this a footnote.]
- *Performance*: Existing smart cubes turn slower than comparable non-smart cubes. [TODO source]
- *Reliability*: Many smart cube owners report inability to connect the smart cube to a mobile device and missed/inaccurate turn tracking.
- *Regulation*: Current competition rules ban the use of electronics during timed solves, thus banning the use of smart cubes. There is no foreseeable change to this rule.

As a result of these obstacles, many speedcubers refrain from purchasing a smart cube, despite expressing significant interest in the opportunities smart cubes offer.

1.3 Purpose of this Thesis

The primary goal of this thesis is to create a proof-of-concept for a smart cube design that mitigates the performance and competitive regulatory concerns of existing smartcubes.

1.3.1 Design Requirements

TODO

Specifically, the smart cube design discussed in this thesis will be assessed against the following criteria:

1. *Compatibility with Standard Speedcubes*: The design must be deployable within a standard (non-smart) speedcube. "How can a standard speedcube be enhanced into a smart cube?"
    (a) The design must not require permanent modifications to the original speedcube.
    (b) The design must not significantly impact the turn-speed of the original speedcube.
2. *Move Tracking Accuracy*: The design must be capable of tracking the face turns of a Rubik's Cube with over 99% accuracy.
3. *Move Tracking Granularity*: The design must be capable of recording the time spent executing each individual face turn of a Rubik's Cube.
4. *Competition Legality*: The design must be competition legal, meaning it results in a cube that either does not violate existing competition rules against the use of electronics or can be easily modified to regain compliance.

1.4 Thesis Overview

TODO give an overview of the rest of the Thesis document.

Chapter 2

Background

TODO Each chapter starts with a paragraph that briefly outlines the purpose of each of the sections.

2.1 A Brief History of the Rubik's Cube

In 1974, Erno Rubik, a Hungarian professor of architecture, sought to help his students visualize space in three dimensions. To that end, he created a special cube whose faces could independently rotate around all three physical axes [1]. When he added colored stickers to further aid in visualizing the movements, Mr. Rubik realized he had created a new puzzle. He patented his cube in 1975, [2] and since then over 450 million units have been sold [3], allowing an estimated 1 in 7 humans on earth to try their hand at solving it [4].

Since then, the cube has been the subject of academic research, competition, leisure, and cultural iconography.

2.2 The Mechanics of the Rubik's Cube

2.2.1 Algorithm Notation

TODO

2.2.2 The Laws of the Cube

TODO Describe the basic concepts of group theory that stipulate what positions are and aren't legal. It might also be fun to discuss the derivation of the 43 quintillion possible positions on the cube.

2.3 Speedsolving

TODO

2.3.1 The World Cube Association

TODO

2.3.2 Competition Regulations

TODO

2.4 The Rise of Smart Cubes

TODO

Chapter 3

State of the Art

3.1 Introduction

TODO, be a *neutral* presentation of the current state of this technology. Give a big information dump to the reader.

3.2 Commercial Smartcubes

Commercial Smartcubes are special Rubik's Cubes built around sensors that can detect face turns and transmit that information over Bluetooth. Some models can also measure and transmit data about the cube's orientation.

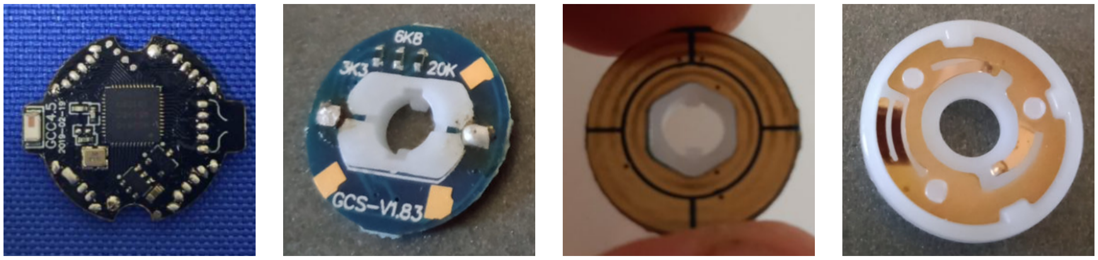
At the time of writing, there are four major smartcubes on the market: the Giiker Cube, the Go Cube, the Rubik's Connected (which is powered by GoCube technology) and the Gans 356i. This section will discuss the internal components of each of these cubes that provide this move-tracking functionality.

