Wireless Embedded Control System for Atomically Precise Manufacturing

Yasser Khan[#1], John Randall[$2]
[#]*Department of Electrical Engineering, King Abdullah University of Science and Technology*
Thuwal 23955-6900, Kingdom of Saudi Arabia
[1]*yasser.khan@kaust.edu.sa*
[$]*Zyvex Labs*
1321 N. Plano Road, Richardson, Texas 75081, USA
[2]*jrandall@zyvexlabs.com*

Abstract

This paper will explore the possibilities of implementing a wireless embedded control system for atomically precise manufacturing. The manufacturing process, similar to Scanning Tunneling Microscopy, takes place within an Ultra High Vacuum (UHV) chamber at a pressure of 10^{-10} torr. In order to create vibration isolation, and to keep internal noise to a minimum, a wireless link inside the UHV chamber becomes essential. We present a MATLAB simulation of the problem, and then demonstrate a hardware scheme between a Gumstix computer and a Linux based laptop for controlling nano-manipulators with three degrees of freedom.

Key Words: Atomic Precision, OMAP Processors, Gumstix, Scanning Tunneling Microscopy, Wireless Data Transfer.

1. Introduction

Throughout history, technological advancement has been limited by the manufacturing capabilities existing at that time. In some cases, the lack of accuracy and precision in the manufacturing process has delayed innovation by scores of years. Since miniaturization has been the key to increasing performance in electronics, the downscaling to maintain Moore's Law will require fabricating circuits on the atomic level on the not so distant horizon [1].

Thus, the motivation for Atomically Precise Manufacturing (APM) becomes apparent – to achieve the highest degree of precision possible, and ideally leading to atomically identical structures. All signs point towards APM becoming an eventuality, and Zyvex Labs intends to establish their position as one of the forerunners of the field. Figure 1 presents a general approach behind APM. Further information is available in reference 2.

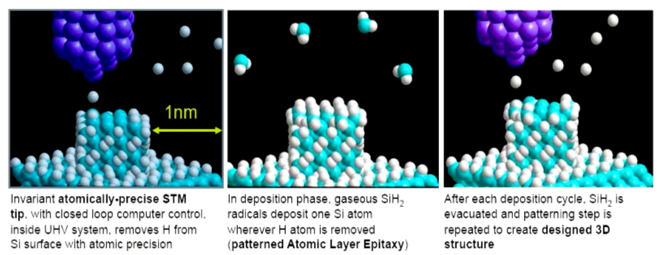

Figure 1. Systematic removal of H from Si surface shows the concept of manipulating single atom [2].

2. Atomically Precise Manufacturing process and necessity for setting up a wireless link

The manufacturing process itself takes place within an Ultra High Vacuum (UHV) chamber at a pressure of 10^{-10} torr. At normal atmospheric pressure gas molecules in the air will saturate any reactive surface in less than a microsecond, making any sort of controlled surface reaction with atomic precision impossible. Within the UHV chamber, small area reactive surfaces can remain clean for an hour before such saturation occurs [3]. However, while working in a UHV environment is necessary, it creates an additional set of challenges.

Heat generation inside must be minimized and should be kept constant. Devices within the chamber need to survive bake-outs at 150°C to take out any moisture present, and the materials themselves must be UHV compatible. The mechanisms inside are also extremely sensitive to any vibrations from wires, which leads to our problem.

The atomic manipulation is performed with a Scanning Tunneling Microscope (STM). The tip of the STM has a minimum of four wires: XYZ coordinates and a current

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output. With a future goal of running more and more STMs in parallel for fabrication, the mass of wires running inside the UHV chamber will also increase, leading to a larger susceptibility to vibrations. The need for a wireless form of communication becomes an inevitable problem as the scope of APM increases.

3. Wireless data transfer for APM

The initial problem that Zyvex needed a solution for was to reduce vibrations to their STM chamber. There are numerous wires coming into and out of the STM chamber, and these wires cause sub-nanometer vibrations that affect scanning. Since these wires affect the scanning they are in turn disrupting many of Zyvex's diagnostic tests. Thus, the motivation for a wireless solution stems from the desire to avoid any excess vibration inside the chamber. At first the possibility of Bluetooth protocol was explored because it was already tested in High Vacuum settings by Murari and Lotto [4]. But Scanning Tunneling Microscopy requires faster data rate, which can only be satisfied by IEEE 802.11 protocol [5].

