

# *Open Design of Manufacturing Equipment*

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## *Overview*

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- ◆ Open Design is a method for designing, testing, and improving manufacturing equipment
- ◆ Open Design provides a framework for sharing design information
- ◆ Open Design is similar to Open Source software
- ◆ This paper:
  - introduces the principles of Open Design
  - reviews on-going projects related to manufacturing equipment

# *Outline*

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- ◆ Introduction
- ◆ Background and Prior Work
- ◆ Open Design Foundation
- ◆ Principles of Open Design
- ◆ Current Open Design Projects
  - Linear Motion Stages and Modular Machine Tools
  - Microfabrication and Nanofabrication Equipment
- ◆ Software Tools for Open Design
- ◆ Summary

# *Introduction*

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- ◆ Advances in design and manufacturing technology have reduced time-to-market
  - CAD, CAE, rapid prototyping,
  - CNC, Flexible Manufacturing Systems
- ◆ Automated manufacturing systems for new products remains a challenge
  - specification, design, fabrication, start-up, and validation consume major portion of time-to-market
  - we need agility: an ability to adapt and reconfigure existing manufacturing automation

# *Introduction*

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- ◆ To achieve agility, manufacturing equipment must be:
  - modular
  - easily reconfigured
  - computer controlled through open interfaces
  - exhibit predictable performance
  - scalable (downward and upward)
- ◆ Agility can be achieved through maximizing reuse, i.e. open collaboration

## *Introduction*

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- ◆ Open Design encourages collaboration in design of manufacturing equipment by:
  - providing incentives to share information
  - providing mechanisms for sharing information
- ◆ Design documentation is shared
  - CAD data, FEA data, spreadsheets, analyses, etc.
- ◆ Performance data is shared
  - precision, reliability, yields, etc.
- ◆ The Internet is a key enabling technology

## *Background and Prior Work*

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- ◆ Principles of Open Design are derived from ideas applied in software development
  - Free Software, Open Source, Copyleft
  - GNU/Linux OS, Apache Web Server, Mozilla Browser
  - Small/modular (object oriented) code
- ◆ “Open Source” adopted in 1998
- ◆ Open Source software has been the *ONLY* force keeping the Internet open, i.e. www, email, and data exchange

# *Background and Prior Work*

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## ◆ “Free Software”

- Richard M. Stallman established GNU Project & Free Software Foundation -- software like scientific knowledge
- “Free Software” ensures the following freedoms
  - run software for any purpose
  - modify source code to suit your needs
  - distribute copies of original software/source code (gratis or fee)
  - distribute modified copies of software/source code (gratis or fee)
- These freedoms are protected through legal license agreements
- “Free Software” struggled with acceptance
  - confusion between *liberty* and *gratis*
  - required entirely new business models



# *Background and Prior Work*

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## ◆ Openness in hardware

- OpenCores ([www.opencores.org](http://www.opencores.org)), established to develop open semiconductor cores
  - “Design can be free in exactly the same senses as software can be free” -- OpenIP Core Definition

## ◆ Mechanical design, and especially manufacturing equipment, can benefit from similar open exchanges of information

## *Open Design Foundation*

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- ◆ Open Design Foundation (ODF) was founded as non-profit organization in 1999
- ◆ Objectives of the ODF:
  - support open design
  - evaluate open design license agreements
  - distribute documentation for open designs via internet
  - recommend software for exchanging information
  - author instructional documents

*<http://www.opendesign.org>*

# *Principles of Open Design*

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## ◆ Open Design is

- publicly publishing design documentation
- granting conditional rights to use, modify, or redistribute the original or modified design documentation
- granting conditional rights to manufacture and distribute artifacts based upon the original or modified design documentation

# *Principles of Open Design*

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- ◆ License agreements ensure freedoms:
  - documentation of a design is available for free
  - anyone is permitted to use or modify the design by revising the design documentation
  - anyone is permitted to redistribute the original or revised documentation for free or for fee
  - anyone is free to produce/distribute artifacts for free or fee
  - modifications must be published if artifacts are distributed
- ◆ License requirements are outlined in the *Open Design Definition*
  - standard for suitable license agreements
  - living document published at [www.opendesign.org](http://www.opendesign.org)

# *Principles of Open Design*

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## ◆ Common points of confusion:

- Open Design is not Public Domain
  - documentation is not available for public domain designs
  - obligation to publish documentation on revised designs insures that early contributors will have access

*(Much equipment sold today is partially or fully public domain)*
- Open Design is not Open Architecture
  - documentation on more than the interface must be published
- Open Design is not a replacement for standards
- Open Design does not oppose intellectual property
  - open design allows proprietary and free systems to be used

# *Principles of Open Design*

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- ◆ Longevity is critical to agile, reconfigurable, manufacturing systems
  - Components regulated by standards
    - e.g. NEMA motors and AGMA gears
  - Market / Technology leaders
    - e.g. Heidenhain encoders
  - Build in-house
    - e.g. Structure of machine
  - Open Architecture -- ability to blend components
    - e.g. Machine controllers, drives, sensors

# *Principles of Open Design*

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## ◆ Analogy between Internet and Open Equipment

WWW  
e.g. HTML Standard  
↓  
e.g. Apache Webserver  
↓  
Rapid development and  
expansion of  
WWW

Open Equipment  
e.g. NEMA Standard  
↓  
e.g. Open Linear Stage  
↓  
Rapid development of  
agile, reconfigurable  
equipment

# *Current Manufacturing Equipment Projects*

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- ◆ Linear Motion Stages for Modular Machine Tools
  - Machine Dynamics Lab, MIT (S. Nayfeh)
  
- ◆ Open Microfabrication and Nanofabrication Equipment
  - Precision Systems Lab, Univ. of Kentucky (R. Vallance)



## *Motion Stages for Modular Machines*

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- ◆ Linear and rotary stages are *the* functional building blocks of machine tools
- ◆ “Buy” Commercial vs. “Build” Custom
  - Commercial stages require less design effort
  - Commercial stages are often less expensive
  - Requires selection among quantized performance
  - Fixed size and shape make them difficult to integrate into machine
  - Precision and accuracy is difficult to predict -- little performance data
- ◆ Custom stages at the heart of the process and commercial stages in less critical operations

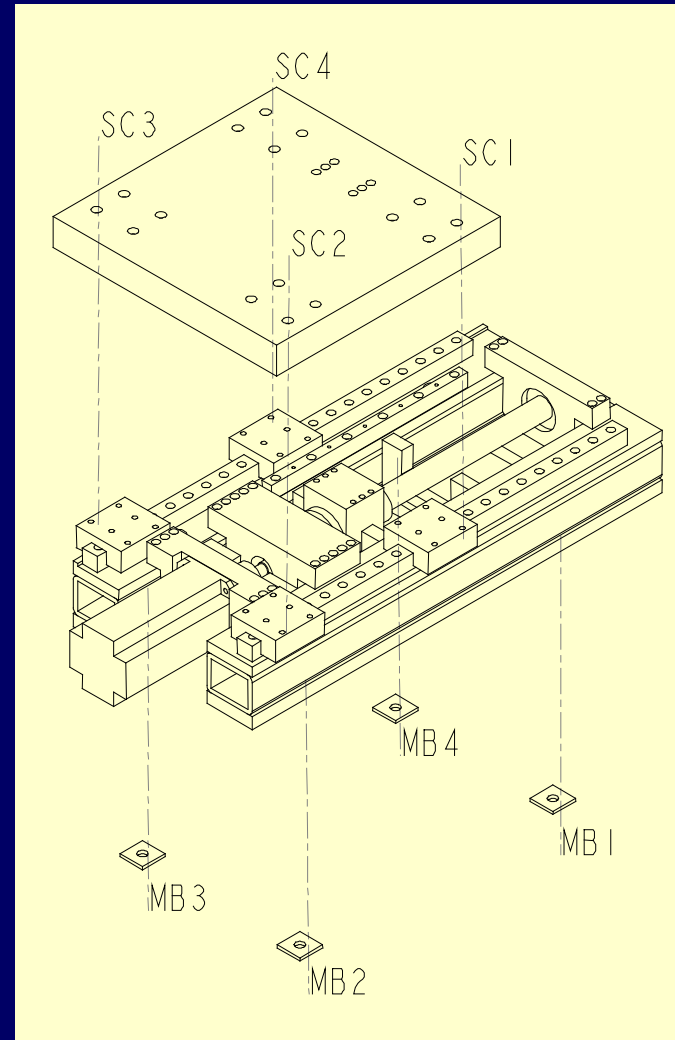
## *Motion Stages for Modular Machines*

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- ◆ Open Designs provide a new alternative in the “buy” vs. “build” decision
  - Open Design stages can be used in proprietary machines (like commercial stages)
  - Open Designs can be modified for better integration
  - Open Designs can be built with in-house production controls
  - Emphasize publishing analysis techniques and performance data
  