3.2.1 Giiker Cube

The Xiaomi Giiker Cube was released in September 2018 making it the first commercial smartcube on the market [5]. This "Supercube" as it was branded, used a relatively simple system for tracking the cube's movements. The core of the cube is built around a small circuit board with a microcontroller that measures the cube's movements and a bluetooth antenna that transmits those moves wirelessly (Figure 3.1a). The microcontroller detects each face turn by reading the voltage drop across a small circuit embedded within each center cap (Figure 3.1b). The center cap circuit controls its output voltage by using a copper brush to change between four separate electric paths, three different resistors and ground, as each face rotates (Figure 3.1d). [6]

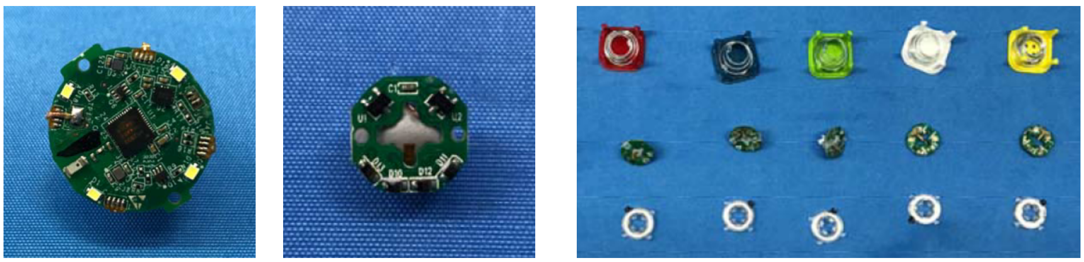
3.2.2 Go Cube

Announced on Kickstarter in June 2018, Patricula's GoCube was the first smartcube to include a gyroscope that would track a Rubik's Cube's orientation in addition to the face turns applied to it. [8] Like the Giiker Cube before it, the GoCube's core contains a small circuit board with the main electronics including a microcontroller, bluetooth antenna, and the added gyroscope (Figure 3.2a). Though the teardown pictures from



(A) Internal Board [6] (B) Center Cap Board [7] (C) Center Cap Pads [7] (D) Center Cap Brush [7]

FIGURE 3.1: The internal components of the Giiker Cube



(A) Internal Board (B) Center Cap Board (C) Full Center Cap Teardown

FIGURE 3.2: The internal components of the Go Cube [10]

the Go Cube's FCC filing aren't particularly clear, it appears that the cube registers face turns similarly to the Giiker Cube: by producing a voltage drop via changing which one of the four resistors shown across the bottom of the center cap board in Figure 3.2b is in series with the circuit.

GoCube also serves as the underlying technology for the Rubik's Connected, the official smartcube from The Rubik's Company. [9]

3.2.3 Gans 356i

Released in July 2019, the Gans 356i was the first commercial smartcube produced by a traditional speedcube manufacturer. [11] While the Gans 356i also uses a microcontroller to process the face turns and Bluetooth to transmit the move data, it tracks moves not through changing resistors in and out of a circuit, but via six plastic rods that connect the outer center caps to internal rotary encoders (Figure 3.3).

3.3 Academia

In addition to the various commercial smartcubes, many academic research projects have involved some element of tracking the state/face turns of a Rubik's Cube.

This section explores the current state of academic research into using Computer Vision, Magnetic Resonance, and a Muscle-Tracking armband to track the state of a Rubik's Cube.

