# Towards Automatic Nanomanipulation at the Atomic Scale

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# Outline

- Introduction
- System Overview
- Workpackages
  1. integration of nM into an STM-Measurementsystem
  2. segmentation/labelling of atoms and molecules
  3. navigation/calibration
  4. manipulation skills
  5. planning/simulation
- Outlook

# Introduction

Definition:
Manipulation of nanometer size objects with a nanometer size tool-tip with (sub)nanometer precision.

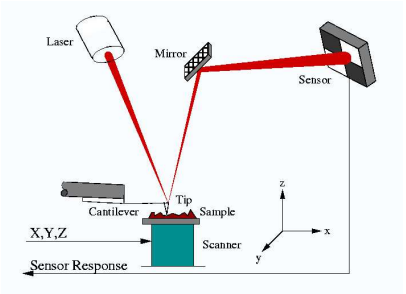
Application:
manual (scan – manipulate – scan) cycle

Motivation:
Nanomanipulation will soon be a standard preparation technique for experiments in physical and biological science.

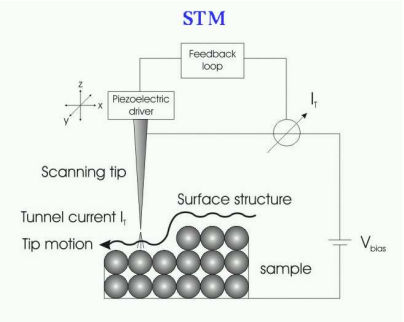
$\Rightarrow$ automation of nanomanipulation mandatory

# Tools

- Atomic Force Microscope (AFM)
  - manipulation of nanoparticles
  - push, pull, pick and place, bend, twist etc.



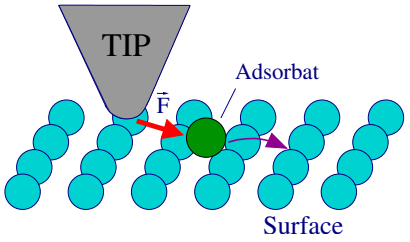

- Scanning Tunneling Microscope (STM)
  - manipulation at the atomic scale
  - repulsive, attractive and vertical mode



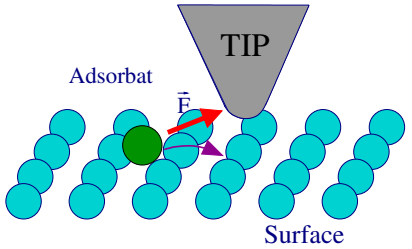

- special tools integrated into a microscope

# STM Manipulation Modes

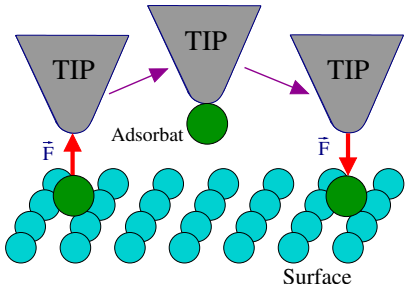
- repulsive mode (pure pushing)
  - constant current mode




- attractive mode (pure pulling)
  - constant current mode




- vertical mode
  - voltage pulse to attain atom to tip
  - move in imaging mode
  - voltage pulse to attain atom to surface

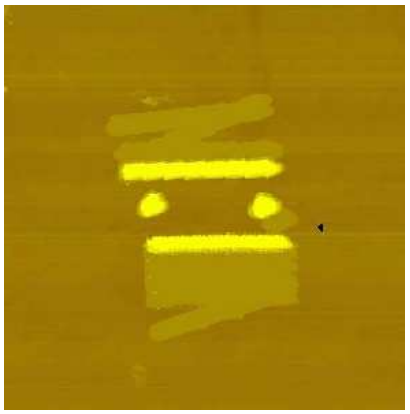


# Advanced User Interfaces

- several user interfaces intended for manual nanomanipulation under development
- features:
  - advanced graphics
  - haptic device and reliable force feedback
  - teleoperation
  - contact models, modeling of nanoobjects
  - drift compensation
- designed for ambiant AFM