- ◆ Open Designs should have predictable performance -- even if they are modified or scaled

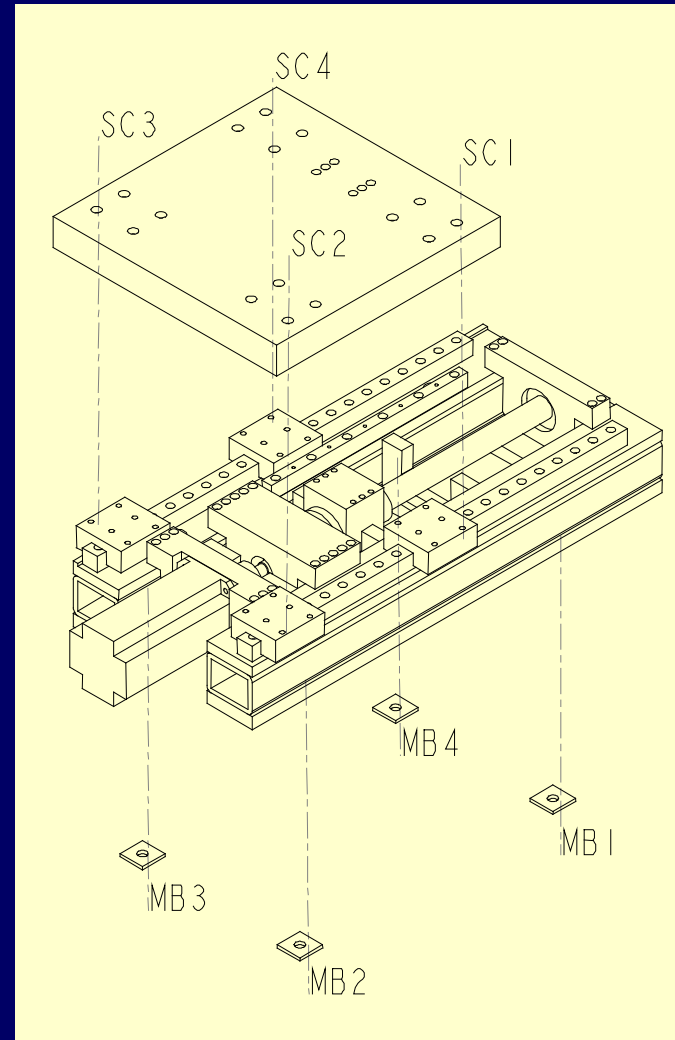
# *MIT Linear Motion Stages for Modular Machines*

- ◆ Parametric solid models driven by analysis script that generates a plausible design
- ◆ Initial design revisions use a conventional construction
  - rotary motor and encoder
  - ballscrew drive
  - modular linear-guide bearings
  - machined and ground welded structure



