HCMUTE

FACULTY OF MECHANICAL ENGINEERING

REPORT

ARTIFICIAL INTELLIGENCE SOLVE RUBIK'S CUBE

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Table of Contents

Part 1: Introduction

1. Rationale

Since the invention of computers or machines, their ability to execute various jobs has increased at an exponential rate. In terms of their drivers' working domains, growing speed, and shrinking size over time, humans have enhanced the power of computer systems. Artificial intelligence is a subfield of computer science that aims to make computers or other devices as intelligent as humanity. Making machines — particularly computers — execute tasks that need intelligence when carried out by humans is the focus of the artificial intelligence (AI) research field. It has experienced stunning achievements as well as equally dramatic disasters during the course of its 60-year history. Today, AI is a significant and necessary component of technology and business, and it offers solutions to some of the most difficult computer science challenges. However, Strong AI hasn't yet and might never achieve its initial objective of giving robots real human-level intelligence. AI researchers are now able to build machines that are capable of performing tasks that are challenging for humans, such as logic, algebra problem-solving, path planning, or playing chess. But Pierre Baldi, professor of computer science at the University of California, Irvine – said that “Artificial intelligence can defeat the world’s best human chess and Go players, but some of the more difficult puzzles, such as the Rubik’s Cube, had not been solved by computers, so we thought they were open for AI approaches”. Inspired by this assertion, an AI project was created to examine the knowledge of artificial intelligence and investigate the reliability of the assertion.

2. Aim of the study

This project aims to design a network as simply as possible so that an AI can learn how to solve a Rubik's cube. The images of each Rubik's face are the input, while the solution is the output.

3. Object and range of study

The primary goal of this project is to develop an AI network that can solve a cube and produce training datasets. Due to the computer's limitations and the researcher's gaps in knowledge, this project only attempts to solve Rubik's cubes that require fewer than 10 moves to solve.

4. Research methods

The project uses:

- Empirical research: the project trains and evaluates the AI network's performance.
- Quantitative research: Find a technique to convert a Rubik's cube's characteristics into a number for analysis.

Part 2. Theoretical foundation

1. Artificial Intelligence (AI)

The primary problem of just defining AI as "creating intelligent machines" is that it does not explain what AI is or what makes a machine intelligent. AI is an interdisciplinary discipline with various methodologies, but advances in machine learning (ML) and deep learning are causing a paradigm shift in nearly every sector of the IT industry.

However, several other tests have lately been developed that have got mostly positive feedback, including a 2019 research paper titled "On the Measure of Intelligence", François Chollet, a senior deep learning researcher and Google engineer, argues in the study that intelligence is the "rate at which a learner turns its experience and priors into new skills at valuable tasks that involve uncertainty and adaptation". In other words, the most intelligent systems can use a limited bit of experience to predict the outcome of many different circumstances.

Meanwhile, authors Stuart Russell and Peter Norvig address the subject of AI in their book Artificial Intelligence: A Modern Approach by uniting their work around the theme of intelligent agents in machines. With this in mind, AI is defined as "the study of agents that take perceptual input from their surroundings and perform actions".

While these concepts may appear esoteric to the average person, they assist to focus the discipline as an area of computer science and provide a framework for infusing ML and other subsets of AI into machines and programs.

2. Types of Artificial Intelligence

2.1. Reactive Machines

A reactive machine refers to the most fundamental AI principles and, as the name suggests, is only capable of using its intellect to observe and react to the world in front of it. Because a reactive machine lacks memory, it cannot depend on prior experiences to influence real-time decision making.

Because reactive machines perceive the world immediately, they are only designed to do a few specialized tasks. However, intentionally reducing a reactive machine's worldview is not a cost-cutting tactic; rather, it means that this type of AI will be more trustworthy and reliable — it will respond consistently to the same inputs.

Though limited in scope and difficult to modify, reactive machine AI can achieve a level of complexity and reliability when designed to perform recurring tasks.

