Fast characterisation and detection platform for ultra-thin monolayer semiconductors

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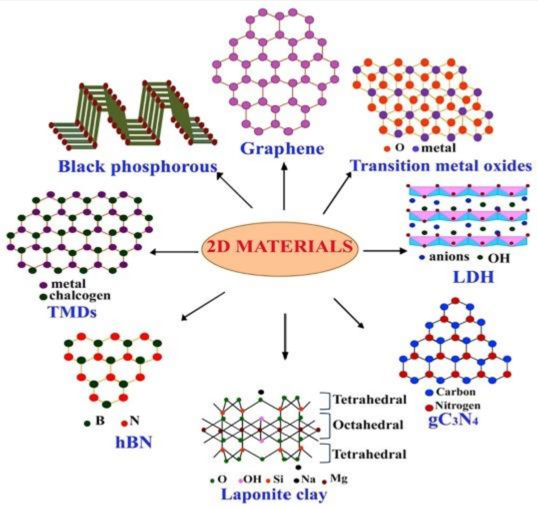
1. What is 2D material?
2. Software for automatic detection
3. User-friendly
4. Benefits of automation

CSIRO

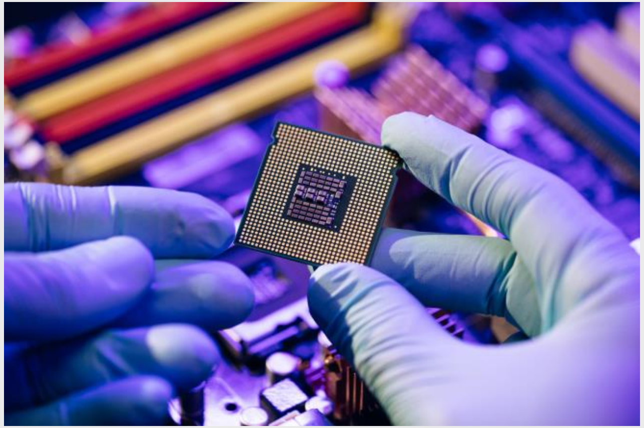
MACQUARIE University

Motivation

- 3D Semiconductors are a well researched technology
- Narrow this down to 2D devices - monolayers
- Efficiency!



https://www.sciencedirect.com/science/article/abs/pii/S0378517318307002

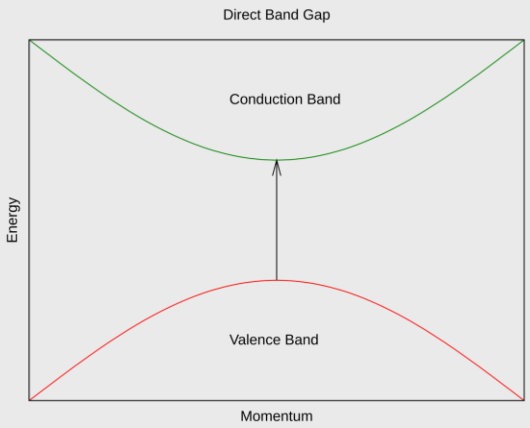


mpohodzhay / shutterstock.com

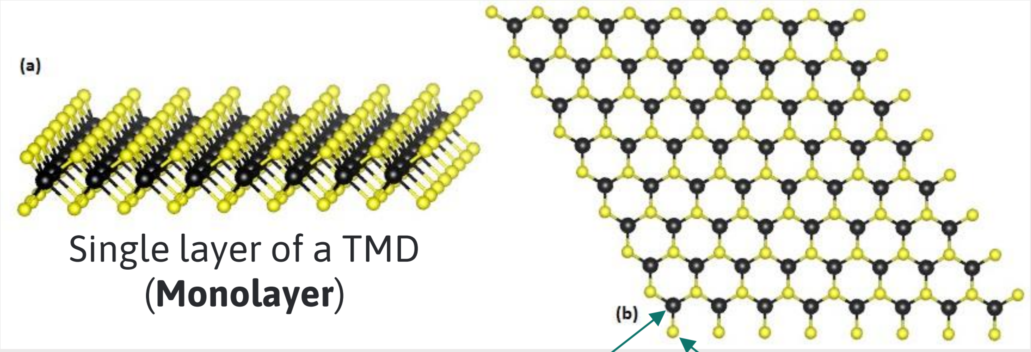
https://www.linkedin.com/pulse/how-focus-business-efficiency-productivity-year-robert-ford/

