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# Vibrating Wire Control System

FERMILAB SummerSchool Project

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*Author:*

Federico NESTI

*Supervisor:*

Thomas STRAUSS

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### **Abstract**

Aim of this report is to show and explain the automation process for the Vibrating Wire System, a custom FERMILAB setup for Zero Field Line Detection in Quadrupole Magnets.

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# 1 Introduction

The Project described in this report has been developed during the two-months work of the FERMILAB Summer School, in the Magnet Department of the Technical Division.

## 1.1 The Vibrating Wire System

The **Vibrating Wire System** is a FERMILAB custom setup designed in order to detect as precisely as possible the **Zero Field Line of Quadrupole Magnets**.

### 1.1.1 Quadrupole Magnets

Quadrupole Magnets are one of the most common magnets at FERMILAB. They are used for particle beam focusing.

The peculiarity of these magnets is that in the center, theoretically, there is no magnetic field. This is what the setup described in this report measures.

### 1.1.2 Working Principle

The idea behind the setup is simple. Consider a wire in which a **AC current at resonance** is flowing; when we place this wire in a magnetic field, it starts **vibrating** at resonance frequency. This principle can be used in order to understand where the magnetic field of the quadrupole is zero, that is theoretically equal to **find zero oscillation on the wire**.

This is just the ideal situation, because of a set of non-idealities:

- The presence of Earth magnetic field
- The presence of a set of disturbances in the experiment area

These factors force us to look for a **minimum in wire oscillation**. Figure 1 describes the idea graphically.

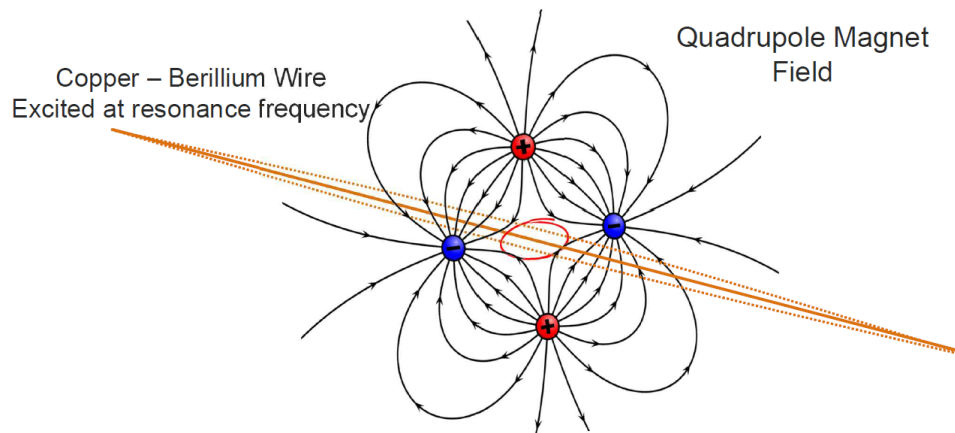


Figure 1: Vibrating Wire Working Principle

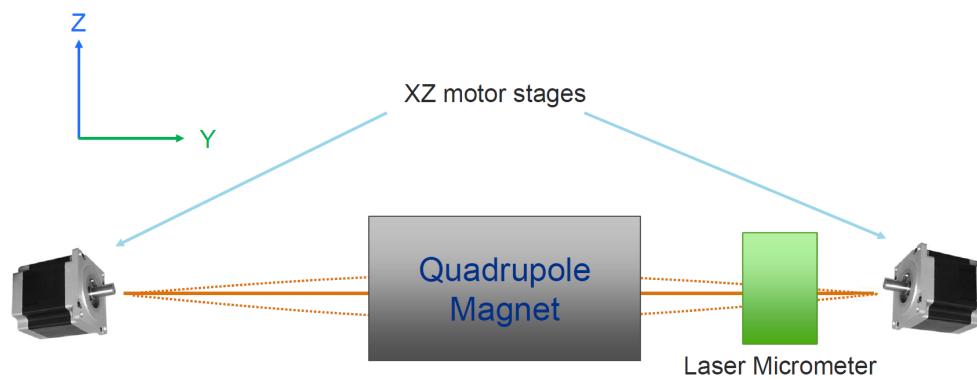


Figure 2: Vibrating Wire Setup

### 1.1.3 The Setup

The setup is simple: the wire is stretched between **two motor stages**; each stage allows an independent XZ movement. There is one last **motor for the torque** on the wire.

The wire passes through the quadrupole and a **micrometer** (composed by two Keyence LS-9006R), which is able to measure with high resolution and accuracy the vibration of the wire in the two directions.

In Figure 2 the setup is shown.



Figure 3: Vibrating Wire Setup Photo

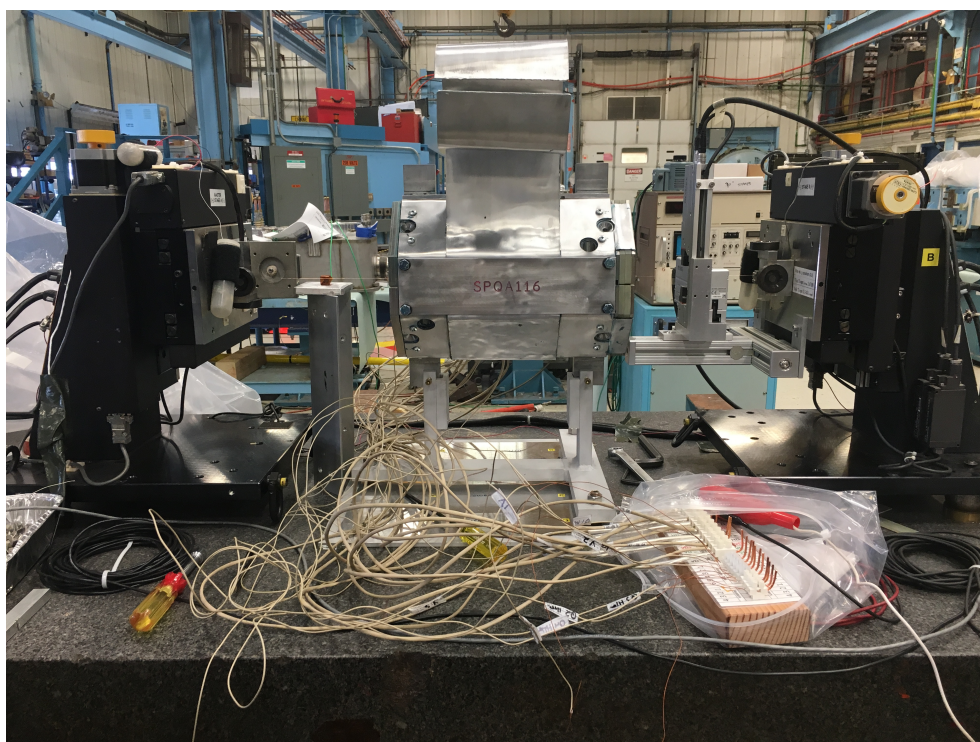


Figure 4: Vibrating Wire Setup Photo



## 1.2 Objectives

The search for minimum oscillation is now done **by hand**.

The **Goal of the project is to automate this search** from scratch.

## 2 Understanding the Problem

In order to design a suitable controller for this non-standard application, the first step is to **understand how the search is currently done**.

### 2.1 Data Processing

The **data available** for the search are the following (they are always available for both directions):

- **Raw micrometer output** (Raw Oscillation)
- **FFT data** and graph of the Oscillation
- Value of the **FFT peak** in each iteration

### 2.2 The Steps

The steps the operator must go through are the following:

1. Set the **Resonance Frequency**
2. Find the **Minimum Oscillation**
  - 2.1. Find Minimum **Mean** (at Resonance Frequency)
  - 2.2. Find Minimum **Amplitude** (at **Resonance Frequency**)
  - 2.3. Find Minimum **Amplitude** (at **Double** of Resonance Frequency)

#### 2.2.1 Set the Resonance Frequency

During the Minimum Search, the wire must be excited with an AC current at Resonance Frequency and at double of Resonance Frequency, which means that in presence of a magnetic field a **standing wave with one or two**

**arcs** forms on the wire.

Assuming that the wire behaves ideally (which is a good hypothesis), the resonance frequency  $F_r$  is settable as

$$f_r = \frac{1}{2L} \sqrt{\frac{T}{w}} \quad (1)$$

where  $L$  is the **length** of the wire,  $w$  is the **linear density** (known parameters), and  $T$  is the **torque** on the wire.

Given a certain Frequency, chosen in order to avoid particular frequencies where the disturbances are prevalent (multiple of 60 Hz, for example), the only parameter to be changes is the torque on the wire.

Once the torque (currently set by hand, by looking at the Peak Amplitude of the Oscillation FFT, when a small fridge magnet is placed close to the wire) is set in order to have the frequency in an acceptable range, the search can start.

**Important Note:** The **torque motor** experienced some problems and **cannot be used**. No control has been developed for this task.

### 2.2.2 Minimum Oscillation Search

The Minimum Oscillation Search is a complex, time-consuming task.

Once the Resonance Frequency is set, the little magnet is removed, while the **Quadrupole Magnet is turned on**, at very low current, and with a given **polarity switch frequency** (about 100mHz).

In Figure 5 an example of the **FFT peaks sequence** in time is shown. This kind of pattern resembles a **square wave** (due to polarity switch of the Quadrupole), with two parameters we mostly care about: the **Mean** and the **Amplitude**.

**Find Minimum Mean (at Resonance Frequency)** It is possible to **minimize the Mean** by moving the motors in order to **keep the wire always parallel to itself**. The strategy is to **give the motors a step in one direction**, understand from the new value of the mean if it was the right

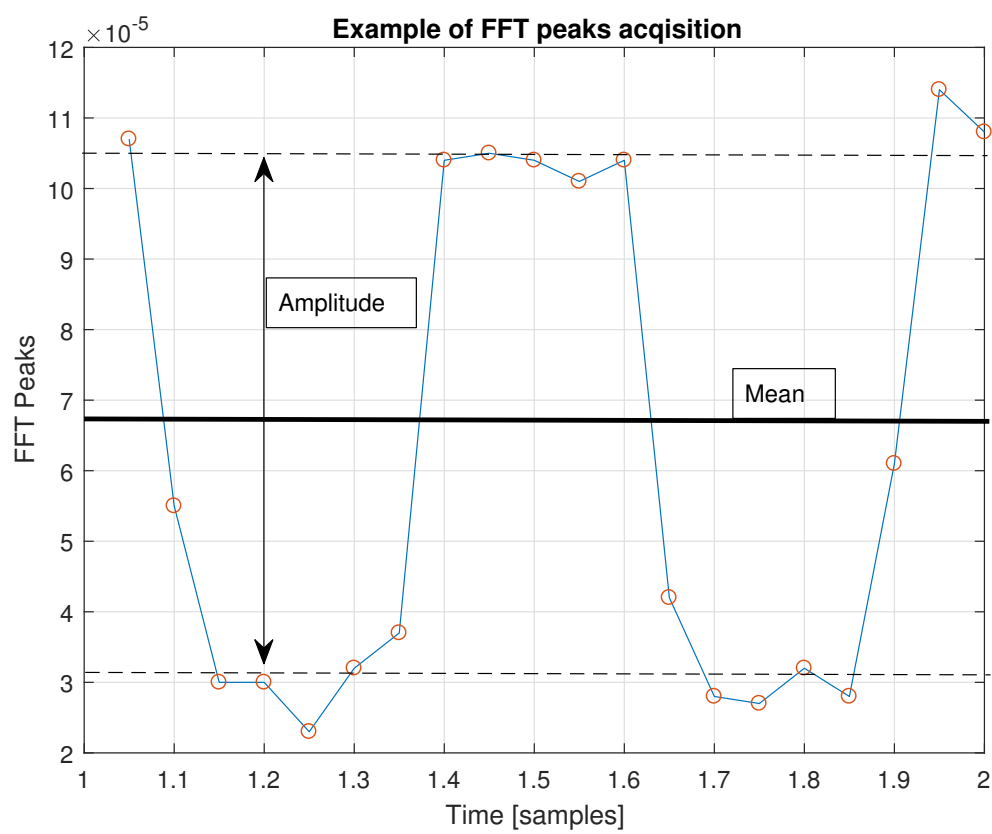


Figure 5: FFT Peaks Time Sequence Example

choice, and **correct or move on**. When the minimum seems to be reached, the steps must be reduced, until the minimum is found with a resolution of 5 to 10  $\mu\text{m}$ .

**Find Minimum Amplitude (at Resonance Frequency)** The same procedure is to be done for the Amplitude of the square wave **once the Minimum Mean is reached**; the steps resolution is smaller than in the Minimum Mean search.

**Find Minimum Amplitude (at Double of Resonance Frequency)** The minimization procedure could be stopped at the previous step. But in case there is a **misalignment between the Magnet and the wire**, this could introduce some **coupling** between the X and Z axes. In order to minimize the angular displacement between the wire and the magnet, it is convenient to **double the excitation frequency of the wire**. This makes the wire **sensitive to the magnet-wire angular displacement**. The minimization of the amplitude in this case helps with the decoupling between the two axes. After this step is completed, another run of Amplitude Minimization at Resonance Frequency is needed.