3.1. Conceptual design

Designing a wireless communication link with Ad hoc Wi-Fi protocol and a control system protocol for Atomically Precise Manufacturing is a feasible solution. Implementation steps included: setting up an 802.11 Ad hoc wireless communication link, interfacing a computer system with ADCs and DACs, and controlling an STM tip from tunneling-current feedback. Our main hardware for the project was Gumstix. Gumstixs are full equipped computers but in the size of gum sticks [6]. TI offers a similar line of products call Beagleboards, but we chose Gumstix because of their built-in 802.11 compatibility [7]. On the transmission side, we had a laptop running Linux, which will link up to the receiving side through ad-hoc Wi-Fi. On the receiving side, we have a Gumstix Overo Fire with OMAP 3530 carrying ARM Cortex-A8 CPU and C64x+ digital signal processor (DSP). In addition to the Gumstix, on the receiving end, we have a TI ADS8364 16 bit Parallel 6 Channel ADC, a TI DAC8565 16 bit SPI 4 Channel DAC, and a custom daughter board for parallel communication.

Our approach is to utilize the Gumstix COM to read current from the ADC and apply correction voltage to the DAC for controlling the STM. Furthermore, the information to and from the STM must be at a rate of at least 100KSPS. Then, we used an ad-hoc wireless network to control the Gumstix from a Linux terminal. Finally, in order to obtain the data rate that we required we needed to use parallel communication that commercially available Gumstix daughter boards were incapable of doing. Therefore, we designed a daughter board that can communicate with the ADC and DAC at 250KSPS.

3.2. MATLAB simulation

To demonstrate our conceptual designed, we developed a MATLAB simulator where one laptop simulated an atomic surface, and the other controlled the STM tip. We used a basic control loop the tunnelling current as a function of tip-sample separation [8].

$$I \approx \frac{4\pi e}{\hbar} e^{-s\sqrt{\frac{8m\varphi}{\hbar^2}}} \rho t(0) \int_{-eV}^{0} \rho s(\epsilon) d\epsilon \qquad (1)$$

Figure 2 depicts our simulation control loop.

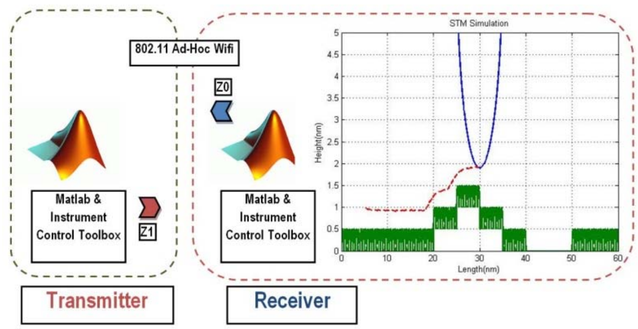

Figure 2. MATLAB simulation for controlling a STM tip through 802.11.

4. Hardware implementation

Below the schematic design of our complete system is given:

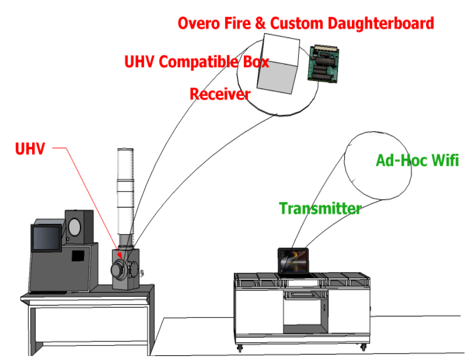

Figure 3. Hardware overview of the complete system.

4.1. Receiving side

Since STM needs UHV environment, we plan to place the receiver inside a UHV compatible box, which will be kept inside the UHV chamber. Our receiver design consists of two main segments: an Overo Fire module, which does all the computation for STM control and a custom daughterboard that, provides essential inputs and outputs of the system. The Overo Fire module is connected to the custom daughterboard by means of two 70-pin connectors: AVX 5602 series.

The Overo Fire module features an OMAP 3530 Applications Processor with ARM Cortex-A8 CPU, and a C64x+ digital signal processor (DSP) core. At this moment, the OMAP 3530 Applications Processor handles all the computations and I/O operations. Ideally, upgraded system can share the workload, where OMAP 3530 Applications Processor will take care of the computations and C64x+ digital signal processor (DSP) core will handle input-output operations via ADCs and DACs.