Background

- Transition-metal Dichalcogenide (TMD) Semiconductors
- Many TMD monolayers have direct (optically excitable) band gap



- Good candidates for transistors, and optical devices



Transition Metal
(e.g. Mo, W)

Chalcogen
(e.g. S, Se, Te)

Thin layers are obtained by:
Mechanical Exfoliation (ME)

https://www.sciencedirect.com/science/article/pii/S0022509618300280

Methods – Overall Picture

Fluorescence Microscopy to detect only the monolayers, as since they have a direct band gap, thus can be excited optically.

Motorised stage and scientific camera to move and image the sample.

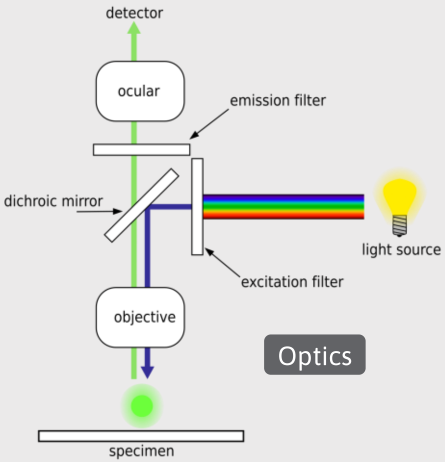
Post-processing with OpenCV to detect regions of fluorescence.

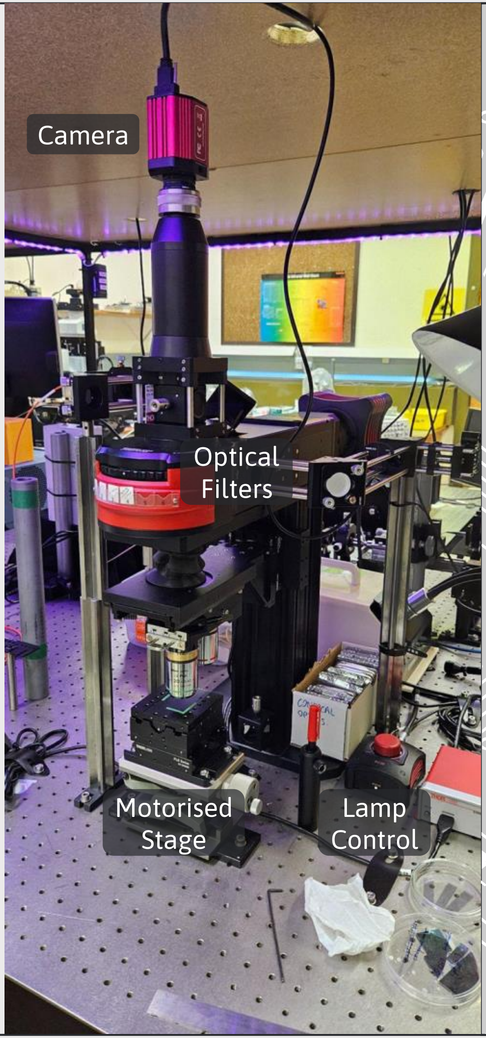
Analysing images to determine location, area, quality.

Displaying these results in an accessible format.