2.2. Limited Memory

When gathering information and considering prospective options, AI with limited memory can preserve previous facts and forecasts – effectively peering into the past for indications on what may happen next. AI with limited memory is more complicated and has more potential than reactive systems. Memory limitations AI is developed when a team regularly trains a model to analyze and use fresh data, or when an AI environment is built to allow models to be automatically trained and renewed.

Six actions must be taken when using restricted memory AI in ML: The training data must be created, the ML model must be formed, the model must be capable of making predictions, the model must be capable of receiving human or environmental feedback, that feedback must be recorded as data, and these processes must be repeated in a cycle.

There are numerous ML models that make use of AI with limited memory:

- Reinforcement learning, which improves its predictions through trial and error.
- Recurrent neural networks (RNN), which uses sequential data to affect the current input and output by using information from previous inputs. These are widely employed for ordinal or temporal problems such as language translation, natural language processing, speech recognition, and image captioning. Long short term memory (LSTM) is a subclass of recurrent neural networks that uses past input to predict the next item in a sequence. When

making predictions, LTSMs prioritize recent information and discount data from the past while still using it to draw conclusions.
- Evolutionary generative adversarial networks (E-GAN), which increase over time, exploring slightly different paths based on previous experiences with each new option. This model is always looking for a better path and uses simulations, statistics, or chance to forecast outcomes throughout its evolutionary mutation cycle.
- Transformers, which are node networks that learn how to accomplish a specific task by training on existing data. Instead of having to group components together, transformers can conduct operations that ensure that every element in the incoming data is aware of every other element. This is referred to by researchers as "self-attention," and it means that a transformer can perceive traces of the full data set as soon as it begins training.

2.3. Theory of Mind

Theoretical psychology is exactly that: theoretical. Humanity have not yet developed the technological and scientific capabilities required to reach this next level of artificial intelligence. The concept is based on the psychological idea that other living creatures have thoughts and feelings that influence one's own actions. This would imply that AI machines may know how people, animals, and other machines feel and make decisions through self-reflection and determination, and then use that information to make their own conclusions. Machines would essentially have to be able to grasp and process the concept of "mind," the changes of emotions in decision making, and a slew of other psychological concepts in real time, establishing a two-way communication between people and AI.

2.4. Self-Awareness

Once theory of mind has been established, AI will be able to become self-aware at some point in the future. This type of AI has human-level consciousness and recognizes its own presence in the world, as well as the presence and emotional condition of others. It would be able to grasp what others may require based not only on what they convey to them, but also on how they communicate it.
Self-awareness in AI is dependent on both human researchers comprehending the concept of consciousness and then discovering how to replicate it so that it may be incorporated into machines.

3. Rubik’s cube

3.1. History

Ernő Rubik worked at the Department of Interior Design at Budapest's Academy of Applied Arts and Crafts in the mid-1970s. Although it is often assumed that the Cube was designed as a teaching tool to assist his students grasp 3D things, his true goal was to solve the structural difficulty of moving the components independently without the entire mechanism collapsing. He didn't realize he'd made a puzzle until he jumbled his new Cube and tried to restore it for the first time. On 30 January 1975, Rubik registered for a patent in Hungary for his "Magic Cube" (Hungarian: Bvös kocka), and HU170062 was awarded later that year.

The Magic Cube's first test batches were created in late 1977 and sold in Budapest toy stores. Unlike Nichols' design, Magic Cube was held together by interlocking plastic parts that prevented the puzzle from being readily ripped apart. Tibor Laczi, a businessman, took a Cube to Germany's Nuremberg Toy Fair in February 1979, with Ernő Rubik's consent, in an attempt to popularize it. Seven Towns creator Tom Kremer recognized it, and in September 1979, they secured an agreement with Ideal Toys to distribute the Magic Cube globally. Ideal sought to trademark at least a familiar name; this arrangement put Rubik in the spotlight when the Magic Cube was titled after its inventor in 1980.

Following its international debut, the Cube's march towards Western toy store shelves was temporarily stalled so that it could be built to Western safety and packaging criteria. Ideal chose to rename the Cube as it became lighter. The names "The Gordian Knot" and "Inca Gold" were considered, but the business ultimately chose "Rubik's Cube," and the first batch was exported from Hungary in May 1980.

