

DIPOLE LATTICE

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Upscaling a nano-structure

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Atul Singh Arora: *Dipole Lattice*, Upscaling a nano-structure,

Every honest researcher I know admits he's just a professional amateur. He's doing whatever he's doing for the first time. That makes him an amateur. He has sense enough to know that he's going to have a lot of trouble, so that makes him a professional.

— Charles F. Kettering (1876-1958) (Holder of 186 patents)

ACKNOWLEDGEMENTS

I thank Dr. Ravi Mehrotra for well conceiving the experiment and guiding me through the process of its realization.

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¹ This section can be skipped, without any loss of continuity.

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ACRONYMS

PROLOGUE

Atoms and molecules are far too small to be observable as individual entities, with our eyes alone. Scientists have come a long way at understanding *their* world. It has been attempted to recreate a specific micro-structure, at a scale where we can directly observe it.

The configuration we've studied here, is that of a Magnetic Dipole Lattice, viz. Magnetic Dipoles that can only rotate about their axis, placed on a grid. Their physics by itself is rather interesting and can be simulated to observe the dynamics. The experiment is expected to show the same dynamics, that of the microscopic world, only directly observable.

1.1 PRIOR ART

TODO: Complete this part after understanding the physics and simulations on the system.

1.2 EXPERIMENTAL SETUP

The upscale version consists of Physical Magnetic Dipoles, that rest on near zero friction spots on a grid. A camera sits on top, with all the dipoles in its field of view. The Lattice Analyser takes the input from the camera and simulates the given temperature through a hardware unit and the coils attached to each dipole. It is that simple.

For implementation details, you may read the following sections.

1.2.1 *The Dipole*

According to the current design (as of May 19, 2013), the Magnetic Dipole is built off of two small cylindrical rare earth magnets, attached to a needle, with their flat face's surface normal perpendicular to the axis of the needle. The needle rests in an assembly with a glass slide at the bottom. This keeps it upright and nearly free of friction. Each dipole further has a circular disc on top, with its centre passing through that of the dipole. The disc has a pattern printed, designed to find its angular position using a camera. Further, the dipole assembly also has two coils along an axis perpendicular to the needle.

1.2.2 *Lattice Analyser*

This is the application that

1. records the dynamics of the system
2. calculates the required field strength of each electromagnet

using a webcam and computer vision techniques. The results of the latter part depend on the temperature that is to be simulated; temperature is not maintained by providing heat, but instead by providing a certain distribution of speeds to the dipoles.

1.2.3 *Temperature*

This is the hardware unit, (will be built around an ATmega 16) that provides the coils with the current as calculated by the Lattice Analyser (using a USB interface).

2

WATCH IT GROW

2.1 SENTIMENTAL INTRODUCTION¹

Science often seems like a blackbox that relates observables. Even more often, it is rather convenient to lose touch of observables altogether, and wander in the blackbox. Performing an experiment, gets one closer to nature, to the roots of the subject.

2.2 THE JOURNEY

2.2.1 *Look it has begun*

This experiment wasn't started from scratch. My guide, Dr. Ravi Mehrotra, had already worked with a team and created the Dipoles as described earlier. The team had also worked on the image detection algorithms, but their work wasn't usable.

There were three tasks at hand, of which one had been significantly simplified by the prior work.

1. The Dipole

This had one apparent problem; the dipoles had to be made virtually frictionless (which is not to say they had excessive friction, infact they would oscillate atleast about 8 times before stopping aligned with earth's magnetic field)

2. The Image Analysis

This part I had to start from the beginning with two basic objectives, as stated earlier; measuring the angle of the dipoles and evaluating the current to be pumped based on the temperature selected.

What was known soon, was that C++ will be used for programming and linux would be the operating system, to facilitate USB interface with the AVR (next step)

3. The Current Control Hardware

This is simply for providing a current pulse proportional to the intensity calculated by the lattice analyser. Some schematics for this were available, but were found to be inaccurate and incomplete.

¹ this section can be skipped, without any loss of continuity.

2.2.2 Time Line

Listed below is the event log, which has the progress as and when it was made.

Time Line

```
SUMMER '13 TIMELINE
-- 

* July 3, Wednesday: Realised that a DIY air hockey table would
be a better way of searching and it was. In the
latticeAnalyser implemented dual graphs (one for the angular
position and the other for the velocity). Also implemented
the atan2 function for correcting the angle problem that used
to occur.

* July 2, Tuesday: Figured how to use plplot, the basics. Got it
up and running for 3d points and surfaces. Figured how to use
grids, labels and enabling realtime support. Built and
merged a minimalistic version of the same to the
latticeAnalyser

* July 1, Monday: Air hockey tables were searched for some toy
ones found too. Attempted the writing of an algorithm for
auto numbering of points in a lattice. Figured it was not
straight forward to implement with the usual C++ syntax. Will
instead made provision (partially) for swapping manually.
Also, plplot, a suitable plotting library was found and
installed.

** June 9 - 21 : Monsoon School; Physics of Life, NCBS Bengaluru

* June 7, Friday: [Project Milestone] It was realized that
neither the sachetIO was required (the data length can be
increased to 128 bytes without any difficulty just by
changing the report length in the USB HID configurations),
nor was a current amplifier. However, today a dipole was made
to turn continuously using the latticeAnalyser and the
temperature. It was found that the current is more than
sufficient for the current task. Further, for now, pins of
the MCU can directly be used. Stage one has been accomplished
. Now it remains to reduce friction (for the damping is far
too high) and to finalize the circuit for the setup. Then the
actual experiment begins.

* * June 6, Thursday: Added a buffer function to the sachetIO
library. Looked up methods for current amplification

* * June 5, Wednesday: Created and tested sachetIO, a library for
sending large arrays, required for communicating over HID
USB. This was debugged and tested. Non buffered version is
ready.
```

- * June 4, Tuesday: Successfully linked the latticeAnalyser (after compiling half of it with C, the rest with C++). Modified temperature to include a simple protocol and using that controlled the electromagnet of a single dipole from latticeAnalyser.
- * June 3, Monday: Started with the hardware. Configured SP12 (the programmer) then bootloadHID, flashed a board to support a bootloadHID interface.
- ** June 1 and 2, Saturday and Sunday: Updated the documentation
- * May 31, Friday: Tried all sorts of methods for air suspension which failed to work satisfactorily. Despite suspension, we couldn't achieve a state that had low enough torque (either perturbation or friction, atleast one was visible)
- * May 30, Thursday: The vacuum cleaner setup had to be used. The box was drilled accordingly and the test failed partially anyway. Which is to say that if it is light enough, the suspension does take place, however the vertical oscillations can not be removed.
- * May 29, Wednesday: The pump was built but it failed the test. The air pressure generated was negligible. i7 was configured alongside and the Lattice Analyser was built on it (had to make the multi threading optional using macros) using OpenCV with OpenTBB. Tests were run and it was found to be fast enough for an 8 x 8 dipole matrix.
- * May 28, Tuesday: Multi-threading retried, wasn't quite functional last time. Looked up various techniques for multi-threading and froze an algorithm. The pump couldn't be built for parts weren't available.
- * May 27, Monday: Multithreading attempted and succeeded, although not a very good release. Making progress in installing IPP.
- * May 21 - 26, Tuesday to Sunday: Not well; Succeeded in compiling the code in windows. It's slower. Looked up multithreading using C++ 11
- * May 20, Monday: Time Lag measured and found to be roughly 3 to 4 frames behind. Not quite acceptable. Attempting to install OpenCV with IPP
- ** May 18 and 19, Saturday and Sunday: Completing the documentation for the same. Thought of a way of testing the time lag.
- * May 17, Friday: The algorithm was successfully completed to measure 360 degrees. PLUS, completed the frame recording, identification of each dipole as unique and dumping the data out in file AND its testing with uniform motion which it passed with flying colours (which is to say in the visible range!, because proper standard deviation tests haven't quite

been done yet) The vision part of the anlyser is almost done .

- * May 16, Thursday: Working on dipole detection. The algorithm has started to work partially. It still does a mod 180 detection.
- * May 15, Wednesday: The magnetic lifting worked, but friction reduction failed. Rather interestingly the dipole would align to the suspension magnet's field. Plus, today the spot recognition algorithm was finalized and it seemd to be perfect.
- * May 14, Tuesday: Trying to get the webcam to work, eventually acceded to installing everything on a desktop machine. Worked on reducing the friction further
- * May 13, Monday: Completed the proof of concept version of the latticeAnlyser. Tomorrow we plan to print the coloured ovals and test
- ** May 11 and 12, Saturday and Sunday: Read the opencv tutorials when the algorithms started appearing and fitting the bill!
- * May 10, Friday: Continued with the setup, finetuning, installing other applications, making a documentation alongside for better support next time, added a shared folder between windows and linux
- * May 9, Thursday: Managed to get a few things up and running, still setting up ubuntu to run with hardware acceleration, failed at trying to get the webcam to work, installed the build tools, opencv etc.
- * May 8, Wednesday: Met with Dr. X (forgot the name of the person at NPL I'm working with) and concluded OpenCV and linux are what I'll use. Initiated the downloading of required applications, including virtual box and an ubuntu image

2.2.3 Construction of the Dipole

To remove the friction, there were various ideas, including use of a super conductor. However, eventually three methods were considered and experimentally tested.

1. Ferro-Fluid:

As it turns out, there are substances that have a ferro magnetic properties but in the liquid form. Consequently, a strong enough magnet would glide if coated with this substance.

Experimentally, it was found that the friction was higher than the ‘needle on glass’ setup.

2. Magnetic Levitation:

A magnet can easily suspend another magnet, granted it doesn’t flip. This idea was used and a magnetic cylinder was placed coaxial to the needle, using a cylindrical eraser and glue. Beneath the glass slide, an identical magnet was placed with the face that repels upwards.

Experimentally, again it was found that the motion was more damped than the ‘needle on glass’ setup. The reason for this case was obvious after a little analysis and closer observation. The dipole would align to the field of the magnet, viz. the magnetic field was interfering with the dipole.

3. Air Levitation:

To test this, the very first requirement was a source of stream of air. For this, we started small. We arranged for a small USB fan from a colleague. The next task was to channel the flow of air. This was accomplished by attaching the front part of a Pepsi Bottle such that the larger diameter was closer to the fan and the mouth of the bottle had the chord stuck to it (could still be moved if required), as diagrammatically given in [Figure 1](#). The final setup has been given in [Figure 2](#).