# *MIT Linear Motion Stages for Modular Machines*

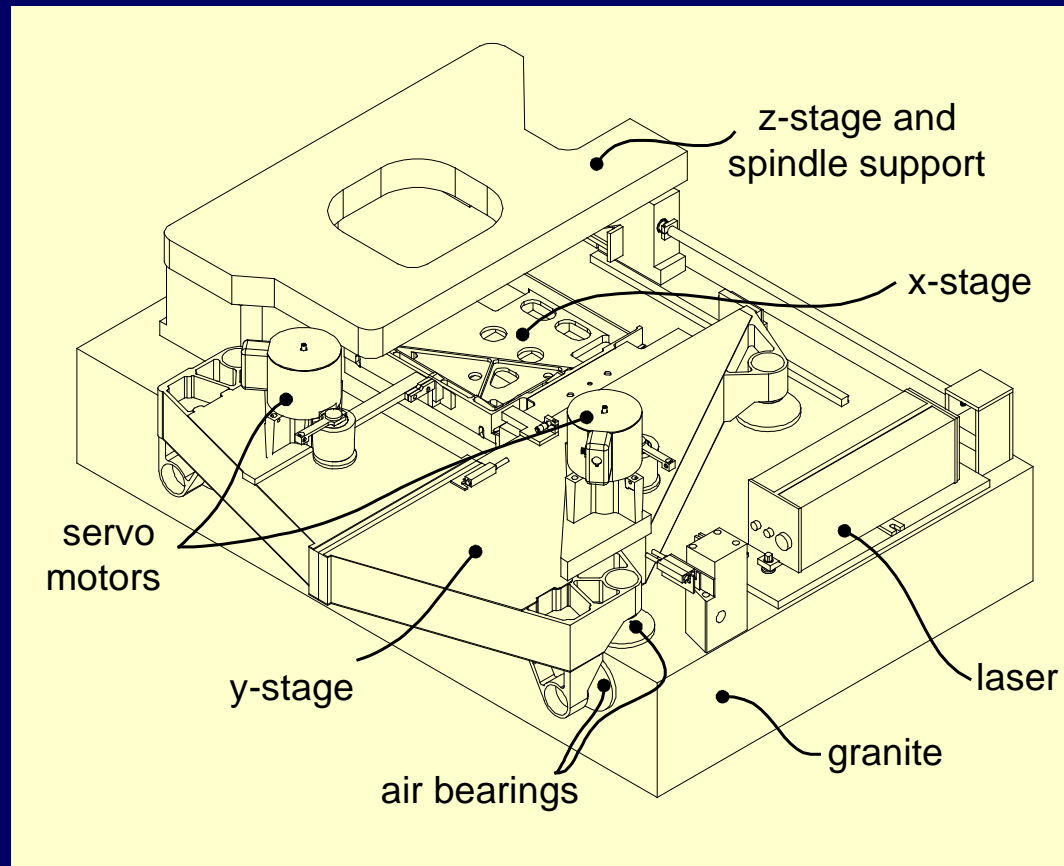
- ◆ Predictable dynamic performance
- ◆ Analytical Vibration Model
  - Method of Substructuring [Mead]
  - Stages bolted at 8 hard points
  - Knowledge of blocked and free receptances at hard points
  - Combine receptances in machine “impedance budget”
- ◆ High damping -- replicated viscoelastic dampers



# *UK Open Micro EDM Machine*

## ◆ Reconfigure existing x-y stage

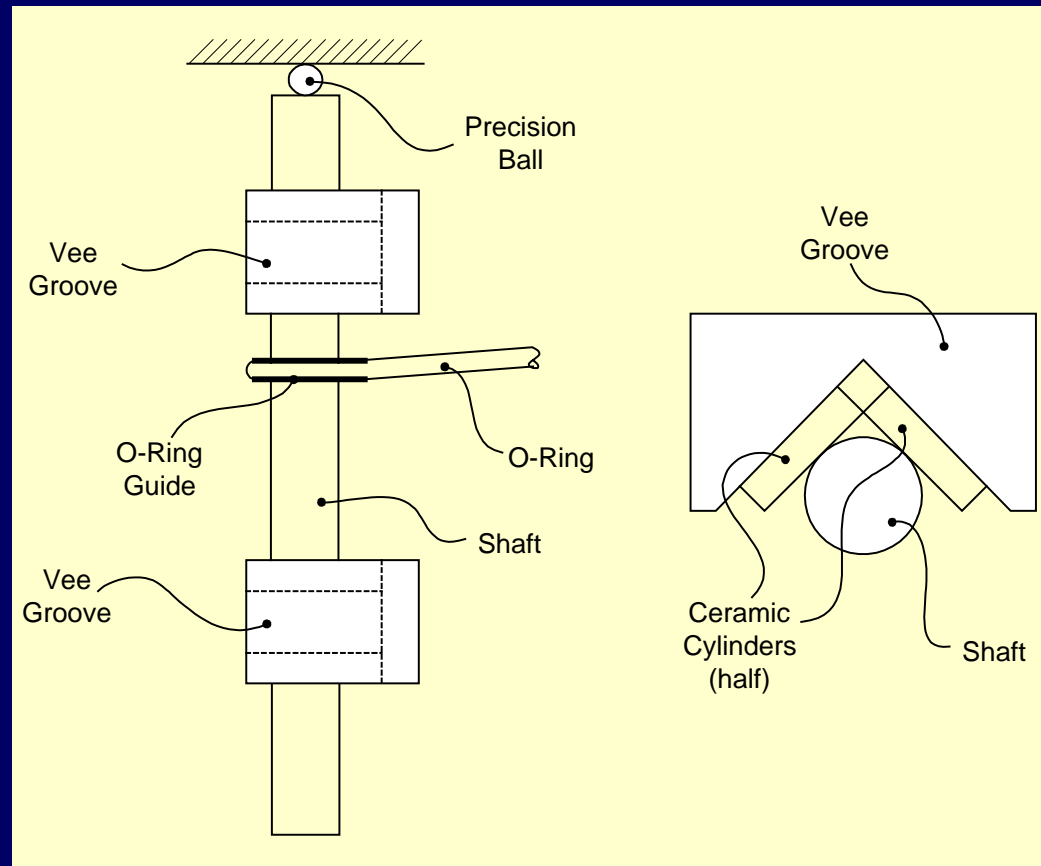
- Granite base
- Vacuum preloaded air bearings
- plane-mirror laser interferometer
- friction-drive transmission
- rotary motors and tachometers