The strategy for this search is the **same as in the previous step**, with the difference that the motors steps must be set in **opposite directions** and not in the same direction, in order to incline the wire.

## 2.3 Raster Scan

In order to better understand what kind of controller is the most suitable for the process, the first thing was to **sample the XY<sup>1</sup> plane**, with some raster scans (with different resolutions), in the neighborhood of the Zero Field Line.

### 2.3.1 Mean

The Mean of the Square Wave formed by the time series of the FFT peaks has to be minimized in the first place. In Figures 6 and 7 a raster scan of an area 10mm  $\times$  10mm with a resolution of 0.125mm is shown, for both X and

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<sup>1</sup>Z axis is from now on renamed Y, and everything is considered on that plane.

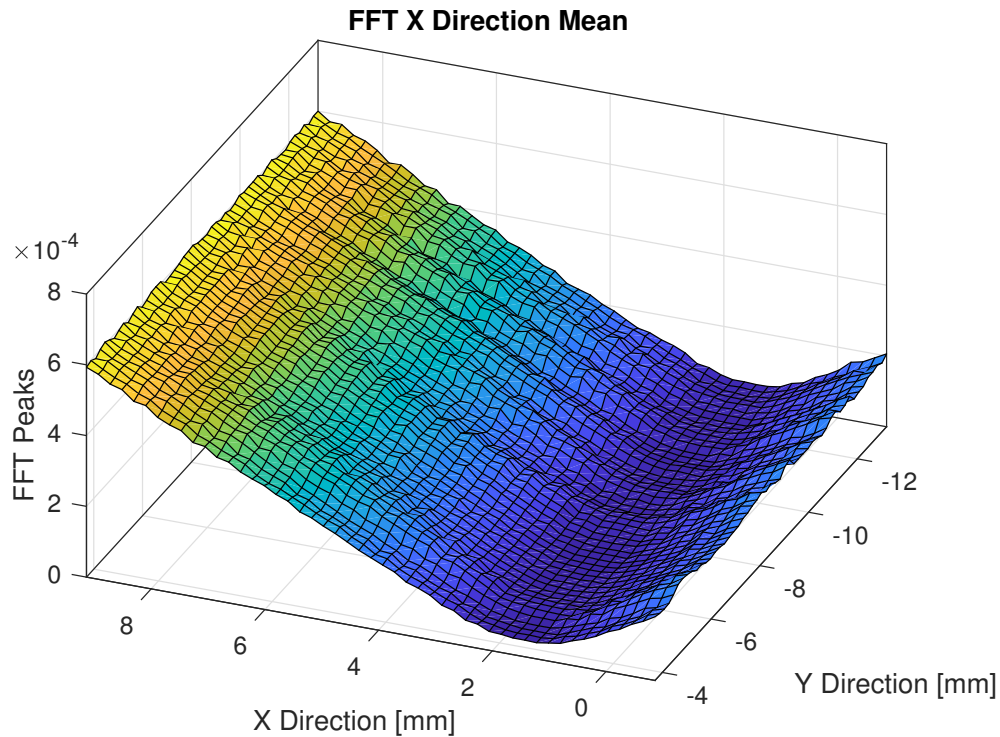


Figure 6: FFT Peaks Mean in space - X Direction

Y axes oscillation.

It is clear that there is a **"valley"**, a line with constant x or y coordinate (depending on the oscillation direction we are looking at) where the mean is minimum. If the wire is aligned with the magnet, the two **oscillation patterns are decoupled**, which means that a movement on an axis doesn't imply a change in oscillation on the other.

In Figure 8 the **Total Mean** is shown. Total Mean is the 2-norm of the vector considered with x and y coordinate the Mean on each axis. It is possible to see that there is a zone where the Mean is minimum.

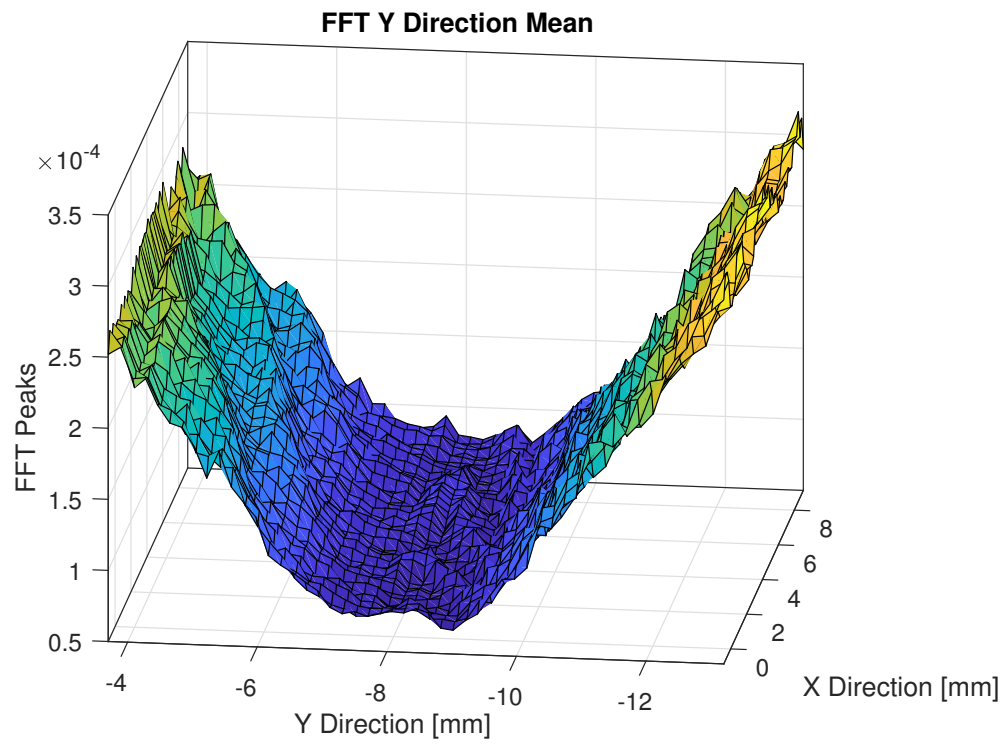


Figure 7: FFT Peaks Mean in space - Y Direction

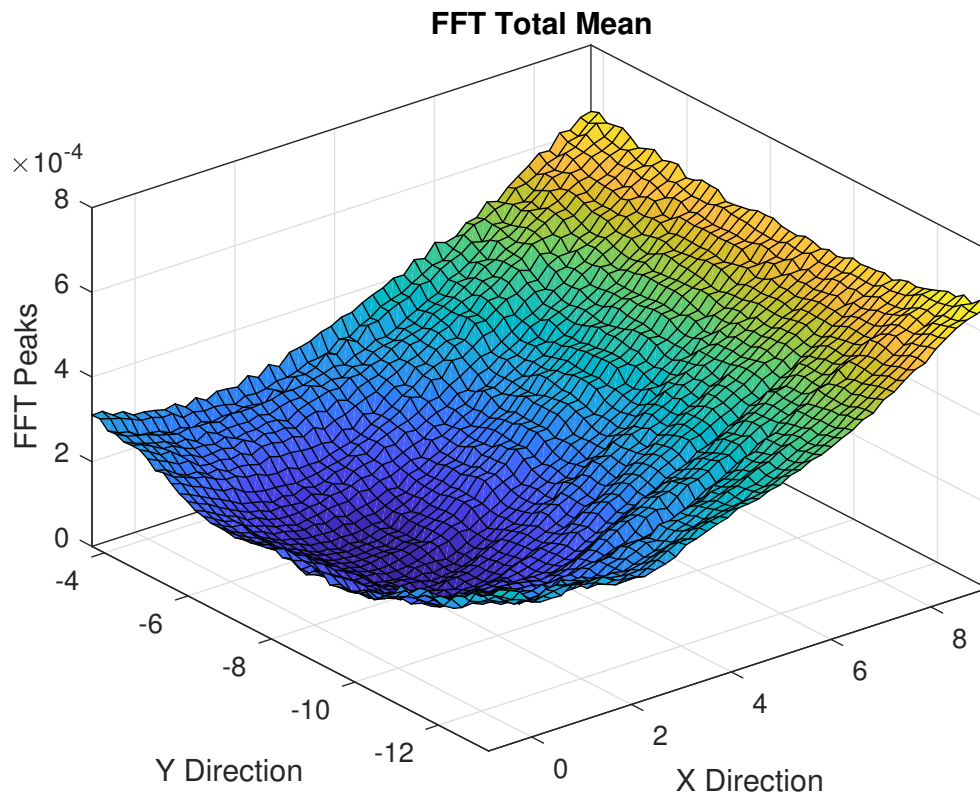


Figure 8: FFT Peaks Mean in space - Total

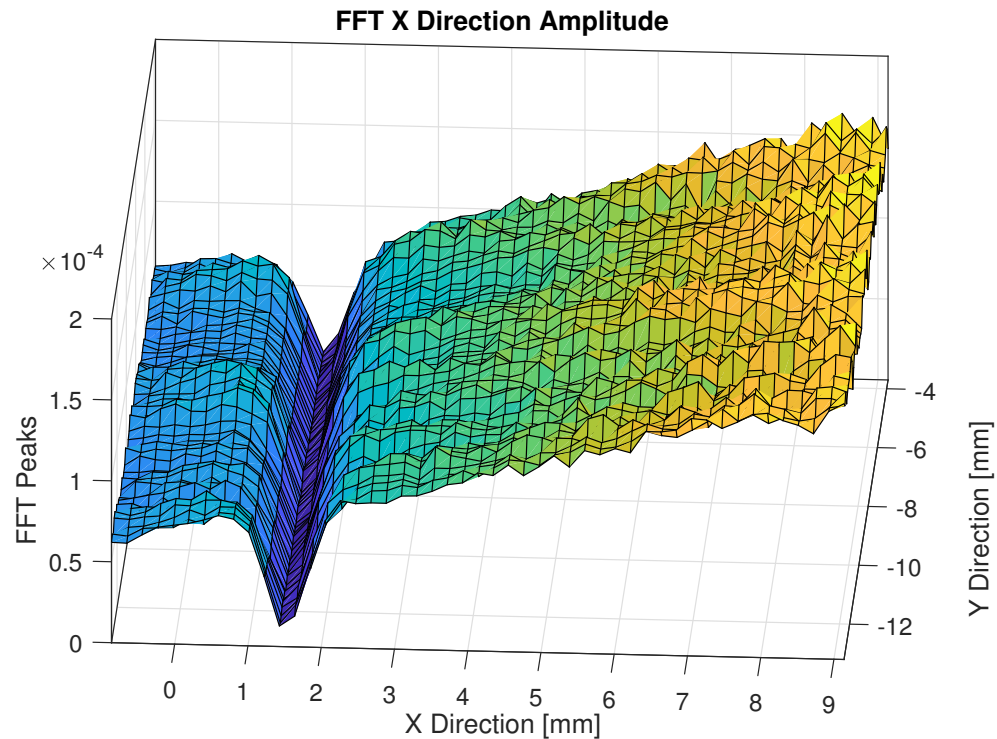


Figure 9: FFT Peaks Amplitude in space - X Direction

### 2.3.2 Amplitude

The Amplitude has a **similar behavior** as the Mean. The difference is that the measure is **much more noisy** and has not a particular pattern **too far** from the Zero Field Line. But in a close neighborhood of the Zero Field Line the **fashion is once again linear** and abruptly goes to the minimum, as shown in Figures 9 and 10.

In Figure 11 the **Total Amplitude** is shown.

### 2.3.3 Amplitude at Double of Resonance Frequency

There could be a **XY axes signal coupling**. This is due Magnet - wire misalignment. In Figures 12 and 13 the raster scan results for the amplitude at double of Resonance Frequency are shown<sup>2</sup>.

