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Scalability of precision design principles for machines and instruments

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ABSTRACT

The implementation of precision engineering principles in the design of precision systems is fundamental to achieve high accuracy. Although these principles may be independent of the system working range, their implementation is not. The working range, the accuracy, and the load of the system limit, for instance, the selection of materials, the structural design, or the positioning system. This article analyzes the applicability of precision engineering design principles depending on the working range of the system in order to establish their scalability or lack of it in small, medium, and large range machines and instruments.

1. Introduction

For more than 60 years the demand for precision manufacturing of components for applications such as electronics, energy, astronomy, and micro- and nanotechnology has been increasing [208]. The functionality of these products depends on the precision of the manufacturing and metrology systems, often requiring less and less positioning or measurement uncertainty. Back in 1974 Taniguchi [195] proposed a plot indicating such an evolution of precision manufacturing machines and instruments as a function of time from 1900 to beyond 2000. This graph predicted the capability to deterministically 'nano-process' materials at atomic levels in the 21st century. Nowadays, the importance of increasing precision is not only present at micro- or nano-level, but also in other industrial sectors that demand high-precision systems, making precision engineering significant in practically every field and industrial sector, from semiconductor industry, power generation, to astronomy and gravitational research [185].

The final accuracy [101] and precision [154] of a system (instrument or machine) are affected by the deviations caused by geometric, kinematic, and dynamic effects [176] that need to be minimized by applying precision engineering design principles in a deterministic way. This idea of determinism is described from an historical point of view by Evans [49] giving an overview of advances in precision engineering along the history and in the field of design in the 19th, and, mainly in the 20th century, with the development of all kinds of measuring instruments and precision machines. Precisely, in the 20th century Loxham [123], Bryan [18,20], and Donaldson [38], among other authors, formally introduced, promoted, and implemented the deterministic approach in order to solve practical precision design problems. Since then, design principles of precision machines have been studied by many authors over the years [74,12,134,137,176]. McKeown compiled "eleven principles and techniques" of precision machine design in 1986 [134]. Teague and Evans formulated mechanical design aspects for precision instrument design in 1989 [196]. On the basis of those works, Schellekens et al. reviewed and updated the status and trends of design for precision principles in 1998 [176].

By analyzing these principles, it is inferred that design for precision encompasses multiple domains, including not only materials and mechanics but also electronics, control, thermo-mechanics, dynamics, and software [176]. For this reason precision engineering has been described as a 'new grouping of scientific and engineering skills' [135] for manufacturing to tolerances smaller than one part in 10^4-10^5 [91,134]. This definition refers to relative accuracy, understood as the ratio of tolerance to dimension, whilst the absolute dimensions of the system can be of any size, from microchips to large-scale telescopes [208]. This idea of precision engineering applied to systems with different sizes or working ranges is also present in the general definition proposed by Leach and Smith [111], that establish that "*the goal of precision engineering design is to create a process for which the outcomes are deterministic and controllable over a range of operation, with unpredictable deviations from a desired result being as small as is physically and economically possible*".

Based on this idea, in this paper, precision systems will be classified according to their working range and comprise both precision measuring instruments, whose output is information, and precision machines, whose output is a component or a final product.

Implementing precision engineering principles in the design of the aforementioned systems is required to achieve low positioning or measurement uncertainty in their performance. Precision design principles applied for all the precision systems are basically the same and are mainly based on the mentioned compilation made by McKeown [134]. Nevertheless, there are also some interesting and important differences when designing a precision system with a small, medium, or large working range. That working range and the accuracy of the system limit the selection of drives, actuators, components, sensors, and materials which in turn constrains the architecture of the system. For

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instance, piezo actuators are capable of providing position resolutions of less than one nanometer [139] and they are currently used in many nanopositioning stages [30,109,220]. However, even with flexure mechanisms amplifying the motion, the maximum stroke is usually limited to about one millimeter [96,194]. Thus, electromagnetic motors are commonly used in applications that require a larger range of motion. In addition, large systems are extremely sensitive to environmental influences [177]. While a temperature and vibration controlled environment is crucial to ensure submicrometer accuracy in ultra-precision systems, when measuring large workpieces, the measurements are commonly taken at the workshop without a temperature-controlled environment where the temperature can both temporally and spatially fluctuate during the day [157]. Similarly, in small-range precision systems the gravity effects of the workpiece can usually be disregarded. Nevertheless, in medium and large-range precision systems, the load of the structure elements and the workpiece have a significant influence in the final accuracy of the system [47,178].

The above examples are a sign of the interest of studying the applicability of precision engineering design principles depending on the working range of the system. Scalability in design and operation of manufacturing and metrological systems has been analyzed in previous works [161,188]. It was recognized that the term 'scalability' has no commonly accepted precise definition. Consequently, a list of definitions and terminology was presented in Sun and Rover [191]. In this paper, a design principle is considered scalable when its applicability is independent of the working range of the precision system in an adaptable, flexible, and robust way. In other words, 'scalability' describes the degree to which the application of a precision design principle is independent on the working range of the machine or instrument.

The aim of this paper is to indicate the state of the art and future trends from a point of view of the scalability of the application of precision design principles in small, medium, and large range systems. For that, a review of representative examples of precision systems is carried out and general conclusions are obtained about how the different precision design principles are applied depending on the working range of the system. These conclusions are explained in the text and summarized in a visual way in tables. In Section 2, precision design principles are reviewed and classified in groups in order to simplify the study of their scalability. Section 3 proposes a classification criterion for precision systems according to the maximum range that they are capable of operating. Then Sections 4–6 are dedicated to the three groups of principles established in Section 2: Structure and alignment principles; motion measurement and control principles; and error reduction and correction principles, respectively. Their different sub-sections are focused on the main similarities and differences of application of the precision design principles for small, medium, and large systems. Finally, Section 7 gathers the main conclusions of the paper in terms of scalability of the principles and future trends expected in the field.

2. Precision design principles for machines and instruments

As it has been mentioned in Section 1, the implementation of precision design principles reduces or even eliminates the non-repeatabilities of the system. As McKeown stated, the objective is to design machines with very high, totally predictable, work-zone accuracies. In addition, it should also be taken into account that the workpiece accuracy depends not only on the work-zone accuracy of the machine but also on environmental effects and on how the machine is operated [134].

Following, a list of eleven precision engineering design principles is presented, as updated from McKeown [134] and Schellekens et al.[176]:

2.1. Structure

A correct structural design should consider the use of improved structural materials with high specific stiffness and high internal damping [134]. Moreover, the mechanical components and joints in the transmission path from the drive to the point of reaction must also have a high stiffness to avoid deformations under changing load [176]. In addition, symmetrical designs are preferred because they often allow more accurate measuring and manufacturing methods [74] and simplify the analysis in terms of stresses and dynamic and thermal response [111]. The principle of force compensation defined by Schellekens et al. [176] is captured in this principle, which considers the compensation of weight, reaction force, and parasitic stiffness.

2.2. Kinematic/semi-kinematic design

A kinematic design considers rigid bodies and its basis is constraining the exact number of degrees of freedom [176]. In an exact-constraint design [187] parts will fit together precisely and without backlash [74].

2.3. Abbe principle

When the point of action and the measuring scale do not lie along the same line but rather are separated by an offset, known as Abbe offset, a sine error appears [19]. Abbe errors should be avoided or minimized because they can make the largest contributions to the dimensional systematic error pattern [81,134].

2.4. "Direct" displacement transducers

Indirect displacement transducers add errors due to misalignments, angular deflection, compression and extension of parts and any backlash in the path from the indirect transducer to the motion to be controlled. Therefore, direct displacement transducers; e.g., scale, laser interferometers, capacitive sensors, and optical gratings are preferred over indirect displacement transducers, such as, for example, rotatory encoders in leadscrews.

2.5. Metrology loop/frames

The metrology loop(s), also called frame(s), which make up the measuring system should be isolated from the structural loop(s) and force paths, which are subject to machine distortion. In addition, the external forces upon the metrology system should remain constant [21].

2.6. Bearings

Bearings allow motion between parts in selected directions, while maintaining defined positions in other directions [13]. Non-contact bearings may be used to reduce friction. Also fluid film bearings optimized for minimum temperature variation and avoidance of micro-instability are capable of providing high averaging effects for smooth motion [134].

2.7. Drives/carriages

The first version of the principles established by McKeown in 1986 [134] treated in separate principles the Drives (8th principle) and Carriages (9th principle). Here, as in other versions of those principles, they have been joined in one. Drives should be set to operate through the axis of reaction of friction and acceleration forces. Motion drive systems (actuators) are integrated into moving components (e.g., carriages) through various different mechanical interfaces (couplings). Since such interfaces are also sources of disturbance to intended motion, non-influencing couplings are preferred in precision systems in order to avoid over-constraint and to provide maximum smoothness of motion [134].

2.8. Thermal effects

Schellekens et al. [176] states that the most common cause of non-repeatability is temperature. Therefore, temperature of structures and work-zones should be stabilized, especially in critical thermal loops. In addition, low expansion materials should be used and the thermal loop should be made as small as possible to minimize the influence of spatial thermal gradients. In Mayr et al. [133], an overview of the latest research activities in the field of thermal errors in machine tools (MTs) is presented.

2.9. Servo-Drives and computer numerical control (CNC)

As Schellekens et al. stated, in order to get good dynamic behavior, the control strategy should be matched very carefully to the dynamics of the mechanical system. The optimized design of the control system highly depends on the behavior of the mechanical system, e.g., its natural frequencies, the presence of friction, and disturbing forces [176]. Using very high response position-loop bandwidth servo-drive motor systems in direct drive mode (i.e., based on sensors that directly measure the position) enhances operating speed and accuracy. The CNC works in close-loop and can implement feed forward control technology in multi-axis machines in most cases.[134].

2.10. Error budgeting

The error budget is defined in Hale [74] as "an important deterministic tool that provides a systematic way to predict and/or control the repeatable and non-repeatable errors of a machine". The error budget helps to identify the main contributors to a precision system uncertainty [73], which can be classified based on its sources as: geometrical, thermal, and force induced. Although error budgeting was not initially included as one of McKeown "eleven principles and techniques" [134], it was mentioned as an essential step in all stages of design. Related to it, Schellekens et al. [176] includes repeatability as one of his nine design principles and states that it is essential to predictive modeling: "the closer the instrument is resembled by the model, the better the prediction of its behavior and the more scope for software error compensation".

2.11. Error compensation

Error compensation can be linear, planar, and volumetric [136]; quasi-static and dynamic. Evaluation procedures allow characterizing the systematic errors of a system, then, error compensation techniques are used to correct the systematic errors in order to improve the system uncertainty. The work presented in Schwenke et al. [178] reviews the fundamentals of numerical error compensation and the available methods for measuring the geometrical errors of a machine (or instrument).