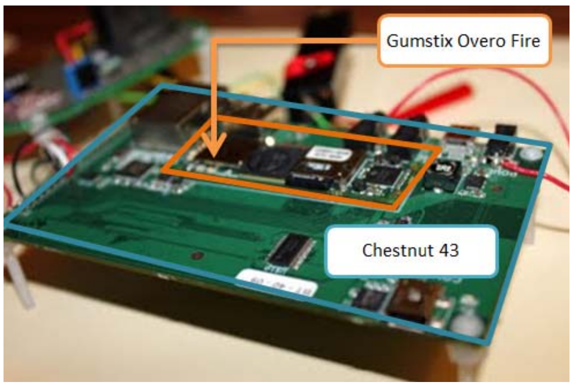

Figure 4. Receiver (a): Gumstix Overo Fire module on a Chestnut 43 Daughterboard.

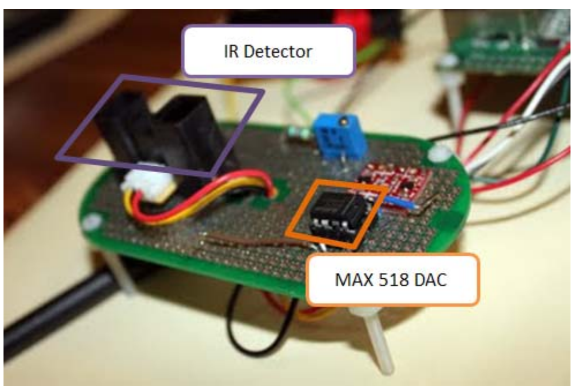

Figure 5. Receiver (b): Daughterboard expansion to host additional DAC and IR detector for demo purpose.

4.2. Transmission side

A laptop equipped with Wi-Fi and running Ubuntu 9.10 OS is on the transmission side. Basically, an Ad-hoc Wi-Fi link capable of roughly 100KBps speed at this moment, gives terminal access to the embedded Angstrom Linux of the Gumstix Overo Fire. This 100KBps speed can be upgraded with a patch available in Kernel 2.6.33. Besides, using an FTP server, we can access the file system on board the Gumstix.

5. Current results

We took a systematic approach to evince our concepts. The implementation steps included simulation, hardware implementation with readily available daughterboard, and final setup with enhanced Gumstix and custom daughterboard, which is yet to done. Since current models of Gumstixs are not UHV compatible actual testing was done in air. Recently Gumstix released their upgraded version which is able to sustain high temperature bake-outs [9].

5.1. Simulation results

Our Matlab simulation successfully scanned simulated atomic surface. Since there were quite a large number of abstraction layers, and computation for sub nanometer step sizes were intense, we observed some fluctuation in results, which can be fixed with enhanced control loop algorithm and low level hardware interaction. Below screenshots of real-time scanning is presented.

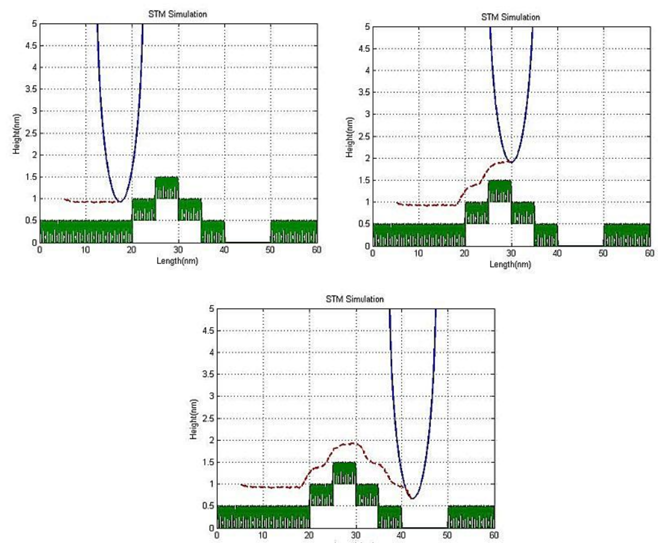

Figure 6. Simulation results for real-time scanning of simulated randomized atomic surface.