<sup>2</sup>In this case the motors steps are set in opposite directions, inclining the wire



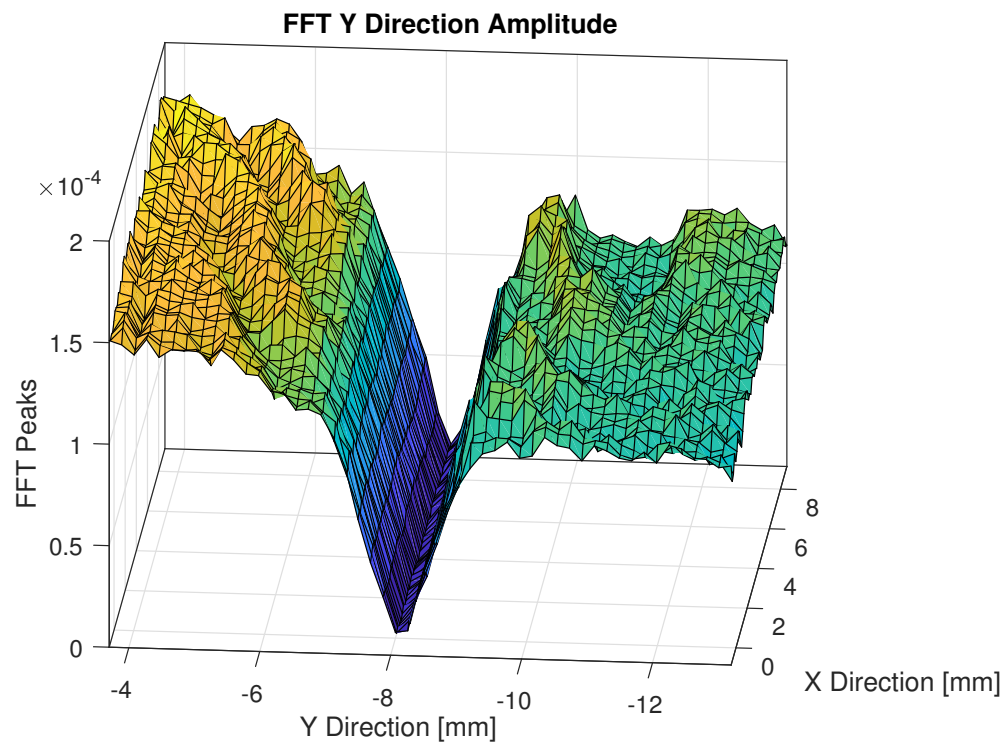


Figure 10: FFT Peaks Amplitude in space - Y Direction

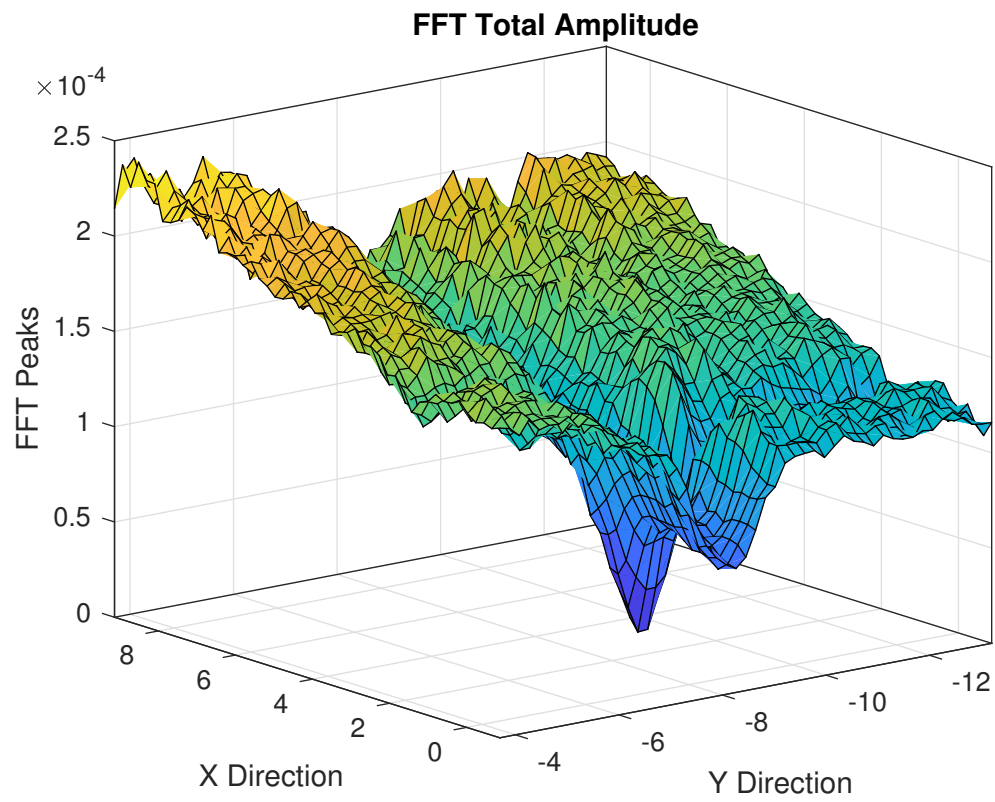


Figure 11: FFT Peaks Amplitude in space - Total

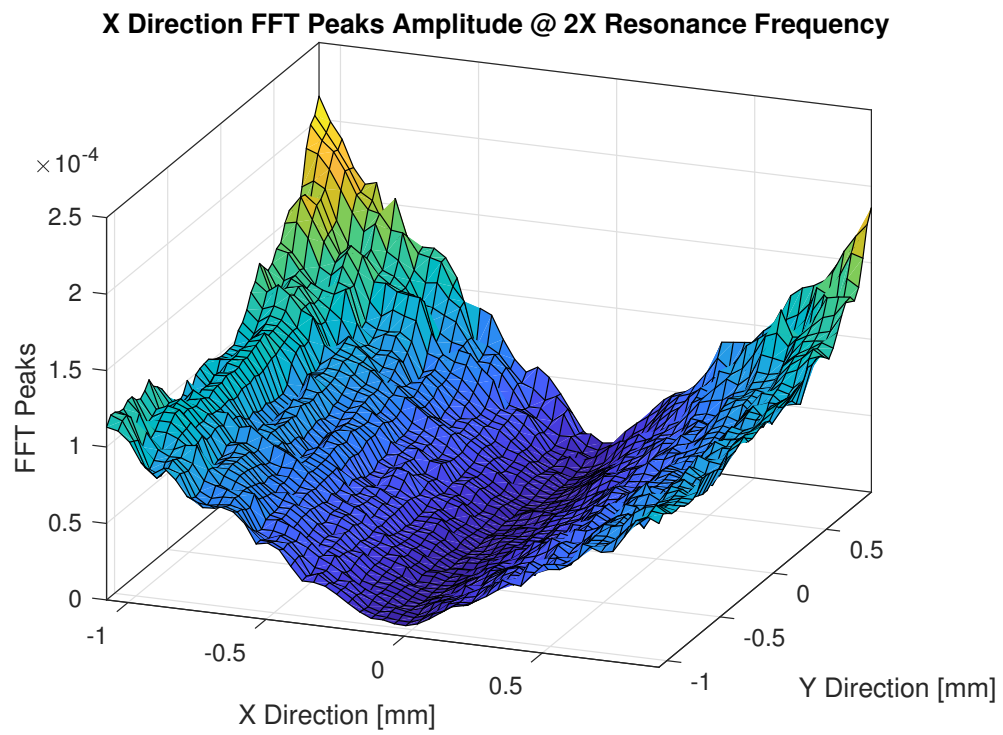


Figure 12: FFT Peaks Amplitude in space - X Direction

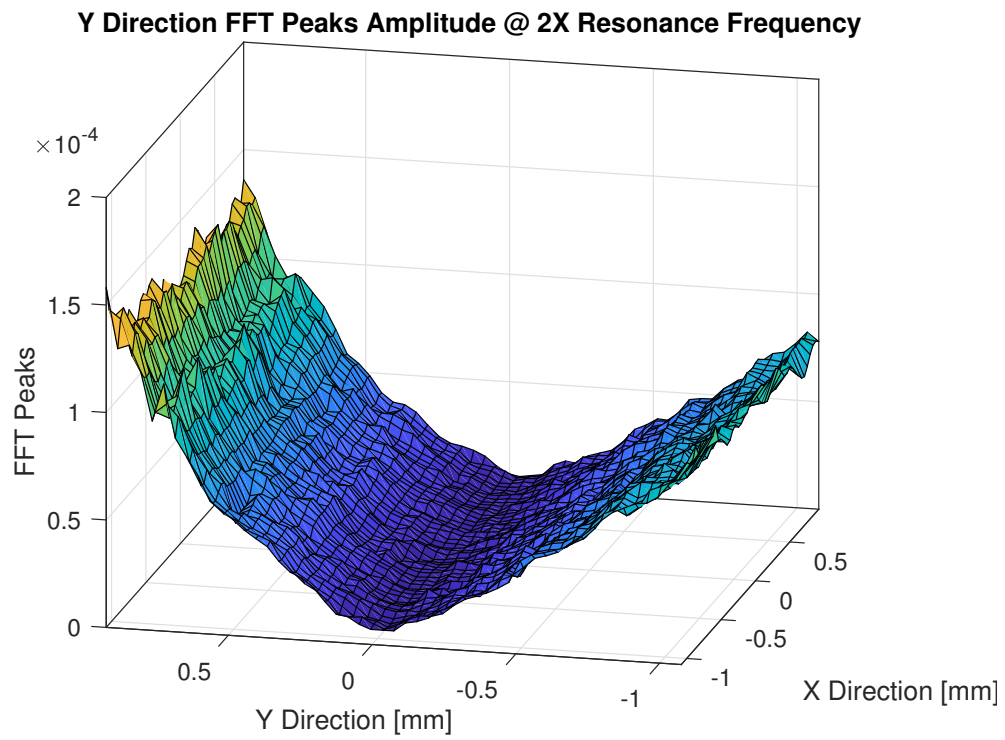


Figure 13: FFT Peaks Amplitude in space - Y Direction

### 3 Control Design

Taking a look at the raster scans, it becomes clear that the **control strategy can follow exactly the strategy of the human operator**, since in reasonable ranges the functions are convex<sup>3</sup>. No control has been developed for the Resonance Frequency Setting because of a problem on the torque motor.

The raster scans highlight the linear fashion with which the Mean and the Amplitude go to the minimum. This feature makes the controller used for the Mean Minimum Search suitable for the Amplitude Minimum Search too.

The Minimum Search is a complex task, with the following properties:

- The Process is **Non-Linear**
- The Process is **not known**
- The Process is **time-varying**
- The **Magnet must be changed** every week for survey
- The FFT peaks change with the **current flowing** in the magnet and with the **resonance frequency**

These factors lead to a control design that **must be robust**.

Standard Controllers are not suitable for this kind of application; the two ways of approaching this problem were:

- A **Fuzzy** Controller
- A **Convex Optimization Algorithm**

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<sup>3</sup>The Functions are not convex, and if analysed with smaller steps resolution they highlight a great number of local minima; this doesn't affect the convex property at larger steps resolution.

### 3.1 Fuzzy Controller

Fuzzy Controller is the perfect choice when the process is **not known, non-linear** and too complex to be controlled with a standard controller. Fuzzy Controller allows the user to control the system with rules of thumb, using **linguistic logic variables**.

The Fuzzy Controller, if well dimensioned, behaves like a human operator. This kind of controller needs:

- Definition of **Inputs and Outputs**
- Definition of **Membership Functions**
- Definition of **Rules**

#### 3.1.1 Controller Inputs and Outputs

Considered that the Control Strategy is

1. Give a random step
2. Check if Mean is Growing
3. Continue in that direction or Correct

the Inputs should be

- **Previous Mean**
- **Current Mean**
- **Previous Motor Step**

While the output is the **Motor Step**.

#### 3.1.2 Membership Functions Definition

The Membership Functions must be carefully defined, because the fuzzification and defuzzification process depends on it. Plus, they must be used for different magnets.

In Figure 14 the Membership Functions definitions are shown.

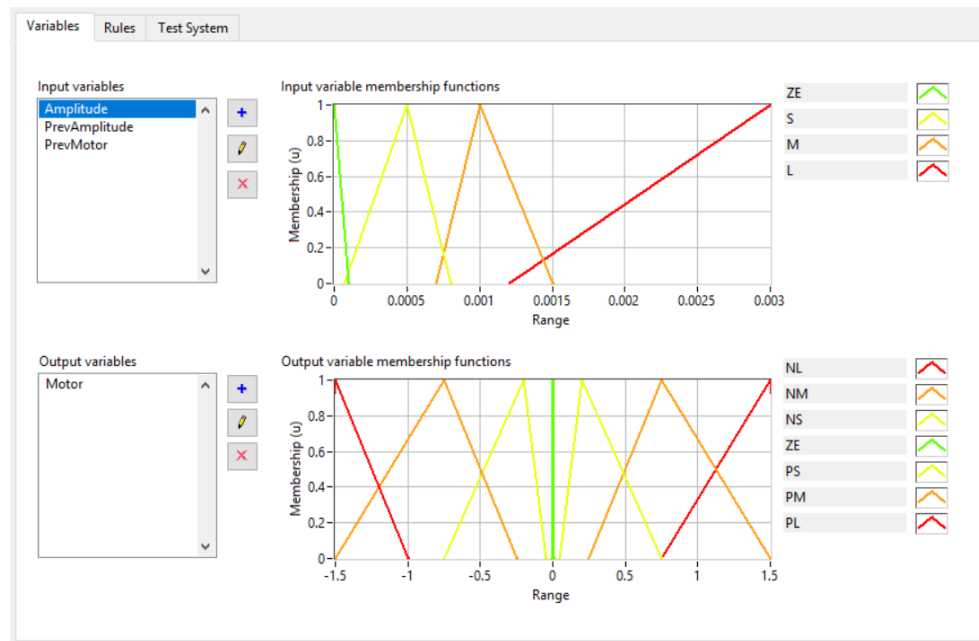


Figure 14: Membership Functions for Fuzzy Variables

### 3.1.3 Rules Definition

The Rules are the logic inference on which depends the convergence or non-convergence of the Controller. The Rules have been divided in two different subsets:

1. **Convergence Rules:** they make the motors move towards the smaller amplitudes
2. **Non Divergence Rules:** they make the motors move in the opposite direction of larger amplitudes.

### 3.1.4 Simulations

The Fuzzy Controller **has been tested** on the first raw data coming from the **raster scan**. The results are in Figures 15, 17 and 16.