For simplification, in this paper, precision design principles have been divided in three groups which are addressed in the following sections, where the progresses made are explained:

- Structure and Alignment Principles (Section 4). In this section the following principles are analyzed: structure, kinematic/semi-kinematic design, Abbe principle, metrology frames, and thermal effects. It considers the selection of materials in precision systems according to their properties such as thermal response, stiffness and damping. In addition, it also considers the alignment of components in the assembly.
- Motion Measurement and Control Principles (Section 5). This group includes the following principles: direct displacement transducers, bearings, drives/carriages, servo drives, and control. It studies the selection criteria of precision positioning components such as actuators, power transmission mechanisms, guiding systems, sensors, and controllers, and how they affect the implementation of precision design principles.
- Error Mitigation Principles (Section 6). This group includes the principles of error budgeting, error avoidance, reduction, correction, and compensation. In this section, methods for obtaining and correcting (or compensating) error are reviewed.

3. Classification of machines and instruments

Each of the following sections studies the implementation of the principles in precision systems depending on their working range. For this reason, in this paper, machines and instruments have been classified depending on their maximum ranges in order to facilitate the analysis of the scalability of precision design principles. This range refers to machining range in the case of MTs, to measuring range in coordinate measuring systems, and to focal length for vision systems. This classification considers three main groups based on the characteristics of the systems analyzed.

- Small range machines and instruments: Systems with a working range smaller than 100 mm. This group comprises measuring systems such as 3D optical microscopes, scanning probe microscopes and small/micro- coordinate measuring machines (CMMs). A small CMM and a micro CMM are defined by Leach as a CMM with ranges of 50 mm × 50 mm and 10 mm × 10 mm, respectively [111]. A trend of miniaturization of CNC MTs has been observed in the past two decades. A miniaturized MT has the advantages of reduced machine cost, low energy supply, and small workshop foot print.
- Medium range machines and instruments: Systems with a working range between 100 mm and 5 m. Most MTs and measuring instruments are within this range.
- Large range machines and instruments: Systems with a working range larger than 5 m. MTs in this range are required for machining large parts used in power plants, air crafts, ships, railway vehicles, oil drilling equipment, mining machinery, and construction. In addition, extremely large measuring instruments are necessary for large telescopes and Big Science projects [129,130].

Nevertheless, the classification is not rigid and there are some exceptions. In some cases, a slightly modified criterion is used for clarification. In Section 5, the working ranges of the actuators use a different classification: very small range machines (working range smaller than ±1 mm), small to medium machines (working ranges from 1 mm to 5 m) and large machines (working ranges larger than 5 m). In addition, there are several principles and considerations which are not affected by the dimension of the machine, and, thus, they are treated with a general approach.

4. Structure and alignment principles

4.1. Structure and alignment scalable principles

A structure positions and orients the relative pose of their components and change these poses under forces and moments [143]. Structure and alignment principles are the study of the effects of part, assembly, product, and system-level mechanics, acoustics, and thermodynamics on accuracy and precision. The part level includes characteristics down to the crystal lattice while the system level includes influences up to the level of the metrology room, the factory, or in extreme cases, big scientific facilities such as the Large Hadron Collider (LHC) built by the European Organization for Nuclear Research (CERN). This section summarizes precision design principles bottom-up from part (e.g., material selection), assembly (e.g., kinematic design), product (e.g., symmetry), to system-level (e.g., isolation). This approach is a scalable one that can be applied to systems of every size. Then, the other three sections discuss the specific applicability of those principles in small, medium, and large range case studies.

Material selection is a complex and decisive factor in the successful design, manufacture, and operation of precision systems [210]. Materials are selected to minimize deviations from the design intent to maintain structural (force, thermal) and metrology loops [198] while keeping the total cost of ownership acceptable. Although in some precision applications cost may not be a significant concern [70]; however, in most precision applications and products such as, for example, machine tools, coordinate measurement machines, or medical equipment, it is [201].

Key material characteristics are Young's modulus, damping [147], density, thermal expansion, thermal conductivity, and specific heat. As a rule of thumb, precision systems require high stiffness, damping, thermal conductivity, and specific heat as well as low thermal expansion.

Young's modulus is a property inherent to the material, and is not influenced by component geometry. Stiffness, on the other hand, is a structural property, influenced by the geometry (shape and size) of the component, the intrinsic material of which is comprised, as well as by the interaction of the contact surfaces of the unconstrained components [117]. Stiffness is a measure of a component to resist a change of geometry (deformations) under load. The stress levels in MT components and their connecting joints have to be kept significantly below allowable levels. Therefore, design of MTs and their components are highly influenced by structural stiffness requirements [166]. General-purpose machine tools are designed with a stiffness of 10 N/μm, precision machines with 20 N/μm, and machines for heavy cutting with up to 500 N/μm [122]. For metal cutting MTs, dynamic stiffness is also important and characterized as the frequency dependant ratio between a dynamic force and the resulting dynamic displacement [166].

Damping is a capacity of a vibrating system to partly transform (dissipate) the energy of a vibratory process during each cycle of vibration into another form of energy [166]. These are energy losses in the material and primarily in the interfaces between components [147]. In MTs, joint damping is associated to 40–60% of the total system damping. The importance of added damping in ultra-precision machining is associated with improving surface roughness at higher material removal rates [24]. Although non-contact bearings [151] are used in precision machines and instruments to reduce friction, damping characteristics should also be considered. For example, compared to oil hydrostatic bearings, air bearings have lower damping of high frequency "noise" associated with air movement through the air bearing features. This "noise" can be larger at high load/material removal rates. Air bearing designs that more evenly distributes the air flow through the bearing features can be used to reduce the "noise floor" under steady state conditions [24]. Material and joint damping are challenging to quantify [14]. Several studies have presented the dependability of material and joint damping on alloy composition [127], frequency, stress level and type, and temperature [14]. Therefore, the primary structural and metrology loops of a system require moderately high natural frequencies to reduce the chance of significant resonance within the operation spectrum [111].

Thermal expansion describes how much material changes in linear dimensions due to a change in temperature, while thermal conductivity and the specific heat capacity quantify how quickly a material changes its temperature due to a change in the heat flow. Changes in the heat flow can be imposed by internal sources (electrical drives) as well as external sources (environmental changes). Often, the best strategy to control thermal deformations, as reported by Slocum [187], is to isolate the heat sources from the force and metrology loops, and actively cool them. Otherwise, thermo-elasticity can be addressed mainly during the design phase [133]. The designers aim for equal time constants on all subsystems of the machinery to have a homogeneous temperature gradient and distortion field, i.e., avoiding thermal bending.

In several precision applications, photonic, acoustic, and electric material properties are also of great importance: for example, semiconductors, micro-electro-mechanical systems (MEMS), sensors, and lasers. Additionally, it is essential that materials behave differently at the nanometer scale (e.g., graphene has a significantly higher Young's modulus than most steels [26]) as well as in different metastable states [111] (metal alloys can have remarkable electrical conductivity at low temperatures [102]). Material compatibility (i.e., material's resistance to corrosion, rust or stains when it comes in contact with a chemical) plays a minor role when choosing the material [111], since high-precision systems are likely to be in tightly controlled environments such as the measurement rooms and laboratories. Nevertheless, the effect of acoustics, thermal conditions, optical properties, humidity, and atmospheric pressure on corrosion and degradation must be considered [210].

Material selection often requires trade-offs. Ashby started to give more emphasis to functionally defined combinations of the properties rather than focusing on individual material characteristics [5]. Other works focus on functional trade-offs, sustainability [169] or economic factors [46].

Many precision and ultra-precision systems run under low-speed and low-acceleration conditions, so inertial loads rarely impose significant constraints on design choices. Flexure mechanisms, as depicted in Fig. 1, are often applied to obtain precise and repeatable movement. They are designed for a wide range of motion compared to their size. Flexure systems of modest stiffness and lower density materials are preferred for mass reduction [111].

The alignment of components needs to be considered in the design phase, as the tolerances, both for manufacturing and assembly may force design changes to meet Geometric Dimensioning and Tolerancing (GD&T) requirements of the manufactured components. Tolerances obtained in the component depend mainly on the manufacturing technologies, while the assembly tolerances depend primarily on the design of the components. Manufacturing tolerances are usually significantly tighter than assembly tolerances.

The most critical misalignments are often Abbe (sine and cosine) errors [19]. These errors arise from angular errors in the system that are magnified by the presence of Abbe offsets [178]. The focus is to minimize the effect of Abbe on system performance. A typical example

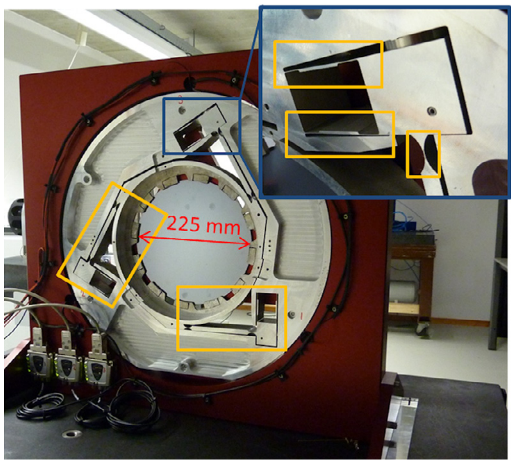

Fig. 1. Dynamic masking stage with a flexure guiding system actuated by voice coil actuators, designed by JPE (adapted from [92]).

of a misalignment, within machine tools, is the squareness between machine tool axes [85]. The magnitude of alignment errors between assemblies can be eliminated using, for example, monolithic designs or minimized using kinematic couplings [19].

Monolithic design aims at merging individual components or assemblies into a single manufactured (instead of assembled) part with all the required functionality of the original assembly [111]. Alternatively, precision couplings, accurate and repeatable structural interfaces, or fixtures [49], can be introduced at the mating surfaces. Precision couplings are grouped, according to their governing mechanics, into kinematic, quasi-kinematic, and elastic averaging.

Kinematic couplings, a special case of kinematic design introduced in Section 2 where the necessary and sufficient number of degrees of freedom (DoFs) is constrained, allowing other DoFs providing motion, need to fully constrain the components to maintain a stress-free condition and a high positioning repeatability. At the same time, wear must not introduce play between mating components, and the temperature gradients across mating components shall not impose part stresses [9]. Each degree of freedom is constrained with a suitable point contact. This is visualized in a Maxwell kinematic coupling in Fig. 2. As a consequence, the coupling is not over-constrained, and it avoids stresses [137]; thus, the system provides a high position repeatability [187].

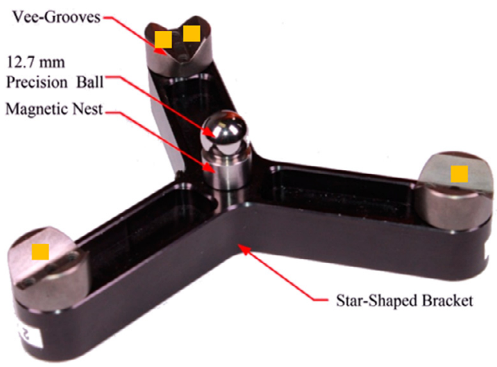

Fig. 2. Kinematic coupling (Maxwell kinematic system consists of three spheres mated with three female vees) platform according to Gaudreault et al [69].