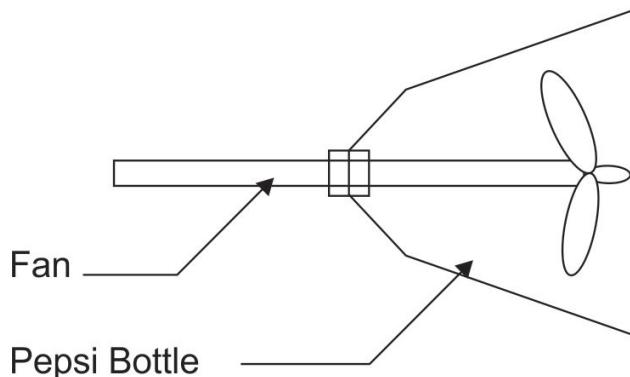


Figure 1: Fan Setup

This failed miserably for the air pressure would fall the moment the assembly covered the fan. Introducing slits to allow air to flow in created no appreciable difference. This idea had to be dropped in favour of the vacuum cleaner setup as shown in [Figure 3](#)

The vacuum cleaner was used as a blower and connected to a box using a pipe. On one of the faces of the box, four holes were drilled (which were later enlarged). These were covered



Figure 2: Final Fan Setup



Figure 3: Vacuum Cleaner Setup

to increase the pressure when required. On the open hole, one dipole was placed (which had to be re built with a minor modification, refer to [Figure 4](#)) with a disc at the bottom. This is when an apparently bizarre observation was made. At a given pressure, it was found that the dipole could remain suspended in air beyond a certain height (and obviously there was an upper bound for the same). However, for heights lower than that, the dipole would fall. The explanation which seemed to resolve this was that the air could spread while rising sufficiently only beyond that height to apply pressure at a large enough surface area, thus create enough force. Albeit the experiment was not performed under precisely the same conditions, when it was repeated with a larger disc, the same problem was encountered, suggesting that there may be more to the explanation that deduced so far. Other geometries at the base (other than the disc)

were also tried, such as a cone and a thermocol sphere, neither of which worked at low pressures which were enough to suspend the disc based setups. Further, at high pressures, disturbances in the form of torque in the dipole's axis of rotation begin to appear, which are fatal for the experiment.

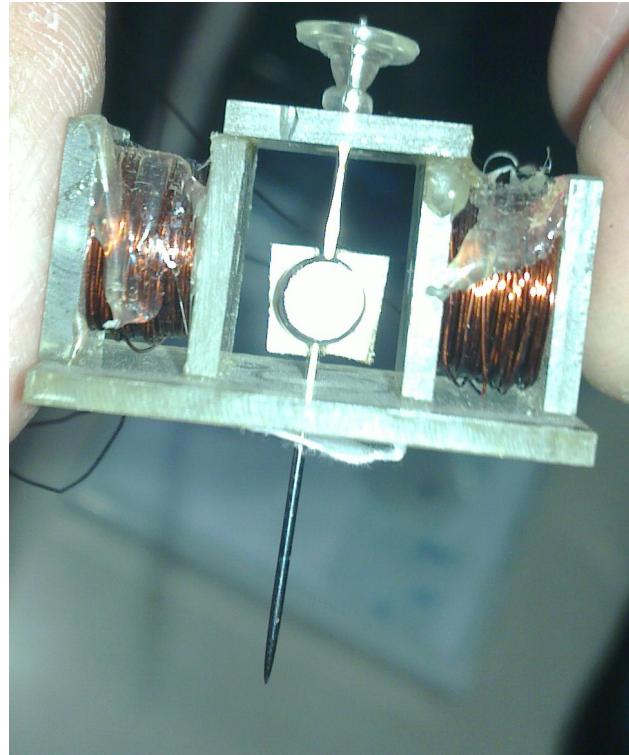


Figure 4: The Modified Dipole

Other problems with air-suspension included damping in the vertical direction. Once the dipole reaches the vertical equilibrium point, it overshoots just as an oscillator. Since the friction at the plates holding the needle vertical is negligible, the oscillations don't get damped quick enough. This was experimentally observed also. The energy ratio between the rotational part and the translation part, in the earth's field, was calculated and found to be approximately one for the given setup.

The most stable we could achieve with this setup was using a cylindrical projection from which the high pressure air escapes and a disc of comparable size attached to the dipole. This did get suspended satisfactorily, unlike the other methods where the suspension could not be maintained at the desired height, however the needle became rather wobbly and unstable resulting in increased friction.

Online research indicated that air-bearings do function well enough and so do the boards of air hockey. These will be explored in

the coming weeks to improve upon the methods to achieve the desired results.

2.2.4 Construction of the Lattice Analyser

The lattice analyser has come a long way. Image detection trials were initiated with [Figure 5](#).



Figure 5: Sample Image

The idea was that once the ellipses have been detected, and they are different in colour, one can evaluate from their centroids, the position and the angle of the dipole. It must be stated that earlier it was attempted to use the greyscale image as was provided. However soon the shadow interference led to using coloured patterns instead. These patterns were not printed but displayed on a screen and the camera aimed appropriately.

So first, the algorithm for detection of relevant part of the image had to be frozen. There were two candidates for this

1. Hough Transform Method

Either one could use the already available in OpenCV, line detection or circle detection, both would've required changing the pattern on the dipole

Or one could use an ellipse modification for the same, which would require programming the algorithm.

2. Contour Detection and Ellipse Fitting

This method detects contours in a given image, and the OpenCV example also shows ellipse fitting for the same. This seemed promising too, but it seemed more expensive (computationally) than looking for predetermined shapes.

This work had been done within the first few days.

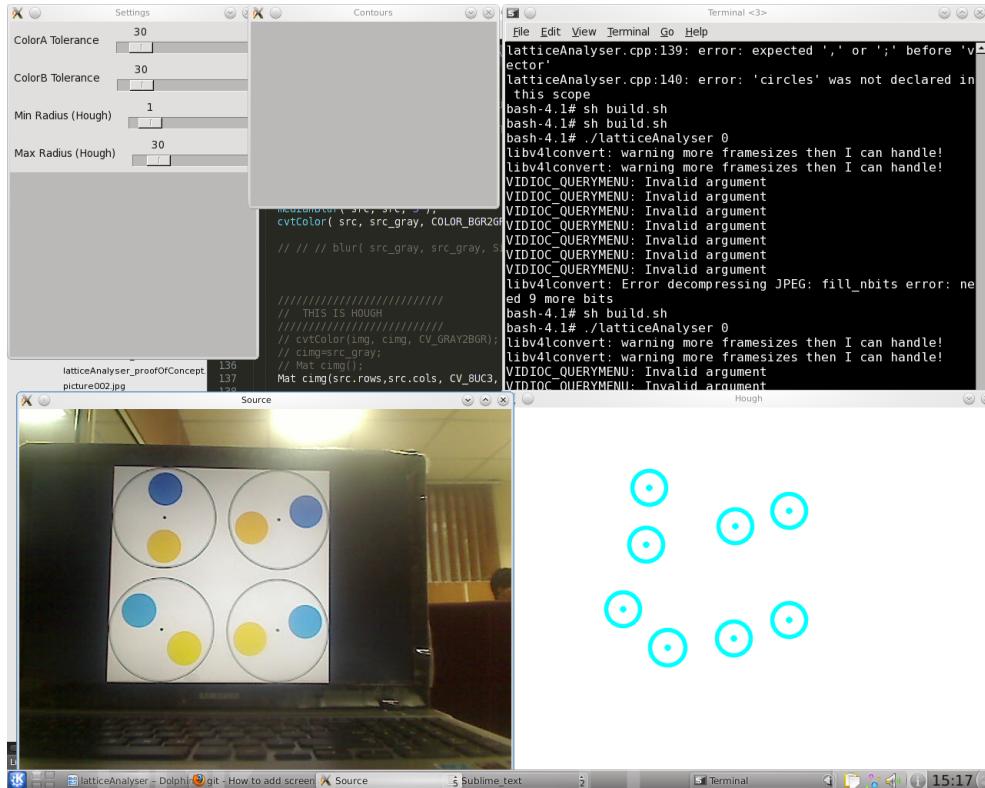


Figure 6: Hough Transform

Next, a colour filter was to setup to improve the accuracy. When the algorithms were implemented, it was found that the Hough Transform method often misses detection of circles, refer to [Figure 6](#) (this is ofcourse after attaching a video stream instead of images to the code) as compared to contour detection [Figure 7](#).

After the detection, according the plan, two colours were to be used for the ellipses. However, running the hough transform twice would've dropped the detection speed to half, which wasn't worth it. It was then decided that the shapes should be made different instead of relying on two colours for the same information. After looking at various combinations, [Figure 8](#) was finalized, with an ellipse at the centre, and a circle along the minor axis for breaking the symmetry. This method did infact work as shown in [Figure 9](#).

The next challenge was to realize that a dipole detection can be missed and therefore mess up the counting, if that is the only way of uniquely identifying them. Unique identification is obviously re-

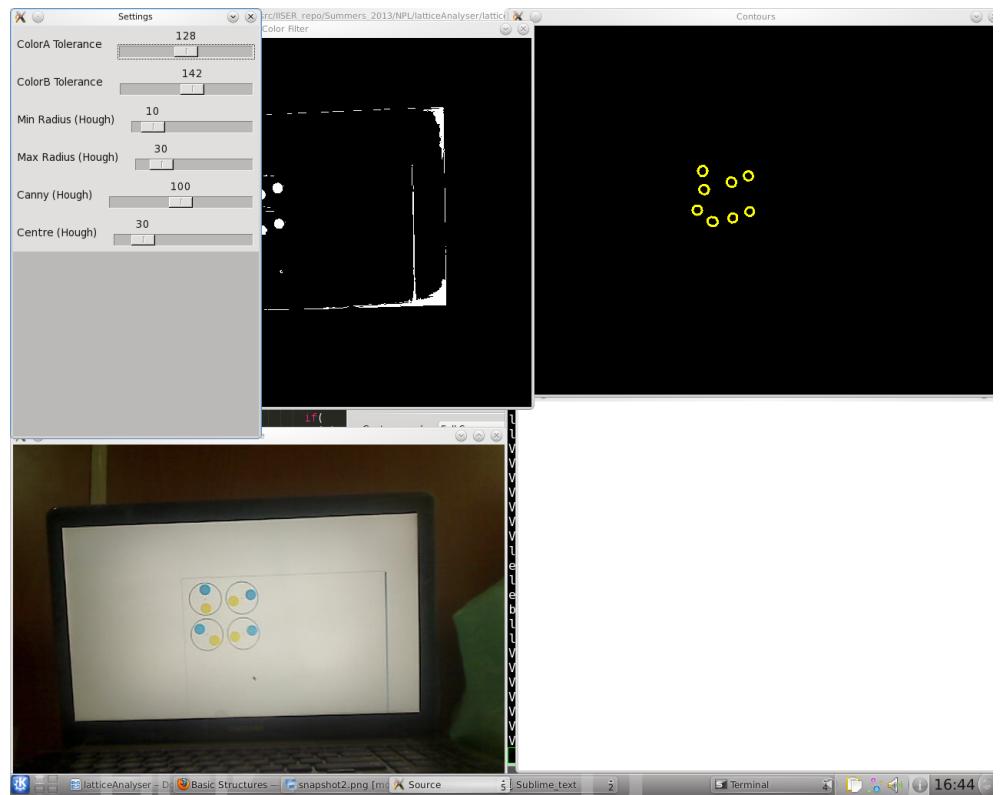


Figure 7: Contour Detection

quired, as the external hardware must fire the coils of the right dipole. Thus a reference frame was used to uniquely identify the dipoles initially. This is expected to happen when they are stationary to get a good reading. In each frame, whenever a dipole is detected, it is associated with the dipole in the reference frame, by matching its location. If a dipole is not detected in a given frame, the software knows it was unable to record it and doesn't mess up neither the numbering nor the observations.