As we can see, the convergence of the Controller is not perfect, it has an error of about  $100 \mu\text{m}$ , that is acceptable for the first step of minimization

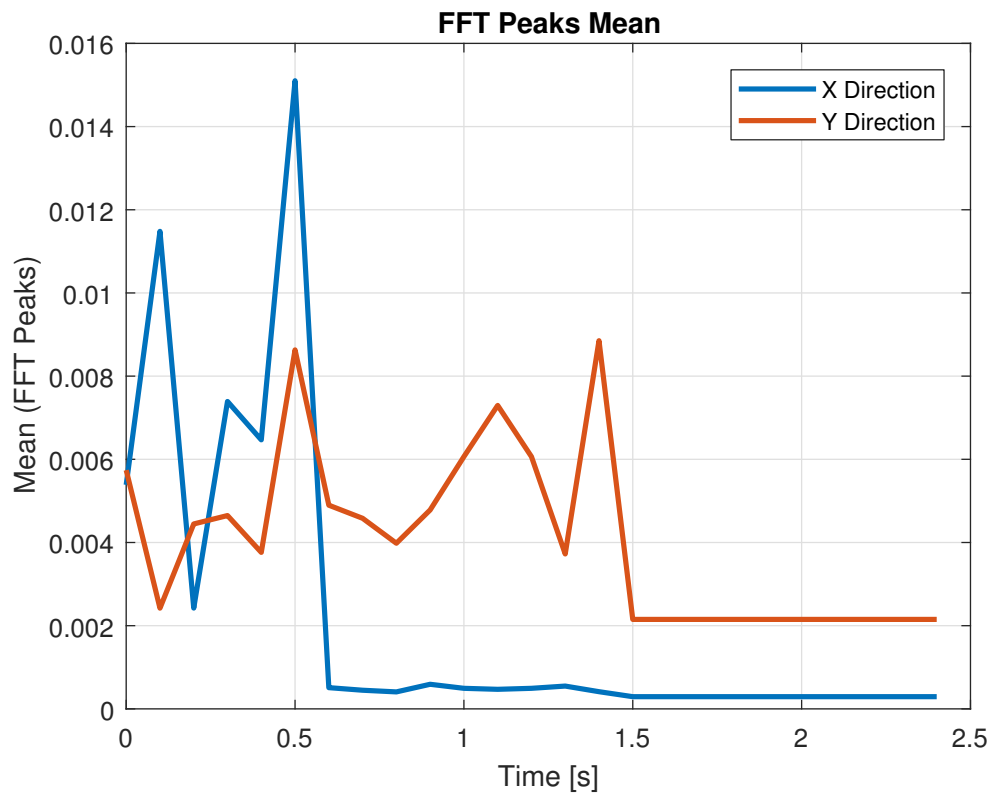


Figure 15: FFT Peaks Mean with Fuzzy Controller (on Measured Data)



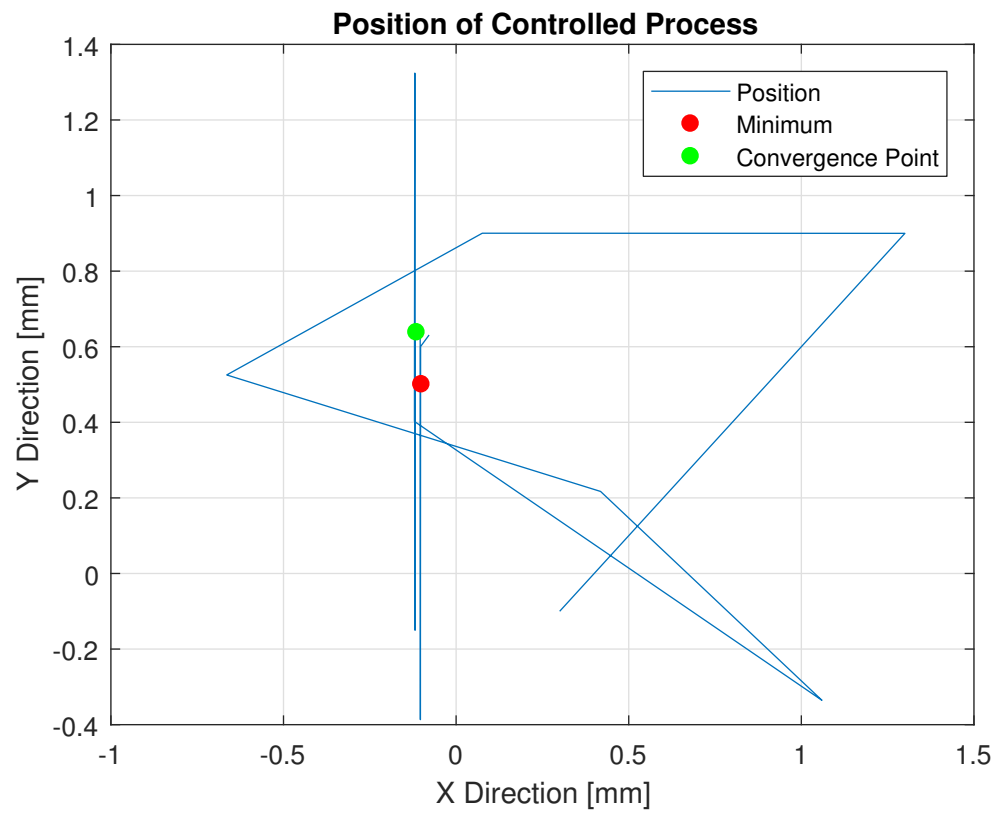


Figure 16: Position with Fuzzy Controller (on Measured Data)

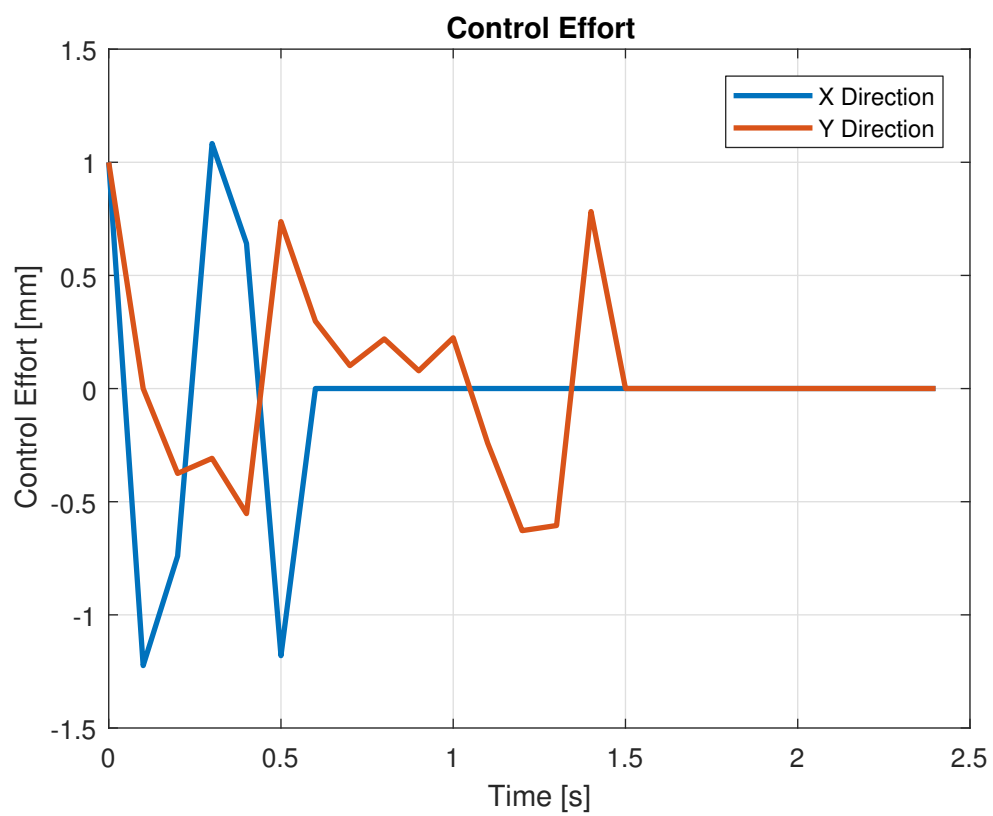


Figure 17: Fuzzy Controller Control Effort (on Measured Data)

of the mean, considering the successive minimizations that should lower the error.

### 3.1.5 Results

The Results of the Controller applied to the Vibrating Wire System (only for the Mean) are shown in Figures 18, 20 and 19.

The behaviour of the controller is similar, but the **result is completely different**.

- The **Amplitude grows much more** (before getting lower) than in the Simulation. This is due to the fact that the Membership Functions are defined in specified ranges, and it takes some iterations to go from a Membership Function to another one.
- **There is not Convergence** (on Y axis). This is due to the fact that the lowest Membership Function has a threshold for the convergence. If, for any reason (noise, different magnet, magnet inclined with respect to the wire, different current in the Magnet or the wire) **the minimum is above the threshold**, convergence can not be achieved.

These problems could be solved with an **Adaptive Fuzzy Controller**, but the complexity of this kind of controller doesn't guarantee a good payoff. A better solution is a **Convex Optimization Algorithm**.

### 3.1.6 Limits of Fuzzy Controller

There is a set of limits to this kind of Controller:

- **Convergence is not proved**
- **Convergence** may be very **slow**
- Presence of **chattering** on the limits between the Membership Functions
- **Not robust to noise** (Air Conditioning flowing or people stepping close to the system) or different magnets