The principal disadvantages of kinematic couplings are the sag of the body as well as potentially high stresses in the contact areas [111]. Both originate from static deflections of the components mainly due to their weight. The sagging of simple geometric shapes such as gauge blocks is addressed through the selection of adequate Airy or Bessel support points. However, these consider only simple beam theory instead of plane stress theory and are inapplicable for most other precision systems [149]. The high contact forces in the support points lead to local deformations such that the point contacts become Hertzian contact ellipses, consequently decreasing the position repeatability as the ideal point contacts are transformed into area contacts. In such cases, couplings based on quasi-kinematics and elastic averaging can be considered.

Quasi-kinematic (pseudo) couplings are designs with convex and grooved mates resulting in nominally line type contacts. Although these designs are over-constrained, they are nearly kinematic, and they ensure uniform thermo-mechanical deformations [32]. They are less expensive to manufacture than the compliant kinematic coupling and allow for slightly higher precision also at larger scale [32].

The principle of elastic averaging follows from the requirement of mating surfaces with capacities to carry higher loads and exhibit higher contact stiffness [187]. The line- or area-type connections lead to a distribution of the contact pressure on more than the ideally required contact points. However, it is clear to see that this type of system forces geometric congruences and is over-constrained. Besides the presented designs, pinned joints are also an economical solution for the coupling of components, although of significantly reduced accuracy [32].

Components and assemblies can be connected in series or parallel. Prominent examples for serial kinematic machines (SKM) are most of CMMs and MTs and for parallel kinematic machines (PKM) Stewart-Gough platforms [179] (see Fig. 3). SKMs have comparatively bigger workspaces and less complex configurations compared to PKMs. The bigger workspaces are a result of the length of the structural loop. This design also amplifies the effects of imperfect components and assemblies. As a rule of thumb, the structural loop must be as short as possible to increase the resistance to distortions as well as vibrations and it shall contain a minimum number of joints, and use internally damped materials [176]. The structural loop for MTs is the path from the Tool Center Point (TCP) to the workpiece through the structure. PKM based designs require that all actuators move simultaneously, and their individual feed mechanisms can be measured using linear measurement instruments. However, applying the Abbe principle requires more space per actuator which implies a high footprint compared to the work volume. They are likely to offer higher static stiffness and high speed motion capabilities than SKM. On the other hand, the mechanical structures and models of PKMs are more complex, e.g., non-linear force transmission and stiffness characteristics and complexity in drive (spherical) joints in terms of accuracy/repeatability and larger number of error components.

Fig. 3. Stewart platform multi-axis positioning system from Physik Instrumente [158].

The components and assemblies within a precision system form force and thermal loops as well as the metrology loops [176]. The force and thermal loop contain all components which are in the flow of thermo-mechanical loads. The metrology loop contains all components of measurement required to determine the relative pose of two precision system components. These loops should be separated from one another so that the metrology frame can maintain an accurate reference under operational conditions. In the case of MTs it is the determination of relative pose of tool with respect to workpiece. In a typical MT, the metrology loop is the same as the structural (force) loop, but it is not in precision MTs. Metrology frames separate the two. For the identification of translational stiffness matrices of five-axis MT using quasi-static circular trajectories metrology frames can be used to isolate the applied load from measured deformations [110] If metrology frames are not used, the effect of forces and heat on the force and thermal loop must be minimized. One approach to establish this separation is the application of symmetry; another is isolation of error sources (see Section 6).

The structural symmetry (rotation symmetry, mirror reflection in a plane, parallel displacement along an axis) of the whole machine is essential, as it leads to similarly symmetric thermo-mechanical stress distributions. Symmetry facilitates the design (simplified finite element models), manufacture (repetitive features), as well as the operation (on- and off-line compensation of highly repeatable deterministic models) of a system. Hence, symmetry must be included to the maximum extent into component, system, and system environment. Any departure from symmetry should be carefully assessed. Symmetry from a thermo-elasticity point of view is complex as it requires equal time constants and homogeneous temperature fields to prevent thermal bending.

The development of customized materials like *Invar* [33] or *Zerodur* [86], the use of athermal designs which use two or more materials with different properties in order to compensate deformations [89], as well as on-line compensation techniques embedded in the instrument's controller through multisensor measuring systems [48] widen the field of application of some precision systems aiming at fulfilling strict metrological requirements in not well-controlled production environments [158].

When considering the scale of the precision system, the mentioned structure and alignment principles are applied, but not in the same way. In the following sections the different criteria for its application depending on the system range are discussed through different representative examples.

4.2. Small range systems

Manufacturing and measuring of small size parts are challenging tasks with a growing presence in industry [152]. For example, the Geometric Dimensions and Tolerances (GD&T) of LEGO toy bricks are tighter than those associated with most other injection molding applications in the literature; the tight GD&Ts are partly founded in the precise injection molds [114]. This precision benefits the service life of the mold, some of which have been retired from operation after the production of 120,000,000 bricks. The mold plates and dies feature mirror and rotational symmetry. Due to the increased demand of micro components, conventional injection molding was downscaled into micro-injection molding. As highlighted in Calaon et al.[23] a lighter structure and tighter tolerances of the new design of micro injection screw, allows faster reaching the desired injection accelerations, enabling a more effective, accurate and precise injection phase.

Measurement of micro manufactured components such as aspheric lenses with often complex 3D faces requires ultra-precision CMMs with nanometer uncertainty [81]. Most common ultra-precision CMMs utilize parallel kinematic design and drives. Trinano N100 is an ultra-precision CMM that achieves volumetric measurement uncertainty of 100 nm in a volume of 200 cm^3. It utilizes a parallel drive configuration using linear encoders to support the workpiece stage and a stationary probing sensor (see Fig. 4). Exact constraint design for the workpiece stage, constraining three DoFs - two rotations and one translation – using vacuum preloaded air bearings on each side of the workpiece stage, ensures high repeatability and reduced influence from thermal disturbances. Temperature variations in critical parts of the metrology loop are measured by negative temperature coefficient (NTC) thermistors. Additionally, low expansion materials are used for the encoder scales in the linear drives and the coupling points to the air bearings. The functional axes of the linear encoders intersect at a single point that coincides with the center of the probe tip satisfying the Abbe principle.

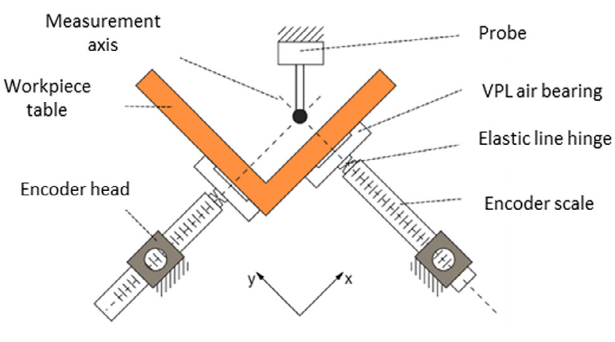

Fig. 4. Working principle of Trinano N100 CMM [142].

4.3. Medium range systems

Probably this is the range where more examples of machines and measuring systems applying precision design principles can be found, since medium range systems have been developed for many years [50]. However, interesting improvements and representative examples have been developed in recent years. They combine different structure and alignment precision design principles.

ISARA 400 ultra-precision CMM [162] is a notable example for ultra-precision CMMs. It features an Abbe compliant system that can achieve a length measuring uncertainty of 100 nm (coverage factor $k = 2$) in a measurement volume of 400 mm x 400 mm x 100 mm. The mutual alignment of the laser beams and their alignment to the probe tip does not change during motion, thus fulfilling the Abbe principle in 3D. The system consists of a metrology frame that holds three laser interferometers and the probe system of the CMM and a workpiece carrying structure (see Fig. 5). The metrology frame which can move in *Z*-axis direction is an assembly of silicon carbide (SiC) beams. It offers a low mass structure with high specific stiffness, thermal stability, and is statically determinant in six degrees of freedom by employing five preloaded flat air bearings. The workpiece carrying structure consists of a monolithic *Zerodur* mirror table with reflective sides which moves in *X*- and *Y*-direction. An additional product table made of SiC is located by three supports directly on top of the mirror table supports, acting as an interface between mirror table and part, eliminating deformations of the mirrors due to component weight. Both metrology frame and mirror table are supported and guided on stable granite bases.

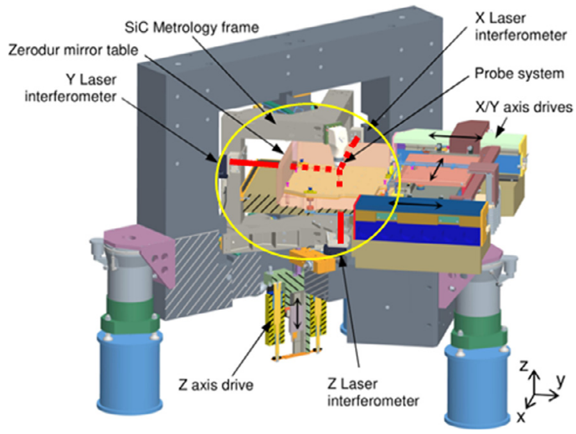

Fig. 5. CAD design; Overview of the ISARA 400 CMM [162].

The French National Metrology Institute (LNE) developed an ultra-high precision measuring machine for cylindrical and spherical form measurement with a nanometer accuracy level in a cylindrical working volume of 350 mm diameter and 150 mm height [200]. The system consists of two frames; the first one carries a rolling spindle, a table, and a reference cylinder all supported by isostatic linkages. The second is a metrology frame that carries eight capacitive reference probes providing alignment to the reference cylinder and four capacitive measurement probes for the measurement of the cylindrical parts. Laser interferometers are aligned to the measuring probes in compliance with the Abbe principle.

The manufacturing of dies or molds made of hard and brittle materials, such as tungsten carbide, with nanometer level surface quality and sub-millimeter dimensional accuracy requires ultra-precision MTs. In order to reach high productivity, one of the limiting factors in such application are vibrations generated by the machining process and movement of feed axes. Alumina ceramics can be used in structural members to reduce the effect of the mass of movable components and to improve stiffness [29]. Moreover, a counter motion mechanism driven at the center of gravity can be used to eliminate the vibration caused by high accelerations/decelerations.

Lithography scanners are some of the most technologically advanced machines of the modern world, to achieve an overlay error better than 2 nm [22] and full-wafer critical dimension (CD) uniformity of less than 0.5 nm [141]. Design of the mechanical system of the scanners adheres to the precision design principles. A metrology frame, made of *Invar* for increased thermal stability, vibration isolated from the supporting base frame, supports critical measurement systems such as the alignment system, leveling, focus sensors, and the exposure lens. Stiff encoder grid plates made of *Zerodur* are kinematicaly mounted on the metrology frame as part of the plane encoder system in combination with the short-fixed beam interferometers mounted on the wafer stages. The short beam interferometers reduce sensitivity to the refractive index changes, achieving a significant reduction in noise levels. The wafer stages are located on top of a magnetic plate which has a kinematic coupling to the base frame by air bearings. The reticle stage holds the mask with the exposure patterns. Heavy balance masses guided on air bearings and compliant mechanisms are counter-acting inertial effects and absorbing reaction forces. Additionally, the reticle stage is acoustically shielded.

4.4. Large range systems

Large-scale precision machines and measuring systems represent a research frontier since technological advances introduced and perfected at a conventional scale may imply additional challenges which increase non-linearly with size [177]. Perfect examples of that can be found in the fields of astronomy and gravitational science, that present significant precision engineering challenges [185].