After implementation of the last part, an animation sequence was created in Power Point, with the dipoles rotating with a constant speed and the camera was aimed at the screen. A still from the same

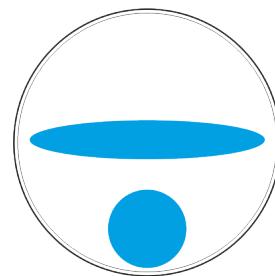


Figure 8: Final Pattern

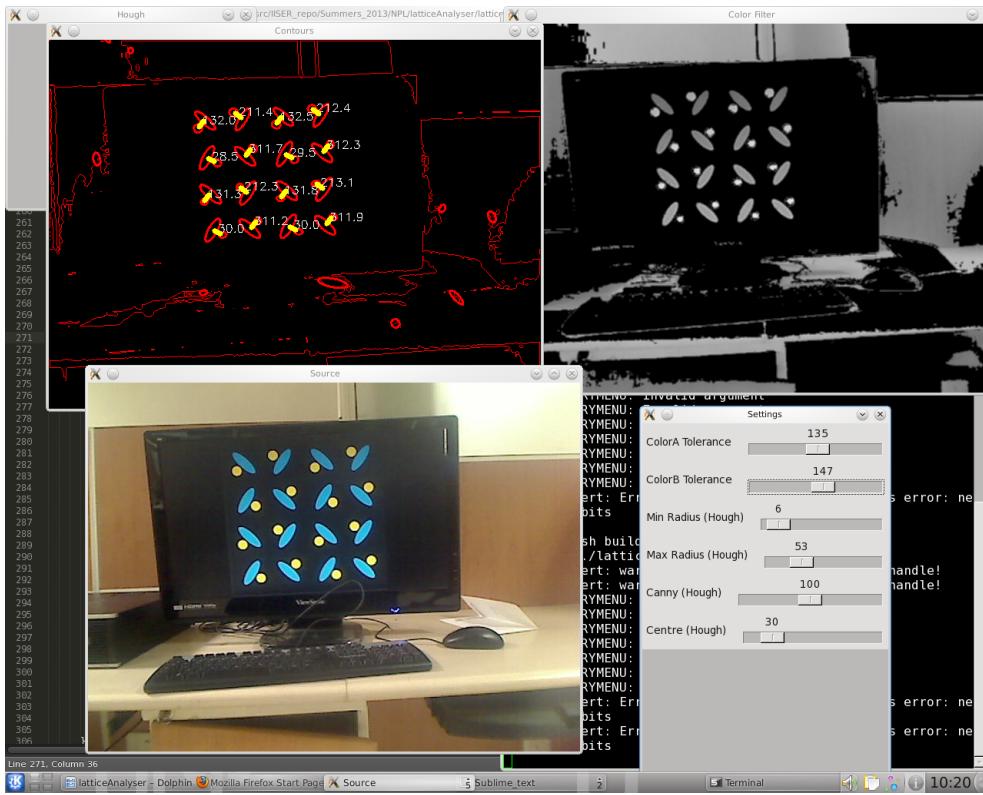


Figure 9: Multi Shape, Single Colour

is given in [Figure 11](#). [Figure 10](#), shows the angular position versus time plot, for the first dipole and yes, it is linear, just as expected. Standard deviation tests are still to be done.

Further tests, relating to its timing were done and it was found that the processing itself was taking longer than the time taken by one frame in a 30 FPS video stream. This could be improved with the following

1. Intel Performance Primitives (IPP)

These are libraries that provide optimized algorithms for performing some of the basic tasks in OpenCV to speed up the overall computation

2. Multi Threading

Rendering the frames in a different thread could perhaps increase the render speed or atleast ensure it doesn't affect the rate of processing of the image

3. Camera Initial Delay

Despite a 30 FPS smooth video, there seemed to be an initial delay which persisted in the video preview of the camera. This can be corrected for by polling the camera quickly instead of processing the image each time.

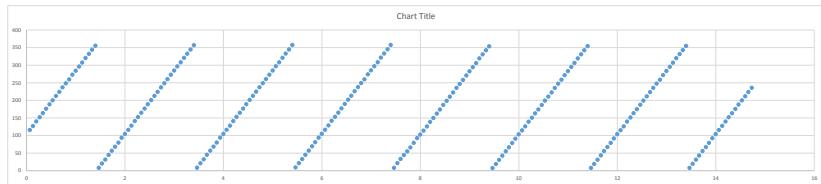


Figure 10: First Observation

4. OpenTBB

To enable multi-threading within OpenCV to speed up the algorithms

5. Hardware

The results obtained earlier were for a Pentium 4 HT system. A faster multi-core processor could produce potentially, better benchmarks.

Painstakingly, IPP was downloaded, built and integrated with OpenCV and re-built. There were various issues, starting from an incompatible version of IPP, to faulty documentation in OpenCV. The results did not improve however despite this. Perhaps the algorithms used do not rely on the methods optimized by IPP

Multi-threading was implemented using C++ 11. Various synchronization methods were looked up, including mutexes, unique locks; eventually atoms were used and tested with Visual Studio Express 2012 on windows (implicitly implying the application was first made to run on windows), as the linux machine had an older kernel and upgrading GCC wasn't recommended.

The camera's initial delay is caused by the initial stream. To rectify this, OpenCV has two methods, one for grabbing a frame, and the other for decoding it. If in a separate loop, the camera is polled regularly for frames, the delay is minimized. The frame can be decoded as

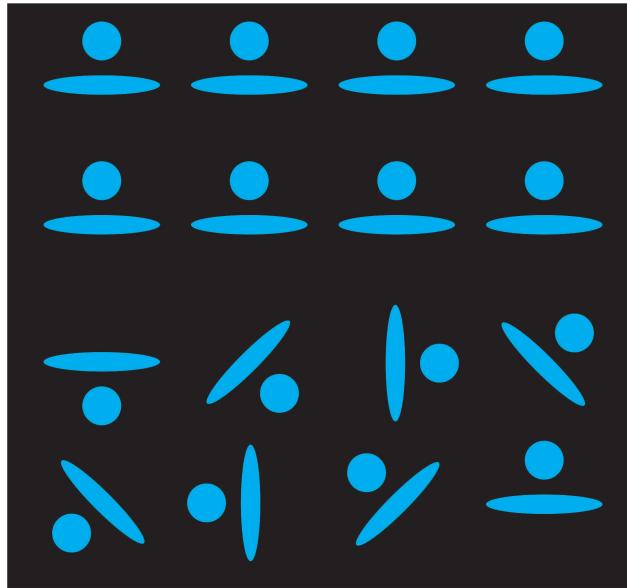


Figure 11: Final Test Pattern

soon as processing of the previous frame is over. This, as is suggestive, also requires multi-threading

OpenTBB is a library that is required to enable multi-threading support in OpenCV. This too had to be fiddled with for a while, before being built successfully.

The hardware was changed to an i7 machine which has more than enough cores and computation power.

These modifications were all combined and the code compiled using GCC (except certain parts of multi-threading, due to a compiler issue) and it was found to be able to process in about 25 milliseconds for an 8×8 matrix of dipoles. For a 16×16 matrix, the resolution of the camera (Logitech Pro 9000, 640×480 at 30 FPS) was found to be insufficient. Higher resolutions in the same camera did not have a 30 FPS temporal resolution. The alternative seems to be a camera for the Raspberry Pi which can be used over ethernet.

Further, the CLI of the program was modified to add support for inputting various commands, which would be required for testing the hardware (which is scheduled to be built this week).

And surprise surprise, the hardware interface was in fact done in the following week. Dr. Ravi Mehrotra had already created a simplified version of the Ob-Dev firmware for USB interface of an Atmega with the PC which was used. More on that is there in the temperature section (which follows). The Lattice Analyser had to pump in energy to the system by providing angular velocity to the system of dipoles repetitively at suitable time intervals, viz. when the temperature of the system drops. The temperature is calculated in realtime using the RMS angular velocity of each dipole in the system. It was

immediately realized after a closer look that since the time window between two frames is roughly 30 ms, it is not possible to energize all the dipoles with velocities picked from a given distribution of temperature. Further, since the motion of the entire system is coupled, it suffices to energize *some* dipoles sufficiently to maintain the temperature.

To achieve this the following were done (or algorithms for achieving them written)²

1. The tools for compiling and programming the AVR installed
2. Bootloader programmed into the micro-controller along with the sample program given by Dr. Ravi Mehrotra
3. Communication with the PC was tested using the corresponding C example program for the PC
4. USB libraries were incorporated into the latticeAnalyser and linked (had to compile C objects with C++ objects)
5. A simple IO protocol between the Lattice Analyser and the microcontroller was written and tested.
6. The coil of a dipole was tested with a set of 4 A4 batteries and some basic current calculations were done
7. The hardware was setup to include a small current limiting resistor (about 120 ohms) and the coil powered using the Lattice Analyser
8. (was not required) Worked on sachetIO; a library for breaking down a large chunk of data into sachets intended to be transmitted and combined after being received.
9. (was not required) Looked up methods to amplify the current, since the micro-controller's current wasn't found to be strong enough to align the needle of the dipole to it.
10. Discussion about how to implement the energy pumping (which is how the previous two steps were found to be pointless)
11. A 2×2 lattice of dipoles was setup.
12. The angular velocities of each dipole calculated
13. With each frame, the RMS angular velocity calculated
14. An algorithm for position and velocity based energy pumping written

² For completeness sake, it must be stated that some modifications had to be made before the colour filtration became functional

15. Interface added to test the same by supporting inversion of force direction (so that it results in halting) and an option to make blind (viz. disable the algorithm and instead send pulses periodically in time)

The final result was that energy could be pumped into one dipole satisfactorily. The next step was to extend the algorithm to an arbitrarily sized matrix. Certain steps such as velocity calculations when dipole detection fails (at high speeds) has arbitrary inaccurate behaviour in the said version. Algorithms for finding the axis of the coil in the dipoles also needs to be finalized, for there are more than one ways of doing this, viz. powering the coils and reading the angular position of the dipole, finding the axis of the lattice by noting the Cartesian positions of the dipole, deduce it from the rest (initial) angular position of the dipoles which should be known given the lattice size, etc.