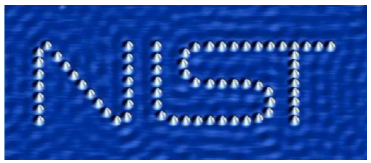
# Automation in Nanomanipulation

- manipulating nanoparticles with an AFM
  - first steps towards automation
  - CAD-models of nanostructures
  - drift calculation



Michigan State University

- manipulation at atomic scale with a STM
  - Autonomous Atom Assembler (AAA)
  - tool for automatic positioning of tens of single atoms
  - rule-based path planning
  - no drift compensation



National Institute of
Standards and Technology

# Where we are

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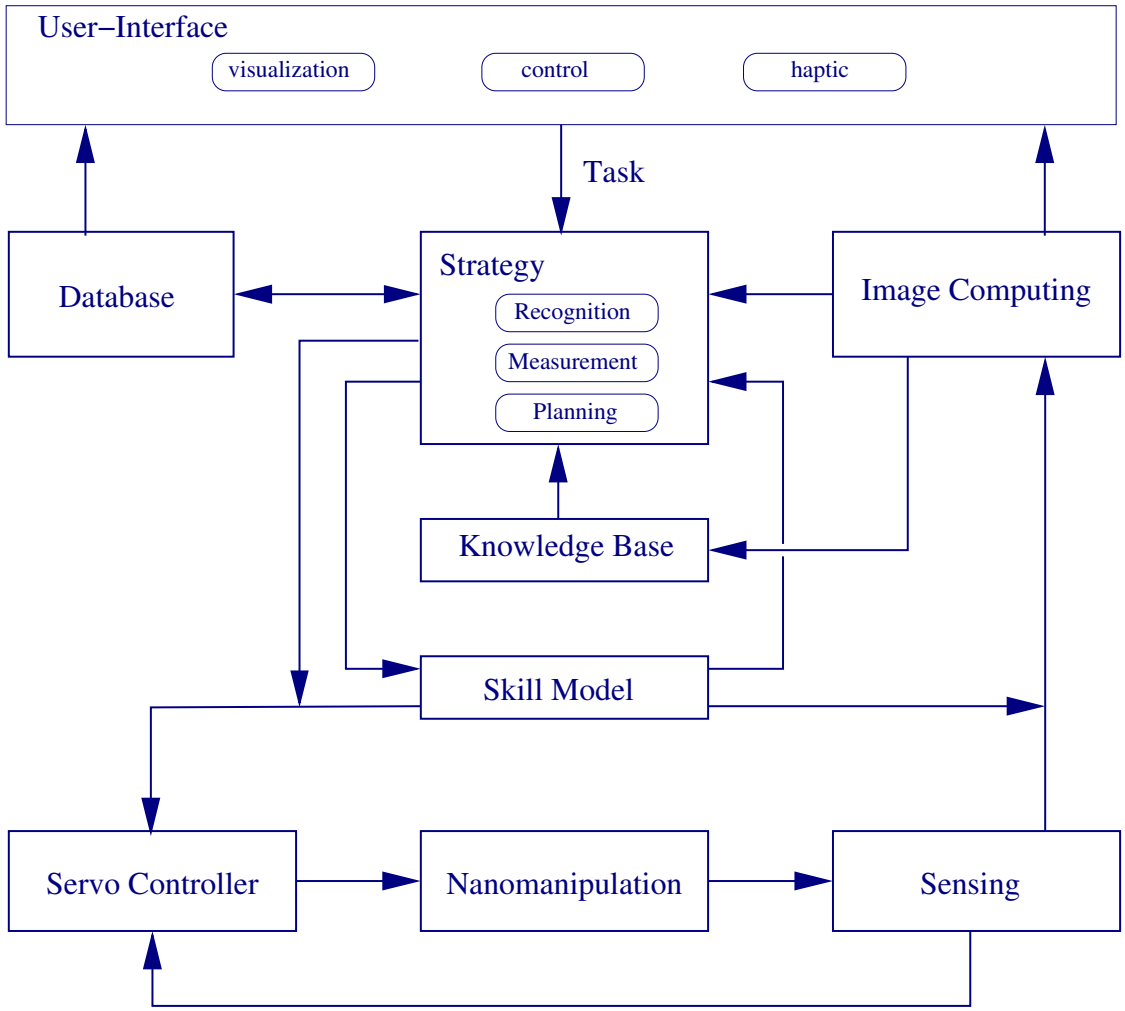
# Automatic Manipulation of Atomic Structures in Hamburg (AMASH)