Two gravitational wave detectors were built in recent years. The Laser Interferometer Gravitational-Wave Observatory (LIGO), built in 2002, consists of two identical observatories separated by more than 1000 km in the U.S. operated in unison to detect gravitational waves. Virgo is another gravitational wave detector built in 2015 in Europe. Michelson laser interferometer formed by two orthogonal long distance arms (4 km long for LIGO, and 3 km long for Virgo) are used in each of these observatories (see Fig. 6). Two ultra-high vacuum pipes are hosted in the two arms through which the laser beam runs and test masses (reflecting mirrors) are stabilized by several anti-seismic dampers inside vacuum enclosures. To increase the detector sensitivity, the basic Michelson configuration was modified to increase the carrier power in the arms by adding resonant Fabry-Perot cavity to the extremities of each arm. This arrangement significantly increases effective length of the optical path of each leg, the carrier power, and phase shift for a given strain (displacement) amplitude [2]. In this power recycled Fabry–Perot Michelson configuration, the power in the arms is increased by a factor of ≈8000 with respect to a simple Michelson configuration [130]. As a result, for both LIGO and Virgo observatories, Michelson interferometer length measurement resolution is 10^{-18} m for achieving the targeted strain sensitivity of 10^{-21}. Virgo established the Global Navigation Satellite System (GNSS) baselines, a unique geodetic reference system. GNSS is used for the alignment of equipment and for the determination of the position of internal components of the

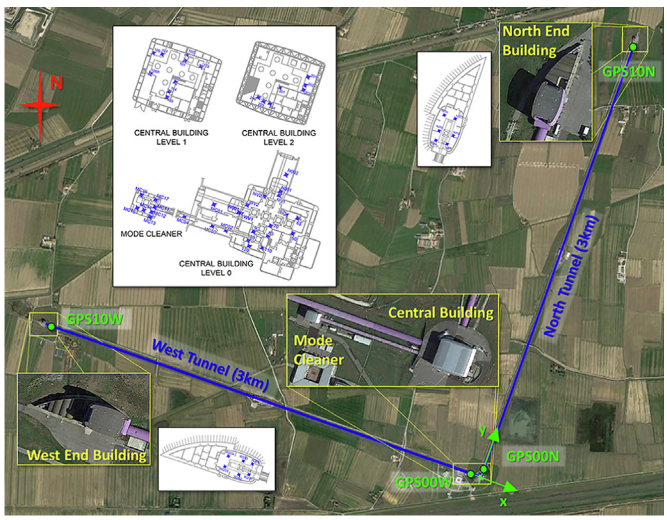

Fig. 6. Complete layout of the Virgo facilities and main VRS internal reference points (blue points), located inside the four experimental buildings. Green points show the position of the four GNSS stations used to integrate the total station survey [129]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

system. Several reference points located in the buildings and in the arm tunnels formed the primary control network. Four high precision local secondary reference point networks inside the buildings were introduced defining the Virtual Reference Station (VRS) frame. Along each arm, 11 points are located by Global Positioning System (GPS) to monitor their horizontal and vertical displacements. In addition, about 30 concrete pillars distributed along the arm tunnels and the buildings enable the connection between inside and outside reference point networks.

Inside each tunnel of Virgo, the vacuum tubes are aligned with respect to fixed reference points located every 300 m along the tunnel and 19 intermediate points equally spaced at 15 m between the reference points. The 19 points are fitted, with precision brass bushings with cylindrical/conical hole, with a position accuracy of 2 mm root mean square (RMS) with respect to GNSS, ensuring reproducibility when plugging in targets or measurement instruments [129]. Additionally, due to the extremely high sensitivity of the detector, thermal compensation is required for several of the optics. Even though the mirrors and test masses are in a vacuum and thermally isolated from the environment, thermal lensing due to the high-power laser beams can change the radius of curvature, thus affecting the detector's sensitivity. Different approaches are implemented to mitigate the phenomena. For example, the mirrors and test masses material, a type of fused silica, has a small absorption in the order of 0.2 ppm/cm at 1064 nm wavelength. Also, the test masses are hanging by monolithic suspensions made of fused silica fibers, same material as the masses themselves thus reducing thermal noise [168].

Another example of challenging conditions to apply precision design principles in large-scale systems is the Large Hadron Collider (LHC). It is a 27 km long particle accelerator located underground in an inclined plane between 50 m and 100 m below the surface of the earth. The LHC consists of 1232 dipoles (15 m long) to bend the beam, 392 quadrupoles (5–7 m long) to focus/defocus the beam, 12 low beta quadrupoles (12 m long) to squeeze the particle beams just before their collision in the detector [16]. All the dipoles and quadrupoles must be aligned along a smooth curve with a 1σ deviation of 0.15 mm in a 150 m long sliding window [140]. To reach this goal the LHC uses metrology frames: First, is the implementation of a geodetic network on the surface and its transfer in the tunnel, to reach a determination of the underground geodetic points within $a \pm 2$ mm accuracy close to a GPS antenna, and $\pm$ 4.5 mm for those located in the middle of two GPS antennas. Then, the initial alignment of each component is performed, using direct leveling. The alignment procedure uses wire offsets with respect to a stretched wire to perform the final relative alignment of the nearby components, not referring anymore to the geodetic network [90]. The low beta quadrupoles need tighter and continuous monitoring of their position [3]. They are equipped with alignment sensors and supported by motorized jacks allowing their remote adjustment within a few micrometers resolution [58].

One of the two general-purpose detectors of the LHC is A Toroidal LHC Apparatus (ATLAS). Six different detecting subsystems are arranged in layers to record the trajectory, the momentum and energy of the new particles created after the collisions occurring in the center of the detector. ATLAS is a 46 m long, 25 m high, and 25 m wide detector, weighing 7000 tons. The alignment challenge of the detector remains in the fact that all the different layers of detectors have to fit together, leading to very tight relative position between the layers (20 µm as an example concerning all tracking systems setting up and the mounting systems), requiring the implementation of internal alignment devices. To prepare such an implementation, a key step is put in place for each layer/component of a detector: its fiducialization, i.e., the definition of fiducial marks with respect to the reference axis of the component and their determination in the referential frame of the component, in the manufacturer premises. Then, in the detector area, each component is installed with respect to a primary network, using its fiducials.

The primary error sources for these two large systems come mainly from ground motion, the uncertainty of measurement of the instrumentation, the propagation of error, the refraction error (especially in the case of the LHC where measurements are performed in a long narrow tunnel), and the thermal stability. To reduce errors, CERN surveyors combine different types of measurements. They get redundancy and can perform a least square adjustment of data. The same alignment strategy is applied to all the accelerators at CERN, whatever their size is: the fiducialization of a component, the determination of a surface geodetic network, its transfer to underground, the initial alignment of the components with respect to this geodetic network, and their smoothing [7].

4.5. Discussion on structure and alignment

Table 1 summarizes a qualitative evaluation of the scalability of the implementation of structure and alignment principles in precision systems, depending on their working range. This may be due to both functional and economic reasons. The blacker the circle is the more applied the principle is. It gives a visual insight of the scalability of each of the principles. For instance, if a principle is marked with a full black circle for all the three ranges, i.e., small, medium, and large, it indicates that this principle is very much scalable. Since all the precision design principles are theoretically applicable to all the precision systems, the classification shown in the table is based on the real applications found in literature.

Table 1
Applicability of structure and alignment precision design principles.

Precision Design Principles	Small range systems	Medium range systems	Large range systems
Symmetry	●	●	◕
Kinematic Design	●	◑	◔
Abbe Principle	●	◕	◔
Metrology Frames	●	◕	◕
Thermal effects	●	◕	◔

Legend: the blacker the circle is the more often the principle is applied in the indicated range.

In small range systems usually most of the precision design principles concerning structure and alignment are applied. Applying all those principles (e.g., Abbe principle or Metrology frame) usually force the system to have a relatively large volume compared to its effective working volume. However, at that scale it is in many situations affordable. The use of materials with low thermal expansion coefficient is also usual in the metrology frames of precision small range systems, since it is more economically affordable than in larger systems.

For medium range systems many of the principles are also often applied. However, in this case the machine work volume and the economical restrictions force that some of these systems renounce applying some of the structure and alignment principles in exchange for applying error correction or compensation techniques.

In the case of large range systems, the gravitational effects (heavy constructions with large masses) on the structure make its stiffness more critical. Additionally, environmental influences such as thermal effects may cause significant loss of accuracy. The application of the structure and alignment principles for those systems is usually less frequent due to economic reasons and size limitations, and the use of error compensation techniques is often applied. However, there are also examples of high precision large-scale systems, as the ones presented in Section 4.4 that show a very interesting application of the mentioned structure and alignment principles.

5. Motion measurement and control principles

5.1. Motion measurement and control main components

Measurement and control of positioning, which is referred as precision positioning, is a fundamental function in precision machines and instruments [59]. To achieve desired levels of performance, in addition to previously listed mechanical design principles, all such devices utilize motion control systems of varying degrees of sophistication. Fig. 7 shows the main components of precision positioning systems, which are the actuator, motion transmission mechanism, motion guide, position sensor, and the controller, used for precision positioning of a moving table over different travel ranges. For a linear positioning system, a schematic of the relationship between these components is shown in Fig. 8. Rotary positioning systems for precise angular positioning utilize similar

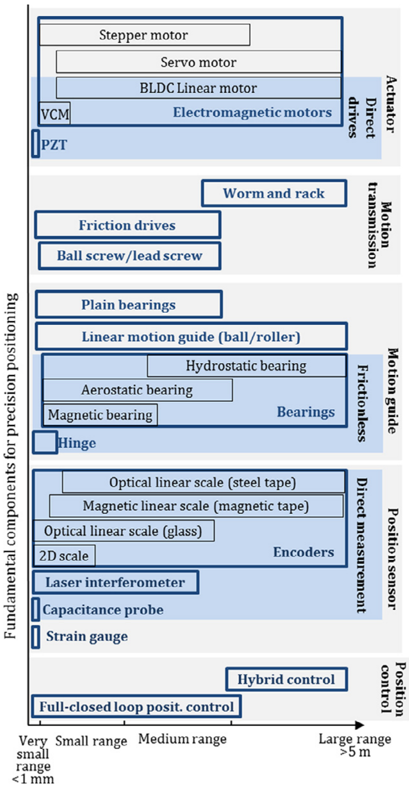

Fig. 7. Main components for precision positioning in different travel ranges. Blue boxes indicate typical range of application (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

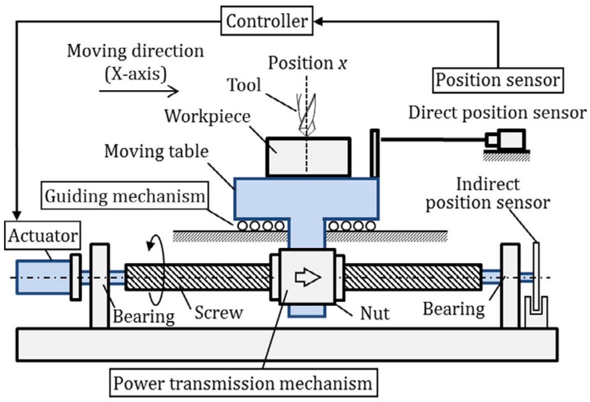

Fig. 8. Relationship between the components in a precision positioning system.

principles and similar functional components, albeit in different physical forms. This section focuses on the linear positioning systems only. The moving table is driven by an actuator, either directly coupled to the table, in case of a piezoelectric actuator such as lead zirconate titanate (PZT) or a linear motor, or coupled through a transmission mechanism such as a ball screw and nut assembly or friction drive, in case of a rotary motor. A guiding mechanism guides the moving table along the axis of motion. Single-axis motion control is conventionally achieved by drive systems implementing proportional-integral-derivative (PID) based feedback control laws [104], using the output of the position sensor as the feedback. The position sensor can be a direct position sensor such as a laser interferometer or an indirect position sensor such as a rotary encoder.