Following is the source code of the same, which has been made available online.

latticeAnalyser.cpp

```
/*
filename: latticeAnalyser.cpp
description: This is the main application which analyses the
lattice and
    1. controls 'temperature'
    2. records dipole position (thus angular
       velocity) as a function of time
baby steps (TM):
    1. Proof of concept stage
        a. Find a suitable algorithm
        b. Make the required modifications
            i. Add a colour filter
                Implement two colours [done]
                Add two sliders for adjusting tolerance [done, but
                   need to refresh something!]
                Add GUI for selecting the colours [done, but not a
                   gui so to speak]
                save settings [not doing it]
    2. Look at it grow!
        a. Enable screen cropping [done]
        b. Write an algorithm for ellipse to dipole conversion [
           completed]
        c. Save data for each frame using a circular array of
           sorts [done]
        d. Output the data perhaps in a text file [done]
    3. Testing
        a. Test OpenCV's computation time [done]
            b. Compiling it on Windows [done and as it
               turns out, useless]
    4. Optimizing
        a. Multi-threading frame fetching [done]
```

```

        b. Multi-threading display update [done, but failed to
           improve, infact made it worse]
        c. Multi-thread using mutex [done, no real difference but
           not slow either][it is actually very slow]
              d. Atomic Sync for frame fetching [done]
        f. Atomic Sync for display update [done, and apparently
           faster! Yey]
              [There's something wrong though, since the frame
               jitters like a bad codec.]
              [resolved]
        g. Double Buffer for display [skipped]
5. Hardware Interface
    a. Modify the CLI to include menus [done]
    b. Fagocytosis of USB demo program [done]
    c. Working on the Proof of Concept for temperature
        i. Velocity calculation [done]
        ii. Realtime graphs [library installed; plplot; basic
             functionality tested]
            I. Test separate [Done]
            II. Fagocytosis [Done]
    d. Find the axis of the lattice to find the coil angle [
           after experimentation, discontinued]
*/
#include "opencv2/highgui/highgui.hpp"
#include "opencv2/imgproc/imgproc.hpp"
#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <thread>
#include <mutex>
#include <chrono>
#include <string>

#include <atomic>

// #include <string.h>
// #include <array>

#define GRAPHS_ENABLED

#ifndef GRAPHS_ENABLED
    #include <plplot/plplot.h>
    #include <plplot/plstream.h>
    plstream *pls=new plstream();
#endif

//Configuration
//#define ATOMIC
//#define MULTI_THREAD_DISPLAY

```

```

//##define ATOMIC_DISPLAY
//##define MULTI_THREAD_CAMERA_UPDATE

// #define TEMPERATURE_ENABLED

//TODO: Either calculate it at runtime, or allow the user to
//      input
//This is the detected angle of the dipole when it is aligned
//      with the coil (least energy configuration)
#define COILANGLE 180

const float version=0.6;
#define MINANGULARVELOCITY 10000000

int tempCandidate=0; //This is the dipole that is accelerated
bool blind=false; //This is the blind option, meaning
// hardware tracking is turned off
bool invertPush=false; //This is to invert the moment of
// pushing
#ifndef TEMPERATURE_ENABLED
inline void fireElectro(long frame);
// for USB interface
extern "C"
{
    #include "DataTypes.h"
    #include "usbIO.h"
}
// 
#endif

#ifndef ATOMIC_DISPLAY
#ifndef MULTI_THREAD_DISPLAY
#define MULTI_THREAD_DISPLAY
#endif
#endif

//#if (defined(ATOMIC) || defined(ATOMIC_DISPLAY) || defined(
//    MULTI_THREAD_DISPLAY) || defined(MULTI_THREAD_CAMERA_UPDATE))
//#include<atomic>
//#endif

#ifndef ATOMIC
    //##include <atomic>
    atomic<bool> threadsEnabled=false;
#else
    bool threadsEnabled=false;
#endif
using namespace cv;
using namespace std;

```

```

#ifndef MULTI_THREAD_DISPLAY
#ifndef ATOMIC_DISPLAY
    mutex drawnow;
#endif
#endif

#ifndef ATOMIC_DISPLAY
atomic<bool> updateDisplayRequested=true;
atomic<bool> updateDisplayCompleted=false;
#endif

mutex processingImage;
mutex grabbingFrame;

//For computation time
double tCstart,tCdelta,tCend; //time for computation
vector <double> computationTime;

vector <Mat> buf;

Mat grabbedFrame;
#ifndef MULTI_THREAD_CAMERA_UPDATE
atomic<bool> frameGrabbed=false,frameRequested=false;
#else
    bool frameGrabbed=false,frameRequested=false;
#endif

Mat srcPreCrop; Mat cimg; Mat src; Mat src_gray; Mat
srcColorFilter; Mat src_process; Mat srcColorA; Mat srcColorB
;Mat drawing;

// int lastBuf=1;
//for the cropping
int cropped = 0;
Point origin;
Rect selection;
bool selectRegion;

// Mat cimg;
Mat<Vec3b> srcTemp = src;
int thresh = 100;
int max_thresh = 255;
int canny=100;
int centre=30;
int minMinorAxis=1, maxMajorAxis=73;
int mode=0;
float theta=3.14159;

//mode
//0 is screen select

```

```

//1 is colour select

RNG rng(12345);

///////////DIPOLE DETECTION

class dipole
{
public:
    float angle,order; //angle is the angle, order gives a rough
    size of the dipole detected
    int x,y,id; //centre, id tells where its mapped
    int e1,e2; //index number of ellipse
    static int count[2]; //double buffer
    static int current;
};

int dipole::count[2] = {0};
int dipole::current=0;

//Not using a dynamic array, doesn't matter for now
//TODO: Use a dynamic array
// array<dipole,500> dipoles;
// array<dipole,500> lastDipoles;
#define DmaxDipoleCount 1000
dipole dipoles[2][DmaxDipoleCount];
// Colour read
// Point origin;

///////////DIPOLE INFORMATION STORAGE IN RAM
bool dipoleRec=false;

class dipoleSkel
{
public:
    float angle;
    int id; //For the dipoleData, this refers to the id of
    seedDipole
    //in seedDipole, this should refer to the hardware ID
    vector<int> neigbour;
    vector<float> neAngle;
    int x,y;
    float instAngularVelocity;
    bool detected; //stores whether the dipole was detected at
    all
};

//This class is for storing dipole data of a given frame
class dipoleFrame
{

```

```

public:
    double time; //time elapsed since the seed frame
    float order; //gives the rough size of the dipoles
    int count; //number of dipole detected in the frame
    float meanSquaredAngularVelocity; //mean of squares of angular
        velocities of each of the dipoles
    vector<dipoleSkel> data;
};

// #define DframeBufferLen 5000
dipoleFrame seedDipole;
//NOTE: You have to fix the numbering problem right here.
vector <dipoleFrame> dipoleData;

#define DframeBufferLen 5000
////THIS IS FOR STORING IN FILE
FILE * pFile;
char fileName[50];

////////////////////////////

// This is a colour filter for improving accuracy
// 20, 28, 41 [dark]
// TODO: Allow the user to select the colour
// Scalar colorB=Scalar(245,245,10);
Scalar colorB=Scalar(126,88,47);
Scalar colorA=Scalar(10,245,245);
int colorATol=30;
int colorBTol=35;
int brightInv=10; //this is to increase the brightness after
processing
//
const char* source_window = "Source";
const char* filter_window = "Color Filter";
const char* settings_window="Settings";

//////////TIMING
long t,tLast;
double deltaT;
static void onMouse( int event, int x, int y, int, void* )
{
    if(mode==0)
    {
        if( selectRegion )
        {
            selection.x = MIN(x, origin.x);
            selection.y = MIN(y, origin.y);
            selection.width = std::abs(x - origin.x);
            selection.height = std::abs(y - origin.y);
        }
    }
}

```

```

        selection &= Rect(0, 0, src.cols, src.rows);
    }

    switch( event )
    {
    case CV_EVENT_LBUTTONDOWN:
        cropped=0;
        origin = Point(x,y);
        selection = Rect(x,y,0,0);
        selectRegion = true;
        break;
    case CV_EVENT_LBUTTONUP:
        cropped=0;
        selectRegion = false;
        if( selection.width > 0 && selection.height > 0 )
            cropped = -1;
        break;
    }
}

else if(mode==1)
{
    switch( event )
    {
    case CV_EVENT_LBUTTONUP:
        cout<<x<<" , "<<y<<endl;
        colorA=Scalar(src.at<Vec3b>(x,y)[0],src.at<Vec3b>(x,y)
                      [1],src.at<Vec3b>(x,y)[2]);
        cout<<"Color A's been changed to "<<endl<<colorA.val[0]<<
                      endl<<colorA.val[1]<<endl<<colorA.val[2]<<endl;
        break;
    case CV_EVENT_RBUTTONUP:
        cout<<x<<" , "<<y<<endl;
        colorB=Scalar(src.at<Vec3b>(x,y)[0],src.at<Vec3b>(x,y)
                      [1],src.at<Vec3b>(x,y)[2]);
        cout<<"Color B's been changed to "<<endl<<colorB.val[0]<<
                      endl<<colorB.val[1]<<endl<<colorB.val[2]<<endl;
        break;
    }
}
#endif __GNUC__
void tGrabFrame(VideoCapture&& capture)
#else
void tGrabFrame(VideoCapture& capture)
#endif
{
    while(threadsEnabled)
    {

        capture>>grabbedFrame;
        if(frameRequested)

```

```

        {
            grabbedFrame.copyTo(srcPreCrop);
            frameGrabbed=true;
        }

        //buf.push_back(frameGrabbed);

        // if(processingImage.try_lock())
        // {
        //     buf.copyTo(srcPreCrop);
        //     processingImage.unlock();
        // }
    }

}

void updateDisplay()
{
    if(!drawing.empty())
        imshow("Contours", drawing );
    if(!cimg.empty())
        imshow("Debug", cimg);
    if(!src_gray.empty())
        imshow( filter_window, src_gray);
    if(!srcPreCrop.empty())
        imshow( source_window, srcPreCrop );

}

#ifndef MULTI_THREAD_DISPLAY
#ifndef ATOMIC_DISPLAY
    void tUpdateDisplay()
    {
        while(threadsEnabled)
        {
            drawnow.lock(); //this is to ensure it updates only once
                            // the processing has been done and not repetitively the
                            // same frame
            drawnow.unlock();

            updateDisplay();

        }
    }
#else
    void tAtomicDisplay()
    {
        while(threadsEnabled)
        {

            // && updateDisplayCompleted==false)
            if(updateDisplayRequested)

```

```

    {
        updateDisplay();
        // this_thread::sleep_for(chrono::milliseconds(10));
        // updateDisplayCompleted=true;
        updateDisplayRequested=false;
    }
    // else
    // this_thread::sleep_for(chrono::milliseconds (1));
    // this_thread::yield();

}

}

#endif
#endif

#endif GRAPHICS_ENABLED
void clearGraph()
{
    pls->col0(1);
    // cout<<"1"<<endl;
    double xmin2d = -2.5;
    double xmax2d = 2.5;
    double ymin2d = -2.5;
    double ymax2d = 4.0;
    // pls->wind( 0.0, 1.0, 0.0, 1.0 );
    // pls->env(xmin2d, xmax2d, ymin2d, ymax2d, 0, -2);
    pls->adv(1);
    pls->clear();
    pls->vpqr( 0.0, 1.0, 0.0, 1.0 );
    pls->wind( -2.5, 2.5, -3.0, 3.0 );

    double basex = 2.0;
    double basey = 4.0;
    double height = 3.0;
    double xmin = 0.0;
    double xmax = 10.0;
    double ymin = 0.0;
    double ymax = 1000.0;
    double zmin = 0.0;
    double zmax = 360.0;
    double alt = 45.0;
    double az = 30.0;
    double side = 1;
    pls->w3d(basex, basey, height, xmin, xmax, ymin, ymax, zmin
              , zmax, alt, az);
    pls->box3( "bnstu", "Dipole Count", 0.0, 0,
               "bnstu", "Frame Count", 0.0, 0,
               "bcdmnstuv", "Angular Position", 0.0, 4 );

}

// This is for selecting the second view