- tool for automatic nanomanipulation at atomic scale
- manual manipulation and user intervention possible anytime
- target description via graphic editor or algorithmic description
- rule-based pathplanner
- open-end knowledge base

# System Overview



# Workpackages

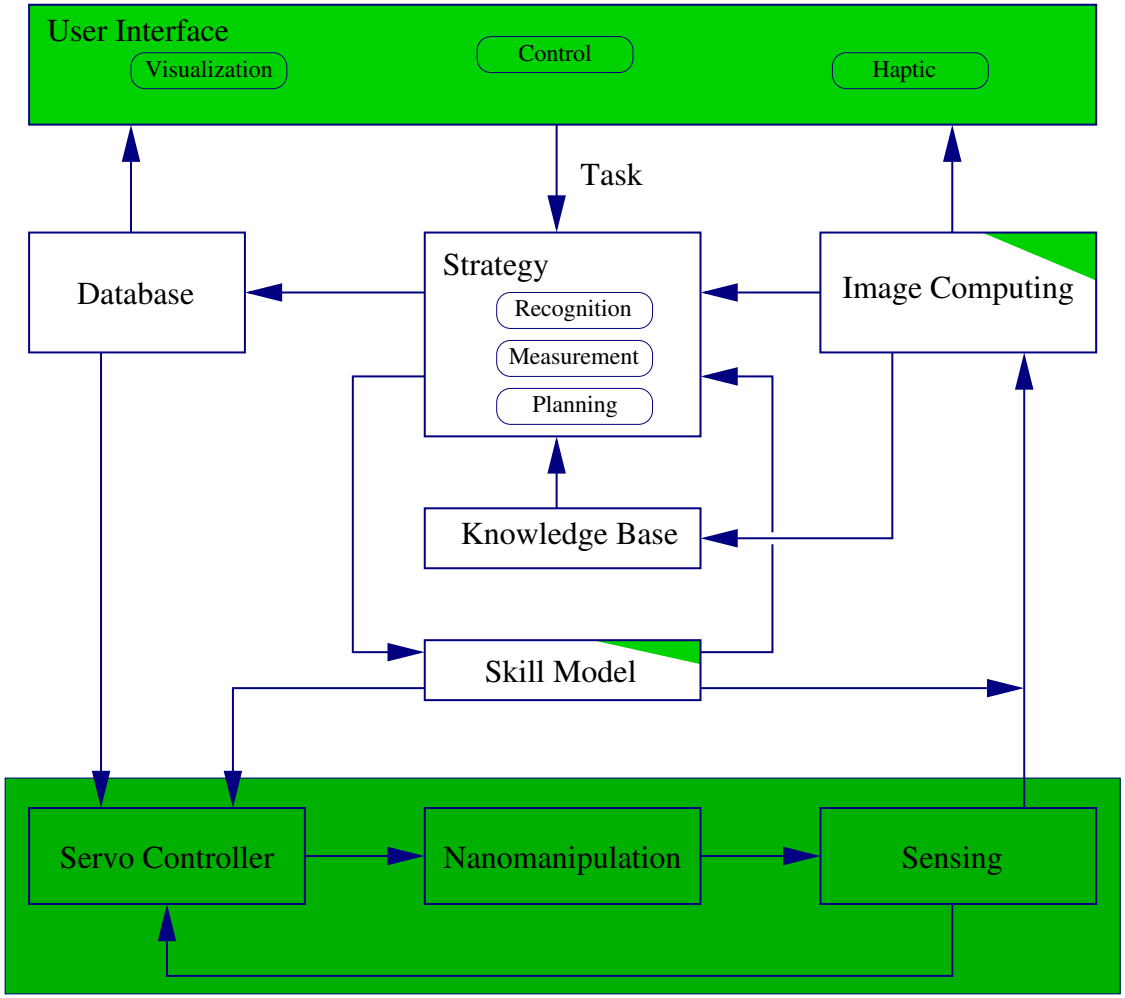
1. enhanced user interface & STM
2. segmentation/labelling of atoms and molecules
3. navigation/calibration
4. manipulation skills
5. planning/simulation