3.2. Mechanics

The puzzle comprises of 26 unique small cubes, sometimes known as "cubies" or "cubelets". Each of them has a hidden inside extension that interlocks with the other cubes while allowing them to move to different places. The center cube of each of the six faces, however, is only a single square façade; all six are attached to the core mechanism. These serve as the framework for the other pieces to slot into and rotate around. As a result, there are 21 pieces: a single core piece made up of three intersecting axes that hold the six center squares in place while allowing them to rotate, and 20 smaller plastic pieces that slot into it to make the assembled puzzle.

Each of the six centre pieces pivots on a screw (fastener) held by the centre piece, a "3D cross". A spring between each screw head and its corresponding piece tensions the piece inward, allowing the entire assembly to stay compact while still being easily manipulated. The screw can be tightened or loosened to alter the "feel" of the Cube. Newer official Rubik's brand cubes include rivets instead of screws and cannot be modified. However, old Rubik's Brand Ltd. and dollar shop cubes lack screws and springs, instead relying on a plastic clip to keep the center piece in place and freely rotating.

Six central pieces depict one colored face, twelve edge pieces depict two colored faces, and eight corner pieces depict three colored faces. Each item features a distinct color combination, however not all combinations are represented (for example, if red and orange are on opposite sides of the solved Cube, there is no edge piece with both red and orange sides). The position of these cubes relative to one another can be changed by twisting an outer third of the Cube in 90-degree increments, but the position of the colored sides relative to one another in the completed state of the puzzle cannot be changed; it is fixed by the relative positions of the center squares.

Figure 1. Rubik's mechanics

3.3. Permutations

The original Rubik's Cube ($3 \times 3 \times 3$) has eight corners and twelve edges. The corner cubes can be arranged in $8! = 40320$ different ways. Each corner has three different orientations, but only seven (of eight) can be orientated independently; the orientation of the eighth (final) corner is dependent on the preceding seven, for a total of $3^7 = 2187$ options. There are $\frac{12!}{2} = 239500800$ ways to arrange the edges, with the number limited to $12!$ because the edges must be in an even permutation when the corners are.

When center arrangements are permitted, as stated below, the combined arrangement of corners, edges, and centers must be an even permutation. Eleven edges can be flipped independently, with the twelfth depending on the previous ones, for a total of $2^{11} = 2048$ possibilities.

Therefore, the Rubik's cube contains up to

$$8! \times 3^7 \times \frac{12!}{2} \times 2^{11} = 43{,}252{,}003{,}274{,}489{,}856{,}000$$

which is approximately 43 quintillion.

3.4. Move notation

Many ($3 \times 3 \times 3$) Rubik's Cube fans utilize "Singmaster notation," which was invented by David Singmaster, to represent a sequence of moves. Because of its relative nature, algorithms can be developed in such a way that they can be used regardless of which side is declared as the top or how the colors are organized on a certain cube.

F (Front): the side currently facing the solver

B (Back): the side opposite the front

U (Up): the side above or on top of the front side

D (Down): the side opposite the top, underneath the Cube

L (Left): the side directly to the left of the front

R (Right): the side directly to the right of the front

When a prime symbol (′) follows a letter, it denotes an anticlockwise face turn; while a letter without a prime symbol denotes a clockwise turn. These directions are as one is looking at the specified face.