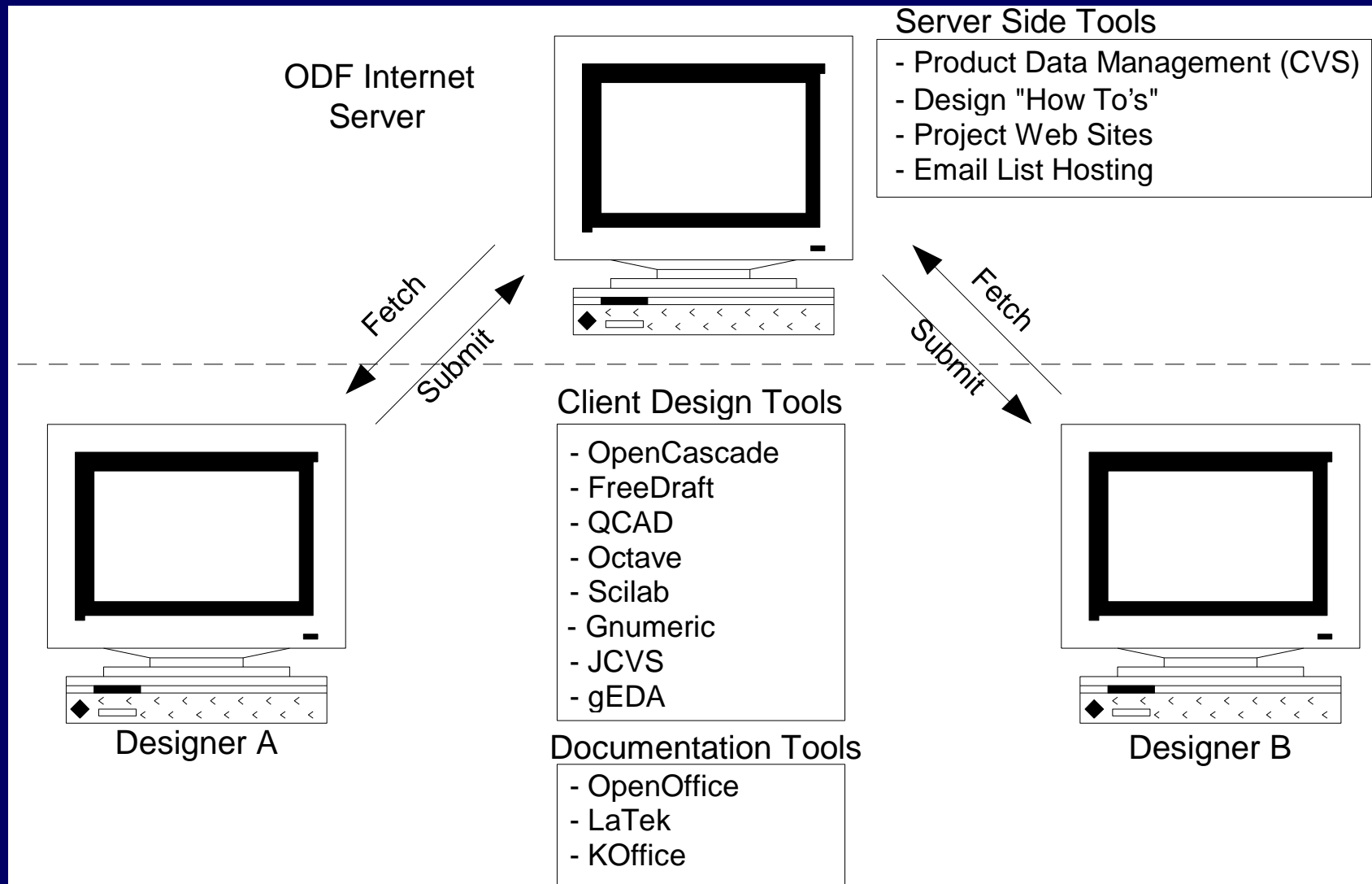
# UK Open Micro EDM Machine

## ◆ Concept #1: Kinematic Constraint

- 5 contact points
- Axial preload
- Rotary motor with belt drive
- Actuate precision ball for axial motion
- errors due to shaft roundness



# Software Tools for Open Design



## *Summary*

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- ◆ Open Design is a framework for sharing design information
  - Principles derived from Open Source software
  - License agreements regulate information exchange
  - Software tools enable collaborative exchange
- ◆ Open Design compliments modular, scalable, and reconfigurable machines