The monolayers of interest could then be marked for further study.

python™

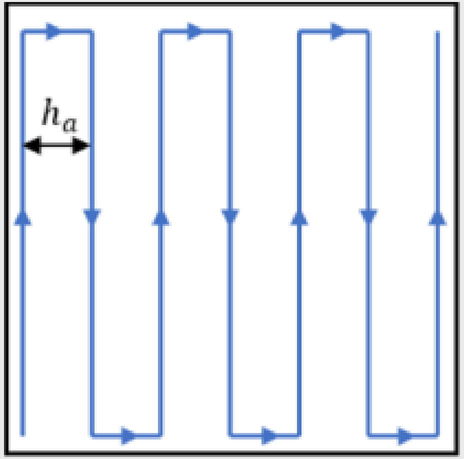




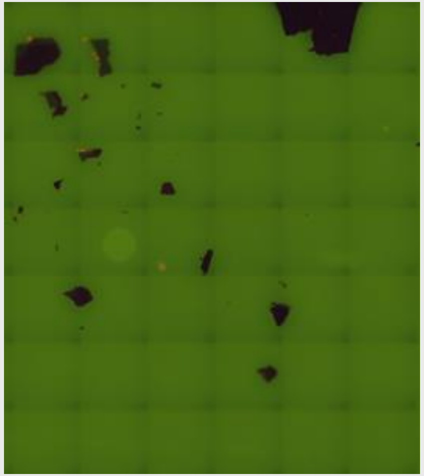
Methods – Overall Scan and Detection Logic

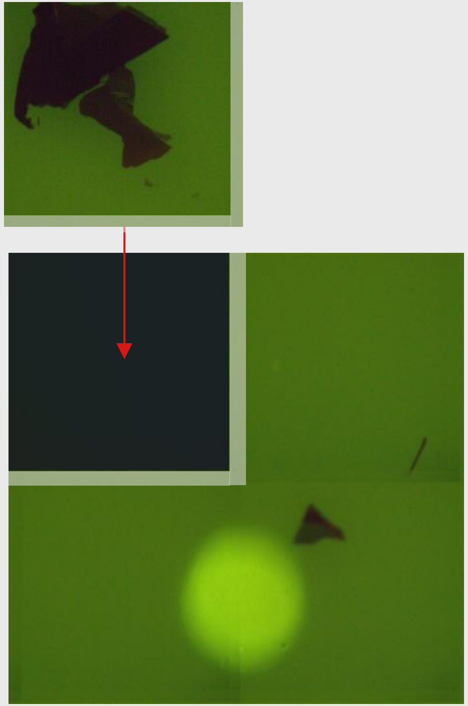
Serpentine search over the whole sample:

1. Move the microscope stage a precalculated distance, just enough to have some overlap in the image
2. Take an image, and place it onto a larger canvas, based on where the image was taken and blending the edges



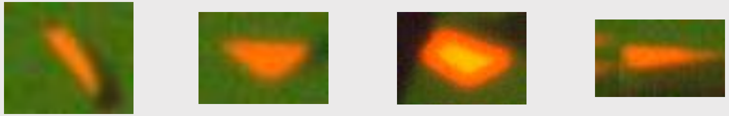
https://www.researchgate.net/figure/Examples-of-different-scan-strategies-a-and-b-are-the-vertical-serpentine-pattern_fig1_339275138

