Introduction

We've all tried solving a Rubik's Cube and a few of us may have solved it at least once in our lifetime. But those who could not, they would already be aware of the fact as to how hard it can get to solve the world's best selling toy – The Rubik's Cube or as originally called, 'The Magic Cube'. After all there's just 1 correct solution and 43 quintillion wrong ones for a Rubik's Cube! For humans it may be a tough job but certainly not for computers. Well, if you are thinking of bruteforcing all those 43 quintillion possible permutations with a computer, that ain't the answer. Thanks to some wonderful recent research, any given permutation of a rubik's cube can be solved within just 20 steps! And it's the God's algorithm that solves the puzzle in the least number of moves.

Overview

The basic aim of this project is to design and implement a autonomous machine capable of solving a rubik's cube given in any possible permutation. .

Our idea was to design a mechanical setup on which six stepper motors can be mounted, each of which would be connected to the centre of the six faces of a rubik's cube, thus allowing all the six faces to rotate independently. The mechanical setup contains a solved rubik's cube. The camera is used to take the input of the colours of a scrambled cube and the information is then fed to a computer program that analyzes it and generates the sequence of steps required to solve the cube. The sequence is then sent to a microcontroller that drives the steppers accordingly with the help of motor driver ICs and the cube is solved.

History of the Cube

One eighth of the world's population has laid hands on 'The Cube', the most popular puzzle in history and the colorful brainchild of Erno Rubik. Erno Rubik was born in Budapest, Hungary during World War II. His mother was a poet, his father an aircraft engineer. Rubik studied sculpture in college, but after graduating, he went back to learn architecture at Academy of Applied Arts and Design.

Erno Rubik

Rubik's initial attraction to inventing the Cube was not in producing the best selling toy puzzle in history. The structural design problem interested Rubik; he asked, "How could the blocks move independently without falling apart?" In Rubik's Cube, twenty-six individual little cubes or cubies make up the big Cube. Each layer of nine cubies can twist and the layers can overlap. Rubik's initial attempt to use elastic bands failed, his solution was to have the blocks hold themselves together by their shape. Rubik hand carved, assembled the little cubies together, and started twisting.

An Inventor Dreams

"It was wonderful, to see how, after only a few turns, the colors became mixed, apparently in random fashion. It was tremendously satisfying to watch this color parade. Like after a nice walk when you have seen many lovely sights you decide to go home, after a while I decided it was time to go home, let us put the cubes back in order. And it was at that moment that I came face to face with the Big Challenge: What is the way home?" - Erno Rubik

That was how the Cube as a puzzle, was invented in the spring of 1974, when the twenty-nine year old Rubik discovered it was not so easy to realign the colors to match on all six sides. He was not sure he would ever be able to return his invention to its original position. He began working out a solution, starting with aligning the eight corner cubies and within a month, he had the puzzle solved and an amazing journey lay ahead.

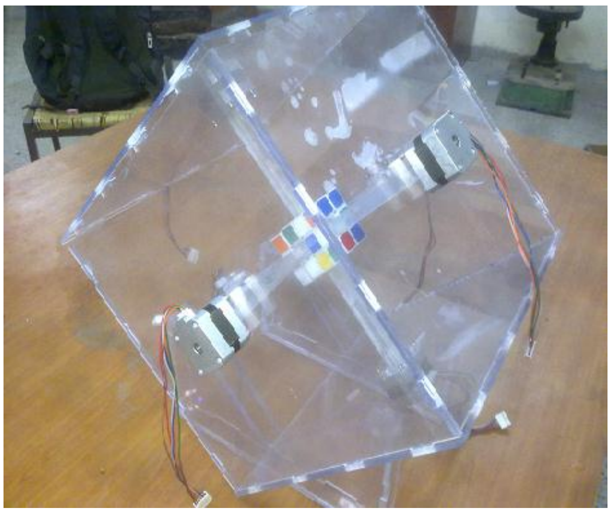
Design

The work done during the project can be categorized under three sections-

- *Mechanical Design*
- *Programming*
- *Electronics*

Mechanical Design

Mechanical part was undoubtedly the most demanding aspect of the bot. The final pic of the completed mechanical structure is shown below.



