Overview of scaling issues: macro- to meso-scale systems

Stuart T. Smith and Richard M. Seugling, Center for Precision Engineering, UNC Charlotte, NC 28223

Summary

This paper addresses some of the issues associated with scaling the size and accuracy of conventional machines and instruments from macro down to meso-scales and beyond. Although, small scale machine tools and instruments, such as lathes, have been built for many years in the watch-making and other industries, a limited number of these types of systems have been incorporated into modern manufacturing. Most of the small scale machine tools and instruments are merely a scaled down version of a normal machine, but the accuracy or precision is no better than that of a high-quality macro-machine/instrument. In an effort to identify areas of future research, fundamental considerations are used to assess the fidelity of possible approaches to common design problems. Key features common to the systems being considered are the ability to provide work in a controlled manner and the use of sensors for feedback of process condition, in particular, relative motions. From this we are able to consider two areas to be addressed;

1. Actuators to provide position and/or generate work.
2. Sensors for detecting surfaces and measuring relative motions.

These considerations provide a guide to those techniques that scale favorably using current technologies. However, machine systems are considerably more complex than their parts and there are a large number of other factors that must be considered. As a first step toward identifying future machine design approaches, we have undertaken an assessment of two representative systems, a coordinate measuring machine (CMM) and a lathe.

This abstract represents a condensed summary of an extensive review currently being prepared for publication.

Overview

Precision at macroscopic scales is usually considered to start when range to accuracy or range to resolution performance is around 1 part in 10^5 or better. A similar criterion applied to meso-systems immediately implies that total errors should be below 10^{-8} m or so. In many processes, to control to the relevant precision requires metrology and actuation systems of considerably better performance. Consequently, simple considerations indicate that dimensional metrology and machine design for small-scale machines must achieve reliable measurement and positional accuracy at, or approaching, nanometer levels. Major differences are

1. It is likely that the metrology system will be integrated with the manufacture and/or assembly process.
2. There are likely to be more metrology systems, possibly one for every device.
3. It must be possible to manufacture these cheaply and utilize automated assembly.
4. Power consumption must be low.

5. New methods of communication and data handling will be required.
6. It will be necessary to achieve bandwidths comparable to the manufacturing process and higher resolution than normally required of common shop-floor metrology instruments.
7. Alignments and subsequent errors will be particularly difficult to adjust and measure.
8. Measurement frames encompassing the whole instrument, and therefore modular, should not add significant cost.
9. Evaluation of force and measurement loops will be critical to the performance of the system.

As stated, to achieve precision, two major enabling technologies of meso and smaller scale systems will be small actuator and sensor systems. Fortunately, there is a limited number of possibilities enabling a reasonable assessment of the relative merits of available options in terms of the effects of scaling.

Actuator methods currently considered include; piezoelectric, electrostatic, electromagnetic, magneto-strictive, hydraulic/pneumatic, thermal and shape memory. One particular measure of the fidelity of these actuators is the theoretical maximum amount of work and/or power that can be produce per unit volume occupied by the actuator (called the work density or power density). Considering specific implementations it is found that some of these methods maintain performance (piezo-electric, hydraulic, electrostatic) as scales reduce while electromagnetic actuators tend to degrade and thermal-based actuators appear to improve. Identification of the scales at which different techniques dominate will help the designer to select the appropriate technology for a given application. Such analysis also provides information about other parametric scaling factors such as drive voltage amplitudes, forces etc. There are also a number of implementation issues that will be presented.

A similar approach has been applied to sensors for small scale systems such as optical (line scale, interferometric, diffractive, position sensitive detectors) and electromagnetic. In this later category it is necessary to split the categories into transducers and displacement sensor systems. In our study we have attempted to identify the relevant scaling parameters and assess their relative influence as scale reduces.

Below, is presented an overview of the issues that we identify when trying to reduce the scale of conventional CMM's and lathes.

CMM

Coordinate measuring machines (CMMs) are in use by a wide range of industries covering a broad array of applications[i]. Common state-of-the art CMM systems have work volumes that are on the order of cubic meters with micrometer measurement uncertainties[ii],[iii]. There have been high accuracy, small-scale CMMs developed at The National Physical Laboratory in the U.K.[iv]. This type of precision[*] allows for comprehensive analysis of parts and subsequent processes at an extremely high level. This type of performance does not come without costs. To acquire this performance level, metrology systems, such as CMMs, require special environmentally stable areas and operate at a considerably slower pace than that of standard manufacturing processes. To

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[*] Precision, in this case is defined by the ratio of operation range to the minimum detectable resolution of the system.

provide the required information, CMMs are comprised of a number of different systems working in unison. These can be differentiated into a number of different categories as shown in Table 1.

Table 1: Scaling a coordinate measuring machine.