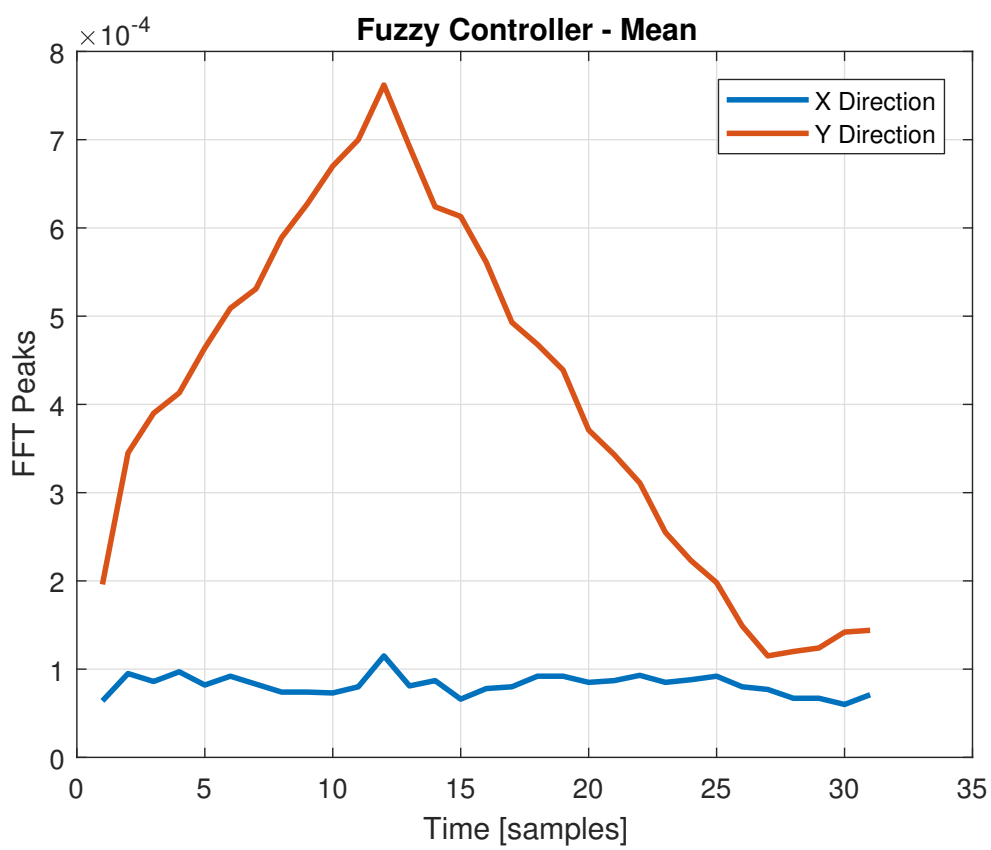


Figure 18: FFT Peaks Mean with Fuzzy Controller

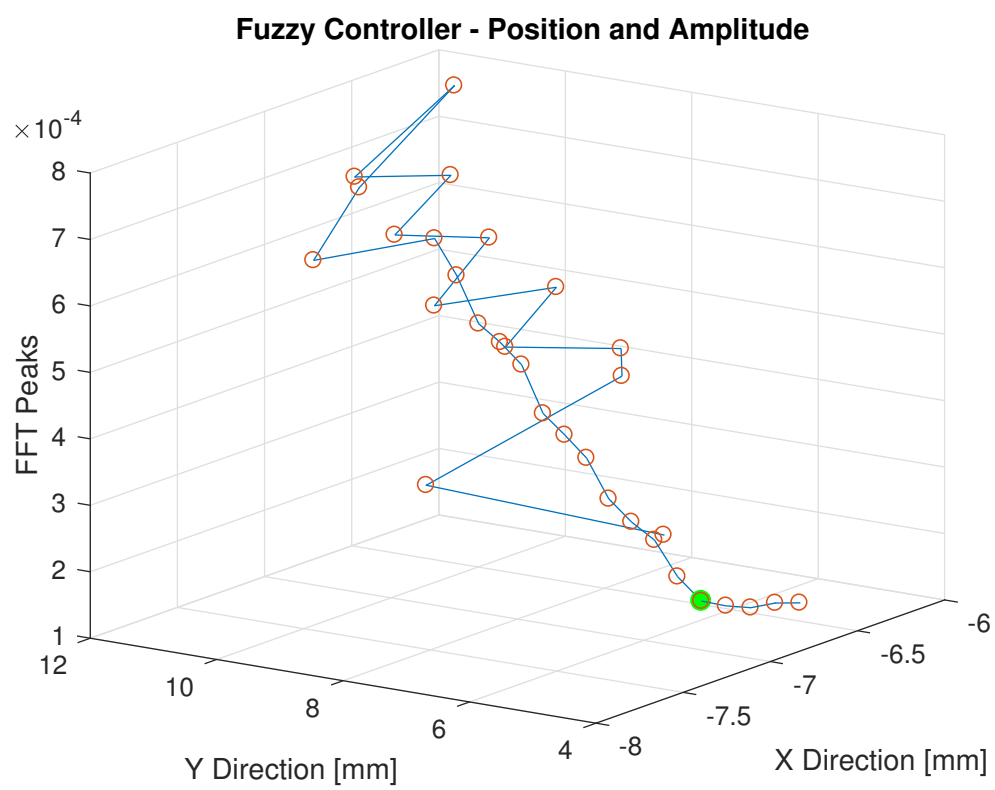


Figure 19: Position with Fuzzy Controller

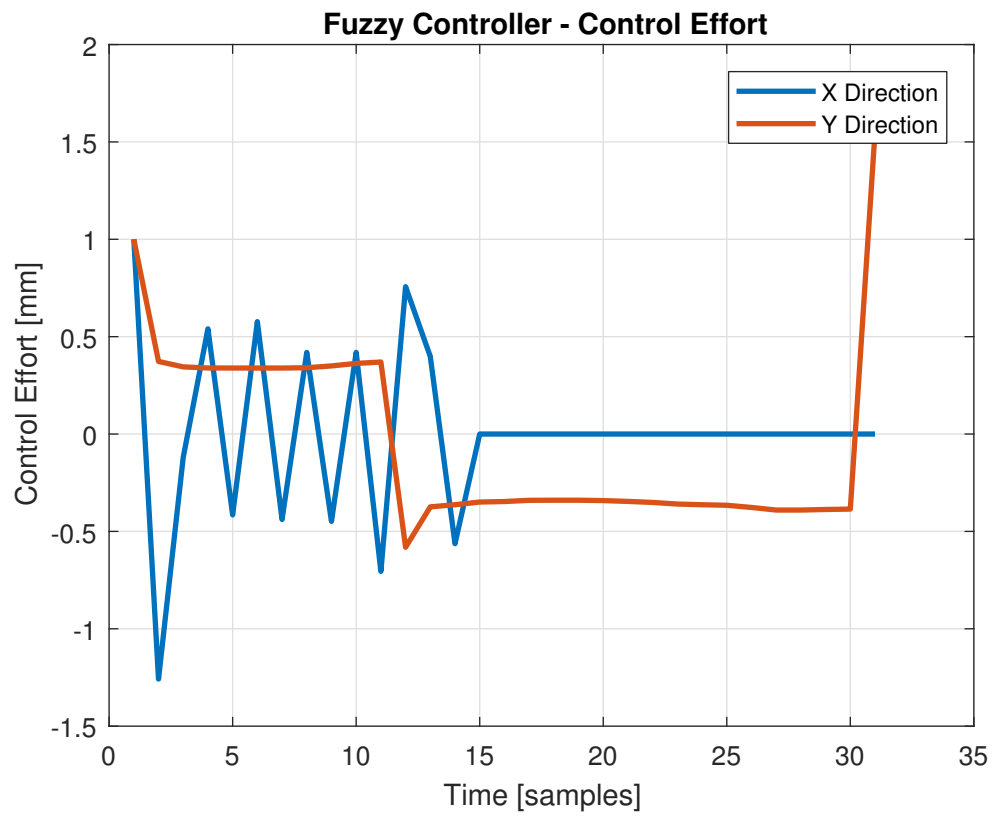


Figure 20: Fuzzy Controller Control Effort

- **Not robust** to change in **current flowing** in the Quadrupole: Membership Functions must be defined each time in order to have convergence
- The **Accuracy** of the result is not in the specified range

These limits are visible from the results, in the previous subsection. The behaviour of the controlled system is the one expected from the simulations. The problem is that **the measurements on the system are not so repeatable**, and numeric values of these measures can change with a great number of factors, listed above.

## 3.2 Bisection-Like Algorithm

This Algorithm is conceived for **convex functions** (only one minimum), and with a good approximation, the raster scans highlighted this kind of property, within certain ranges.

### 3.2.1 Working Principle

The Algorithm follows these instructions:

1. **Initialization:** Place the wire on a random point, choose a certain step resolution
2. **Iteration:** Step in one direction;
  - 2.1. If the signal decreases, repeat from the new point
  - 2.2. If the signal increases, step in the other direction (from the previous point)
  - 2.3. If the signal increases in both directions, half the step resolution and repeat
3. **Termination:** when step resolution is under a certain threshold.

In Figure 21 the graphical explanation of the algorithm.

### 3.2.2 Simulations

In Figures 22 and 23 the results of the Bisection-Like Algorithm applied to measured data.

In this case, the Minimum Amplitude is reached perfectly.



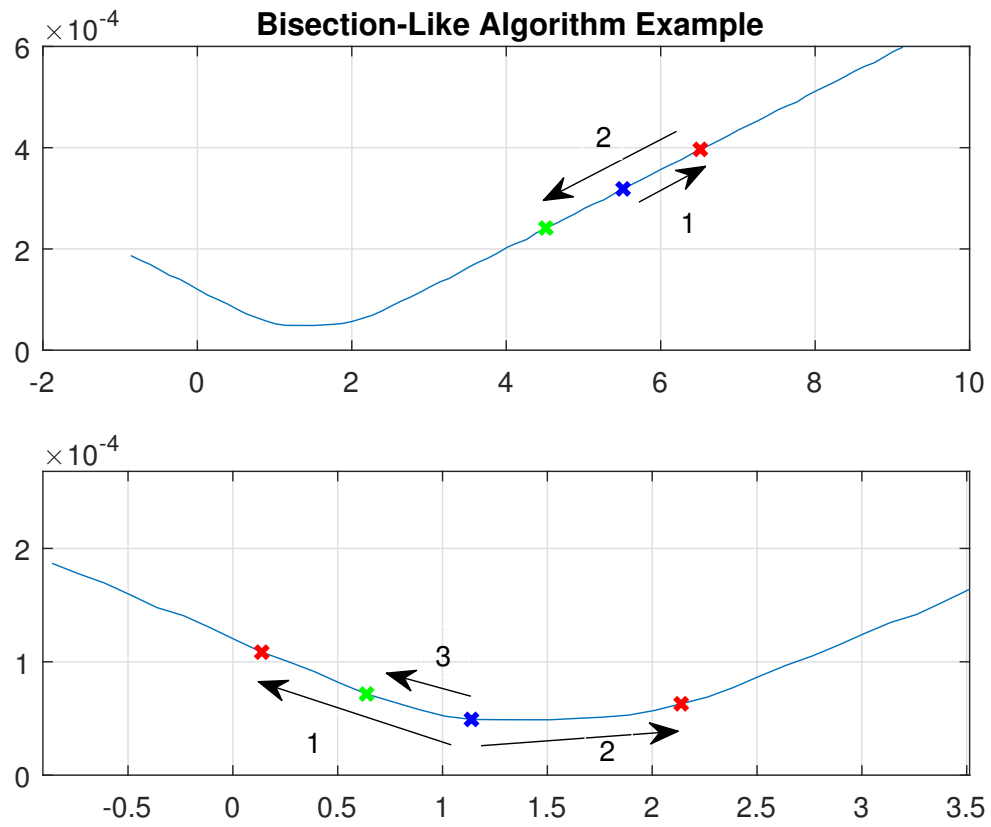


Figure 21: Graphical Interpretation of the algorithm

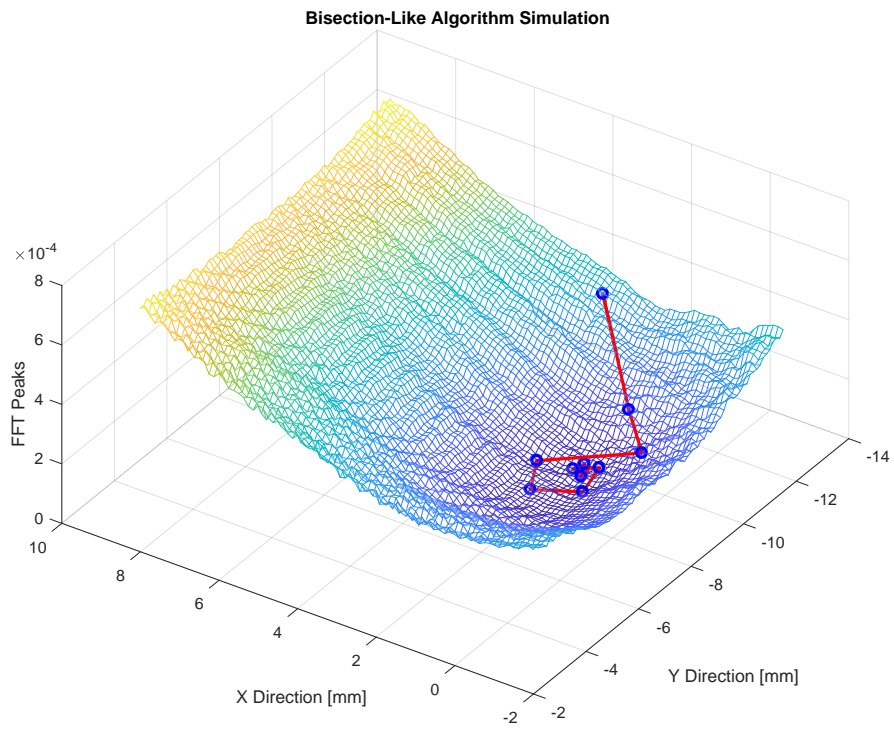


Figure 22: Position with Bisection-Like Algorithm (on Measured Data)

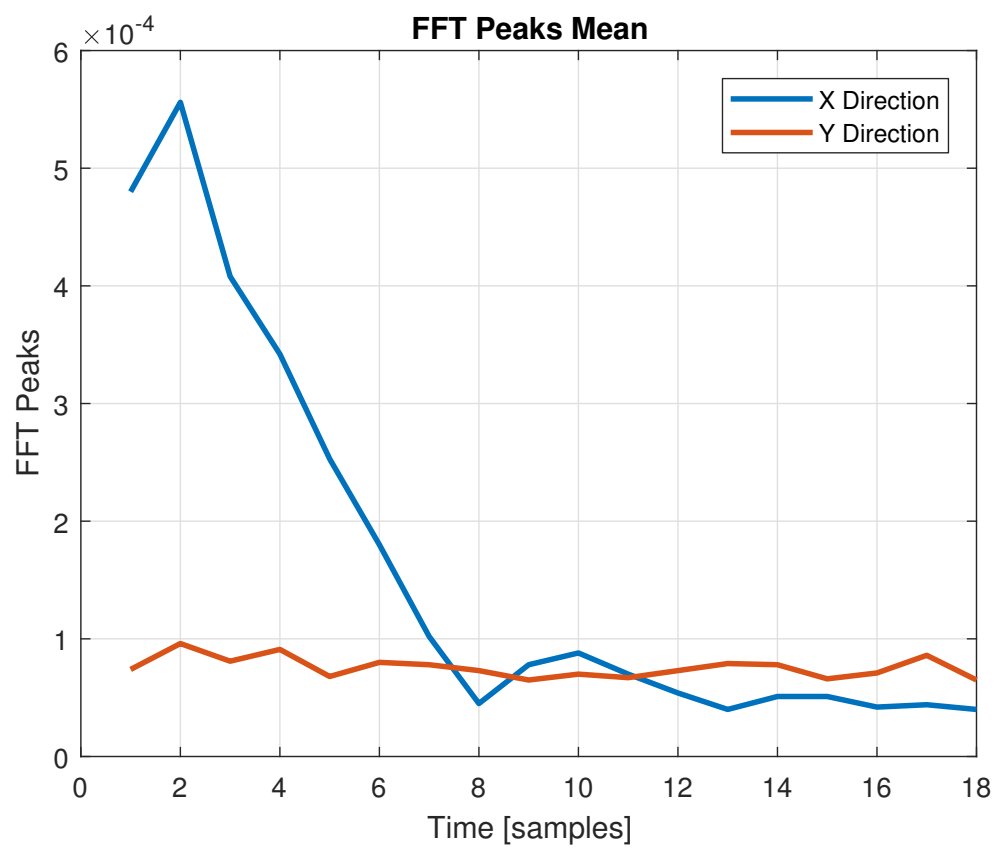


Figure 23: Mean with Bisection-Like Algorithm (on Measured Data)