  - Linear motion stages (MIT)
  - Micro and nano fabrication equipment (UK)
  - Invited to start new projects or participate in current projects



## *Contact Information*

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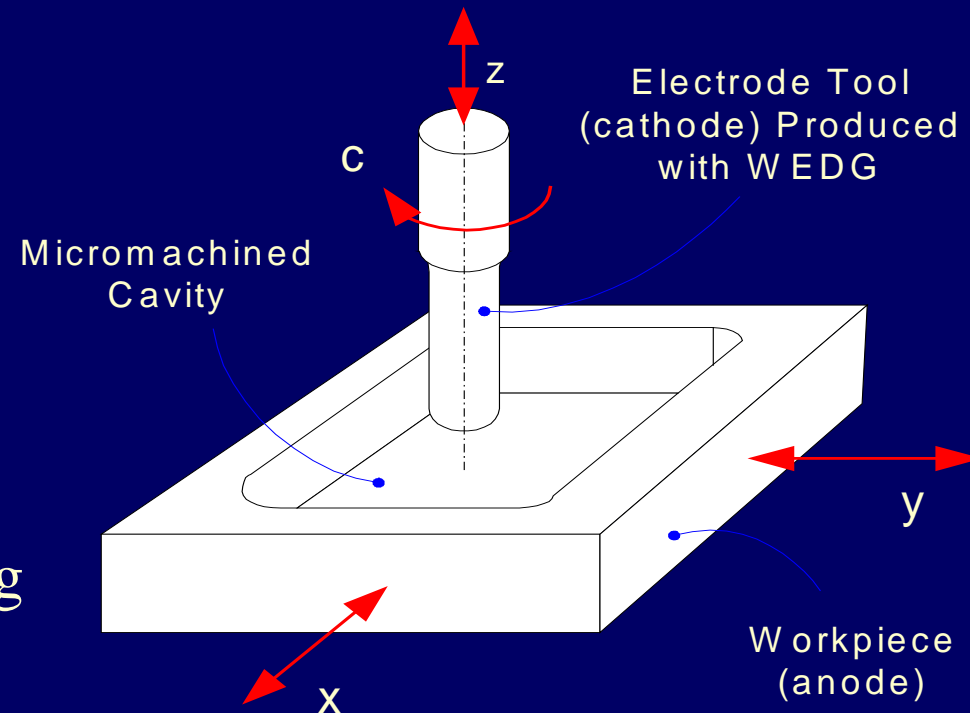
[www.opendesign.org](http://www.opendesign.org)

# *Backup Slides*

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# *UK Open Micro EDM Machine*

- ◆ Develop and construct a machine for 3D micromachining using electro-discharge micro milling [Yu et al.]
- ◆ Electrodes generally produced using wire electro-discharge grinding (WEDG) [Masuzawa]