Components	Macro	Meso	Micro
Structure	Orthogonally stacked precision slides with well aligned scales. Metrology and motion control structures are the same.	Precision slides not available and alignments considerably more difficult. Metrology and motion frames have little additional material cost.	Open loop, ill defined.
Slide ways	Air bearings. Wide rails enable low rotation errors. Large forces, high stiffness.	Air bearing less suitable. Flexures have limited range for a small relative volume.	Use flexure
Probe	Large sphere on a rigid rod attached to flexure-based load cell.	Scaling macro requires novel manufacture. AFM not robust enough for a manufacturing environment. Probe and specimen mass may be comparable.	AFM made using MEMS technology.
Scales	Scales represent small volume of machine.	Nothing commercially available, lots of research in meso-scale optical systems.	No scales, nor metrology systems for 6 dof calibration/compensation.
Drives	Feedscrew, linear motors	Motors lose power in proportion to volume and radius. PZT has inadequate range.	PZT
Connectors	Insignificant.	Limited in size, current state of art is cell phone/laptop. Even wireless receivers are relatively large.	Significant portion of the instrument
Controller	Adjacent cabinet	Cell phone also state of art. Wall power supplies probably smaller than cell phone battery.	Medium sized cabinet

Lathe

A machine tool, almost by definition, functions as an instrument for doing work to a specimen or blank to produce a functional product. To provide work to a sample at nanometer levels the system must have high stiffness and high positional accuracy. A question arises, how much work is required to produce a part whose geometry is on the order of millimeters? For a simple lathe system as the part gets smaller the influence of the machine on the part increases quite dramatically. Deformation during the manufacturing process can cause large errors in the designed geometry and subsequently in the performance of the part in operation. Table 2 represents some of the most influential components of a common lathe and what types of systems could be used to scale the size and accuracy. A miniature machining system has been developed in Japan that machines work pieces on the order of 0.3 mm diameter[v].

Table 2: Scaling a lathe.

Components	Macro	Meso	Micro
Structure	Orthogonally stacked ground and lapped slides with linear scales. Metrology and motion control structures are the same.	Precision slides not available and alignments considerably more difficult. Metrology and motion frames have little additional material cost.	Open loop, ill defined.
Slide ways	Hydrodynamic bearings. Wide rails enable low rotation errors. Large forces, high stiffness.	Air bearing less suitable. Flexures have limited range for a small relative volume.	Use flexure
Tool	Common tool steel or carbide.	Diamond tipped.	AFM tip made using MEMS technology.
Scales	Scales represent small fraction of machine volume.	Nothing commercially available, lots of research in meso-scale optical systems and scales.	Currently, no scales, nor metrology systems
Drives	Motor driven feedscrew, linear motors	Motors lose power in proportion to volume and radius. PZT has inadequate range.	PZT, Electrostrictive, Magnetostrictive.
Connectors	Insignificant.	Limited in size, current state of art is cell phone/laptop. Even wireless receivers are relatively large.	Significant portion of the instrument
Controller	Adjacent cabinet, integrated into machine cabinet.	Cell phone also state of art. Wall power supplies probably smaller than cell phone battery.	Medium sized cabinet

Problems with scaling of these types of machine

A major problem is that if systems are produced by the same manufacturing processes, tolerance will be independent of scale whereas the effects of these tolerances may scale unfavorably.

Examples.

1. Bearing tolerances can be accommodated by interference fits to remove play. However, as the bearing gets progressively smaller, the tolerance must scale for a given stress in the interference fit. This is not possible if the process is not refined or changed.
2. Angular errors are inversely a function of the separation of the two rails of a slideway. As the separation reduces these errors increase. However, as rotational errors increase there is a tendency for the error itself to produce misalignment forces that propagate the error.

Both of the above examples indicate the possibility that scaling not only increase the errors that exist at macroscopic scales but can also promote further, and sometimes new, disturbances that degrade performance. The information shown is a rudimentary representation of extremely complex systems, which illustrates the variability of components as they scale. Further research in these areas will need to be undertaken in order to more fully account for the issues associated with which components or technologies should be adopted and adapted for the meso-, micro- and nano-scale machinery and instrumentation.

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[i] Bosch, J.A., 1995, *Coordinate Measuring Machines and Systems*, Marcel Dekker, Inc., New York, NY, 444 pgs., ISBN: 0824795814.

[ii] *Carl Zeiss, Inc*., UPMC CARAT Universal Precision Measuring Centers, December 2002, <http://www.zeiss.de/us/imt/home.nsf>.

[iii] *Brown&Sharpe, Inc*., Product Detail, PMM-C, December 2002, <http://www.brownandsharpe.com>.

[iv] Peggs, G. N., Design for a compact high-accuracy CMM, *CIRP Annuals – Manufacturing Technology*, **48** (1), pg. 417-420.

[v] Lu, Z. and Yoneyama, T., 1999, Micro cutting in the micro lathe turning system, *International Journal of Machine Tools & Manufacture,* **39** (7), pg. 1171-1183.