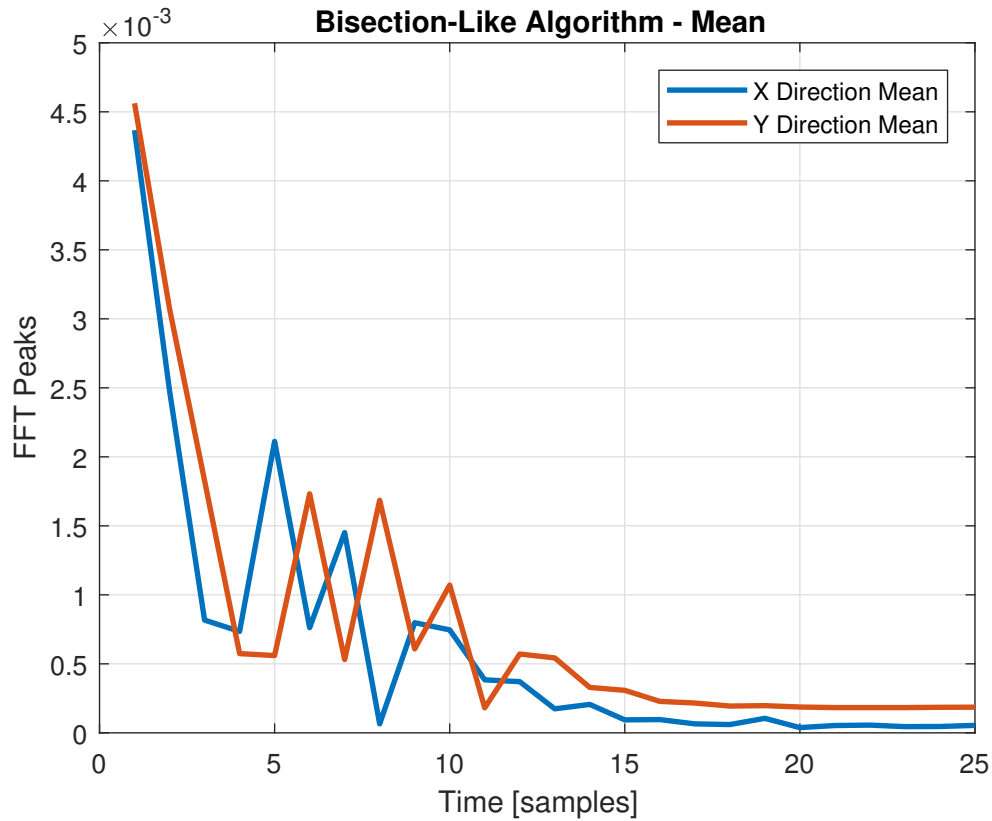


Figure 24: Mean with Bisection-Like Algorithm

### 3.2.3 Results

In Figures 24 and 25 the results for the **minimization of the Mean** are shown. The Algorithm converges and the final Mean is the minimum.

In Figures 26 and 27 the results for the **minimization of the Amplitude** are shown. The Algorithm converges and the final Mean is the minimum.

In Figures 28 and 29 the results for the **minimization of the Amplitude at double of Resonance Frequency** are shown. The Algorithm converges, even if there is a lot of noise in the measure; it finds the minimum anyway.

In Figures 30 and 31 the results for the **second minimization of the**

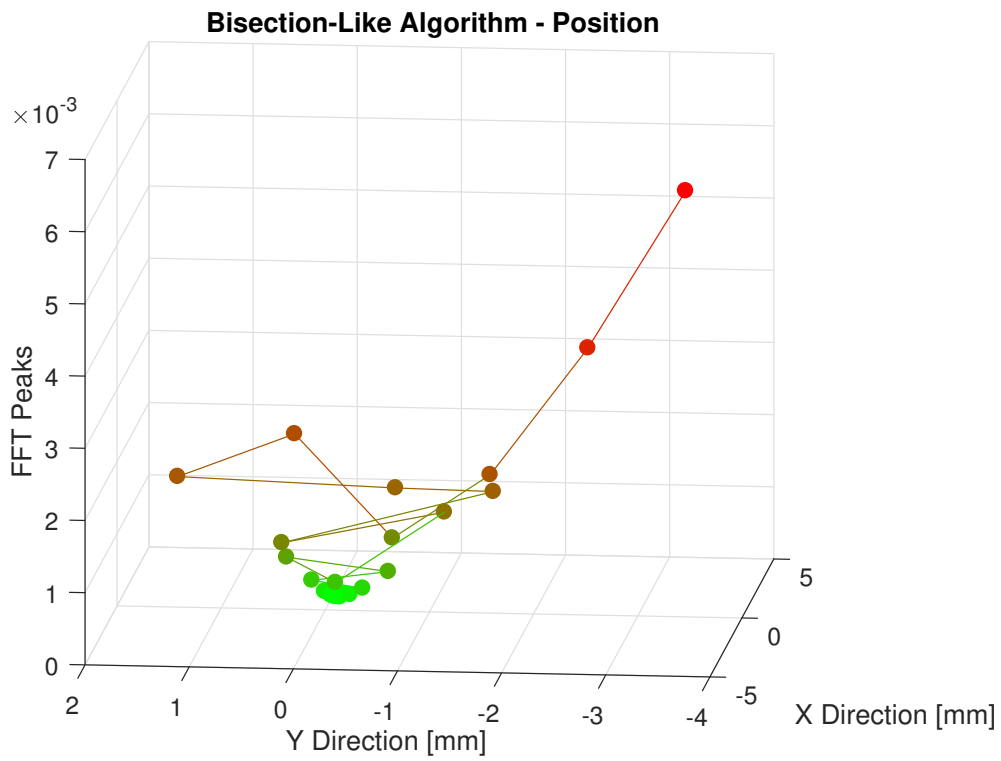


Figure 25: Position with Bisection-Like Algorithm

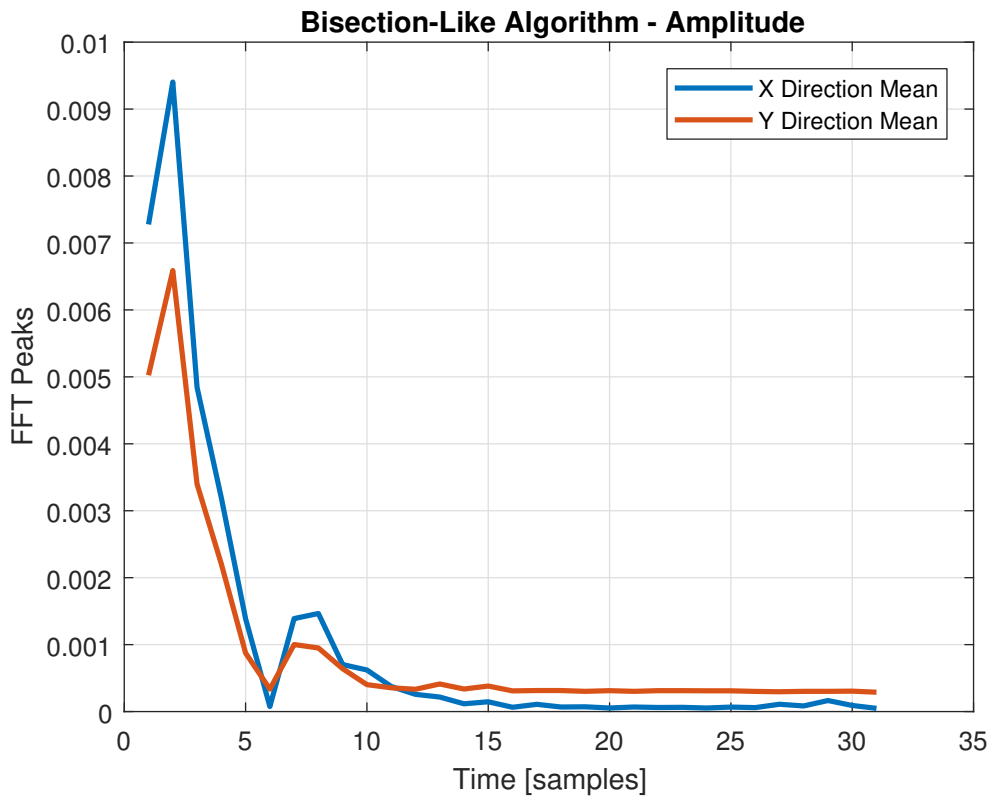


Figure 26: Amplitude with Bisection-Like Algorithm

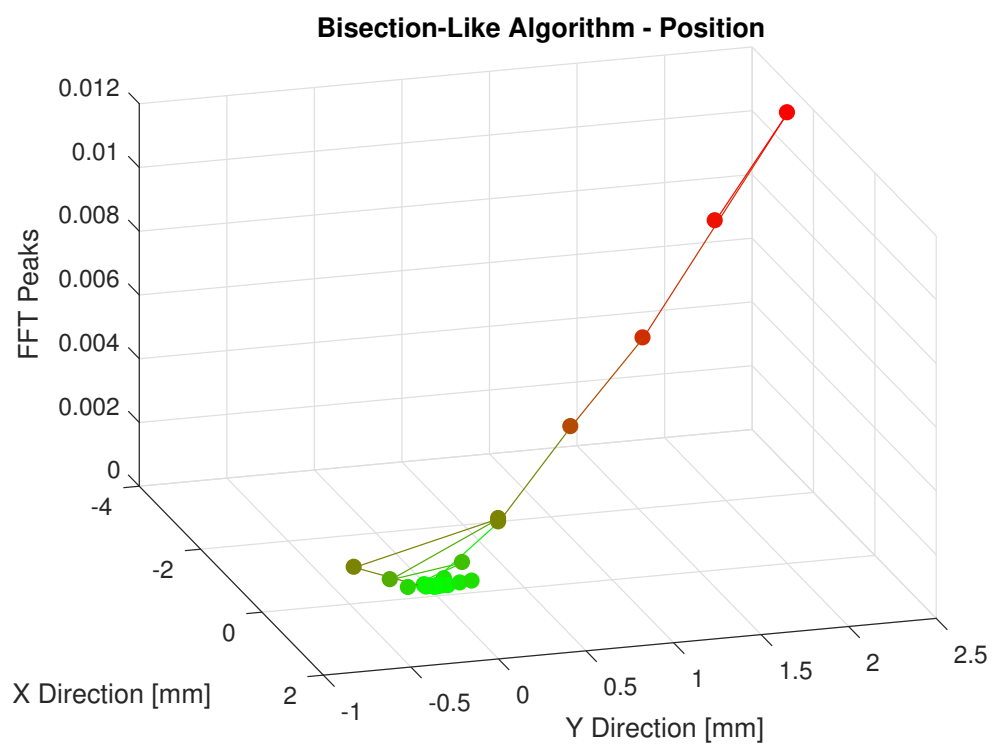


Figure 27: Position with Bisection-Like Algorithm

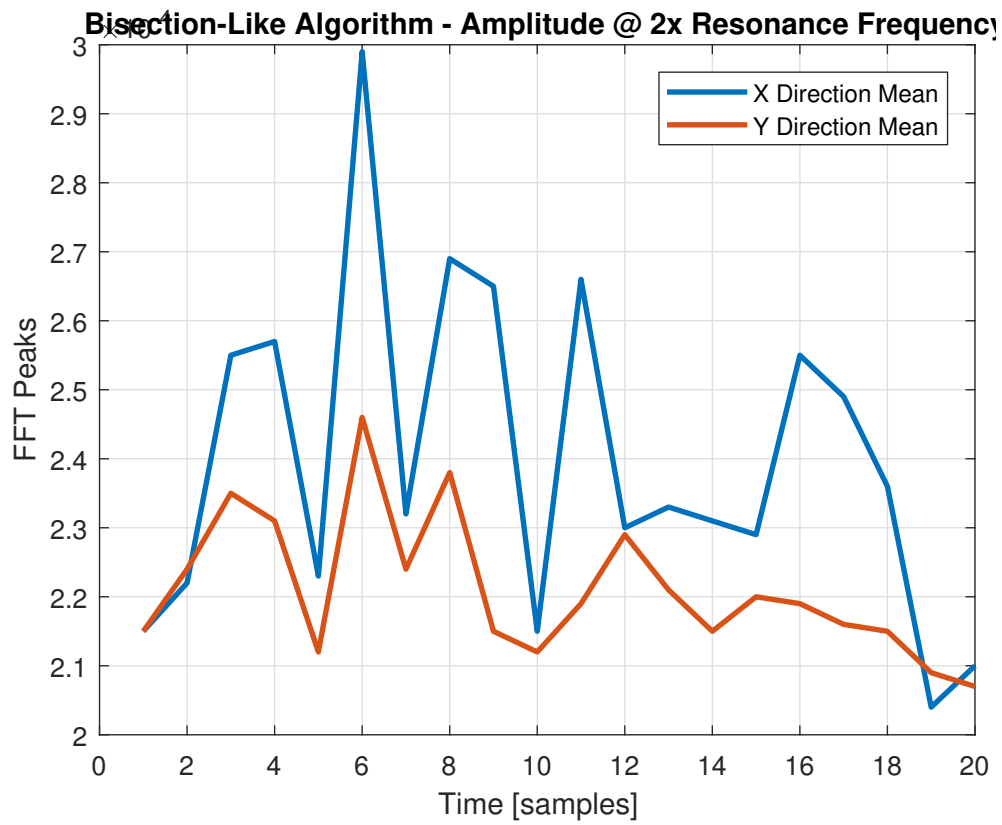


Figure 28: Amplitude at Double of Resonance Frequency with Bisection-Like Algorithm