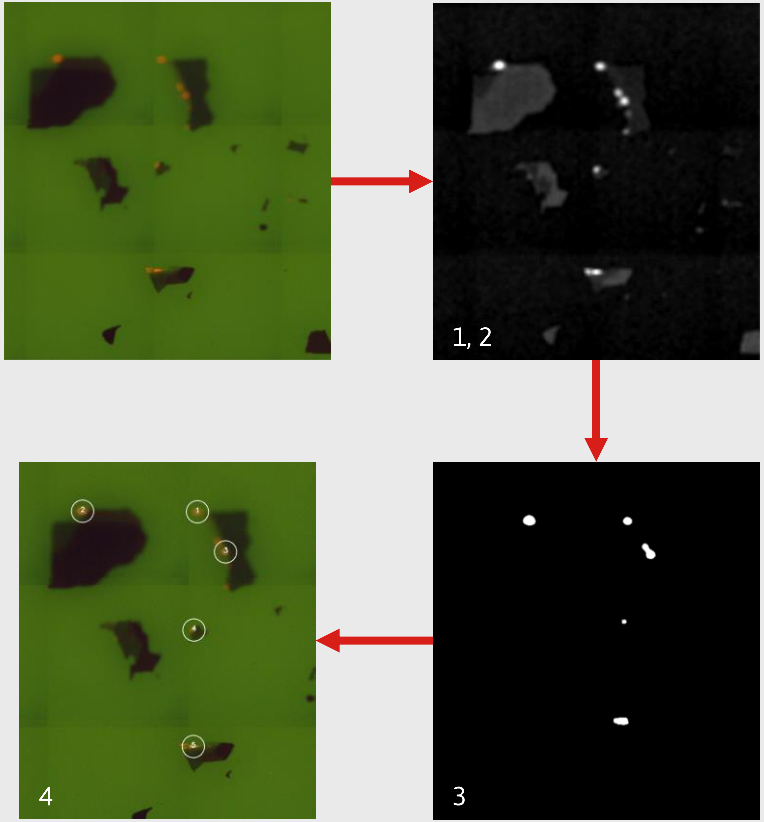




Methods – Overall Scan and Detection Logic

1. Downscale & blur to reduce noise and speed up processing
2. Convert to grayscale, with a bias towards the fluorescence colour.
3. Apply a threshold to remove all low intensity pixels
4. OpenCV - *Find Contours* - to outline the bright areas (hopefully monolayers)
5. Use the contour data to approximate area, location and to save individual Monolayer images for analysis





Methods – Issues we had to overcome

- Camera Resolution
    - Memory Usage
    - CPU usage
- Camera rotation & view rotation
- Exposure
- GUI responsiveness
- Processing speed
- Thorlabs Driver
- Threading issues
- Closing the hardware connections safely
- Focus (particularly in large scans)

Methods – Autofocus Problem

Measuring Focus

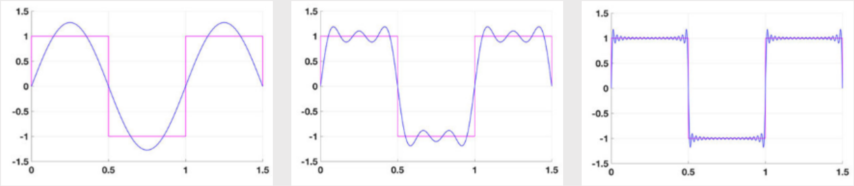
To optimise the focus, first we need to quantify it.

In our case, our parameter needs to be:

- Robust against noise
- Fast enough to calculate
- Exposure independent

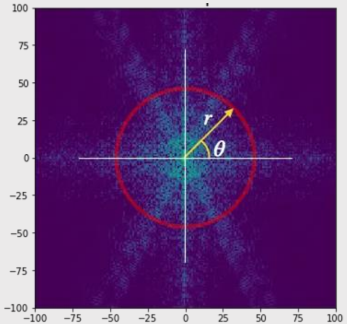
Our final method utilised the Power Spectral Density of the image.

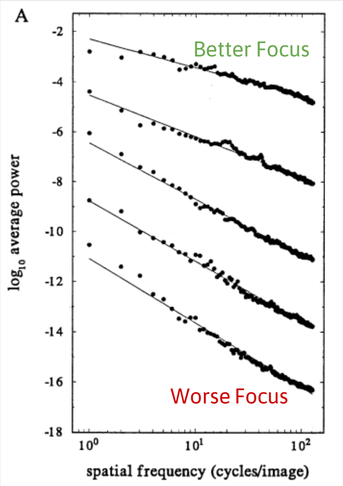
Well-defined edges need more high frequency components in the image.