# Enhanced User Interface & AMASH

nanoManipulator from the University of North Carolinas (UNC) nanoManipulator-project:

- enhanced 3D visualization system
- haptic control system
- force-feedback-driven manual manipulation
- basic manipulation skills
- supports teleoperation
- full source code available to us

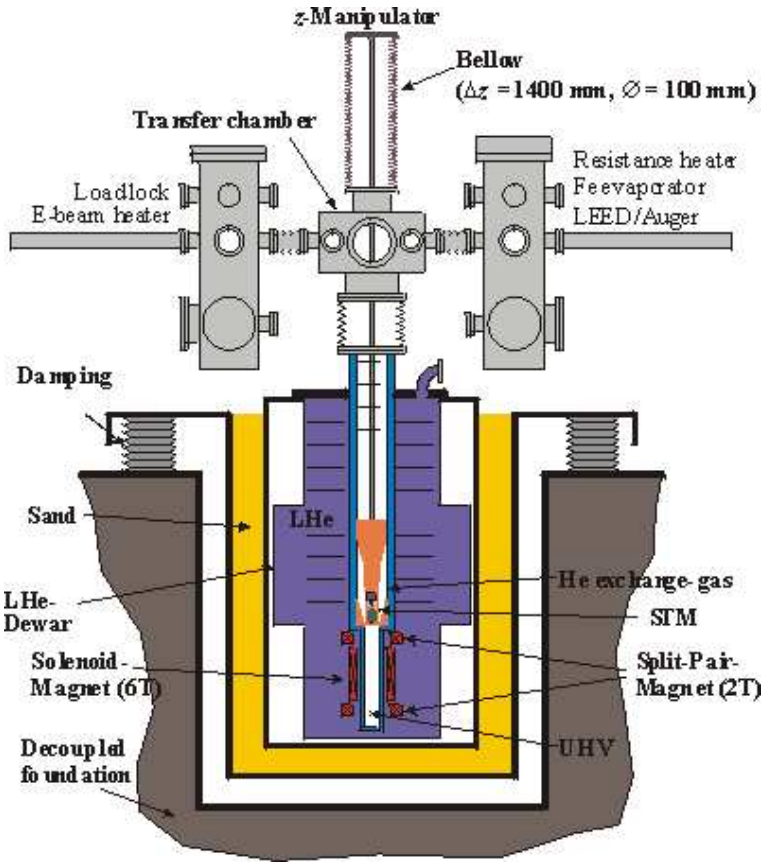
# UNC nM & AMASH




| | |
|---|---|
| green | covered by the nanoManipulator |
| darkgreen | covered by the microscope |

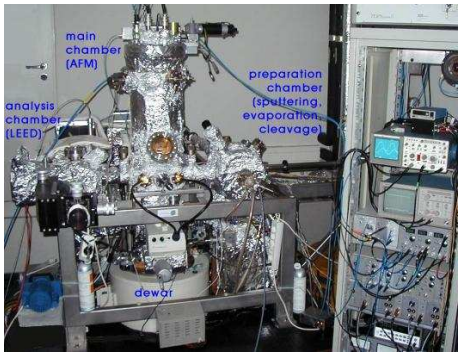
# Hamburg UHV LT-STM & AMASH

- Ultra High Vacuum (UHV)
- Low Temperature down to 6K
- Magnetic field 6T
- Contamination rate $<$ 1 adsobate per 500x500nm per week
- Fe evaporator