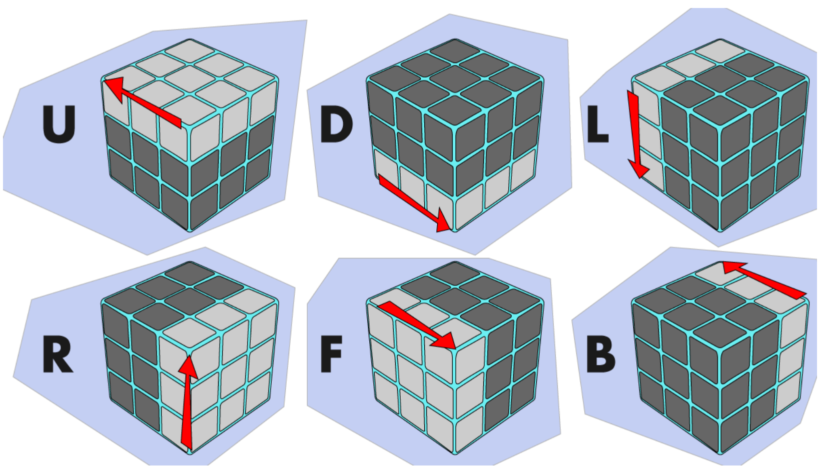

Figure 2. Rubik's move notation

3.5. Solutions

Although the Rubik's Cube has a large number of possible permutations, a number of solutions have been devised that allow the cube to be solved in less than 100 movements.
Many general Cube solutions have been discovered independently. David Singmaster's solution was initially published in the book Notes on Rubik's "Magic Cube" in 1981. This method entails solving the Cube layer by layer, starting with the top layer, then the middle layer, and finally the final and bottom layer. After enough practice, solving the Cube layer by layer takes less than a minute.
Other common solutions include "corners first" approaches or combinations of various other approaches. In 1982, David Singmaster and Alexander Frey hypothesised that the number of steps needed to solve the Cube, given a perfect algorithm, might be in "the low twenties". Daniel Kunkle and Gene Cooperman demonstrated in 2007 that any 3x3x3 Rubik's Cube configuration can be solved in 26 moves or less using computer search methods. Tomas Rokicki reduced that number to 22 moves in 2008, then in July 2010, a team of academics including Rokicki, collaborating with Google, demonstrated that the so-called "God's number" for Rubik's Cube is 20. This means that all initial configurations can be solved in 20 moves or fewer, and some (in fact, millions) can be solved in 20 moves or less.

4. Dataset

A dataset is a collection of several forms of data that is saved digitally. Data is the most important component of every AI project. Without data, humans cannot have an Artificial Intelligence system. Deep Learning models are data-hungry and require a large amount of data to generate the best model or a high-fidelity system. Even if there are fantastic algorithms for machine learning models, the quality of data is just as crucial as the quantity.
This project makes use of the PyCuber library to visualize the Rubik's cube in a programming environment and to generate datasets for training the model. Before that, the following parameters must be defined:

Face	Color	Value
U	White	5
D	Yellow	0
F	Green	1
B	Blue	4
L	Orange	3
R	Red	2

Table 1. Rubik's face notation

The Rubik's cube ($3 \times 3 \times 3$)features 9 color stickers on each face, for a total of 54 color stickers in any configuration. To relate one face to another, the data should be represented as an image, with the pixels representing color stickers from the Rubik's cube. The image can be seen in greater detail as

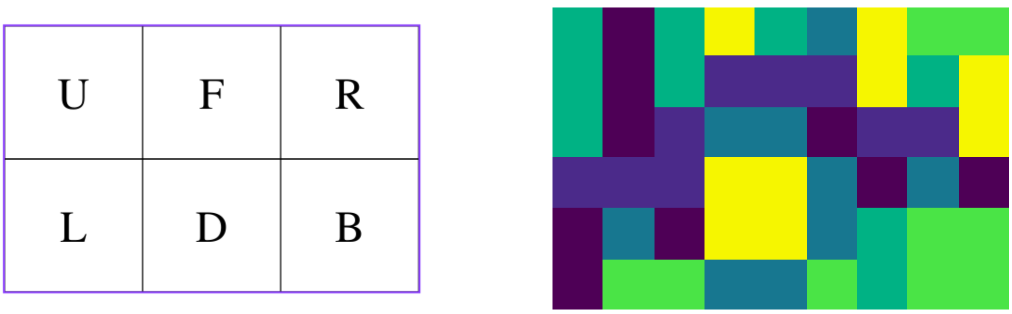

Figure 3. Rubik's data arrangement

Another issue is determining how the label should be created. Because humans cannot decide the optimal step, the simplest method is to spin the Rubik's cube from one state to another and then do the inverse turn, which is the label.