```

```

    // Following are to get the points in the right location!
    pls->adv(2);
    pls->clear();
    pls->vpqr( 0.0, 1.0, 0.0, 1.0 );
    pls->wind( -2.5, 2.5, -3.0, 3.0 );
    // pls->env(xmin2d, xmax2d, ymin2d, ymax2d, 0, -2);
    // pls->wind( 0.0, 1.0, 0.0, 1.0 );
    zmin=-360;
    zmax=360;
    pls->w3d(baseX, baseY, height, xmin, xmax, ymin, ymax, zmin
              , zmax, alt, az);
    pls->box3( "bnstu", "Dipole Count", 0.0, 0,
               "bnstu", "Frame Count", 0.0, 0,
               "bcdmnstuv", "Angular Velocity", 0.0, 4 );
}
#endif

int process(VideoCapture& capture)
{
    #ifdef GRAPHS_ENABLED

        pls->init();
        pls->ssub( 1, 2 );
        pls->adv(1);
        cout<<endl<<"Initializing the interface for graphing"<<endl;

        clearGraph();

    #endif

    #ifdef TEMPERATURE_ENABLED
        vInitUSB();
    #endif

    /// Create Window
    namedWindow( source_window, WINDOW_AUTOSIZE );
    setMouseCallback( "Source", onMouse, 0 );
    //Show the filtered image too

    namedWindow( filter_window, WINDOW_AUTOSIZE );

    //Show the settings window

    namedWindow(settings_window,WINDOW_AUTOSIZE | CV_GUI_NORMAL);
    createTrackbar( "ColorA Tolerance", settings_window, &colorATol
                  , 256, 0 );
    createTrackbar( "ColorB Tolerance", settings_window, &colorBTol
                  , 256, 0 );
    createTrackbar( "Min Radius", settings_window, &minMinorAxis,
                  100, 0 );
}

```

```

createTrackbar( "Max Radius", settings_window, &maxMajorAxis,
    200, 0 );
createTrackbar( "Brightness Inverse", settings_window, &
    brightInv, 255, 0 );
createTrackbar( "Canny (Hough)", settings_window, &canny, 200,
    0 );
createTrackbar( "Centre (Hough)", settings_window, &centre,
    200, 0 );
// createTrackbar( "Theta", settings_window, &thetaD, 3.141591,
//     0 );

/// Show in a window
namedWindow( "Contours", WINDOW_AUTOSIZE );
namedWindow( "Debug", WINDOW_AUTOSIZE );

////Voodoo intializations
// dipoles[0][0].current=0;
// dipoles[0][0].count[0]=0;
// dipoles[0][0].count[1]=0;
/// Load source image
// src = imread( argv[1], 1 );

// std::string arg = argv[1];
///////////
cout<<capture.get(CV_CAP_PROP_FRAME_HEIGHT);
capture.set(CV_CAP_PROP_FRAME_HEIGHT,480);
capture.set(CV_CAP_PROP_FRAME_WIDTH,640);

thread t1(tGrabFrame,capture);
#ifndef MULTI_THREAD_DISPLAY
#ifndef ATOMIC_DISPLAY
    thread t2(tUpdateDisplay);
#else
    thread t2(tAtomicDisplay);
#endif
#endif
#endif

for(;;)
{
    // processingImage.lock();
    //if the video feed has over 1 frame

    // if(buf.size()>1)
    // {
    //     buf.erase(buf.begin()); //remove the oldest frame
    //     srcPreCrop=buf[buf.size()-1]; //grab the latest frame
    // }
}

```

```

// frameGrabbed.copyTo(srcPreCrop);
frameRequested=true;

if(frameGrabbed==true && !srcPreCrop.empty())
    // #ifdef ATOMIC_DISPLAY
    //      // if(updateDisplayCompleted)
    // #endif

{
    frameRequested=false;      //this is so that the frame is
    not processed unless required
    frameGrabbed=false;      //this is so that we know the
    next time a frame is grabbed

#ifndef MULTI_THREAD_DISPLAY
    // drawnow=true;
    #ifndef ATOMIC_DISPLAY
        drawnow.lock();
    #endif
    #endif

{  //IMAGE CAPTURE and CROP
    // capture>>srcPreCrop;
    ////////////////////COMPUTATION TIME CALCULATION
    tCstart=getTickCount();
    /////////////
    tLast=t;
    // t=getTickCount()/getTickFrequency();    //This is give
    // time in seconds
    t=getTickCount();
    deltaT=(t-tLast)/getTickFrequency();

    if(dipoleRec)
    {
        //if this is not the last frame, add a frame
        dipoleData.push_back(seedDipole);
        //This is to avoid overflows
        // if (dipoleData.size()>DframeBufferLen)
        //     dipoleData.erase(dipoleData.begin());
        //for the last frame
        dipoleData[dipoleData.size()-1].time=dipoleData[
            dipoleData.size()-2].time+deltaT;
        dipoleData[dipoleData.size()-1].count=0; //No dipoles
        found before analysis!
        dipoleData[dipoleData.size()-1].
            meanSquaredAngularVelocity=0; //Initially zero
    }

    // long cfInit=dipoleData.size()-1; //last frame

    // //test for current frame
}

```

```

// if(dipoleData[cfInit].time!=t)
// {
//   //if this is not the last frame, add a frame
//   dipoleData.push_back(seedDipole);
//   //This is to avoid overflows
//   if (dipoleData.size()>DframeBufferLen)
//     dipoleData.erase(dipoleData.begin());
//   //for the last frame
//   cfInit=dipoleData.size()-1;
//   dipoleData[cfInit].time=t;
// }

if(srcPreCrop.empty())
{
    cout<<"Didn't get an image";
    break;
}
if(!cropped==0)
{
    src=srcPreCrop(selection);
}
else
    src=srcPreCrop;

// imshow( source_window, srcPreCrop );

}

///////////////
{//COLOR FILTER
//Input src, output src_gray
Scalar lowerBound;
Scalar upperBound;

lowerBound = colorA-Scalar::all(colorATol);
upperBound = colorA+Scalar::all(colorATol);
// Now we want a mask for the these ranges
inRange(src,lowerBound,upperBound, srcColorA);

lowerBound = colorB-Scalar::all(colorBTol);
upperBound = colorB+Scalar::all(colorBTol);
// We do it for both the colours
inRange(src,lowerBound,upperBound, srcColorB);

// Now we create a combined filter for them
addWeighted(srcColorA, 1, srcColorB, 1, 0, srcColorFilter
);

/// Convert image to gray

```

```

        cvtColor( src, src_process, COLOR_BGR2GRAY );

        /// Now keep only the required areas in the image
        // // // multiply(src_process,srcColorFilter,src_gray,1);

        //Change the following to use greyscaled output
        src_gray=srcColorFilter.mul(src_process/brightInv);
        // src_gray=srcColorFilter;

        // // // src_gray=srcColorFilter;

        // Now blur it
        blur( src_gray, src_gray, Size(3,3) );

        // imshow( filter_window, src_gray );
    }

//////////



// BLANK PROCESSING
// medianBlur( src, src, 5 );
// cvtColor( src, src_gray, COLOR_BGR2GRAY );

// // // blur( src_gray, src_gray, Size(3,3) );

//////////
// This is contour Detection
//////////
Mat threshold_output;
vector<vector<Point>> contours;
vector<Vec4i> hierarchy;

// Detect edges using Threshold
threshold( src_gray, threshold_output, thresh, 255,
            THRESH_BINARY );
// Find contours
findContours( threshold_output, contours, hierarchy,
              RETR_TREE, CHAIN_APPROX_SIMPLE, Point(0, 0) );

// Find the rotated rectangles and ellipses for each
// contour
vector<RotatedRect> minRect( contours.size() );
vector<RotatedRect> minEllipse( contours.size() );

for( size_t i = 0; i < contours.size(); i++ )
    { minRect[i] = minAreaRect( Mat(contours[i]) );
      if( contours[i].size() > 5 )
          { minEllipse[i] = fitEllipse( Mat(contours[i]) ); }
    }

```

```

for( size_t i = 0; i< minEllipse.size(); i++ )
{
    //You can add aditional conditions to eliminate
    detected ellipses
    if(!(
        (minEllipse[i].size.height>minMinorAxis && minEllipse
         [i].size.width>minMinorAxis)
        &&
        (minEllipse[i].size.height<maxMajorAxis && minEllipse
         [i].size.width<maxMajorAxis)
    ))
    {
        // minEllipse[i]=RotatedRect(Point2f(0,0),Point2f
        // (0,0),0);
        minEllipse.erase(minEllipse.begin()+i--);
    }
}

///////////////////
// Dipole Detection Algorithm
///////////////////
vector<bool> detected (minEllipse.size(),false);

int k = !(dipoles[0][0].current);
dipoles[0][0].current=k;
dipoles[0][0].count[k]=0; //this count is different from
    that used in frames, they correspond to a subset of
    these which are position wise close enough to the seed
    frame

// dipolesA[0].lastcount=0;
for (int i=0; i<minEllipse.size();i++)
{
    if(detected[i]==false)
    {
        for (int j=0; j<minEllipse.size();j++)
        {
            if((i!=j) && detected[j]==false) //This is so that
                you don't test with yourself and with others that
                got paired
            {
                // if(abs(minEllipse[i].angle-minEllipse[j].angle
                // < 15) //if the orientation matches (less
                // than 5 degrees), then
            }
            //Find the distance between minEllipses

            Point differenceVector=Point(minEllipse[i].
                center.x - minEllipse[j].center.x,

```

```

        minEllipse[i].center.y - minEllipse[j].
        center.y); //find the difference vector
    float distanceSquared=differenceVector.x*
        differenceVector.x + differenceVector.y*
        differenceVector.y; //find the distance
        squared

    //Find the major axis length
    float majorAxis=MAX( MAX(minEllipse[i].size.
        width, minEllipse[i].size.height) , MAX(
        minEllipse[j].size.width, minEllipse[j].
        size.height)); //find the max dimension

    //The ratio is the ratio between the distance
    //between the ellipse and the small circle
    //and the length of the major axis
    float errorPlusOne = distanceSquared /
        ((11.348/30)*(11.348/30)*majorAxis*
        majorAxis) ; //now to compare, just divide
        and see if it's close enough to one

    if (errorPlusOne>0.5 && errorPlusOne<2) //if
        the error is small enough, then its a match
    {
        //This is to ensure these don't get paired
        detected[i]=true;
        detected[j]=true;

        //this is collection of the final result
        int c=dipoles[k][0].count[k]++; //dont get
            confused, count is static, so even
            dipoles[0][0] would've worked, ro for
            that matter, any valid index
        //Note the ++ is after because the count is
            always one greater than the index of
            the last element!

        // dipoles[k][c].angle=(minEllipse[i].angle
        // + minEllipse[j].angle)/2.0;
        // dipoles[k][c].angle=(minEllipse[i].angle
        // );

        // We're using two shapes, one ellipse and
        // one circle.
        RotatedRect largerEllipse = ( MAX(
            minEllipse[i].size.width, minEllipse[i].
            size.height) > MAX(minEllipse[j].size.
            width, minEllipse[j].size.height) )?
            minEllipse[i]:minEllipse[j];
        RotatedRect smallerEllipse = ( MAX(
            minEllipse[i].size.width, minEllipse[i].
            size.height) < MAX(minEllipse[j].size.
            width, minEllipse[j].size.height) )?
            minEllipse[j]:minEllipse[i];
    }
}