The selection of the positioning system components is based on the required precision, operating range, and structure. In addition, the implementation of the components in the positioning control system can be optimized to leverage the capabilities of each of them in order to optimize the positioning uncertainty.

The main function of the actuator in a positioning system is to provide necessary force/torque to overcome static and dynamic loads during positioning. The characteristics of the actuators to carry out this function include range of displacement, maximum force/torque, uniformity of force/torque (cogging and torque ripple), bandwidth, and stiffness. As shown in Fig. 7, there are two main groups: electromagnetic and piezoelectric (PZT) actuators. PZT actuators provide precise, uniform, high-bandwidth, short range displacement (typically in the range of µm) with high load capacity and stiffness. On the other hand, electromagnetic actuators are capable of working in small, medium, and large range positioning systems. Electromagnetic actuators comprise Voice Coil Motors (VCM), stepper motors, and linear and rotary servo motors. Stepper motors are open loop systems providing discrete angular displacements around a full rotation, corresponding to electrical input signal; therefore they are suitable for precision positioning systems. While rotary servo motors provide linear displacements only limited by the motion transmission system, linear servo motors and VCMs provide displacements defined by their working lengths. Typically, VCMs have displacement ranges of up to 20 mm. Independently of the working range, in precision applications, direct drives (PZT; VCM and linear motors) are commonly preferred since they do not need a motion transmission mechanism which add errors, such as backlash, to the system.

Motion transmission mechanisms are needed to convert motion generated by rotatory actuators to linear motion [150,153]. Such mechanisms include ball screws, lead screws, and friction (capstan) drives. The main concerns in selecting transmission elements are the stiffness and their adverse influence on the motion. For example, cyclic pitch errors of ball screws cause positioning errors. Designers sometimes introduce non-influencing couplings between transmission system and the moving table to reduce such errors [25,193]. Friction drives eliminate cyclic errors generating much smoother motion. They also have very low friction compared to ball screws reducing the load on the actuator. On the other hand, due to low mechanical advantage, transmitted forces are low compared to ball screws [221]. In small and medium range machines, ball screws and lead screws are used. Due to their limited stiffness, worm and rack are employed in larger ranges and heavy load machines. In order to provide precise positioning, they should have a minimum backlash. The best strategy to eliminate adverse effects of motion transmission is direct coupling of linear actuators to the moving element of the system, bypassing the need for the transmission system. However, such strategy requires very powerful linear actuators for large systems due to lack of mechanical advantage. It is more practical for systems with short displacement ranges and not needing mechanical advantage, such as PZT driven micro/nano-scale instruments.

Guiding systems support and guide the moving part of the positioning system minimizing geometric error motions (straightness, roll, pitch, yaw), which influence positioning uncertainty. They are selected depending on the working range, load and dynamic requirements. In precision applications, frictionless guiding systems are preferred, such as hinges and magnetic, aerostatic, and hydrostatic bearings if the reduced damping of frictionless guiding is canceled by special axis control algorithms. Hinges are based on flexure mechanism and are limited to very small ranges and very low loads. On the other hand, magnetic (low loads) and aerostatic bearings (moderate loads) are used in small to medium ranges. In larger ranges and heavy load machines, hydrostatic bearings are used. Stiff fluid bearings provide high averaging effects that smooth motion and avoid micro-instability [134].

The guiding system also defines the axes configuration. If the guiding system impedes the displacement in the orthogonal direction, a stacked axes configuration needs to be implemented. Stacked linear axes result in longer kinematic chains with an unfavorable transfer behavior [95,120]. Thus, in precision systems, a planar configuration of the axes is preferred since it minimizes geometrical errors and improves system dynamics [125,213]. Planar motion is allowed when the displacement in X and Y-axis is not impeded, this is achieved in 2D hinges and by magnetic or aerostatic levitation, where geometric accuracy in the plane of motion is achieved by positioning control rather than relying on guiding systems.

Positioning sensors provide the feedback of actual position of the moving part of the system and their accuracy directly affects the total positioning uncertainty of the system [28,107]. While some sensors measure the position directly, others provide position information indirectly (e.g., rotary encoders used in linear positioning systems). In precision positioning, non-contact sensors, directly measuring position, are preferred. Such non-contact sensors include capacitive and inductive sensors, laser interferometers, linear and rotary optical encoders, and magnetic and steel tape scales. While most of these sensors measure position along one line only, laser interferometers can be configured to measure in a planar configuration using plane mirrors and eliminating Abbe error [76]. Planar encoders (2D grid encoders and/or surface encoders) are capable of measuring XY positions in a plane [60], but their use is limited to small ranges since their measurement uncertainty and resolution are dependent on the quality of the pattern, resulting in an incremental error that increases in long range applications.

The control systems are implemented either by simply applying the control laws and algorithms to existing drive systems [180,192] or by introducing additional sensors and actuators [54,124,132,146] to meet the precision motion requirements. In precision systems, full-closed loop position control strategies based on direct position measurement are preferred. However, in larger and heavy load machines, hybrid position controllers are employed to achieve a good positioning performance in a wide frequency bandwidth. Hybrid position controllers additionally implement a semi-closed loop control based on indirect position measurement, such as a rotary encoder.

Many proportional-integral-derivative (PID) control systems suffer from degraded motion accuracy due to errors in plant models and variations in associated parameters, feedback measuring system errors, as well as changes in internal (e.g., torque ripple, friction, thermally-induced stiffness variations) and external disturbances (e.g., varying loads and environmental changes). Sometimes passive damping methods are used in positioning systems to reduce the dynamic effects, such as Eddy current damper s[56] (see Fig. 26). However, traditionally, disturbance rejection is achieved by high control loop bandwidth and proper filtering [17,39,45,53] Feedforward control is introduced to overcome these limitations (see Fig. 9) [112]. Feedforward control, instead of reacting to the measured error, anticipates it based on a priori information about the system dynamics and nonlinearities. Fig. 10 shows the circular path errors in a multi-axis coordinated motion due to ripple and friction (shown as waviness between quadrant spikes) and due to backlash (shown as quadrant spikes) with and without feedforward addition [218].

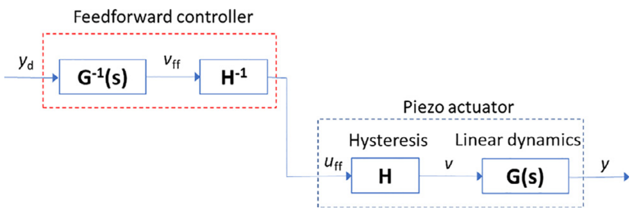

Fig. 9. Block diagram of a feedforward control of piezo actuator (adapted from[112]); y_d: desired output trajectory, v_{ff}: feedforward control action, u_{ff}: feedforward control input, v: control action, y: output.

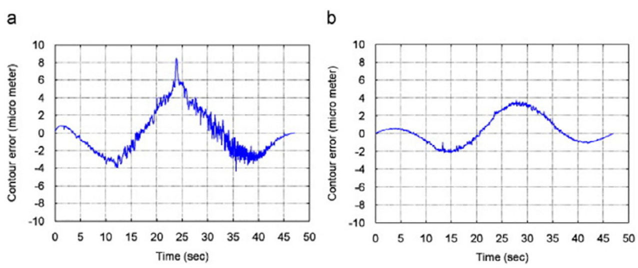

Fig. 10. Comparison of the contouring accuracy for circular trajectory of two controllers, (a) Proportional-integral (PI) controller and (b) PI with additional feedforward control with disturbance observer.[218]

Multi-axis coordinated motion is typically achieved by utilizing real-time interpolators implemented in the machine controllers [176,186]. Such interpolators generate the set points (reference commands) for each motion axis for each sampling interval along the programmed trajectories. The performance of these interpolators is quantified by the resulting contour error and feed speed variations. Multiple interpolation algorithms have been developed to improve the contour accuracy and the efficiency of computations [144]. The most common interpolators used in precision machines and instruments utilize Non-Uniform Rational B-Spline (NURBS) based algorithms [11,103,113].

From Fig. 7 it is inferred that motion and measurement devices attend to a classification that differs from the one that was initially proposed in this paper (Section 3). Therefore, for this section an alternative classification is proposed: very small range machines, with a working range within ± 1 mm (Section 5.2); small to medium ranges, with working ranges between 1 mm and 5 m (Section 5.3), and large range machines, with working ranges larger than 5 m (Section 5.4).

5.2. Very small range (within ± 1 mm) systems

Fig. 11 shows the positioning components combination that can be used for precision positioning over very small ranges. As shown, the combination of PZT and hinges is predominant in this range and it can be combined with different positioning sensors, depending on the application requirements.

PZT
+
Hinge
+

Position sensor	
Capacitance probe	• Standard combination • Trade off between range and resolution
Laser interferometer	• For ultra precision systems • High resolution in extended range • Easy for 2D/3D Abbe error free design
Strain gauge	• For low-cost systems • Trade off between range and resolution
Optical scale	• For robust systems • High resolution in extended range

Fig. 11. Components for precision positioning in very small range within ± 1 mm (controller is not shown for clarity).

For precision positioning within a very small range of ± 1 mm, a PZT is employed as shown in Fig. 11. PZTs are capable of providing position resolutions of less than one nanometer, can achieve extremely high accelerations, and are frictionless and backlash free [139]. They are currently used in many nanopositioning stages based on elastic hinges that allow planar motion [30,109,220]. Even though their travel range is small, a lever displacement amplifier can be employed to amplify its working range [217], obtaining maximum strokes still limited to one or two millimeters [96,194]. It is worth mentioning that PZTs moving stroke can be extended by repeating the PZT motions with methods such as stacking of PZT elements and the walking drive [181]. In Gao et al. [67], a linear-rotary stage that can generate motions along and round *Z*-axis (Z-θ_z) was presented. This stage was actuated by two driving units, each consisting of two PZTs and a friction component made by permanent magnet. It has a working range of 12 mm (Z) and 360° (θ_z). PZT stages can be used as auxiliary fine nanopositioning units to improve the performance of a larger travel positioning stage, in a two stage scheme [44]. PZT displacement is controlled by applying a certain voltage. The work presented in Devasia et al. [36] reviewed some of the control related research in nanopositioning with PZT and discussed their performance. The main disturbances that affect the modeling and control of piezo electric actuators are stated to be the following: creep, hysteresis, vibrations, modeling errors, and bandwidth-precision-range tradeoffs. Similarly, in Dow et al. and Gao et al. [42,66], driving methods and design methodologies for piezoelectric actuators were reviewed.