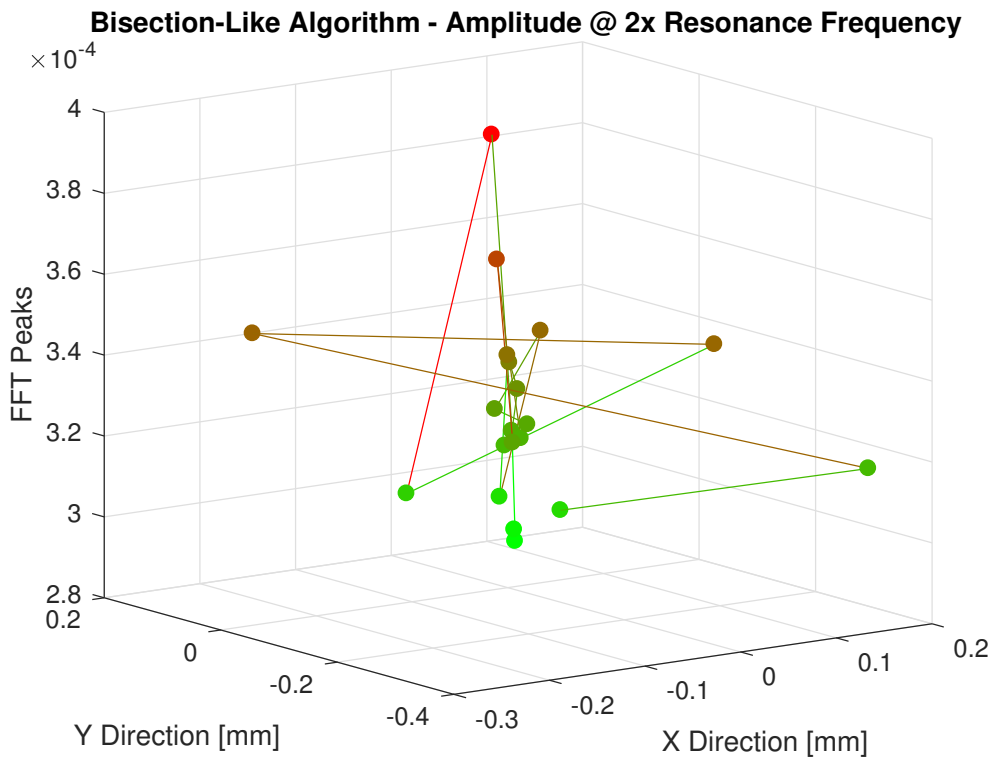


Figure 29: Position with Bisection-Like Algorithm

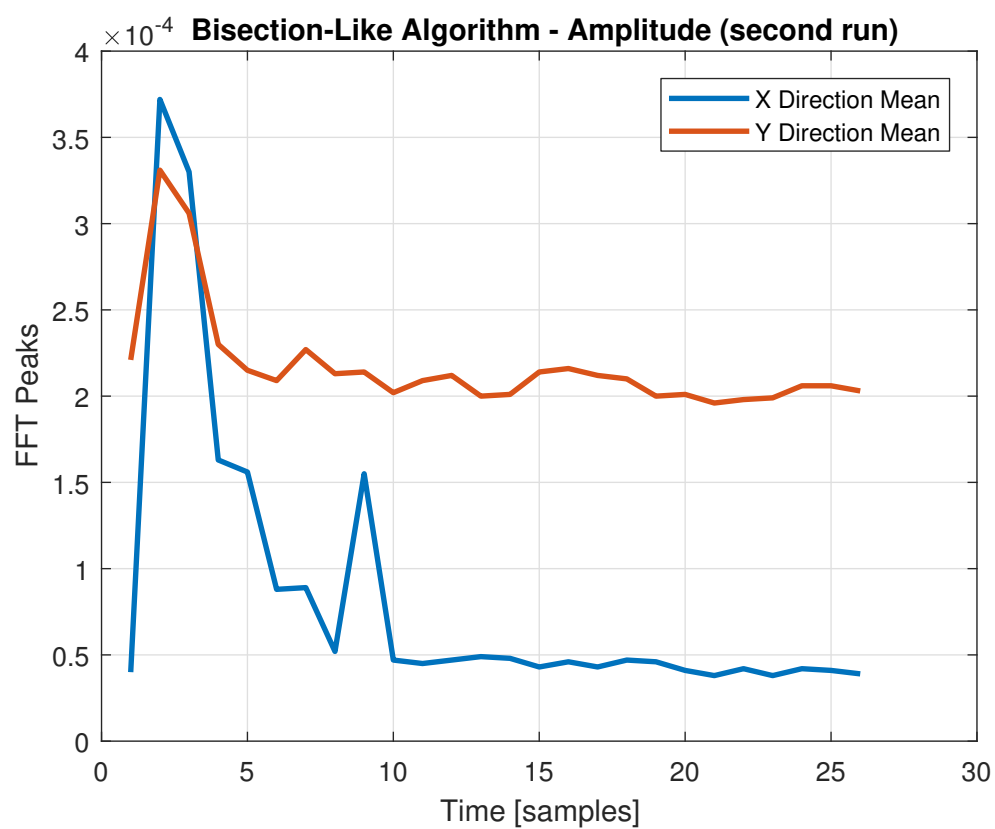


Figure 30: Amplitude with Bisection-Like Algorithm (second run)

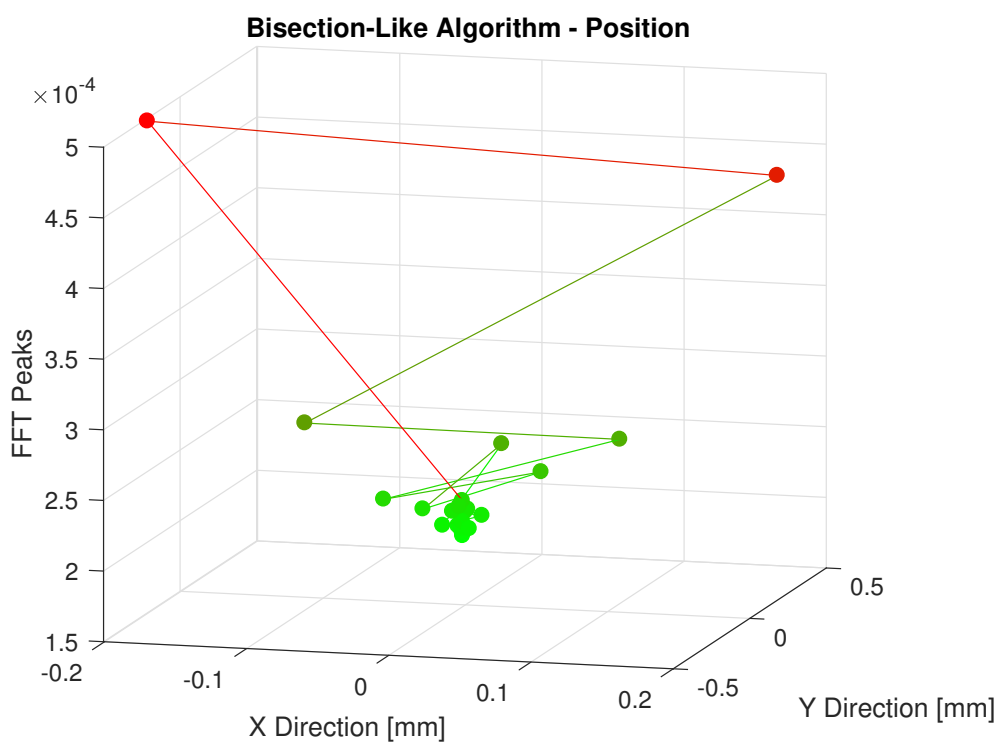


Figure 31: Position with Bisection-Like Algorithm

**Amplitude** are shown. There is convergence in this case too.

## 4 Conclusions

Among the two methods, one is clearly the best. Fuzzy Controller is **not efficient, not accurate, has no guarantee for convergence**. Plus, it is **more difficult to design and to implement**.

On the other side, the **Bisection-Like algorithm finds the minimum** (supposing that there is only one minimum) with **high precision and efficiency**.

### 4.1 Alignment Results

Once the wire is on the minimum oscillation point, the FERMILAB **Alignment Crew**, with extremely precise instrumentation, **survey the Magnet** in order to understand if the wire is placed in the **exact geometrical center** of the Quadrupole.

In table 1 the **error** with which the center has been found with the Bisection-Like Algorithm is shown. The total Error is **below the typical error** accepted in this kind of test, that is about 250  $\mu\text{m}$ .

So, the Bisection-Like Algorithm has been **certified** capable of placing the wire in the center with a certain error in this case. **More measurements must be done in order to estimate the error** with which the Algorithm converges.

LABVIEW code is available for optimization and further usage.

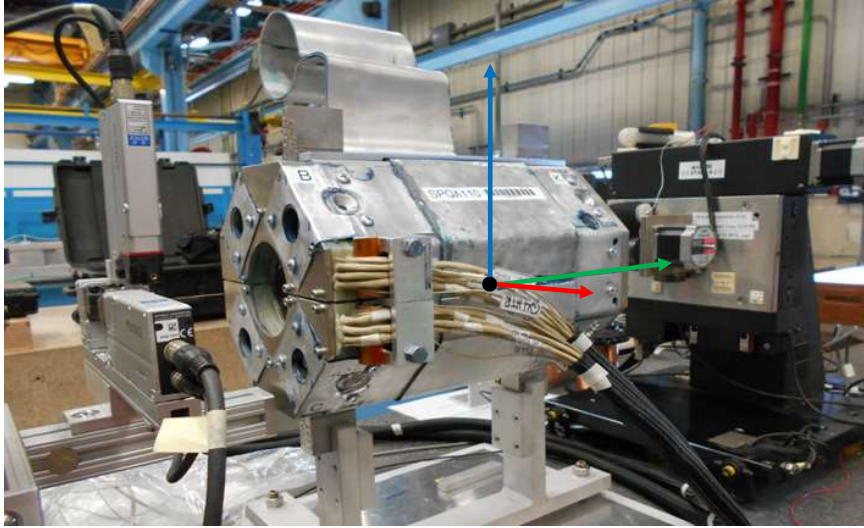


Figure 32: Example of Survey Result

|                    | Error [ $\mu\text{m}$ ] |
|--------------------|-------------------------|
| X Axis             | 127                     |
| Y Axis             | 0                       |
| Z Axis             | 68.6                    |
| <b>Total Error</b> | <b>144.34</b>           |

Table 1: Centering Errors

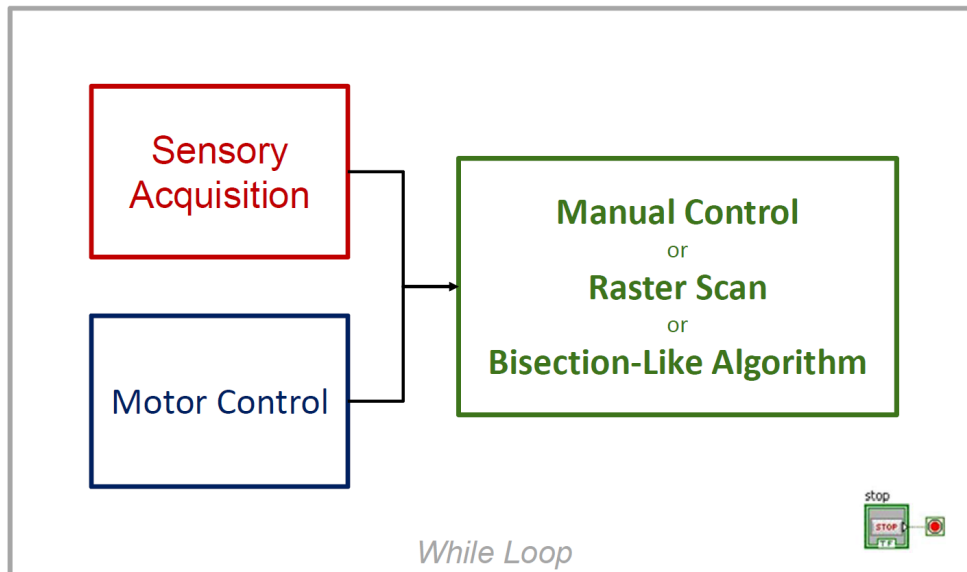


Figure 33: LABVIEW Code Structure

## 5 LabView Code

The Code written for this Project is the extension of the code used for the manual search. In particular, the first version of the code included only the Waveform Generator, the sensory acquisition and the showing and plotting of data.

Based on this first version, the code was extended, keeping the same structure<sup>4</sup>.

The parts that were added are:

- the Motor Control part (using AEROTECH LABVIEW block programming example)
- Manual Part was integrated with an interface for manual motor control
- a new interface for Raster Scan execution

<sup>4</sup>A further work to be done is to re-write the code from scratch, using a State Machine structure

- a new interface for Bisection-Like Algorithm execution
- a new interface for Fuzzy Controller monitoring (removed, once the Bisection-Like Algorithm was chosen as the best one).