The more high frequency components, the better the edge definition

Image
↓
2D Fourier Transform
(spacial freq. & amplitude)
↓
Radial Averaging
(counteracts noise and makes 1D)
↓
Power Spectral Density
(power vs spacial freq.)
↓
Linear fit (log–log plot)
↓
Gradient
(shallower gradient → more high freq. → better focus)

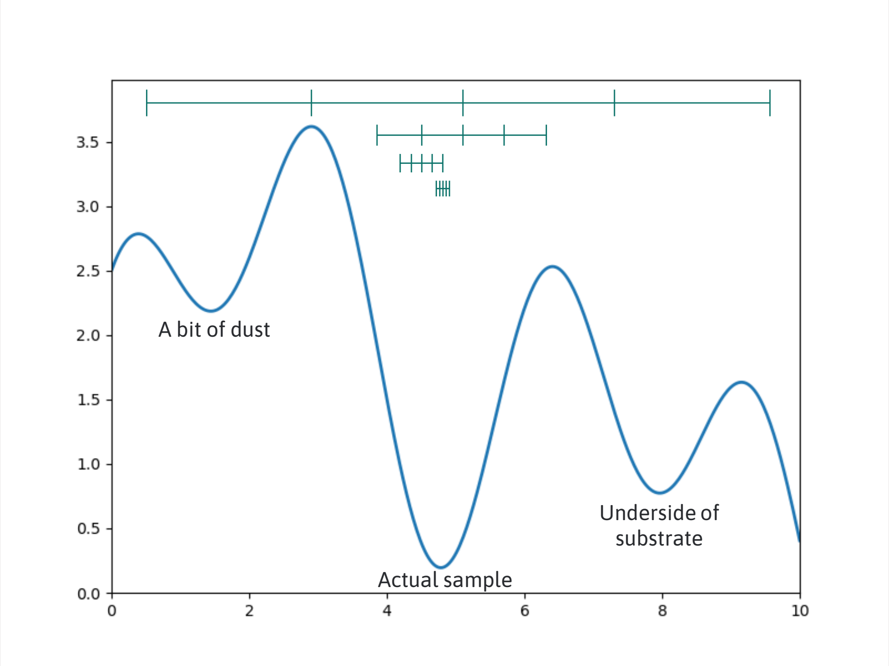


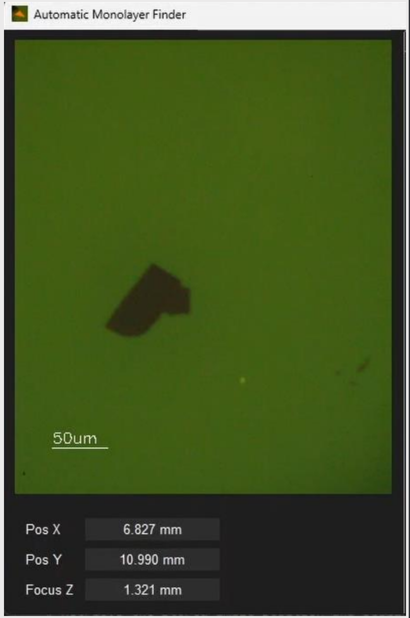


Methods – Autofocus Problem

Finding the focus

Now that the focus can be quantified, finding the optimal focus should be relatively easy................