A common example of increasing the bandwidth of precision machining applications by additional sensor/actuator is the use of fast tool servo (FTS) technology [42,64,155] Lu and Trumper [124] describes the design of an ultra-fast tool servo for diamond turning of complex free form surfaces. This FTS is based on energy efficient normal-stress, permanent magnet motor design with high force density and small armature mass, resulting in higher than 20 kHz bandwidth, 500 g peak acceleration, and 30 µm stroke. To achieve such a high bandwidth, three digital signal processors (DSP) running in parallel at 300 MHz clock rate are used along with a field programmable gate array (FPGA) to interconnect the DSPs. The controller is designed to incorporate feedforward controller to improve tracking performance. Another example of FTS was described in Brinksmeier et al. [15] achieving 500 nm stroke at bandwidth of 5 kHz with high linearity, zero hysteresis and negligible heat dissipation. This PZT-based nano-FTS was used to machine diffractive optical elements on a diamond turning machine with an open loop control system having an input shaping feature to minimize vibrations generated during the process.

An illustration of a very small range measuring system is the commercially-available scanning probe microscope (SPM). In this system, a PZT XYZ scanner tube, in which separated piezo electrodes for *X, Y*, and *Z* are combined into a single tube, is often employed to make XY scans and *Z* tracking of the probe over the sample surface. It can provide a XY scan range on the order of 100 μm $\times$ 100 μm and a *Z* tracking range of 10 μm by using a single PZT scanner. However, with such a scanner tube, the XY scan motion will cause an error motion in the *Z*-axis, which is called the cross coupling error motion [66]. For this reason, in a metrological atomic force microscope (AFM) developed by the National Research Laboratory of Metrology (NRLM), Japan, a combination of a PZT *Z* stack ring and a PZT XY translational stage was employed [72]. As shown in Fig. 12 the *Z* stack ring, with a stroke of 12 µm, was mounted on the XY translation stage with a stroke of 40 $\times$ 40 µm. An XYZ interferometer system following the Abbe comparator principle [1] was employed to measure the position coordinates of the sample with a resolution of 0.04 nm for real-time correction of distorted topographic images.

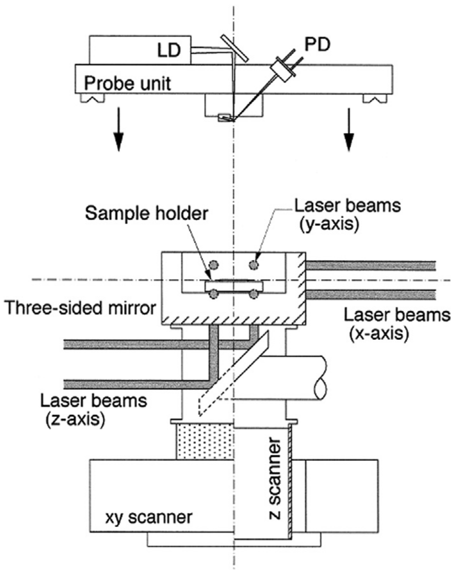

Fig. 12. A metrological atomic force microscope [72]. LD: Laser diode, PD: Photodetector.

In ultra-precision measuring instruments working in this range such as a metrological AFM shown in Fig. 12, laser interferometers are employed to make traceable length measurement where the laser beams are aligned to follow the Abbe principle. Optical linear scales that are robust to electromagnetic noises have also been employed for applications in this range, such as an on-machine AFM probe unit where an optical scale was employed for precision positioning of the tracking motion of the AFM probe tip with a resolution of 1 nm over a range of 70 μm [63].

When working within the range of $\pm$ 1 mm, capacitance probes are typically employed as positioning sensors because their resolution and range are matched with those of PZT/hinge mechanisms. Taking into consideration the high cost of a capacitance probe, a strain gauge is often employed for low-cost positioning applications. In the example shown in Fig. 13, a pair of Cr-N thin film strain gauge-type displacement sensors (X and Y) was integrated into an XY micro-stage with a size of 25 mm (*X*) $\times$ 25 mm (*Y*) $\times$ 6.5 mm (*Z*) to achieve closed-loop nano-positioning of the stage. The stage was driven by a two-axis PZT impact mechanism with a preloaded technique using permanent magnet. Cr-N film strain gauge elements were directly fabricated on the

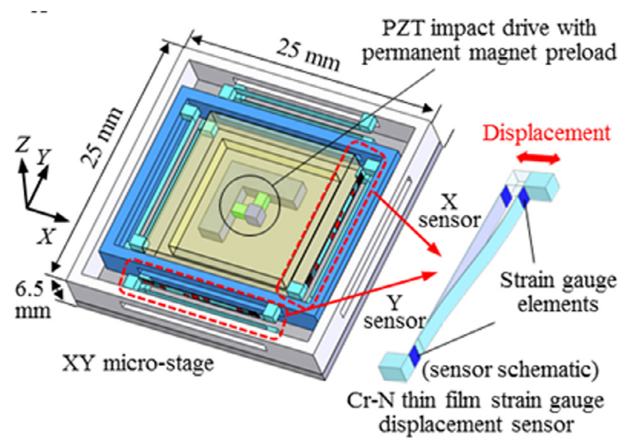

Fig. 13. An XY micro-stage with Cr-N thin film strain gauges [4].

elastic hinges used to guide the micro-stage along X- and Y-directions within a range of $\pm$ 1 mm in each direction [4,156,183]. This made the stage to be in a compact size. The fabricated Cr-N film strain gauge displacement sensors were confirmed to have a resolution of 5 nm.

The state-of-the-art scanning white light interference microscope presented in Zygo [224] is another example of a very small range system. In this microscope, the field of view or the XY measuring range can be adjusted from 40 µm $\times$ 40 µm to 17.49 mm $\times$ 17.49 mm, which is determined by the magnification of the objective lens, the optical zoom and the detector array size. The resolution in the lateral direction is determined by the number of pixels of the detector array as well as the diffraction limit of the objective. For measurement along the vertical *Z*-direction, the objective is scanned vertically over the sample surface by using an actuator. When a PZT scanner is used, the vertical measurement range is 150 μm with a resolution of 0.08 nm. A capacitance gauge is employed for closed loop control of the PZT scanner. The vertical scan range can be extended to 20 mm by using a motor-driven *Z*-stage with 0.1 μm resolution.

Similar technologies can be found in micro-machine tools. Fig. 14 shows the picture of a prototype NC micro-lathe [100]. The lathe had a dimension of 32 mm $\times$ 28 mm $\times$ 30 mm and a mass of 96 g. Two inchworm PZT sliders were used as the carriage and cross-slide of the micro-lathe, instead of conventional ball-screws. In this case linear encoders were employed to make full closed loop control of sliders with a resolution of 0.2 μm.

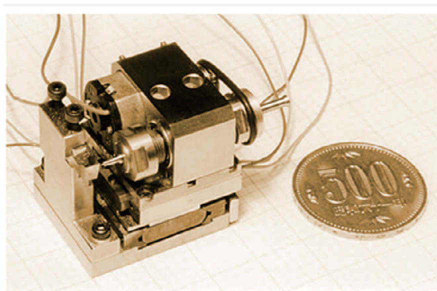

Fig. 14. A prototype NC micro-lathe [100].

5.3. Small to medium range (1 mm–5 m) systems

Fig. 15 shows the positioning components that can be used for precision positioning over larger ranges of up to 5 m. The left column summarizes the components often used in standard combination, while the right column shows the most common alternatives found in literature for precise applications. The standard combination uses servo motors whose rotatory motion needs to be converted into linear. The position measurement is commonly performed by a linear encoder. Nevertheless, this cost-effective solution has a limited speed and resolution. For more precise applications, the combination of linear motors with frictionless bearings is preferred. In the Fig. 15, the type of frictionless bearings that are used in each application is specified. In ultra-

Standard combination	Other components for precise applications	
Actuator		
Servo motor	Linear motor	• For high-speed systems of medium thrust force
+		
Motion transmission and motion guide		
Ball screw + Bearings + Linear guide	Linear guide	
	Aerostatic bearing	• For measuring instrument and machine tools of high speed and moderate load
	Hydrostatic bearing	• For machine tools of moderate speed and high load
	Magnetic bearing	• For 2D photolithography equipment of high speed and low load. Vacuum environment compatible.
+		
Position sensor		
Linear scale	2D scale	• For 2D photolithography equipment of high speed and low load. Vacuum environment compatible.
	Laser interferometer	• For ultra-precision measuring instrument with Abbe error free design
+		
Full-closed loop position controller		

Fig. 15. Components for precision positioning in small and medium ranges.

precision applications the position measurement is performed by a laser interferometer, whereas in lithography applications, 2D grid encoders are preferred.

Fig. 16 shows a full closed-loop position controller design based on the standard combination of components [215,216]. The position measured by the linear scale is used for feedback control of position. The rotary encoder output is employed for velocity control of the motor. However, rotary motors present many disadvantages in accurate positioning systems because they need additional mechanical systems as ball screws to convert rotary motion in linear motion, which introduce backlash, alignment errors, and friction [27,126] (see Fig. 16). In addition, in 2D applications, they must implement a stacked configuration. Nevertheless, they are often used as actuators for low precision coarse motion in a two stage scheme [120] if backlash prevention by double ball screw nuts is not applied.

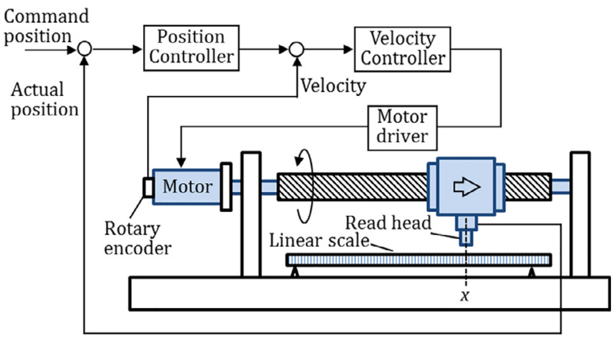

Fig. 16. A full-closed loop position controller for a servomotor positioning system.

Another example of a two stage scheme is presented in Yang et al. [219]. In this case, the positioning system that implements stacked configuration uses *U*-shaped linear motors. The coarse motion performed by the stacked stage is complemented by the fine motion of an ultra-precision piezo positioning system, achieving an accuracy better than 3 µm in a working range of 300 mm × 300 mm. Similarly, in the Nano-positioning and Nano-measuring Machine NMM-1, linear motors were employed to expand the measurement volume of a SPM to 25 mm (X) × 24 mm (Y) × 5 mm (Z) [128]. This travel range is obtained with a stacked arrangement, achieving closed loop positioning stability of approximately 0.3 nm.

For precision positioning, linear drives are preferred because they do not use drive screws or gearheads and are backlash-free. Furthermore, they can also be frictionless when combined with air bearings [80,184], magnetic levitation [209], or flexure bearings, which makes them capable of achieving high precision positioning. The following are the discussions of the most common alternatives found in literature for precise applications (Fig. 15 right column).