**IMPORTANT:** Once the Raster Scan or the Bisection-Like Algorithm has started, don't switch to other tabs. This could cause malfunctioning in the Algorithms behavior.

## 5.1 Manual Mode

From Manual Mode Tab it is possible to monitor:

- Raw X and Y Oscillation Voltage
- FFT Spectrum of each signal
- Time Series of FFT Maximum Peaks
- Average Current and Voltage in the wire

It is possible to control:

- Wire Excitation: Amplitude and Frequency of the AC Current in the wire
- Motors Motion

Manual Mode is useful if the procedure must be run by hand, or if the signals listed above must be visualized (for example, in order to analyze the results of the algorithms).

## 5.2 Raster Scan

The most common way to execute a Raster Scan is on a rectangular path. In order to simplify the algorithm, the Raster Scan is executed on a Square path, where the starting point is the central point of the square, as shown in Figure 35.

The user can choose:

- Square Length ( $l$ )

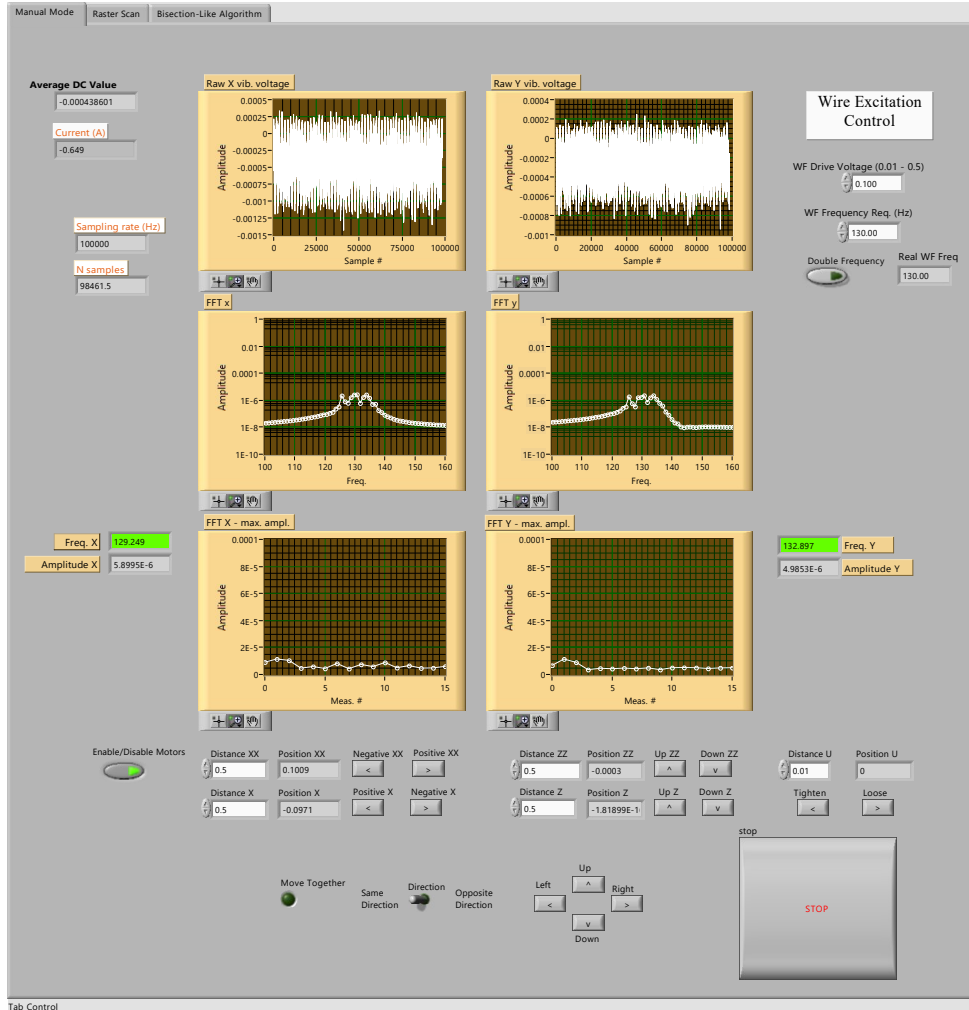


Figure 34: Manual Mode GUI



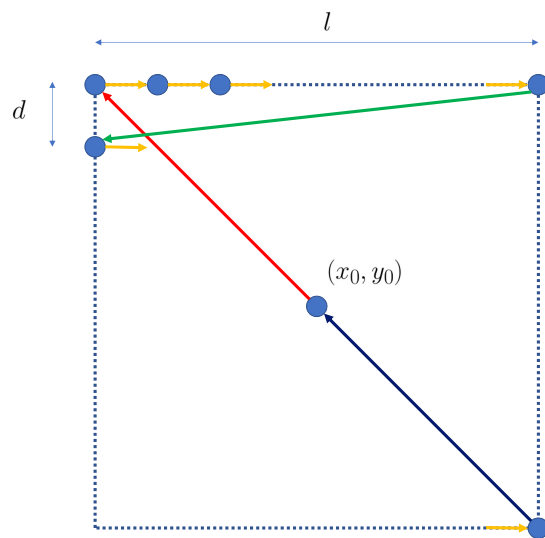


Figure 35: Raster Scan Principle

- Step Size ( $d$ )

After these two parameters are set, the Raster Scan can be started by pressing the **Start** button.

**Note:** In order to have a better noise rejection, the motors hold still for 25 iterations, that corresponds roughly to 25 seconds. To compute the Mean and the Amplitude, the first 5 samples are discarded, since the signal needs some time to stabilize; of course, the best choice would be discarding a much larger number of samples, and computing the Mean and the Amplitude on much more samples. Obviously, a trade-off is needed, to make the Raster Scan last a reasonable time.

### 5.2.1 Output and Analysis

The Output `.xlsx` file is indicated in the GUI; the variables saved are:

- X and Y position
- X and Y Mean
- X and Y Amplitude

The `.xlsx` is plotted with a MATLAB script named `xls_read.m`, which, given the file to be read and the number of signals saved (6 in this case), is capable of re-ordering the data structure in a matrix, and plots the 3D surfaces.

## 5.3 Bisection-Like Algorithm

The GUI for the Bisection-Like Algorithm is very Simple: the user has only to edit the Initial Resolution step, decide if he wants to minimize the Mean or the Amplitude, then press the Start button.

At the moment, the search stops at a resolution of  $5\ \mu\text{m}$  for the Mean,  $1\ \mu\text{m}$  for the Amplitude.

At the moment, the entire procedure is not automatized, due to the fact that when the frequency is doubled the number of samples that must be

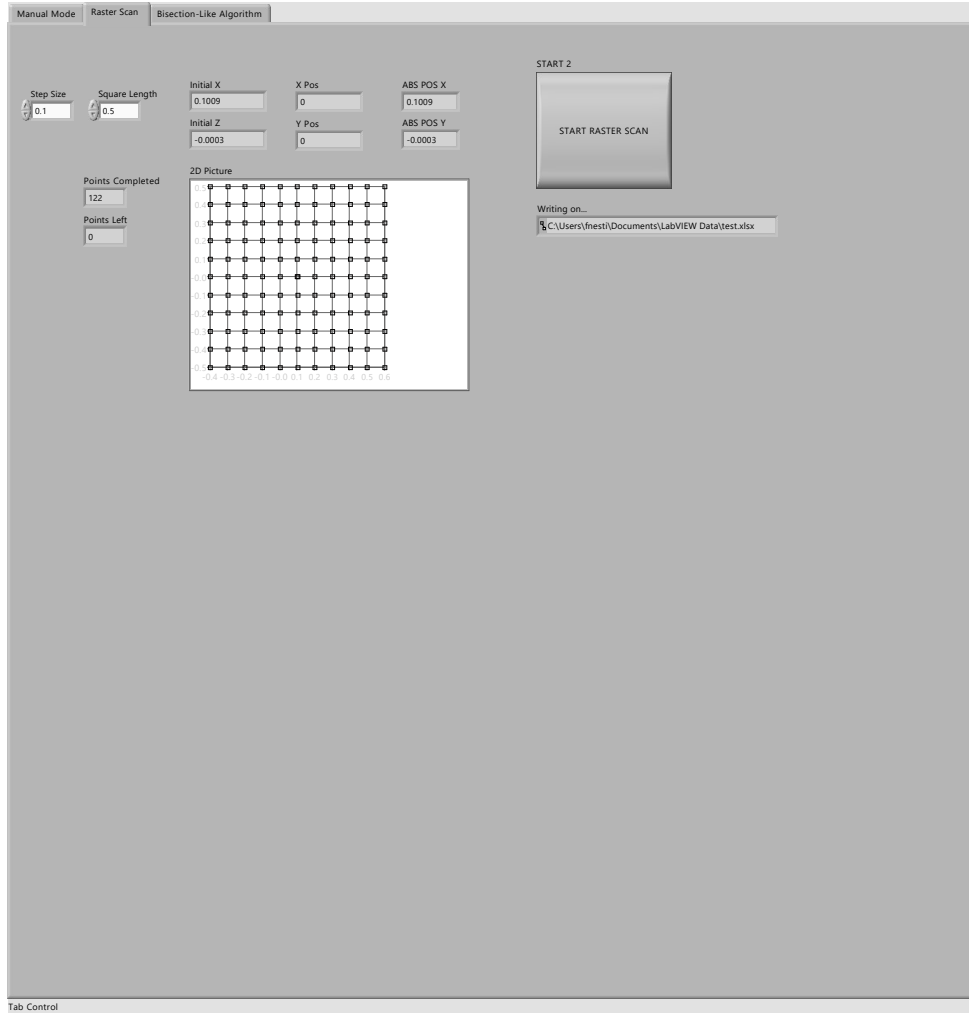


Figure 36: Raster Scan GUI

acquired from the micrometer is doubled, but the modification is not effective if the GUI is not restarted.

For this reason, the four steps of the procedure must be set and started by hand. Future developments of the software must search in this direction, together with a state-machine structure.

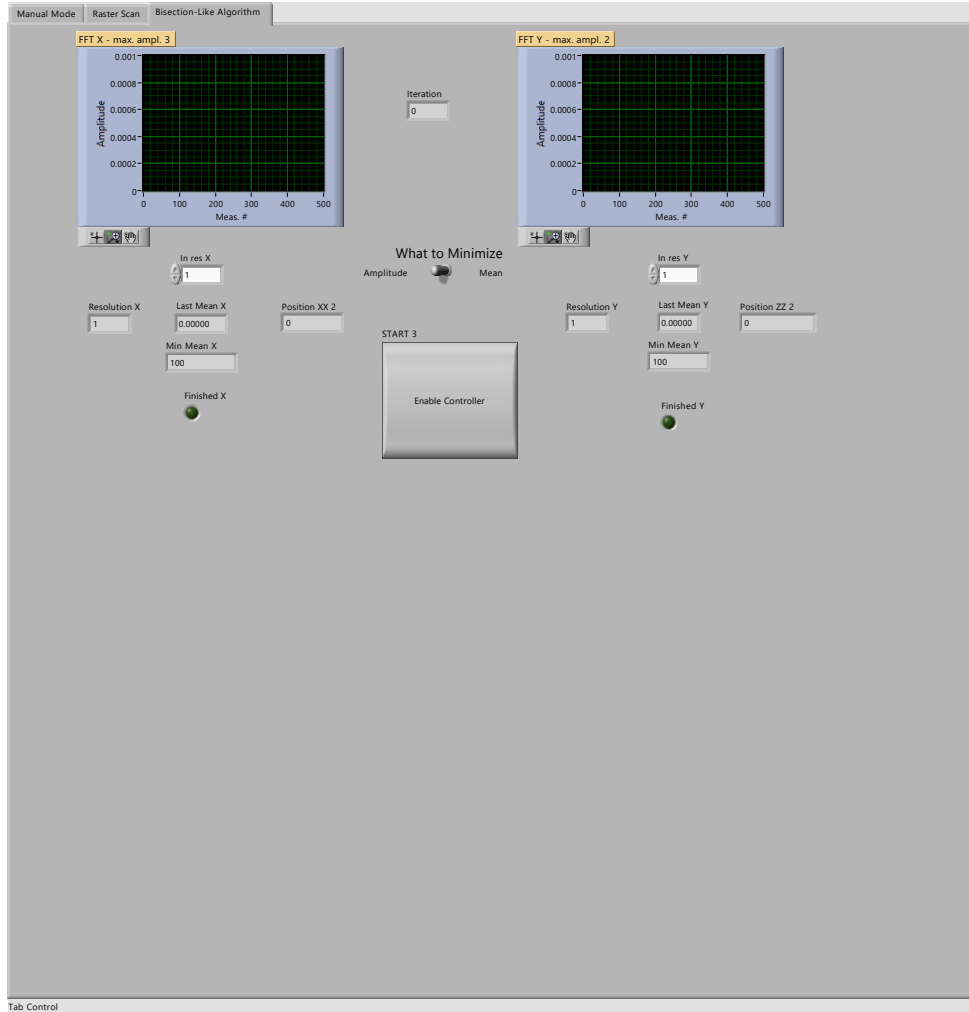


Figure 37: Bisection-Like Algorithm GUI