```

```

].size.height) <= MAX(minEllipse[j].  

size.width, minEllipse[j].size.height)  

)?minEllipse[i]:minEllipse[j];  

float dCenterX=largerEllipse.center.x-  

smallerEllipse.center.x;  

float dCenterY=largerEllipse.center.y-  

smallerEllipse.center.y;

dipoles[k][c].angle=((180/3.1415926535)*  

atan2(dCenterY,dCenterX)) + 180;

//UNCOMMENT THIS PART FOR THE OLD ANGLE  

ESTIMATOR  

// dipoles[k][c].angle=(largerEllipse.angle  

);

// //Now we use the circle to remove the  

mod 180 problem and get the complete  

360 degree position  

// if((smallerEllipse.center.y -  

largerEllipse.center.y) < 0)  

//   dipoles[k][c].angle+=180;  

///////////  

// dipoles[k][c].x=(minEllipse[i].center.x  

+ minEllipse[j].center.x)/2.0;  

// dipoles[k][c].y=(minEllipse[i].center.y  

+ minEllipse[j].center.y)/2.0;  

dipoles[k][c].order=MAX(largerEllipse.size.  

height, largerEllipse.size.width);  

dipoles[k][c].x=largerEllipse.center.x; //(br/>
minEllipse[i].center.x + minEllipse[j].  

center.x)/2.0;  

dipoles[k][c].y=largerEllipse.center.y; //(br/>
minEllipse[i].center.y + minEllipse[j].  

center.y)/2.0;  

dipoles[k][c].e1=i; //don't know why this  

is required  

dipoles[k][c].e2=j;  

///////////THIS IS FOR RECORDING/SAVING  

THE DIPOLE MOVEMENT/////////

```

```

        if (dipoleRec==true)
        {

            long cf=dipoleData.size()-1; //last
                                         //frame

            for(int q=0;q<seedDipole.data.size();q++)
            {
                //This is to test which dipole belongs
                //where in accordance with the
                //seedDipole frame
                // if(MAX(abs(seedDipole.data[q].x -
                //dipoles[k][c].x), abs(seedDipole.
                //data[q].y - dipoles[k][c].y)) < (
                //seedDipole.order/2.0) )
                //Or you could use the last fraame for
                //this
                if(
                    (MAX(abs(dipoleData[cf-1].data[q].x -
                        dipoles[k][c].x), abs(dipoleData
                        [cf-1].data[q].y - dipoles[k][c].
                        y)) < (dipoleData[cf-1].order
                        /4.0) )
                    &&
                    (dipoleData[cf].data[q].detected==
                     false)
                )
                {
                    dipoles[k][c].id=q;
                    // dipoleData.data[q] = dipoles[k][c]
                    //TODO: Make a function for
                    //converting
                    dipoleData[cf].data[q].id=q;
                    dipoleData[cf].data[q].x=dipoles[k][c
                        ].x; //Copy the relavent data
                           //from the dipole data collected
                           //into the temp dipole
                    dipoleData[cf].data[q].y=dipoles[k][c
                        ].y;
                    dipoleData[cf].data[q].angle=dipoles[
                        k][c].angle;
                    dipoleData[cf].count+=1;
                    if(cf==0)
                        dipoleData[cf].data[q].
                        instAngularVelocity=0;
                    else
                        dipoleData[cf].data[q].
                        instAngularVelocity=(dipoleData
                        [cf].data[q].angle - dipoleData
                        [cf-1].data[q].angle)/deltaT;
                }
            }
        }
    }
}

```

```

dipoleData[cf].
meanSquaredAngularVelocity+= (
dipoleData[cf].data[q].
instAngularVelocity*dipoleData[cf].
].data[q].instAngularVelocity) ;
//Add the sqr of inst angular
velocity, averaging is done later
dipoleData[cf].data[q].detected=true;
//This is true only when the
dipole's

dipoleData[cf].order=dipoles[k][c].
order; //This is bad programming
..i should average, but doens't
matter
//Now that it has matched, terminate
the loop
q=seedDipole.data.size();
}
}

}

// magnitude(differenceVector.x,
differenceVector.y,distance);

// point positionVector ((minEllipse[i].x +
minEllipse[j].x)/2.0,(minEllipse[i].y +
minEllipse[j].y)/2.0);

}

}

}

}

///////////AFTER the frame has been processed, evaluate
physical quantities of interest
if(dipoleRec==true)
{
long cf=dipoleData.size()-1; //last frame
if(dipoleData[cf].count>0)
dipoleData[cf].meanSquaredAngularVelocity/=dipoleData[
cf].count;
//else it would be zero, the meanSquaredAngularVelocity

#endif TEMPERATURE_ENABLED
if(!blind)
```

```

    {
        if(dipoleData[cf].meanSquaredAngularVelocity<(
            MINANGULARVELOCITY*MINANGULARVELOCITY))
        {
            if((dipoleData[cf].data[tempCandidate].angle -
                COILANGLE) > 0)
            {
                if (dipoleData[cf].data[tempCandidate].instAngularVelocity>=0) //if it is going in
                the opposite direction
                {
                    if (invertPush)
                        fireElectro(cf);
                }
                else
                {
                    if(!invertPush)
                        fireElectro(cf); //to increase speed,
                        because the force will be towards the
                        coil
                }
            }

        }
        else //if the angle is negative, then
        {
            if (dipoleData[cf].data[tempCandidate].instAngularVelocity<=0) //if it is going
            towards the coil
            {
                if(invertPush)
                    fireElectro(cf);
                }
                else
                {
                    if(!invertPush)
                        fireElectro(cf);
                }
                // fireElectro(cf);
            }
            // fireElectro();
        }
    }
    else
        fireElectro(cf);
#endif
}
///////////
#ifndef GRAPHS_ENABLED
if(dipoleRec==true)
{
    // cout<<endl<<"DID SOMETHING";
}

```

```

static long cfRe=0;
long cf=dipoleData.size()-1; //last frame
long t=(cf-cfRe);
if(t>=1000)
{
    cfRe=cf;
    clearGraph();
    t=0;
    // pls->bop();
    // pls->adv(1);
    // pls->clear();
    // pls->adv(2);
    // pls->clear();
}

for(int i=0;i<dipoleData[cf].count;i++)
{
    if(dipoleData[cf].data[i].detected)
    {
        pls->adv(1);
        pls->vpqr( 0.0, 1.0, 0.0, 1.0 );
        pls->wind( -2.5, 2.5, -3.0, 3.0 );

        double x = dipoleData[cf].data[i].id;
        double z = dipoleData[cf].data[i].angle;
        // double x = i;
        // double z=i;
        double y = t;
        pls->col0(i);
        pls->poin3(1,&x, &y, &z,1);

        pls->adv(2);
        pls->vpqr( 0.0, 1.0, 0.0, 1.0 );
        pls->wind( -2.5, 2.5, -3.0, 3.0 );

        // x = dipoleData[cf].data[i].id;
        z = dipoleData[cf].data[i].instAngularVelocity;
        // double x = i;
        // double z=i;
        // y = cf;
        pls->col0(i);
        pls->poin3(1,&x, &y, &z,1);
    }
}
}

#endif

//////////////DRAWING THE CONTOUR AND DIPOLE
/// Draw contours + rotated rects + ellipses
drawing = Mat::zeros( threshold_output.size(), CV_8UC3 );

```

```

    for( size_t i = 0; i< contours.size(); i++ )
    {
        // Scalar color = Scalar( rng.uniform(0, 255), rng.
        // uniform(0,255), rng.uniform(0,255) );
        Scalar color = Scalar(0,0,255 );
        // contour
        drawContours( drawing, contours, (int)i, color, 1, 8,
                      vector<Vec4i>(), 0, Point() );

        // ellipse
        if(i<minEllipse.size())
            ellipse( drawing, minEllipse[i],
                     color, 2, 8 );

        // rotated rectangle
        // Point2f rect_points[4]; minRect[i].points(
        //     rect_points );
        // for( int j = 0; j < 4; j++ )
        //     line( drawing, rect_points[j], rect_points[(j+1)
        //         %4], color, 1, 8 );
        // }

        // int xx=dipoles[k][i].x;
        // int yy=dipoles[k][i].y;
        // int theta=dipoles[k][i].angle;

        // line(drawing, Point2f(xx,yy),Point2f(xx + 5*cos(
        //     theta), yy + 5*sin(theta)), Scalar(0,0,255),1,8);

    }

    for( int i=0;i<dipoles[0][0].count[k];i++)
    {

        int xx=dipoles[k][i].x;
        int yy=dipoles[k][i].y;
        float theta = (3.1415926535/180) * dipoles[k][i].angle;

        line(drawing, Point2f(xx - 5*cos(theta), yy - 5*sin(theta)
                           ),Point2f(xx + 5*cos(theta), yy + 5*sin(theta)),
              Scalar(0,255,255),5,8);

        // Use "y" to show that the baseLine is about
        char text[30];
        // dipoles[0][0].count[0]=1;
        // sprintf(text,"%f",dipoles[0][dipoles[0][0].count[k
        // ]-1].angle);
        // sprintf(text,"%f",dipoleData[dipoleData.size()-1].
        // meanSquaredAngularVelocity);
    }
}

```

```

int fontFace = FONT_HERSHEY_SCRIPT_SIMPLEX;
double fontScale = 0.5;
int thickness = 1;

int baseline=0;
Size textSize = getTextSize(text, fontFace,
                           fontScale, thickness, &
                           baseline);
baseline += thickness;

// center the text
Point textOrg((drawing.cols - textSize.width)/2,
               (drawing.rows + textSize.height)/2);
// // draw the box
// rectangle(drawing, textOrg + Point(0, baseline),
//            textOrg + Point(textSize.width, -textSize.
//                           height),
//            Scalar(0,0,255));
// // ... and the baseline first
// line(drawing, textOrg + Point(0, thickness),
//       textOrg + Point(textSize.width, thickness),
//       Scalar(0, 0, 255));

// then put the text itself
// putText(drawing, text, textOrg, fontFace, fontScale,
//          Scalar::all(255), thickness, 8);
sprintf(text,"%1.1f",dipoles[k][i].angle);
putText(drawing, text, Point(dipoles[k][i].x,dipoles[k][i].
    .y), fontFace, fontScale, Scalar::all(0), thickness
    *3, 8);
putText(drawing, text, Point(dipoles[k][i].x,dipoles[k][i].
    .y), fontFace, fontScale, Scalar::all(255),
    thickness, 8);

sprintf(text,"%d,%d",dipoles[k][i].id,i);
putText(drawing, text, Point(dipoles[k][i].x,dipoles[k][i].
    .y-10), fontFace, fontScale, Scalar::all(0),
    thickness*3, 8);
putText(drawing, text, Point(dipoles[k][i].x,dipoles[k][i].
    .y-10), fontFace, fontScale, Scalar(255,255,0),
    thickness, 8);

//DEBUG ONLY
if(i==0)
{
    cimg = Mat(src.rows,src.cols+500, CV_8UC3, Scalar
    (0,0,0));
    // sprintf(text,"%1.1f",dipoles[k][i].angle);
    sprintf(text,"Press p to seed");
    // sprintf(text,"%1.1f",dipoleData[dipoleData.size()
    -1].data[0].instAngularVelocity);
}