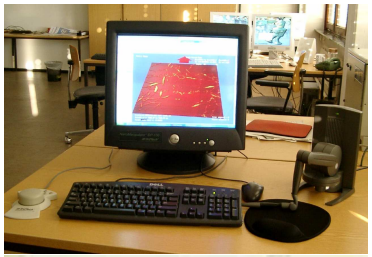
# Measurement System

- TOPS II measurement system from WA Technologie attached to:
  - UHV LT-STM (1)
    - specification see above
  - UHV LT-AFM
    - temperature down to 10 K
    - atomic resolution
  - UHV LT-STM (2)
    - temperature down to 300 mK
    - magnetic field 14 T
- full source code available

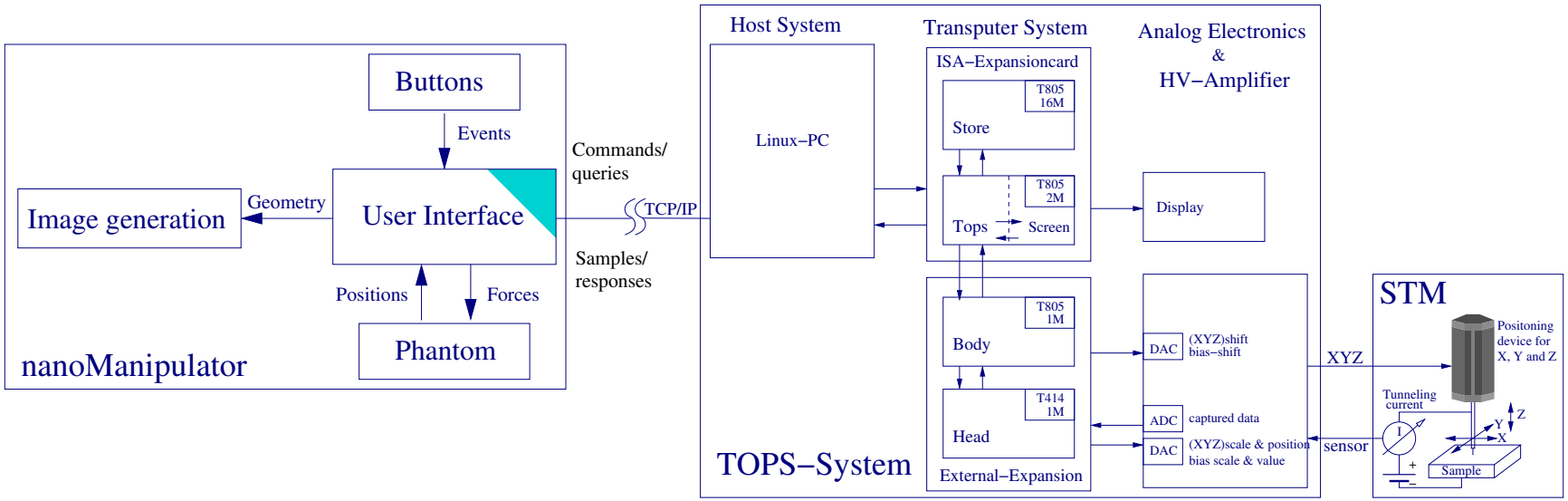



# UNC nM & HH UHV LT-STM

- both user interfaces (primary and nM) should run in parallel
- at least two secondary user interfaces (nMs) should be able to run in parallel
- the architecture of the UNC nM provides an excellent basis for AMASH