Voice coil motors (VCM) are frictionless electromagnetic linear actuators characterized by their good dynamics. VCM are capable of achieving fast responses and high precision positioning without cogging or hysteresis. They have been applied in flexure linear and parallel XY stages [109,171,214]. Nevertheless, their motion range is limited and they produce small output forces. The nanopositioning system described in Jywe et al. [93] (see Fig. 17) integrates these actuators. Its XY–drive system is a stacked configuration of VCMs and linear guides. A flexure structure of four degrees of freedom micro–range stage (ZRxRyRz) is assembled over the platform for fine positioning. It has a working range of 20 mm (*X*) × 20 mm (*Y*), with a positioning error of 23 µm in *X* axis and 22 µm in *Y* axis.

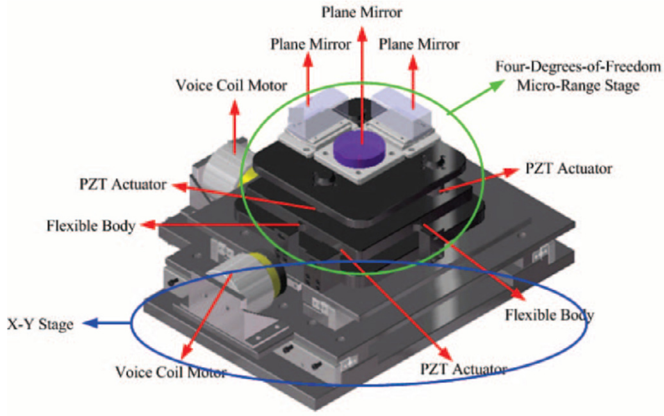

Fig. 17. The structure of the middle-range six-degrees-of-freedom system [93].

In contrast to VCM, in brushless linear direct current (BLDC) motors, non–contact parts are flat and parallel surfaces and they are capable of producing high forces and high speeds keeping a compact design. The positioning control of these motors is performed by commutating the phase currents, which results in low stiffness and vibrations. The different types of BLDC motors can be classified according to their guiding requirements. In commercially available linear motors, the linear displacement is guided by the architecture of the magnet track or the motor design, which can be flat, U shaped, or tubular [71]. However, the guiding system impedes the displacement of the motor along the orthogonal direction of its driving axes, thus, the implementation of planar motion becomes unfeasible. Therefore, they can only be mounted in stacked axes configuration [219].

In order to allow planar motion, a linear motor must be capable of attaining displacement not only along its drive axis, but also along the orthogonal direction. Therefore, only unguided linear motors can be implemented for planar motion. Halbach linear motors, a type of permanent magnet synchronous motor (PMSM) designed by Trumper et al. [205], are considered to be a solution. The Multi–scale Alignment and Positioning System (MAPS) developed at the University of North Carolina at Charlotte (UNCC) [56] implements these type of linear actuators in a planar configuration. This ultra-precision stage has a working range of 10 mm (*X*) × 10 mm (*Y*) and positioning accuracy lower than 2 nm. Similarly, the 6D planar magnetic levitation system PIMag6D [175] is actuated and fully levitated by three coil pairs mounted at the stator which interact with three Halbach arrays in the moving platform, achieving a positioning stability of ±10 nm in a range of 100 mm (*X*) × 100 mm (*Y*). Similar motors are used in Hesse et al. [76] for 2D positioning in a 100 mm diameter area travel range. Nevertheless, in that work, levitation is performed by three vacuum preloaded air bearings.

In precision systems of this range, frictionless guiding systems are commonly preferred, such as flexures, and aerostatic, hydrostatic, or magnetic levitation bearings. The absence of friction between mechanical parts presents benefits such as high accuracy, repeatability, speed, lack of wear, and no use of lubricants. Flexure mechanisms, such as the previously mentioned hinges, allow motion in 1D or 2D by making use of elastic deformation. They are usually combined with PZT actuators [96,220] and VCMs [118,197]. Nevertheless, their working range is limited (<10 mm) [115,211] and flexure-based large-stroke stages generally come at the sacrifice of physical dimension [171]. Other types of frictionless guiding systems mentioned above are used for machines with larger working ranges (>10 mm). Magnetic levitation consists in creating magnetic fields that result in vertical forces that counteract the weight of the part. This vertical force can be controlled in order to attenuate frame vibrations and increase stiffness. Trumper and Kim developed one of the first magnetically levitated positioning stages [97]. This stage was designed for photolithography applications and was able to provide a large displacement of 50 mm (X) × 50 mm (Y) with resolution better than 10 nm and high position stability. In a posterior work, Kim developed a novel magnetically levitated compact platform with a plane motion over 5 mm (X) x 5 mm (Y) area [98]. The previously mentioned PIMag 6D [175] (Fig. 18) implements magnetic levitation of a moving platform with six degrees of freedom in a working range of 100 mm (X) x 100 (Y) mm x 100 μm (Z).

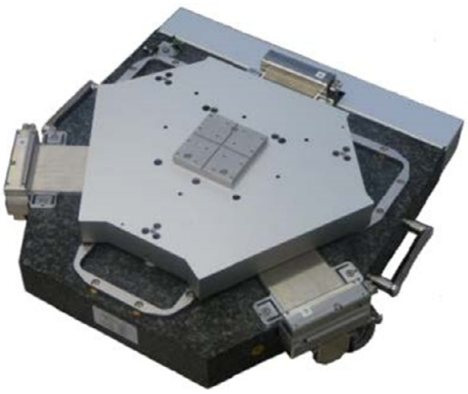

Fig. 18. Setup of the prototype system PIMag 6D [175].

Aerostatic (air) and hydrostatic (oil) bearings provide levitation by maintaining fluid flow through small orifices or porous surfaces, Necessary constraints and high stiffness are achieved by arranging these bearing pads in opposite directions or applying various types of preload, such as magnetic or vacuum [56]. However, they are limited by the stability of the fluid flow and the accuracy of bearing surfaces. Air bearings are also used as guiding systems in guided linear motion and rotatory motion. Fig. 19 shows a unique AFM system in which an air-bearing spindle and an air-bearing slide are synchronized to make a spiral scan over a circular area up to 100 mm diameter [61]. A preloaded PZT actuator was employed to make Z tracking of the AFM probe with the sample surface over a range of 70 μm. The spiral scan AFM has been applied to on-machine measurement of microstructures by utilizing the spindle and cross-feed slide of a diamond turning machine [62,63].

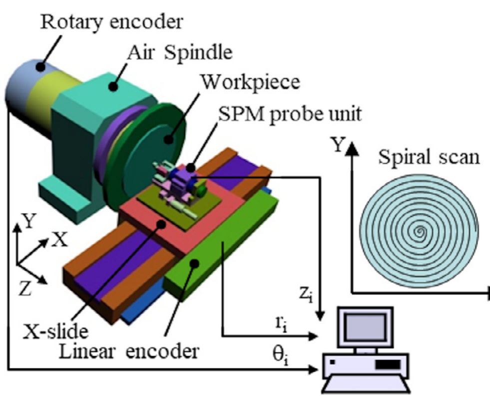

Fig. 19. Spiral scan SPM with 100 mm diameter scan area [61] z_i, r_i, and θ_i are the read-outs from the SPM probe unit, the linear encoder, and the rotary encoder, respectively.

Positioning sensors capable of achieving submicrometer measurement uncertainty can be classified according to the type of measurement they provide, their range, resolution, etc. In this section, distinctions have been made between 2D and 1D sensors, translation or rotation displacements, and long (>10 mm) and short (<10 mm) range devices. Rotation can be measured with autocollimators and angular encoders. In the stage presented by Eves in [52], three autocollimators determinate the orientation of the sample holder and correct its position.

Linear short-range displacements can be measured by capacitive or inductive sensors. These short range devices are typically used for measuring spurious motions in out-of-plane positions in small to medium range systems, such as nanopositioning stages [57].

Linear displacements larger than 10 mm are measured by linear encoders and 1D laser interferometers. Similarly, the available options for measuring planar 2D displacement are 2D grid encoders, combinations of 1D linear encoders, and laser interferometers. Linear encoders scale errors can be evaluated and compensated by software. For the evaluation of these linear errors, heterodyne or homodyne laser interferometers are widely used [78,94]. An example is the prismatic 3D-CMM [210] which implements linear encoders. Nevertheless, due to the narrowness of the linear scale in the orthogonal direction, they are not appropriate for planar designs. The previously mentioned 6D planar magnetic levitation system PIMag6D [175] measures the planar degrees of freedom with a grid encoder. In Ro and Park [167] a grid encoder was used as positioning sensor in a 20 mm × 20 mm planar stage, achieving a XY resolution of 20 nm, before calibration and compensation. Such a design of combing a planar stage and a planar encoder is originated from Gao et al. [65] where a surface encoder was employed as the position sensor. In a surface encoder, a sinusoidal grid surface made by fast tool servo [64] is read by a multi-degree-of-freedom angle sensor unit. In addition to the XY-linear motions that can be measured by a conventional 2D grid encoder, a surface encoder can also measure the tilt motions [35]. The resolution of surface encoder has been improved to sub-nm[99] by using a short-pitched scale grating made by interference lithography [116]. It has also been expanded to a three-axis six-DOF version including Z-displacement measurement[115] with reduced cross-talk errors [131]. In Niiya [148] a 2D scale for absolute position measurement over a range of 600 mm × 500 mm is presented.

Laser interferometer systems provide highly accurate, non-contact measurements and they are capable of working in long distances [189]. In addition, they present direct traceability to the fundamental standard of length and an excellent dynamic range, limited only by the fluctuations of the refractive index of air [190], achieving nanometer or even subnanometer resolution. Moreover, systematic errors can be minimized by monitoring the environment parameters and correcting the refractive index. The laser beam can be considered as a virtual axis that can pass directly through the measurement point of interest to eliminate Abbe offset errors [6]. 1D plane mirror laser interferometer systems with plane mirrors can be combined to result in a 2D positioning sensor. The NNM-1 [128] implements plane mirror laser systems for the measurement of the displacement in 3D: in X, Y, and Z axes.

As in the case of very small range systems, when the feed drives of precision instruments are not adequate to deliver the required performance due to very small positioning resolutions over long travel distances or inadequate control bandwidths, additional sensors and actuators are incorporated to such systems. Michellod et al. [138] describes a control strategy for a high-bandwidth, high-resolution dual-stage nano-positioning system combining a PZT stack actuator, a stepper motor, and a single laser interferometer position feedback. The controller is designed to coordinate control action of both actuators to optimize the positioning. Conventional PI controller was used for the PZT. An observer is used to estimate the position of the coarse stage based on PZT actuator model, its voltage input, reference signal, and the position feedback signal. It is integrated into the coarse positioning loop as shown in Fig. 20. Observers are also effective in precision

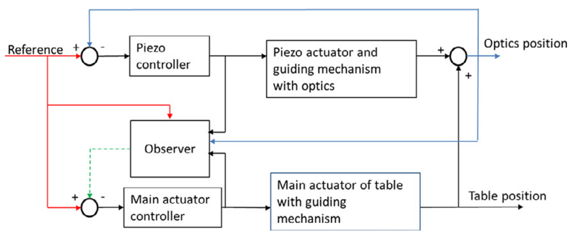

Fig. 20. General control structure of the dual-stage nano-positioning system with a single position feedback (adapted from [138]).

control of planar motion stages driven by surface motors [34,37]. A similar solution based on a compact fast tool servo has also been developed for fabrication of sinusoidal microstructures on a cylindrical workpiece [68].