```

```

        // if(dipoleData[dipoleData.size()-1].
        meanSquaredAngularVelocity >0)
        if(dipoleRec==true)
            sprintf(text,"%1.1f",dipoleData[dipoleData.size()-1].
            meanSquaredAngularVelocity);
        putText(cimg, text, Point(src.rows/4,src.cols/4),
            fontFace, fontScale*12, Scalar::all(255), thickness
            *4, 8);
    }
}

///////////////////////////////
// THIS IS HOUGH
/////////////////////////////
// // cvtColor(img, cimg, CV_GRAY2BGR);
// // cimg=src_gray;
// // Mat cimg();
// Mat cimg(src.rows,src.cols, CV_8UC3, Scalar(255,255,255)
// );

// vector<Vec3f> circles;
// HoughCircles(src_gray, circles, CV_HOUGH_GRADIENT, 1,
//     10,
//     // canny, centre, minMinorAxis, maxMajorAxis
//     // change the last two parameters
//     // // (min_radius & max_radius)
//     // to detect larger circles
//     // );

// // src_gray:s Input image (grayscale)
// // circles: A vector that stores sets of 3 values: x_{c}
// //           , y_{c}, r for each detected circle.
// // CV_HOUGH_GRADIENT: Define the detection method.
// // Currently this is the only one available in OpenCV
// // dp = 1: The inverse ratio of resolution
// // min_dist = src_gray.rows/8: Minimum distance between
// // detected centers
// // param_1 = 200: Upper threshold for the internal Canny
// // edge detector
// // param_2 = 100*: Threshold for center detection.
// // min_radius = 0: Minimum radio to be detected. If
// // unknown, put zero as default.
// // max_radius = 0: Maximum radius to be detected. If
// // unknown, put zero as default

// for( size_t i = 0; i < circles.size(); i++ )
// {
//     Vec3i c = circles[i];
//     // Scalar color = Scalar( rng.uniform(0, 255), rng.
//     uniform(0,255), rng.uniform(0,255) );
//     Scalar color = Scalar( 255,255,0 );

```

```

//      circle( cimg, Point(c[0], c[1]), c[2], color, 3,
//      CV_AA);
//      circle( cimg, Point(c[0], c[1]), 2, color, 3, CV_AA)
//      ;
// }

// imshow("Debug", cimg);

#ifndef MULTI_THREAD_DISPLAY
    updateDisplay();
#endif

#ifdef MULTI_THREAD_DISPLAY
    // drawnow=true;
    #ifndef ATOMIC_DISPLAY
        drawnow.unlock();
    #else
        updateDisplayRequested=true; //Both are required to
        trigger an update
        // updateDisplayCompleted=false; //The request flag is
        used to indicate processing is done, the second
        indicates the same here
        //however, once the frame has been updated, the update
        flag avoids unnecessary refreshing of the frames.
    #endif
#endif

///////////////////
// CLI
/////////////////
char key = (char) waitKey(5); //delay N millis, usually
    long enough to display and capture input
int kMax; //sorry, bad programming, but relatively
    desparate for results..
switch (key)
{
    case 'c':
        mode=1;
        cout<<"Mouse will capture color now. Right click for
            one, left for the other"<<endl;
        break;
    case 's':
        mode=0;
        cout<<"Screen crop mode selected. Mouse will capture
            start point at left click and the other point at
            right click"<<endl;
        break;
    case 'p':
    {

```

```

cout<<"Look what you've done!"<<endl<<"Just kidding
      : This frame will be used as a seed"<<endl;
dipoleRec=true; //Enable dipole recording
seedDipole.data.clear(); //clear the data
dipoleSkel tempDipole; //create a temporary dipole
                      skeleton
k=dipoles[0][0].current; //find the current buffer
                          of dipoles detected (double buffered for
                          possible multithreading)
kMax=dipoles[0][0].count[k]; //find the number of
                               dipoles detected in the last scan

for(int c=0;c<kMax;c++)
{
    tempDipole.x=dipoles[k][c].x; //Copy the relevant
                                   data from the dipole data collected into the
                                   temp dipole
    tempDipole.y=dipoles[k][c].y;
    tempDipole.angle=dipoles[k][c].angle;
    tempDipole.instAngularVelocity=0;
    tempDipole.detected=false; //This is to ensure
                               the dipole was detected, but for the seed
                               frame, it is left false.
    tempDipole.id=c;
    seedDipole.data.push_back(tempDipole); //Add the
                                             data in the seedframe's data stream

    seedDipole.order+=dipoles[k][c].order; //to get
                                             teh average order
    if(c>0)
    {
        seedDipole.order/=2.0;
    }
}
seedDipole.time=0; //Initial time is to be stored
                   as zero
dipoleData.push_back(seedDipole);
break;
}
case 'w':
{
    cout<<"Writing angle vs time for the first dipole
          to file";
    if(dipoleRec==true)
    {
        sprintf(fileName,"latticeAnalyser_%d",
               getTickCount());
        pFile = fopen (fileName,"w");
    }
    //Loop through all the frames
}

```

```

    for (vector<dipoleFrame>::iterator dD =
        dipoleData.begin() ; dD != dipoleData.end();
        ++dD)
    {
        //Within each frame, loop through all dipoles?
        // for(vector<dipoleSkel>::iterator dS = dD.
        //     data.begin() ; dS!=dD.data.end() ; ++dS)
        // {

        // }
        //or just print the first dipole
        if(dD->data[0].detected)
            fprintf (pFile, "%f,%f,%f\n",dD->data[0].
                angle,dD->time,dD->
                meanSquaredAngularVelocity);
            //-->data[0].instAngularVelocity);
        // fprintf (pFile, "%d,%d\n",dD->data[0].angle,
        // dD->time);
    }

    // for (int p=0;p<dipoleData.size();p++)
    // {
    //     fprintf(pFile,"%d,%d\n",dipoleData[p].data.
    //         size(),dipoleData[p].time);
    // }
    fclose (pFile);
    // fprintf (pFile, "Name %d [%-10.10s]\n",n,name)
    ;

}

break;
}
case 'b':
//This is to make blind
blind=!blind;
cout<<"Blind:"<<blind<<endl;
break;
case 'i':
//invert push
invertPush=!invertPush;
cout<<"Push"<<invertPush<<endl;
break;
case 'W':
{
    pFile=fopen("TestComputation","w");
    for(vector<double>::iterator d=computationTime.
        begin();d!=computationTime.end();++d)
    {
        fprintf(pFile,"%f\n",*d);
    }
    fclose(pFile);
}

```

```

        break;
    }
    case 'q':
    case 'Q':
    case 27: //escape key
        destroyWindow(source_window);
        destroyWindow(filter_window);
        destroyWindow(settings_window);
        destroyWindow("Contours");
        destroyWindow("Debug");

        #ifdef TEMPERATURE_ENABLED
            vCloseUSB();
        #endif
        threadsEnabled=false;
        t1.join();
        #ifdef MULTI_THREAD_DISPLAY
            t2.join();
        #endif
        // destroyAllWindows();
        // this_thread::sleep_for( chrono::milliseconds
        // (5000) );
        // waitKey(1000);
        return 0;
    // case ' ': //Save an image
    //     sprintf(filename, "filename%.3d.jpg", n++);
    //     imwrite(filename, frame);
    //     cout << "Saved " << filename << endl;
    //     break;
    default:
        break;
    }
    tCend=getTickCount();
    tCdelta=tCend-tCstart;
    computationTime.push_back(tCdelta/getTickFrequency());
}
// processingImage.unlock();
}
#endif GRAPHS_ENABLED
delete pls;
#endif
return 0;

}

// float distSq(int x1,int y1,int x2,int y2)
// {
//     return (pow(x1-x2,2) + pow(y1-y2,2));
// }
// void latticeAxis(vector<dipoleSkel>& data,vector<float>&
// angles)

```

```

// {
//   int lastDistance=10000;
//   // Calculating the shortest distance squared, between the
//   first point and all other points
//   for(int i=1;i<data.size();i++)
//   {
//     int distance=pow((data[0].x-data[i].x),2) + pow((data[0].y
//     -data[i].y),2);
//     lastDistance=MIN(distance,lastDistance);
//   }

//   float tolLower=0.5;
//   float tolHigher=1.5;
//   for(int i=0;i<data.size();i++)
//   {
//     for(int j=0;j<data.size();j++)
//     {
//       if(i!=j)
//       {
//         float neiDist=distSq(data[i].x,data[i].y,data[j].x,
//         data[j].y)/(lastDistance)
//         if( neiDist > tolLower && neiDist<tolHigher ) //Yup,
//         found a neighbour!
//         {
//           float angleFound=atan2( (data[i].y - data[j].y) / (
//             data[i].x - data[j].x) );
//           angles.push_back(angleFound); //Added the angle
//           found to an array
//         }
//       }
//     }
//   }
// }

// inline void latticeAxisTest()
// {
//   // Calculate shortest distance squared between the first
//   point and all other pointss
//   // for each point, find all neighbours, store the angle
//   determined in an array
//   // TODO: In the previous step, add a method to avoid
//   incorrect counting

// }

// void latticeAxis(vector<dipoleSkel>& data)
// {
//   //Find neighbours
//   //Find the ones with only 3 neighbours
//   //Within these, find the ones with a particular slope missing

```

```

// double a=3.14; // The value you seek
// std::find_if(v.begin(),v.end(),[a](double b) { return a>b-
// epsilon && a<b+epsilon; });

// }
#ifndef TEMPERATURE_ENABLED
inline void fireElectro(long frame)
{
    //this is to avoid too many fires within a short time
    static long lastFrame=0;
    // static bool alternate=false;
    if(frame-lastFrame>3)
    {
        // alternate=!alternate;
        // if(alternate)
        // {
            char usbBuf[REPORT_LEN]={0,1,0,30};
            nWriteUSB((unsigned char*)usbBuf,14);
            lastFrame=frame;

        // }
    }
}
#endif

void temperatureTest()
{
#ifndef TEMPERATURE_ENABLED

    char usbBuf[REPORT_LEN];
    for(int q=0;q<REPORT_LEN;q++)
    {
        usbBuf[q]=0;
    }

    usbBuf[0]=0;
    usbBuf[1]=1;
    usbBuf[2]=0;
    usbBuf[3]=1000;

    cout<<"temperature Test"<<endl<<endl;
    cout<<"Initializing Hardware"<<endl;
    vInitUSB();
    cout<<endl;
    // cout<<"Initialization Successful"<<endl<<endl;

    cout<<"Writing to hardware:"<<usbBuf<<endl;
    int usbLen;
    if( (usbLen=nWriteUSB( (unsigned char *) usbBuf,14)) )