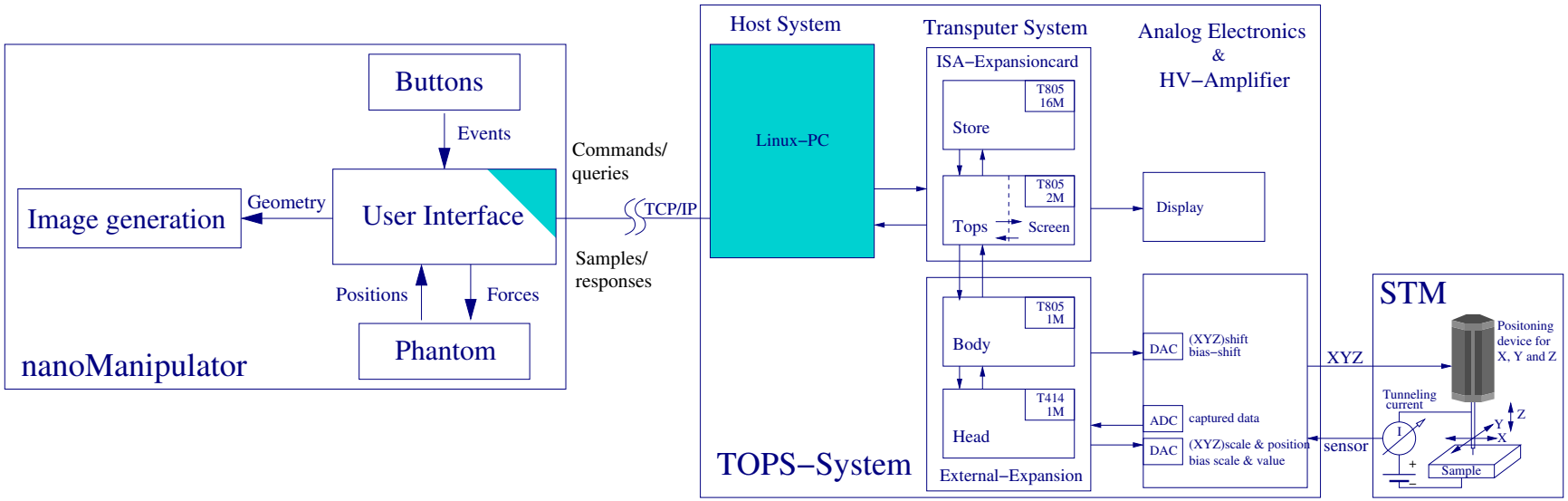


# Integration of nM & STM



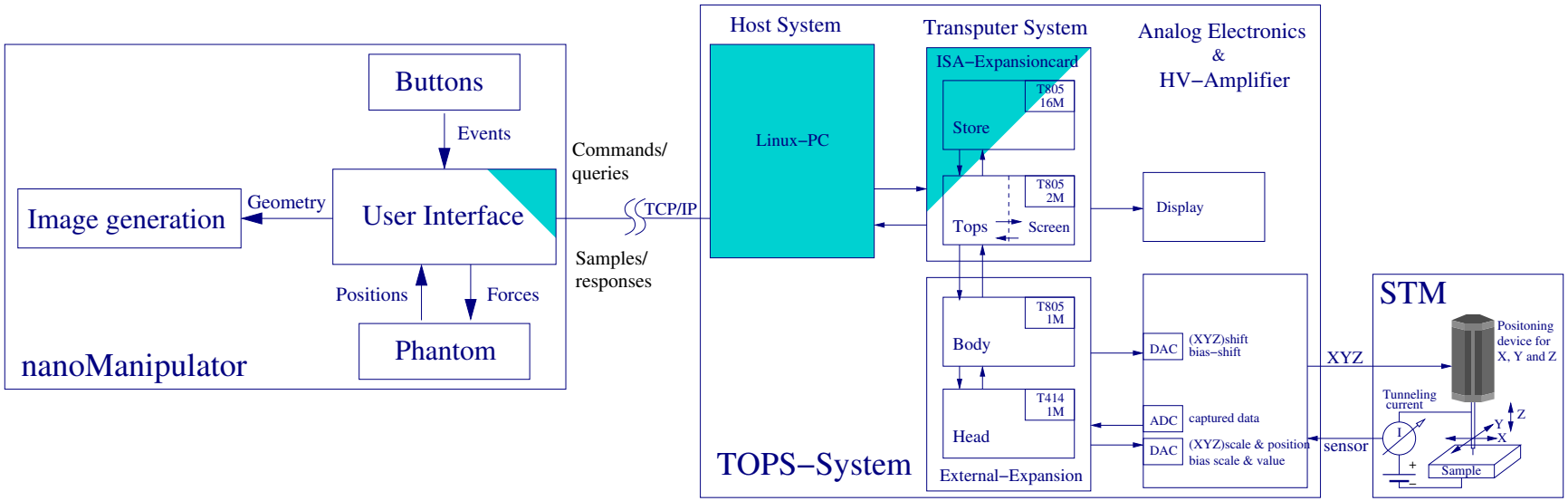

- only minor changes of the nM-software

# Integration of nM & STM




- only minor changes of the nM-software
- the primary user interface of the microscope completely re-programmed