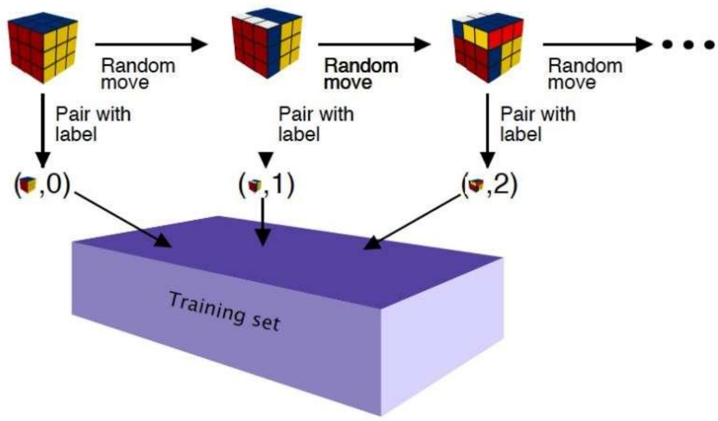

Figure 4. Rubik's data creation

However, because there are 43 quintillion Rubik's cube variations, no computer can store that data. Remember that any Rubik's cube configuration requires at most 20 movements to solve, therefore datasets can be generated by randomly turning the Rubik's cube in 20 moves, it should be spinned in 12 possible turns from the first to the fifth (B, B', D, D', F, F', L, L', R, R', U, U'), and the remaining 15 moves can be turned freely.

When there are numerous repeated configurations, that is, many data with the same values but different labels, a new difficulty is produced. To simplify, the first turn will store 8 images, the second 7, the third 6, the fifth 4, the sixth to tenth 3, the eleventh to fifteenth 2, and the remainder 1.

As a result, the dataset contains $8 \times 12 + 7 \times 12^2 + 6 \times 12^3 + 5 \times 12^4 + 4 \times 12^5 + 30 \times 12^6 = 8575440$ images. There are 8570138 photos in 12 classes after eliminating the finished status. Although the number is enormous, it represents only $1.98 - 1.98^{-11}$ % of Rubik's permutation.

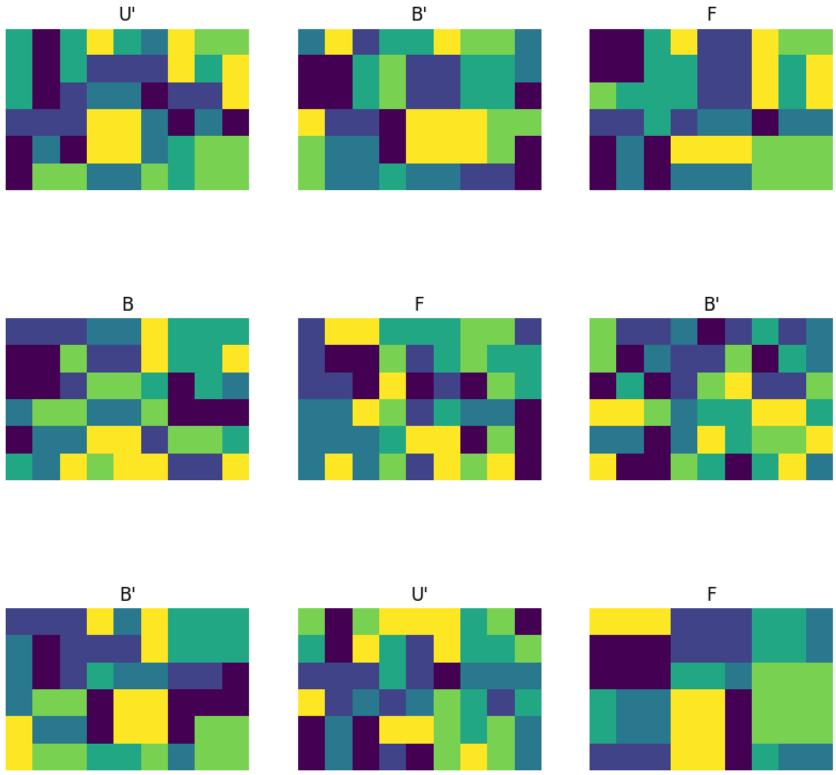

Figure 5. Rubik's data

An image occupies 4209 bytes, and the total dataset is 33.8 GB, with a generation time of 2 hours.