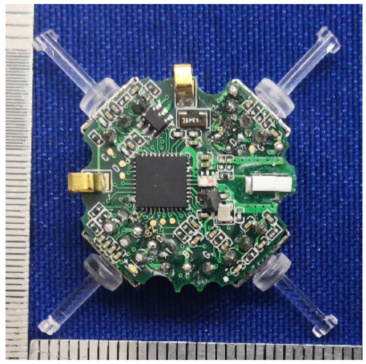


FIGURE 3.3: The Gans 356i Cube's internal components. [12]

3.3.1 Computer Vision

Computer Vision refers to the "field of Artificial Intelligence (AI) that enables computers and systems to derive meaningful information from digital images, videos, and other visual inputs." [13] Since human manipulation of a Rubik's Cube is a physical, observable process, Computer Vision algorithms could be developed to extract face turn information from videos of Rubik's Cube solutions.

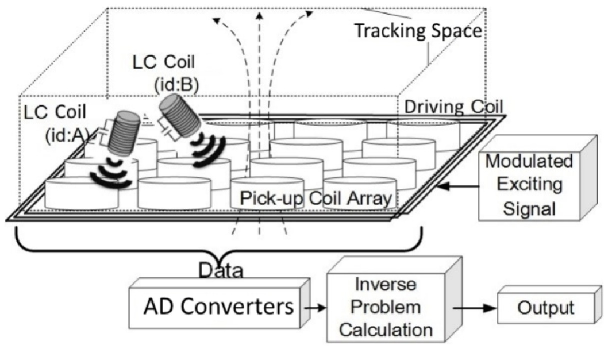
This section summarizes some of the relevant research in this area, including computer vision algorithms capable of extracting individual sticker colors from video, measuring the angle of rotation of a specific face, and detection of entire face turns and face turn sequences.

Sticker Color Classification

In 2015, Jay Hack, an graduate student studying Computer Science at Stanford developed a neural network capable of recognizing the colors of a Rubik's Cube face from video in various lighting conditions. His algorithm could classify frames within 7 milliseconds with 92% accuracy. [14]

Measuring a Face's Angle of Rotation

In 2019, OpenAI et al. published a viral video of a robot hand that had taught itself to solve a Rubik's Cube. While the final, most successful version of the robot hand's software used a Giiker Cube to obtain the current rotational state of the cube, OpenAI et al. also researched the viability of tracking a Rubik's Cube's position using only computer vision. Their most successful vision-only algorithm measured only the rotation angle of the top-most face on the Rubik's Cube and assumed significant hardware requirements: a modified sticker set for the Rubik's Cube, a well-lit environment, three strategically positioned RBG Basler cameras, and a neural network trained on "a pool of optimizer nodes, each of which uses 8 NVIDIA V100 GPUs and 64 CPU cores". At peak performance, their vision-only algorithm's average error (the difference between the predicted face angle and the actual face angle) was 15.92°, nearly three times the 5.90° average error of the hardware-based face angle measurement. [15]



(A) IM3D System Architecture [17]

(B) IM3D trackers in a Rubik's Cube [18]

FIGURE 3.4: The IM3D technology as used in the Cube Harmonic

Classification of Single Moves and Entire Move Sequences

In 2020, Junshen Kevin Chen, Wanze Xie, and Zhouheng Sun, graduate Computer Science students at Stanford created the DeepCube dataset consisting of over 20,000 videos of Rubik's Cube face turns with consistent lighting and backgrounds. They also built a neural network to classify the videos with the face turn they contained. Their best performing model only made "one mistake every 15 moves" which corresponds to a 93.3% accuracy. [16]

3.3.2 Magnetic Resonance

In 2018, Maria Mannone et al. used the IM3D magnetic 3D motion tracking technology introduced by Huang et al. [17] to track the state of a Rubik's Cube across various movements for the purpose of generating a sequence of musical chords. This approach to turn tracking requires a special array of magnetic coils as shown in Figure 3.4a and the installation of "multiple small, light- weight, wireless markers (LC coils) with unique IDs" (a process that requires permanant modifications to the cube as evidenced by the damaged plastic in Figure 3.4b). Mannone et al. reported no issues with mistakes in the move tracking technology.