# Integration of nM & STM



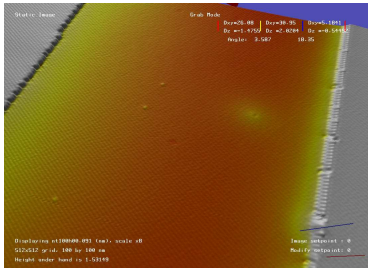

- only minor changes of the nM-software
- the primary user interface of the microscope completely reprogrammed
- some changes of the low-level routines of the measurement-system software also neccessary

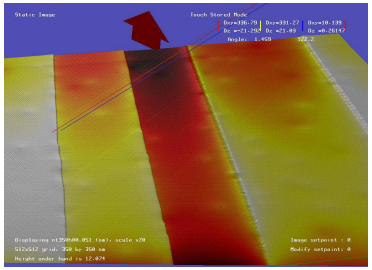
# Requirements for primary user Interface

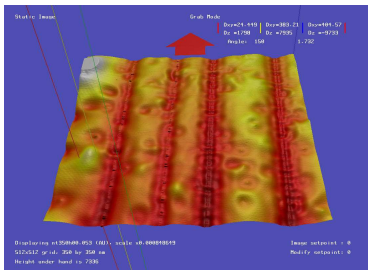
- interface for communication with nM via TCP/IP
- API for controlling the instrument (more flexibility with other microscopes)
- API for IEEE 488 equipment for full control of instruments environment
- script language for rapid prototyping of low-level algorithms
- ability to run instrument in batch mode
- web-interface for monitoring readouts