The final mechanical structure

As seen in the pic, we decided to get the outer frame made using acrylic sheet. We prepared AutoCAD drawings for all the parts of the mechanical structure and got them fabricated using the 4i Lab.
We needed presice 90° rotations of the rubik's cube faces. For this purpose we used high torque stepper motors. The shafts of the motors were also made of acrylic. The biggest mechanical problem we faced was in the alignment of the six shafts of the motors. Successful operation of the bot needed that the opposite shafts should be in a straight line, at an angle of 180°. But this level of precision was hard to maintain due to the manual mounting of motors and shafts and the constant need to dissemble the outer acrylic cube to solve the inner rubik's cube while testing process. Due to this improper alignment, force and torque distribution were not uniform on all sides of the cube and created hinderance in rotation of faces, sometimes preventing precise 90° turns. In a sequence of say 200 steps of rotations, even if one step to make a precise 90° turn fails, the orientation of the cube gets distorted, thus preventing any more further steps. The problem has not yet been solved but we are working on it.

Shaft alignment and attachment

Programming

Programming part was like the backbone of the project. It was basically divided into two parts.

1. **Image Processing**

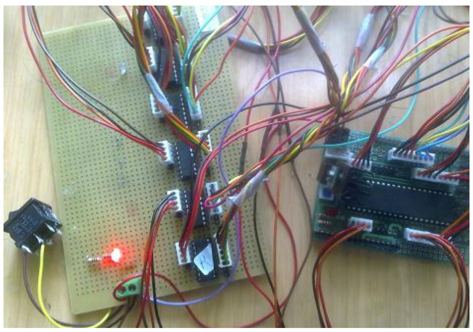
   To take the input of a scrambled cube, we used a simple webcam. The camera simply takes snapshots of the six faces of the cube. The images are then processed using Open CV. The images are stored in the RGB format. Thus by analyzing the content of Red, Green and Blue colour in the pics, the nine colours on each face of the cube may be determined. In this way, the colours of the entire cube are recorded and stored in an array.

2. **Solving Algorithm**

   There are hundreds of algorithms available on the internet for solving a rubik's cube. Some are really fast and some take hundreds of steps. The faster an algorithm is , the more difficult it will be. As of now, we have been able to implement a method used by blind solvers, the Pochmann Algorithm. It would take round about 200 steps to solve a cube.
   We take the array generated in the previous step as an input to this program and the program outputs another array containing a sequence of characters R,L,F,B,T,D,1,2,3,4,5,6.
   This denotes the order in which the motors have to be driven. R stands for a 90° turn of the right motor clockwise and similarly for others. Numbers stand for anti clockwise turns.
   This code runs on a laptop. This array is then transferred to the microcontroller through USART communication.

Electronics

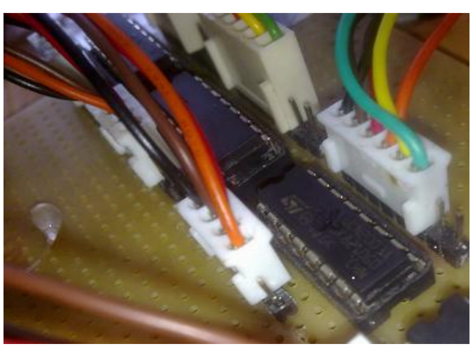
The electronics of the robot includes controlling the stepper motors , microcontroller and doing USART communication between computer and microcontroller.The microcontroller we used is atmega 32 as it was sufficient to drive six stepper motors simultaneously. It was programmed through STK500 Serial programmer.



Atmega 32 connection with motor driver

The USART communication was achieved using MAX232 chip that converts signals from an RS232 serial port to signals suitable for use in TTL compatible digital logic circuits.

The motors we used to execute the controlled rotation of each side are stepper motors. A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied. One of the most significant advantages of a stepper motor is its ability to be accurately controlled in an open loop system means no feedback information about position is needed.
They were controlled using ULN2003 motor drivers which converts 5V signal to 12V.



Motor driver : ULN2003

Here is brief documentation about controlling stepper motors:

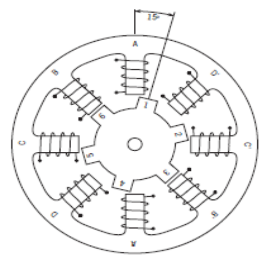
Based on the construction there are 3 types of stepper motor, namely:

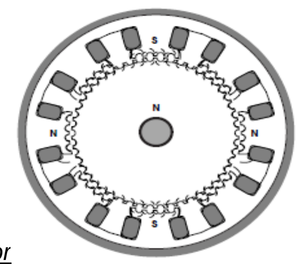
Variable Reluctance (VR) motor:

This type of motor consists of a soft iron multi-toothed rotor and a wound stator. When the stator windings are energized with DC current the poles become magnetized. Rotation occurs when the rotor teeth are attracted to the energized stator poles.