5.2. Hardware implementation with Chestnut 43 daughterboard

Our prototype system uses the Chestnut 43 board. The prototype system can read from the ADC and output correction to the DAC. We fed a sinusoidal signal to the input and were able to read a signal with correction from the DAC output. We used MAX518 DAC, which is I2C capable. To demonstrate functionality, we attached an infrared sensor to another ADC channel on the on-board power management chip and compiled a program to capture the voltage reading from it. After the trace, data are saved in a file and plotted automatically. While the performance is below the specifications, the prototype system demonstrates that the DAC can be controlled via an analog input, and as such, the higher performance parts we selected for the custom daughterboard should be able to surpass the minimum requirements for APM.

We were able to read signals from objects with the IR sensor using SSH and FTP server [10]. The real time data were plotted with KST [11], a plotting program in host Ubuntu machine. Figure 6 shows similar pattern read from same objects. In this case host machine and Gumstix computer were about 20 feet apart. We used the correction factor given in equation 2.

$$Vdac = .1745\ e^{-9.4Vadc} \qquad (2)$$

Raw ADC voltage read from the DAC is given below:

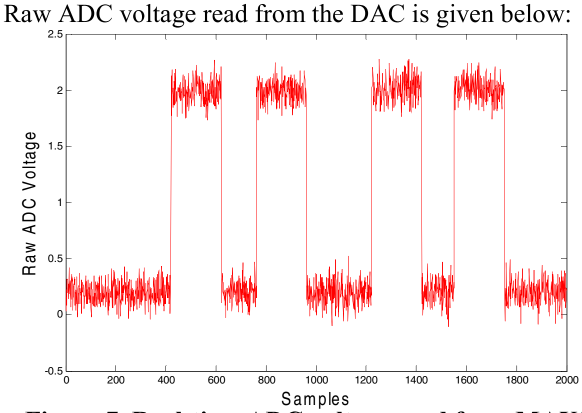

Figure 7. Real-time ADC voltage read from MAX518 DAC shows similar pattern for same object.

5.3. Speed requirements and necessity of a new high speed analog board

The demo system is capable of processing system tasks, but I2C serial bus is not capable of sustaining the required speed of 100KSps 16 bits of resolution. For this reason a new daughterboard, which uses a parallel interface and a SPI serial interface was designed. The new analog daughterboard can provide sufficient speed for STM tip manipulation real time.

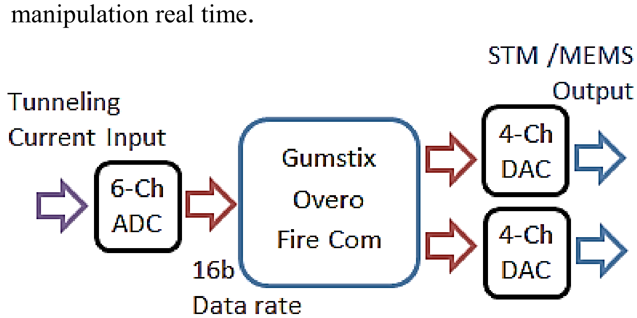

Figure 8. Upgraded system structure with high speed ADCs and DACs

6. Conclusions and scope of future work

Here we presented a technique to implementing wireless control loop for STM, and substantiated the concept with simulation and prototype testing. Although speeds offered by the system were not sufficient, our demonstration unit delineated a rudimentary implementation of the system. We were able to read data from the on-board ADC of a Gumstix, then, put a correction on the signal. And finally, output that corrected signal with an outside DAC. Since speed and data requirement for real-time STM control cannot be satisfied with commercially available Gumstix daughter boards, we propose a high speed solution to the problem with a high speed analog daughter board for the Gumstix. Besides, bake-out at 150C can create a problem while making the system UHV ready; Gumstix new line of product deals with this problem adequately.

For our design, Zyvex required a sampling rate of at least 100 KSPS for both the analog inputs and digital outputs at 16 bits per sample. We originally envisioned using the I^2C bus, as it is a well-known protocol; however, research showed that the I^2C bus maximum frequency of 400 kHz does not have the necessary bandwidth to meet the specifications [12]. Thus, we selected components utilize the serial peripheral interface (SPI) bus since it is capable of operating at 4 MHz (the minimum necessary clock speed for 16 bits and 250 KSPS). In addition to the sampling rate requirement, 8 DAC channels and 4 ADC channels were required. Thus, we selected two DAC8565 digital to analog converters and one ADS8364 analog to digital converter to meet the specification. However, unlike the DAC, the ADC was required to be parallel, to enable asynchronous operation between the ADC and DAC.

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