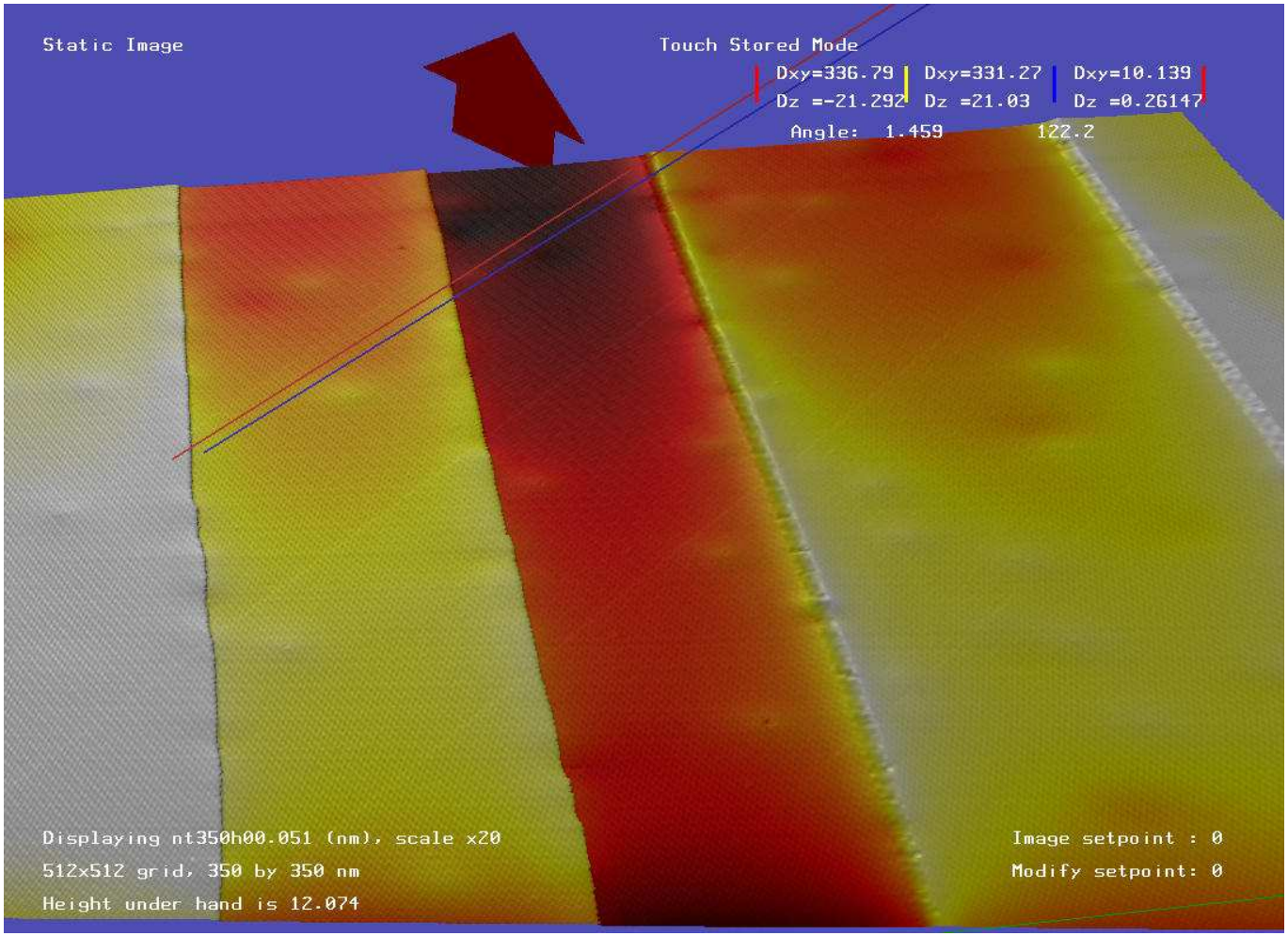
# Results of Integration of nM & UHV LT-STM

- full power of the nM-system is now available to the STM users
- manual manipulation is much more comfortable due to haptic device
- nM-user can access the microscope from all over the world (problem: network latency in manipulation mode)
- excellent platform for developing automation on the atomic scale










Tungsten surface as used for our tests with surface steps and some Fe adsorbat Atoms. The step highlighted by the red and blue line denotes a monolayer step.

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  3. **navigation/calibration**
  4. **manipulation skills**
  5. **planning/simulation**
- Outlook

# Segmentation/Labelling

Robust automatic segmentation/labelling of atoms and molecules:

- Segmentation:
  - several types of adsorbat atoms
  - STM topographic data
  - on-demand local spectroscopy
  - structural and statistical methods

- Labelling:
  - atoms: on/beneath the surface
  - molecules: orientation, shape descriptors

# Navigation/Calibration

- Navigation/Positioning
  - based on results of image processing
  - specialized software-controller
  - off-line training
- Calibration
  - consecutive update and recalibration of internal control
  - Calibrated Synthetic Viewing (CSV) approach
- Drift compensation
  - Kalman filtering
  - restrictive local scan approach

# Manipulation Skills

Hierarchical sensor-based skill library:

- basic skills
  - positioning tool tip
  - moving tool tip
  - pure pushing, pure pulling
  - attain/reattain adsorbat

- advanced skills (composed of basic and acvanced skills)
  - moving (attractive | repulsive | vertical)
  - collision-free path control
  - cleaning area

# Planning/Simulation

- Planning
  - rule-based planning
  - knowledge base with a set of rules for every adsorbat
  - error recovery for uncertainty
- Simulation
  - validating the moves of a path
  - validating the sequence of paths
- Control scheme
  - adjustable autonomy

# Outlook

- realized combination of nanoManipulator and UHV LT-STM not only an excellent platform for AMASH but also eases the usage of the STM
- step by step refinement towards automation
- a working system at every stage of development