Permanent Magnet motor:

In this, the rotor no longer has teeth as with the VR motor. Instead the rotor is magnetized with alternating north and south poles situated in a straight line parallel to the rotor shaft. These magnetized rotor poles provide an increased magnetic flux intensity thereby higher torque.





Rotor

Hybrid motor:

The rotor is multi-toothed like the VR motor and contains an axially magnetized concentric magnet around its shaft. The teeth on the rotor provide an even better path which helps guide the magnetic flux to preferred locations in the air gap.

Stepper motor

Based on the design and working the types of stepper motor are:

• *Bipolar Stepper Motor*
• *Unipolar Stepper Motor*

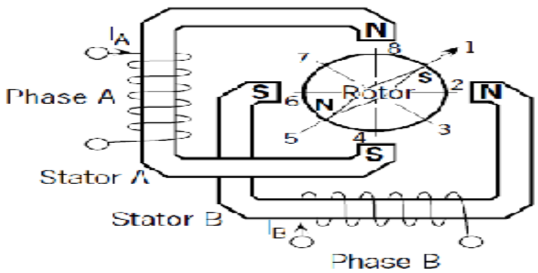
The bipolar and unipolar motors are similar, except that the unipolar has a center tap on each winding.
The bipolar motor needs current to be driven in both directions through the windings, and a full bridge driver is needed. The center tap on the unipolar motor allows a simpler driving circuit limiting the current flow to one direction. The main drawback with the unipolar motor is the limited capability to energize all windings at any time, resulting in a lower torque compared to the bipolar

motor. The unipolar stepper motor can be used as a bipolar motor by disconnecting the center tap.

Stepping Modes:

The following are most common drive modes:

• *Wave Drive (1 phase on)*
• *Full Step Drive (2 phases on)*
• *Half Step Drive (1 & 2 phases on)*



Bipolar wound motor

In **Wave Drive** only one winding is energized at any given time. The stator is energized according to the sequence A -> B -> A -> B and the rotor steps from position 8 -> 2 -> 4 -> 6. The disadvantage of this drive mode is that in the unipolar wound motor you are only using 25% and in the bipolar motor only 50% of the total motor winding at any given time.

In **Full Step Drive** you are energizing two phases at any given time. The stator is energized according to the sequence AB -> AB -> AB -> AB and the rotor steps from position 1 -> 3 -> 5 -> 7 . Here the unipolar motor uses only 50% of the available winding while the bipolar motor uses the entire winding.

Half Step Drive combines both wave and full step (1&2 phases on) drive modes. The stator is energized according to the sequence AB -> B -> AB -> A -> AB -> B -> AB -> A and the rotor steps from position 1 -> 2 -> 3 -> 4 -> 5 -> 6 -> 7 -> 8. This way we can make the step angle finer.

	Wave Drive				Normal full step				Half-step drive							
Phase	1	2	3	4	1	2	3	4	1	2	3	4	5	6	7	8
A	•				•			•	•						•	•
B		•			•	•			•	•	•					
$\overline{A}$			•			•	•				•	•	•			
$\overline{B}$				•			•	•						•	•	•

The motors that we used are permanent magnet unipolar motors and we implemented the half wave drive in our motors in order to get exact 90°rotation. It took around 13 loops of the half wave drive in attaining one fourth i.e. 90° rotation.

Future Scope

There is a lot of scope for further improvement of the bot. Programming would require a good amount of research. Following are the major improvements that can be made-

- The bot, currently, is not efficient as we would have wanted. The mechanical flaws can be worked upon thus lowering the probability of lock-ups while turning the cube.
- The Pochmann Algorithm we have been able to implement as of now takes too many steps to solve the cube. Using better algorithms especially designed for cube solving by computers like Thistlewait's Algo(52 steps max) or Kociemba's Algo(22 steps max) will reduce the no of steps thus making the bot very fast.
- Instead of using ULN2003 as a motor driver IC, a combination of L298 and L297 ICs maybe used for an easier and more efficient stepper control.
- A better quality rubik's cube, probably a Lingyun Dayan maybe installed in the bot. These cubes have better edge cutting properties (upto 40°!) and rotate very smoothly.
- The motors used maybe upgraded to high torque motors.

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