3.3.3 Muscle-Tracking Armband

In 2017, Richard Polfreman and Benjamin Oliver researched ways to use the face turns of a Rubik's Cube as controls for a music synthesizer. They explored the use of a muscle-tracking armband (specifically the Myo Armband) to track the human solver's finger movements while manipulating the cube. However, since "the Myo moved a little when 'cubing'", they ultimately found greater success with a computer vision based tracking solution similar to those discussed in 3.3.1.

3.4 Other Relevant Research

Finally, there are a number of research papers/commerical products that seek to transmit data in highly-constrained environments that are potentially relevant to the challenge of tracking the turns of a Rubik's Cube.

This section discusses some of these potential alternate move tracking mediums, specifically sound, RFID, and off-angle magnetic rotation sensors.

3.4.1 Sound

TODO discuss the viability of using sound for making a smart cube.

Google's "Data Over Sound" Project

TODO discuss the Google's "data over sound" project and its applicability to this problem space.

3.4.2 RFID

TODO discuss the viability of using RFID for making a smart cube.

3.4.3 Off-Angle Magnetic Rotational Sensors

TODO discuss the viability of using Off-Angle Magnetic Rotational Sensors for making a smart cube.

3.5 Choice of Sound for My Thesis

TODO This section might be large enough to merit its own chapter... TODO Briefly detail the rationale for chosing to pursue a sound-based approach.

Chapter 4

Protocol Design

4.1 Requirements

Sound is an easily accessible, and therefore noisy medium of communication. As a result, any data transmission protocol must be resilient to the presence of additional noise.

4.1.1 Signal to Noise Ratio

Each selected tone must be easily distinguished from background noise in a quiet room.

- Lower frequency tones (e.g. < 100Hz) are more prominent in background noise.
- Analysis based on this criterion should also consider the background noise generated by the rotation of the Rubik's Cube itself.
- Most of the concerns involved in this criteria are solved by increasing the volume of the generated tone.
- Contrast with the WCA regulation. Perhaps a protocol that is weaker in noisy environments is more likely to be permissible.

4.1.2 Tone Distinctiveness

Each selected tone must be easily distinguished from each other tone.

- Our testing with smartphone microphones suggested that tones needed to be separated by at least 100Hz to be uniquely detected from each other.
- We can also exploit the fact that only one of each faces four positions will be active at a time.

4.1.3 Ease of Deployment on Consumer Hardware

Each selected tone must be easily produced by a consumer grade speaker and consumed by a consumer grade microphone.

- A typical smartphone can produce and consume tones in the human auditory range of 10Hz - 20kHz (TODO source).

4.1.4 Human Auditory Range

Tone selection shall be biased in favor of tones beyond the typical human auditory range; however, in intial prototypes, this criterion is subordinate to all other criteria.

- Many humans are unable to hear tones above 17kHz (TODO how many? source?)

4.2 Absolute Sound Positioning

Each of the Rubik's Cube's six faces has four possible positions, for a total of 24 unique tones required for our protocol.

TODO finish this protocol proposal.

4.3 Relative Sound Positioning

This strategy seeks to minimize the number of discrete frequencies required to communicate changes in the cube's state. Since the cube consists of 6 faces, and each face can be turned either clockwise or counterclockwise, one could design a two-tone protocol using only 8 discrete audio frequencies to build the smart cube. The first tone would come from one of six predefined audio bands, one for each face of the cube. The second tone would come from one of two separately predefined audio bands, one for each possible direction of rotation. From this, an audio processing model could be designed to process a sequence of these two-tone pairs and reconstruct the sequence of face rotations by recording the rotated face followed by its direction of rotation.

However this model presents challenges. Take for example, a speedcuber averaging 5 turns per second (common for a 12-15 second solver) with bursts up to 10 TPS. The burst TPS would require the successful transmission of 20 sequential tones within a single second - only 50ms per tone, all in the midst of additional noise from the cube's pieces hitting each other harder at the higher turn speed. And, to cap it all off, since each tone is only ever transmitted once, the audio detection model must achieve 100% tone recognition to be able to accurately reconstruct the originating move sequence. As a result, this model fails to support any sort of error correction that would make it resistant to the common challenges to data transmission through sound.