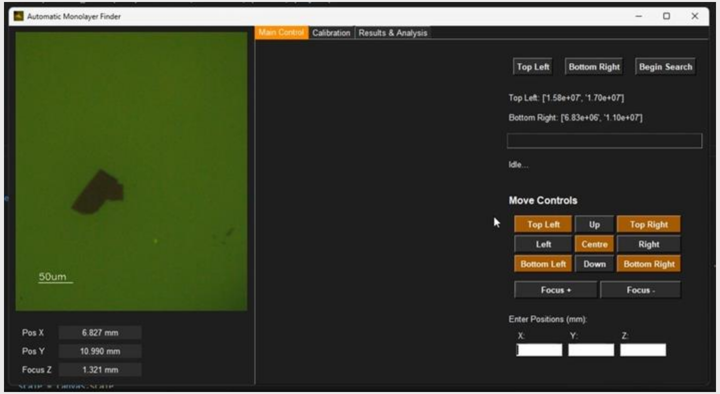




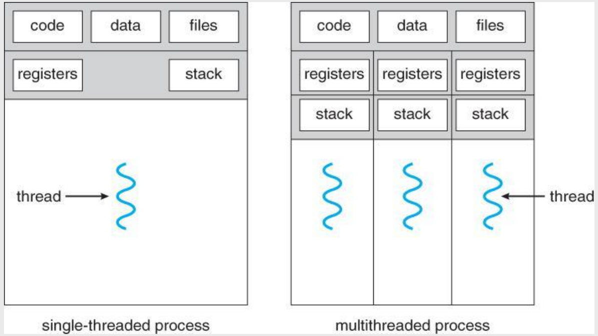
Methods – Designing good software

Bad GUI

Good GUI



Threading

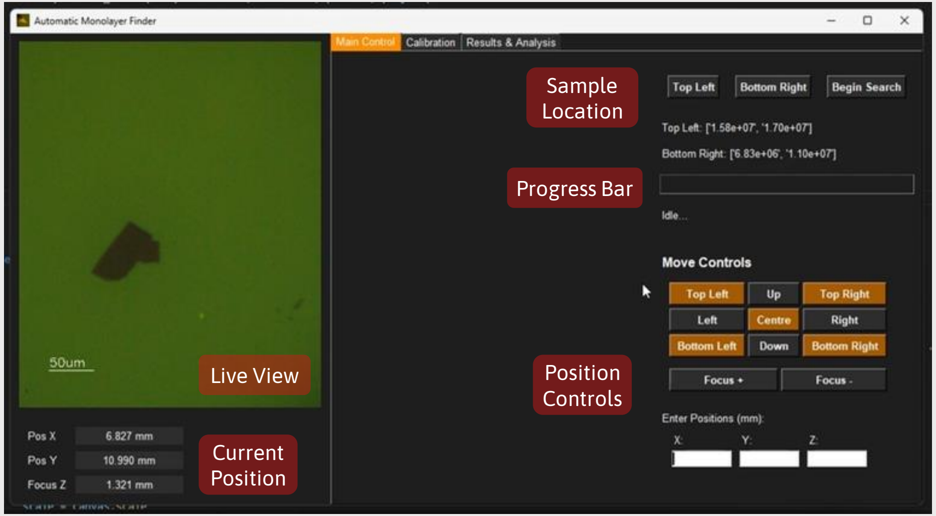


https://www.cs.uic.edu/~jbell/CourseNotes/OperatingSystems/4_Threads.html

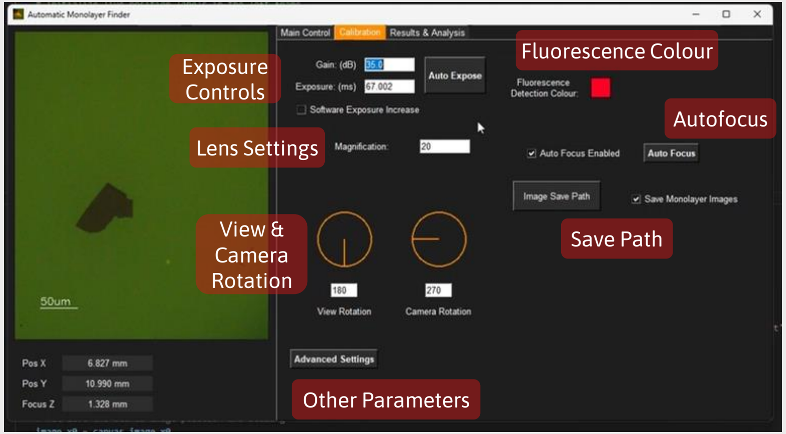
- Easy to use GUI
- Effective Threading

Methods – Designing the GUI

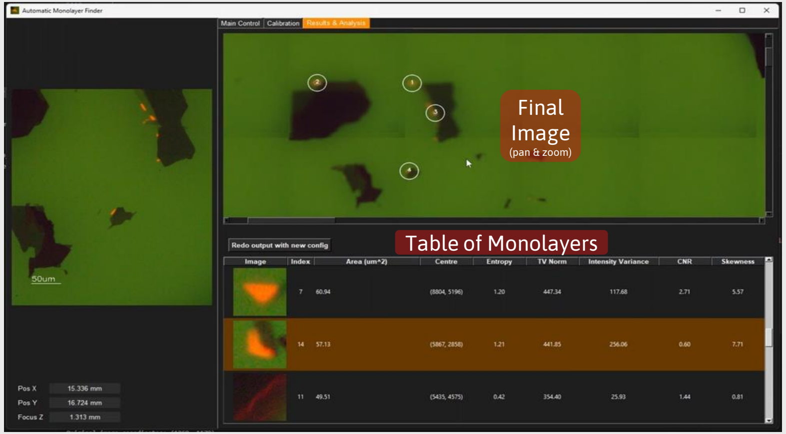
Main Control Tab



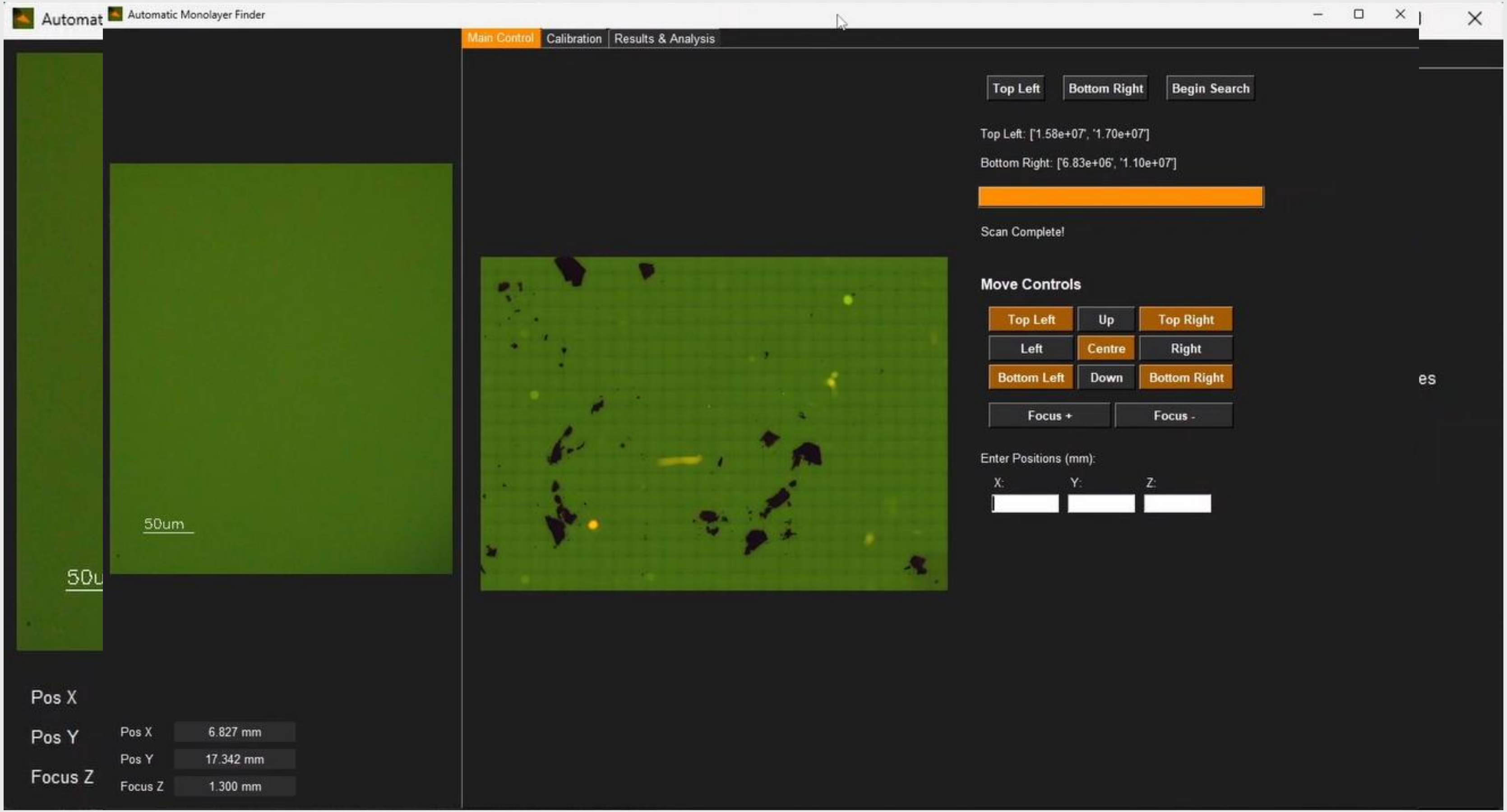