```

```

{
    cout<<"Writing Successful"<<endl<<endl;
}

cout<<"Reading from hardware"<<endl;
usbLen=nReadUSB( (unsigned char*) usbBuf);
if(usbLen==0)
    cout<<"Failed!"<<endl<<endl;
else
{
    usbBuf[usbLen]= '\o';
    cout<<"Data Read: "<<usbBuf<<endl;
    for(int i=0;i<usbLen;i++)
        printf("%d",usbBuf[i]);
    cout<<endl<<endl;
}
vCloseUSB();

#else
    cout<<"Temperature Support not enabled";
#endif
}

/***
 * @function main
 */
int main( int ac, char** argv )
{
    cout<<"Loading";
    cout<<endl<<endl
        <<"Lattice Analyser | version "<<version<<endl
        <<"_____"<<endl
        <<"Created at the National Physical Laboratory, New Delhi
            "<<endl
        <<endl
        <<"Project Repository Folder: github.com/toAtulArora/
            IISER_repo/Summers_2013/NPL"<<endl
        <<endl
        <<"For help type"<<endl
        <<"help"<<endl
        <<"(Like you couldn't guess!)"<<endl<<endl
        <<"\t now what?  ";

    for(;;)
    {
        string a;
        cin>>a;

        if(!a.compare("help"))
        {
            cout<<endl; //for multi line, beauty stuff
        }
    }
}

```

```

cout<<"Command \t Description" << endl
<<"_____ \t _____" << endl
<<"temp \t Launches hardware test" << endl
<<"temperature \t same as temp" << endl
<<"<number> \t Initiates analysis of dipoles using the
    corresponding camera" << endl
<<"q \t exit or quit" << endl;

cout<< endl; //again for multi line console outputs, to
            maintain beauty
}

else if(!a.compare("exit") || !a.compare("quit") || !a.
        compare("q"))
{
    break;
}
else if(atoi(a.c_str())!=0 || !a.compare("o"))
{
    cout<<"Commands for this mode:" << endl
    <<"c \t Enable mouse capture of colour" << endl
    <<"s \t Screen crop is selected, viz Drag with left click
        to select a sub window" << endl
    <<"p \t This frame will be selected as the seed frame" <<
        endl
    <<"w \t Write the angles and dipoles, of the first dipole
        to file" << endl
    <<'W \t Write computation times to file" << endl << endl;

threadsEnabled=true;

VideoCapture capture; //try to open string, this will
                    attempt to open it as a video file
// if (!capture.isOpened()) //if this fails, try to open as
                    a video camera, through the use of an integer param

capture.open(atoi(a.c_str()));
if (capture.isOpened())
{
    process(capture);

}
else
{
    cerr << "Failed to open the video device specified" <<
        endl;
    // return 1;
}
}
else if(!a.compare("temperature") || !a.compare("temp"))
{
    temperatureTest();
}

```

```

    }
    // else if(!a.compare("latticeAxis"))
    // {
    //   latticeAxisTest();
    // }
    cout<<endl<<"\t now what? ";
}

return 0;
}

```

2.2.5 temperature; the rise

'temperature' was built around the Atmega8 processor to start with. Its task was to energize the coils of the dipoles, when instructed by the Lattice Analyser. Its source code was written in C, compiled with the free AVR-GCC compiler using some other sister tools of it. Atmega's interface to the computer was built from Dr. Ravi Mehrotra's library, which was built to simplify the existing ob-dev's virtual USB libraries. The coils are powered directly using the chip for the 2×2 setup. For larger matrices, a multiplexer will be required and built suitably.

The current that was roughly enough to align the dipole to the coil was (after experiments with a 6 Volt battery and resistance of coil measurement, viz. 7 ohms) found to be about 1 ampere. The microcontroller can sync at most 20 mA of current at a given pin. Further for the USB interface, the system was set to run at 3.3 V (this can be pushed up to 5V also, but that would've required redesigning the circuit) and the current limiting resistor was correspondingly chosen to be about 150 ohms. This was put in series with the coil and tested. It was found that the dipole wouldn't, for even a second long pulse, align itself to the coil, starting from some initial angle. However, when further experiments were done for pumping in energy using the algorithms developed for the Lattice Analyser, this push was found to be enough, even with a few milliseconds long pulse. This version of temperature has been given in [Figure 12](#)

The main file for the temperature has been listed herewith.

tempereture.c

```

/*
filename: temperature
description: This is the firmware of the hardware that
            simulates temperature on the dipole lattice

baby steps(TM):

```

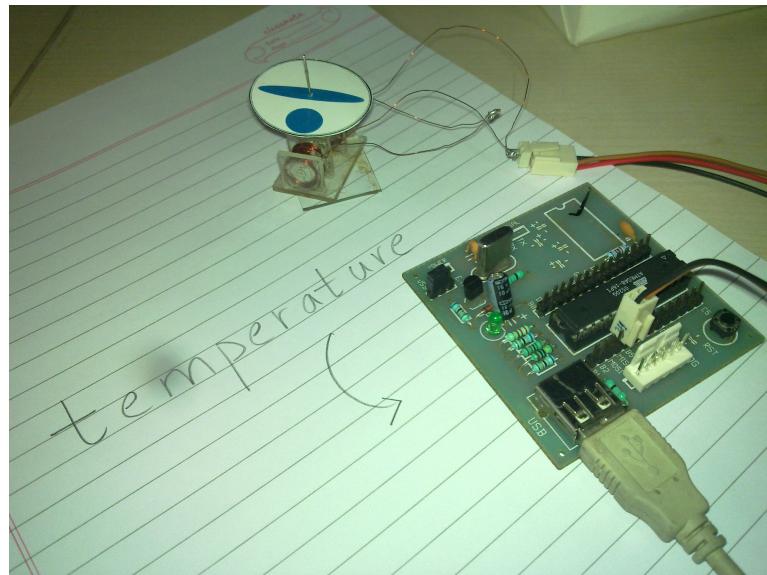


Figure 12: First Version of Temperature

1. Bare Minimum Tests: Communication Test with the lattice analyser [done]
2. Proof of Concept:
The target of this would be to keep a dipole continuously rotating
 - a. Test the kind of currents and voltages required to fire up the magnet
 - b. Make a program and fire up the magnet from the lattice analyser

```

communication protocol [clear text]
fixed length, 10 characters (8 bit each)

xxxxx xxxx
\---/ \---/
|     |
|     +----- Field Intensity
+-----Dipole ID
for
Binary Protocol for testing
fixed length, 10 characters, 8 bit each
0 1 2 3 4   5 6 7 8 9
x x x x x   x x x x x
| | | |     \ - - - /
| | | |           |
| | \ |           +-----Undefined for now
\ | -|-----+-----Dipole Intensity
          (65536 max)
-|-----+-----Dipole ID (65536 max)

*/

```

```

#include "usbIO.h"

// #define DEBUG_STAGE_ZERO

#ifndef DEBUG_STAGE_ZERO
    // U16Bit acknowledge[10] = "Ok";
    U16Bit* dipoleID;
    U16Bit* intensity;
    U8Bit   len;
    U8Bit*  data=0;
#endif

int main(void)
{
    #ifdef DEBUG_STAGE_ZERO
        U8Bit   i;
        U8Bit   ucInDataLen;
        U8Bit*  *pucInData = 0;

        usbInit();

        // ----- enforce re-enumeration.
        usbDeviceDisconnect(); // enforce re-enumeration
                               , do this while interrupts are disabled!
        i = 255;
        while(--i)
            // fake USB disconnect for > 250 ms
            _delay_ms(1);
        usbDeviceConnect();

        sei();
        for(;;)
        {
            usbPoll();
            ucInDataLen = ucGetUSBData( &pucInData );
            if ( ucInDataLen > INBUFFER_LEN )
                ucInDataLen = INBUFFER_LEN;
            if ( ucInDataLen )
            {
                // copy indata and send back
                ascii values incremented by 1
            }
        }
    #endif
}

```

//
also
,

make
the

```

first
value
,
the
length
of
data
recieved

    pucOutBuf[0] = ucInDataLen;
    for ( i = 0; i < ucInDataLen; i++)
    )
        pucOutBuf[i+1] =
            pucInData[i] + 1;
    vSendUSBDATA( ucInDataLen+1 );
}
}

return 0;
#else
// for(;;)
// {
//     DDRB |= (1<<5);
//     PORTB |= (1<<5);
//     _delay_ms(1000);
//     PORTB &= ~(1<<5);
//     _delay_ms(1000);

//     // DDRB=0xff;
//     // // DDRC=0xff;
//     // // PORTD=0xff;
//     // // PORTB=0xff;
//     // // _delay_ms(1000);
//     // // // DDRB=0x0;
//     // // // DDRC=0x0;
//     // // // PORTD=0x0;
//     // // // PORTB=0x0;
//     // // _delay_ms(1000);
// }

DDRB=0;
DDRB &= ~(1<<5);
//Make it high impedance again
PORTB |= (1<<5);
//

usbInit();
//Initialize USB

```

```
usbDeviceDisconnect();
    //Disconnect and re-connect
_delay_ms(255);
usbDeviceConnect();

sei();
    //Enable Interrupts
for(;;)
{
    usbPoll();
        //
        This has to be called frequently
        enough
    len=ucGetUSBData(&data);
        //Get data
    if(len>INBUFFER_LEN)
        len=INBUFFER_LEN;
        //
        truncate if overflow
    if(len)
        //Got
        data?
    {
        dipoleID=(U16Bit*)&data[0];
            //point the
            dipoleID to its location in
            the data

        intensity=(U16Bit*)&data[2];
            //point the intensity
            pointer to its location

        if(*dipoleID==256)
            //if
            the id is for the zeroth
            dipole (testing)
        {
            pucOutBuf[0]=(U8Bit) (*
                intensity);
```

```

        vSendUSBDATA(1);

                //Acknowledge
                receiving data

                //TODO: ADD PORT CODE
                //
                Fire up the magnet
                for a time
                proportional to the
                intensity

                DDRB |= (1<<5);

                //Define as
                output
PORTB &= ~(1<<5);

                //Make port D
                .4 low, to fire the
                magnet
for(U16Bit j=0;j<(*
intensity);j++)
    _delay_us(1);
DDRB &= ~(1<<5);

                //Make it
                high impedance again
PORTB |= (1<<5);

                //

// _delay_us((U8Bit) (*
// intensity/2) );
// _delay_us((U8Bit) (*
// intensity/2) );
//TODO: ADD CODE TO TURN
OFF
}

else
{
    pucOutBuf[0]=':';
    pucOutBuf[1]='(';
    vSendUSBDATA(2);

                //Acknowledge
                receiving data

}
}

return 0;

```

```
#endif  
}
```


COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede, for L^AT_EX.
The style was inspired by Robert Bringhurst's seminal book on typography "*The Elements of Typographic Style*".

The latest version of this document is available online at:

https://github.com/toAtulArora/IISER_repo