However this model inherently precludes robust error checking procedures. Each tone that is not accurately detectedany of the tones are not accurately detected, the data of that particular rotation cannotit becomes impossible to entirely reconstruct the executed move sequence

TODO finish discussing this protocol proposal

Chapter 5

Audio Decoding Algorithm Design

5.1 Synthetic Audio Generation

Prior to investing significant resources in PCB design, we found it prudent to develop a synthetic model of the ideal audio output of the DIY Supercube. This model consists of a synthetic audio generator that, when given a specific move sequence, generates a '.wav' file consisting of the distinct time series tones that the DIY Supercube would theoretically produce. The synthetic data produced by this model then served as the first test cases for the final audio decoding model.

5.1.1 Representing the Audio Protocol

TODO pull from Jupyter notebook

5.1.2 Representing the Rubik's Cube

TODO pull from Jupyter Notebook

5.1.3 Generating the Audio for an Arbitary Algorithm

TODO pull from Jupyter Notebook

TODO show a spectrogram of the generated audio here

5.2 Decoding the Synthetic Audio

TODO pull from Jupyter Notebook

5.2.1 Examining the Waveform

TODO pull from Jupyter Notebook

5.2.2 Conversion to Strength of Individual Frequencies

TODO pull from Jupyter Notebook

5.3 Adding Realisitic Noise to the Synthetic Audio

TODO pull from Jupyter Notebook

5.4 Decoding the Noisy Synthetic Audio

TODO pull from Jupyter Notebook

5.4.1 Optimizing algorithm parameters

TODO - Share the strategy for finding the optimal parameters, and the end results, but defer the detailed analysis for the Evaluation.

Chapter 6

PCB Design

6.1 Requirements

TODO lay out the requirements for the PCB

6.1.1 Accuracy of Tone Generation

TODO Describe this requirement

6.1.2 Tone Response to Cube Rotations

TODO Describe this requirement

6.1.3 Signal-to-Noise Ratio

TODO Describe this requirement TODO Discuss the dampening effect of the plastic enclosure.

6.1.4 Prospects of Miniaturization

TODO Describe this requirement

6.2 Hardware Selection

TODO outline the process of chosing specific hardware to use for this project

6.2.1 Minimizing Sound Obstruction

TODO Discuss the "tupperware" tests -> design of various center caps.

6.3 Prototyping

TODO detail the process of building a prototype. Include pictures of the board and the generated spectrograms.

Chapter 7

Evaluation

TODO review the core goals outlined in the introduction, and methodically review how well my final prototypes stack up against those goals. This section serves to prove (with all the data) that the approach I've described in the previous chapters actually works.

7.1 Compatibility with Standard Speedcubes

TODO discuss how well my design meets this requirement from the Introduction

The design must be deployable within a standard (non-smart) speedcube.

1. The design must not require permanent modifications to the original speedcube.
2. The design must not significantly impact the turn-speed of the original speedcube.

7.2 Move Tracking Accuracy

TODO discuss how well my design meets this requirement from the Introduction

The design must be capable of tracking the face turns of a Rubik's Cube with over 99% accuracy.

7.3 Move Tracking Granularity

TODO discuss how well my design meets this requirement from the Introduction

The design must be capable of recording the time spent executing each individual face turn of a Rubik's Cube.

7.4 Competition Legality

TODO discuss how well my design meets this requirement from the Introduction

The design must be competition legal, meaning it results in a cube that either does not violate existing competition rules against the use of electronics or can be easily modified to regain compliance.

Chapter 8

Conclusion

8.1 Summary

TODO summarize the goals from the Introduction and broadly describe what techniques were most helpful in reaching them. Also detail a summary of exactly how effective they were.

8.2 Limitations

TODO detail the limits to which this research can be more broadly applied. Be clear about the effects various assumptions/decisions have on the reliability of the conclusions of this thesis.

8.3 Ideas for Future Research

TODO If I had more time/resources to work on it, what would I do next with this project?

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