Calibration Tab



Results Tab

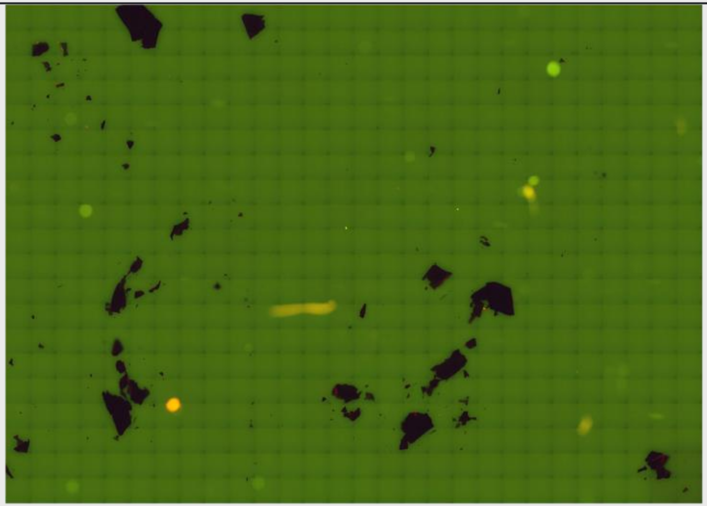


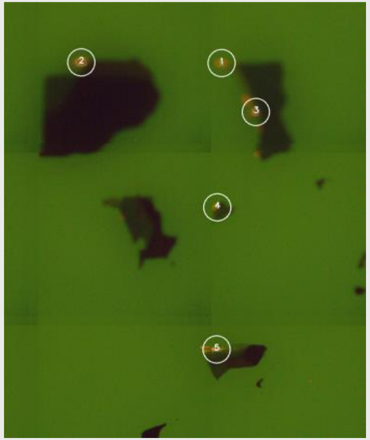
Results Video



Results Images

Examples of stitched images and monolayers





Results

- Produced a reliable software
- Incorporated useful features
  - Auto Focusing
  - Auto Exposure
  - Progress bar
- Increased throughput
- Software produces a stitched image of the scan area
- Excellent detection (with some false positives ~5-20% depending on the contamination)
- Cat button

Approximately 10x

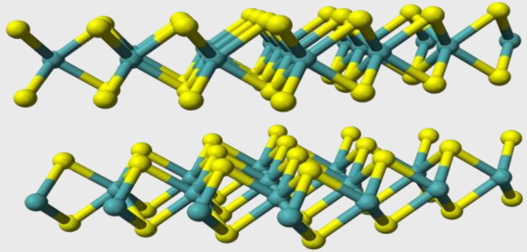
Condensing a day of manual work into about 30-60 mins

Easily removed when inspecting the final result

Conclusions

Takeaways:

- 2D materials are a single or few atoms thick
- Monolayer TMDs are a new and promising area of 2D material science
- Our software makes monolayer detection after mechanical exfoliation much easier



WS_2, an example of a monolayer TMD.
https://en.wikipedia.org/wiki/Tungsten_disulfide