## *UK Open Micro EDM Machine*

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- ◆ Open Design of a spindle with integral z-axis
- ◆ Specifications:
  - Fine Motion Z-Axis: 200 micron travel range
  - Low Speed: 3000 RPM or less
  - Little torque required (no mechanical cutting)
  - Small disturbance forces

## *Recommended License Agreements*

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- ◆ Open Designs consist of hardware and software
  - For Software
    - GNU General Public License (GPL)
    - GNU Lesser GPL
  - For Hardware Documentation
    - Free Documentation License

# *Software Tools for Open Design*

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- ◆ Seek common database and file formats
- ◆ Recommend software that is available and accessible to anyone that wishes to contribute or use open designs
  - Open Source software is free (as in gratis) to all users
- ◆ 3D solid modeling remains “closed”
  - Proprietary database formats restrict reuse and translations lose design intent
  - OpenCascade
- ◆ Concurrent Versioning System (CVS) for product data management

## *Open Design is similar to Scientific Method*

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- ◆ Science involves models of natural phenomena
  - Hypothesis ... Theory ... Law
  - This evolution depends upon ability to test and refine hypotheses/theories based upon data
  - Science is collaborative effort involving open exchange of information
    - Share hypotheses, theories, and laws
    - Share experimental setups and results
    - Share expenses
  - Human Genome Project

# *“The Cathedral and the Bazaar”, E. Raymond*

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## ◆ Cathedral Approach -- GNU Method

- *“I believed that the most important software needed to be built like cathedrals, carefully crafted by individual wizards or small bands of mages working in splendid isolation, with no beta to be released before its time.”*

## ◆ Bazaar Approach -- Linus Torvalds’ Method

- *“No quiet, reverent cathedral-building here -- rather, the Linux community seemed to resemble a great **babbling bazaar** of differing agendas and approaches out of which a coherent and stable system could seemingly emerge only by a succession of miracles.”*



## *Benefits of Open Designs?*

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- ◆ Increase reconfigurability and interchangeability
- ◆ No need to reinvent the wheel
- ◆ Debugging of processes and equipment
- ◆ Develop robust machine and system designs
- ◆ Share development expenses
- ◆ Increase design longevity
- ◆ Establish “standard” common designs
- ◆ Reduce cost of ownership and support
- ◆ Eliminates single-source availability
- ◆ Promotes 3rd party enhancements

# *Open Design Definition, Slide #1*

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## ◆ Free Redistribution

- Licenses may not restrict any party from selling or giving away an artifact as a component within an aggregate artifact

## ◆ Free Design Documentation

- Licenses must require that an embodiment include design documentation or ensure that documentation is available for no more than a reasonable reproduction cost (preferably via Internet download). Documentation must be in a preferred format for modifications.

## ◆ Derived Works

- Licenses must allow modifications and derived works, and they must allow them to be redistributed under the terms of the original license

## *Open Design Definition, Slide #2*

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### ◆ Integrity of Designers' Documentation

- Licenses may restrict documentation from being distributed in modified form only if the license allows distribution of "retrofit documentation". Licenses must require derived works to carry a different name or version number than the original design.

### ◆ Discrimination

- Licenses must not discriminate against any person, group of persons, or any specific field of endeavor

### ◆ Distribution of Licenses

- The rights attached to an embodiment/artifact must apply to all to which the embodiment/artifact is redistributed without the need for executing an additional license

# *Necessary Preconditions for Open Design?*

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- ◆ a community of participants,
- ◆ participants are designers and users
- ◆ low economic cost of converting the design to a useful embodiment
- ◆ low cost of an imperfect embodiment
- ◆ projects should be initiated with a pre-existing design
- ◆ the community should perceive some promise to the pre-existing design
- ◆ the project leader must recognize good designs (and also hopefully originate good designs)
- ◆ the participants must possess certain skills
- ◆ a medium for effective information sharing (such as internet)
- ◆ participants should join the effort by self-selection or volunteering

## *Open Design Definition, Slide #3*

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- ◆ License must not be Product Specific
  - If a subset of an open design is extracted from an aggregate open design, then all rights from the aggregate design must be maintained with the subset design.
- ◆ License must not contaminate other designs
  - Licenses must not restrict other embodiments/artifacts that are distributed along with an Open Design embodiment/artifact