5. Artificial Intelligence Network

The network's input is a 9 x 6 pixel image, and its output is a rotation within B, B', D, D', F, F', L, L', R, R', U, U', labeled from 0 to 11. Then, a network based on Residual Network can be quickly created.

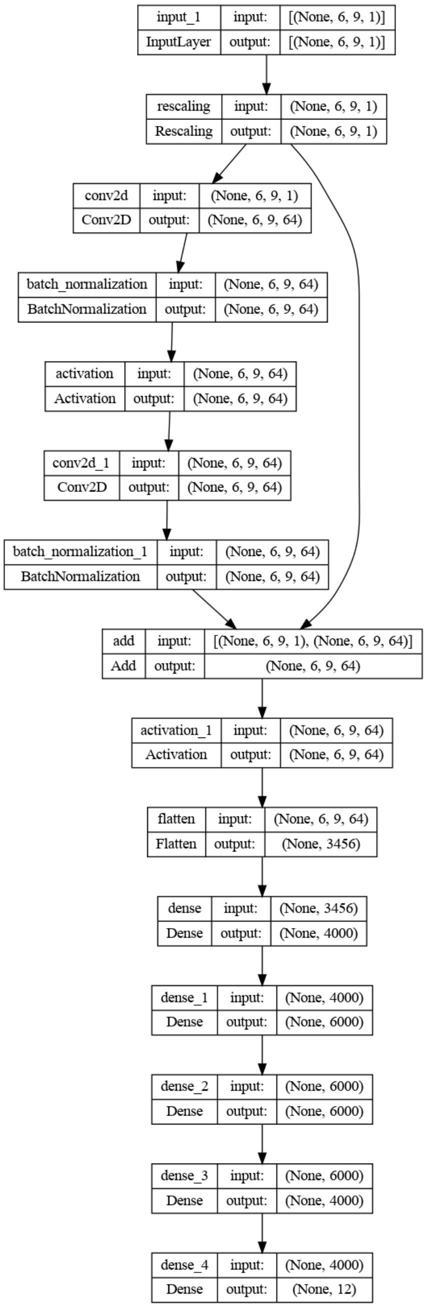

Figure 6. AI model

This model contains:

Total params: 97,930,092

Trainable params: 97,929,836

Non-trainable params: 256

Part 3. Results

With 16 GB of RAM and a GPU RTX 3050 with 4 GB of RAM, a compute capacity of 8.6, the model has an accuracy of 51.83% and a validation loss of 1.634 after 10 epochs (48 minutes per epoch). Several tests are run after the model has been trained as following

Required turns	Number of test case	Accepted	Number of possible test case
1	12	12	12
2	144	144	144
3	1728	1728	1728
4	2676	2670	20736
5	3978	3938	248832
6	4096	3895	2985984
7	3645	3105	35831808
8	3941	2922	429981696
9	3103	1868	5159780352
10	2833	1345	61917364224

Table 2. Model testing

Due to technological difficulties, the number of test cases is quite limited in comparison to the number of available test data. The model's accuracy is adequate because data duplication might reach up to 30%. Therefore, the result is quite good for this weak AI model, yet it works well for the purpose of this project.

Part 4. Discussion and Conclusion

This research has produced an AI capable of solving a Rubik's cube that requires 10 moves to complete. When it takes 13 ms to detect a position, the network is relatively simple, but it does its job properly. The accuracy is relatively low, but it can be improved by using no repetition data status. Furthermore, the inputs are extremely difficult for a convolutional neural network (CNN) to detect. The reinforcement learning (Q learning) network with interaction to the Rubik's cube as inputs must be the best fit for this project. As a result, the future of this research is to use the Q learning model instead of CNN to solve the Rubik's Cube in any state and reach the number 20 - the God's number.

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