5.4. Large range (>5 m) systems

Fig. 21 shows the most usual components used for large range machines. As in Fig. 15, the left column summarizes the components often used in standard combination, while the right column shows the most common alternatives found in literature for precise applications. Since the components indicated in that right column have been described in the previous sections, the following explanations will be mainly focused on the standard combination, exemplified in large range and heavy load machine tools. In such machines, because the masses of the moving table and the workpiece are extremely big, it is difficult to employ a ball screw for motion transmission and rotary-to-linear motion conversion due to the problems of limited stiffness, vibration and permissible rotational speed. A pinion and rack mechanism or a worm and rack mechanism can be used to replace a ball screw. Compared with the pinion and rack mechanism, the worm and rack mechanism is more accurate. Large masses involved in this category of machines also cause large friction leading to positioning errors due to stick-slip conditions. Feedforward control algorithms are used to minimize the effect of such friction as shown in Fig. 10.

Standard combination	Other components for precise applications	
Actuator		
Servo motor	Linear motor	▪ For moderate speed systems of medium thrust force
+		
Motion transmission and motion guide		
Worm/rack + Hydrostatic bearing	Linear motion guide	▪ For measuring instrument with low speed and light load
+		
Position sensor		
Linear scale	Laser interferometer	
+		
Controller		
Hybrid position controller	Full-closed loop position controller	▪ For ultra-precision systems

Fig. 21. Components for precision positioning in large range.

Another approach is to reduce friction in drive systems. Fig. 22 shows an example of friction reduction by a hydrostatic worm and rack mechanism used for a large machine tool [172,173]. The pockets of the unengaged teeth of the worm are filled with supplementary oil with a low pressure and those of the engaged teeth are filled with pilot oil with a high pressure to control the gap between the engaged teeth of the worm and the rack to be tens of micrometers over the entire length of the worm. Since a large number of teeth of the worm and the rack are engaged with each other, not only a high stiffness but also a high accuracy is achieved due to the averaging effect of the engaged teeth.

Hydrostatic bearing is also employed in the guideway of the machine table. In Fig. 23, the gap t between the table and the guideway is controlled to be constant without being influenced by the load applied by the cutting force as well as by the workpiece with a maximum mass of 60 tons.

Linear encoders are typically used as the sensors for direct measurement of position and displacement in this range, except the glass scale, which is generally limited to measurement lengths to about 4 m. A steel tape scale for an optical incremental linear encoder can reach a

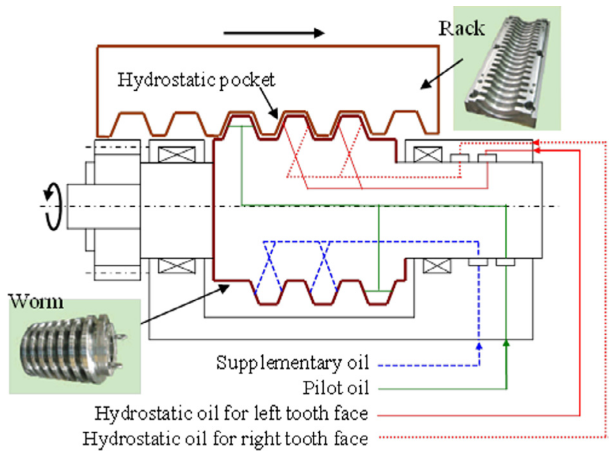

Fig. 22. A hydrostatic worm and rack mechanism for a large machine tool.[172]

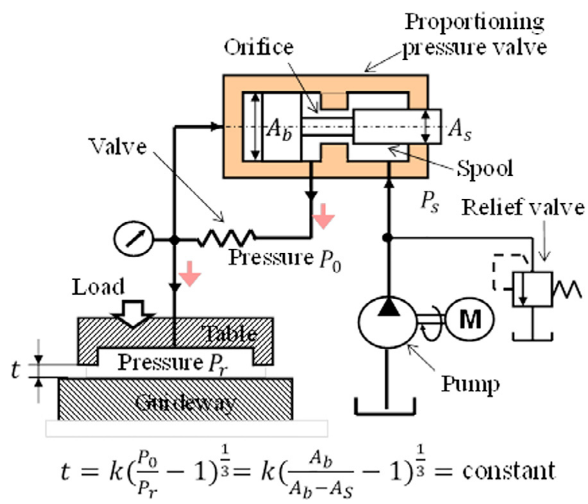

Fig. 23. A hydrostatic bearing for the moving table of a large machine tool [172].

length of 72 m [75]. Magnetic linear encoder is another choice for long range positioning, which can reach a length of 100 m [164]. Laser interferometer can also be used for long range positioning. Fig. 24 shows an example of a homodyne laser interferometer used in a large milling machine for providing reliable and continuous position feedback over a range up to 60 m. [163].

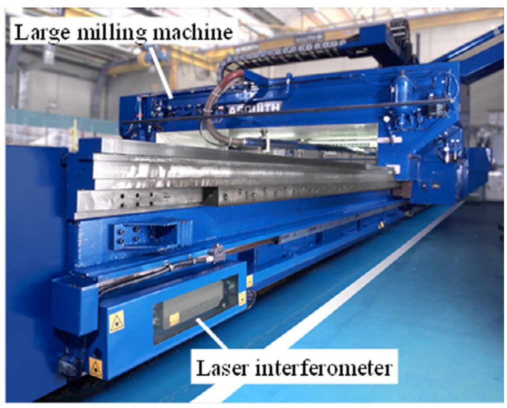

Fig. 24. A laser interferometer used in a large milling machine [163].

A hybrid position controller shown in Fig. 25 is employed for feedback control of the moving object (moving table and workpiece) with a heavy mass [172]. In the full-closed loop control employing only the direct position/displacement measurement of linear scale, the entire mechanical feed-drive including the moving object and the motion conversion mechanism are included in the control loop. Because the natural frequency of the system is extremely low due to the large mass

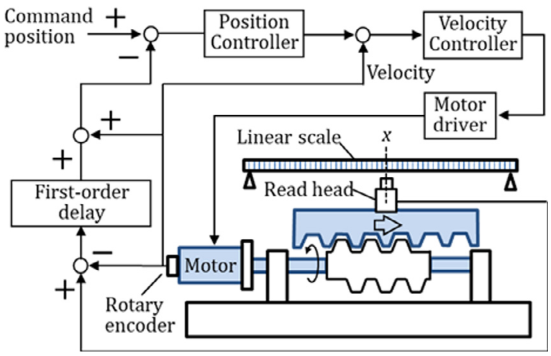

Fig. 25. A hybrid position controller for a large machine tool of heavy load.

of the moving object, a low loop gain of the system has to be taken, which will significantly reduce the performance of the positioning system in terms of positioning accuracy and speed. In the hybrid controller, the full closed loop control based on the direct position/displacement measurement by the linear scale and the semi-closed loop control based on the indirect position/displacement measurement by the rotary encoder are combined. The former is employed for accurate positioning in low frequency bandwidth. Since the latter does not include the heavy mechanical feed-drive, it can realize rapid control over high frequency bandwidth. Consequently, a good positioning performance can be achieved in a wide frequency bandwidth.

5.5. *Discussion on motion, measurement and control*

To summarize, these are the design principles for motion, measurement, and control in precision systems: Direct drives are preferred in order to avoid the use of motion transmission elements which add backlash to the system. In addition, the guiding system should provide frictionless motion, which avoids wear and reduces the number of elements of the system. An illustration of frictionless guides are stiff fluid bearings which also provide high averaging effects [134]. The guiding system defines the structure of the machine: guiding systems that impede the displacement in the orthogonal direction must be mounted in stacked axes. However, in precision systems, planar motion is usually preferred, since it reduces the geometrical errors. Thus, in order to implement planar motion, the guiding system should only provide vertical lift. Regarding the positioning sensors, non-contact sensors are preferred, since they do not affect the dynamics of the system. Additionally, they should provide a direct position feedback to the controller. The control system can implement additional sensors to monitor and correct or compensate the main disturbances of the system. Finally, the control strategy can be improved to achieve a zero following error, with techniques such as feedforward.

Table 2 shows a qualitative evaluation of the scalability of the implementation of precision motion measurement and control principles in precision systems, depending on their working range. In precision machines with very small ranges ($< \pm 1$ mm), PZTs are used as direct actuators due to their high resolution and good dynamics. They are usually combined with capacitance probes and hinge mechanisms, which provide frictionless motion and can also be designed for planar motion. As a low-cost alternative, strain gauges can be used as positioning sensors at the expense of resolution. In ultra-precision instruments, laser interferometers can also be used as positioning sensors. Optical linear scales are another solution that has the main advantage of being robust to electromagnetic noises. It should be noted that the image scanning principle is conventionally employed for an optical linear scale, either incremental type for displacement measurement, or absolute type for position measurement, with a grating period larger than 10 µm, achieving displacement/position measurement resolution of 10 nm to 100 nm. For achieving nanometer or picometer displacement measurement resolution, the interferential scanning principle is generally applied to an optical linear scale of incremental type with a grating period shorter than 10 µm. On the other hand, the image scanning principle has been improved with the significant progress in the image sensor technology. Renishaw plc has released an absolute-type linear encoder based on the image scanning principle where a position resolution of 1 nm and a speed of 100 m/s can be reached by using a high-speed image sensor to read an absolutely-encoded scale structure [165].

In small to medium range machines (1 mm–5 m), electromagnetic motors are used as actuators. VCMs are used in small ranges and can be combined with hinges to extend the range of motion. Architectures with a stacked configuration with linear guides can be used for larger ranges with more than one degree of freedom. Electromagnetic linear motors can perform large travel ranges and can be combined with frictionless guides. For implementing planar motion unguided Halbach linear motors and pneumatic or magnetic levitation are possible solutions. Direct non-contact position sensors such as laser interferometers can provide 2D measurements in planar nanopositioning systems, eliminating the Abbe error. Nevertheless, in precision machines standard rotary motors are more common due to the fact that they are more cost effective. They are combined with ball-screws which convert rotatory motion to linear motion.

In the specific case of large range machines (>5 m), some of the precision motion control principles are more difficult to implement. The use of linear motors is limited to medium thrust forces, and, thus, servomotors in combination with worm/rack transmission elements and hydrostatic bearings must be used for higher loads. Magnetic or steel-tape linear encoders are capable of providing good resolution in large ranges. Similarly, laser interferometers are used in ultra-precision systems.

Table 2
Application of motion measurement and control precision design principles.

Precision Design Principles	Very small range systems	Small to medium systems	Large range systems
Direct (linear) drives	●	◑	◔
Frictionless motion/bearings	●	◑	◔
Planar motion	●	◔	○
Direct position sensor	●	●	◕
Non-contact position sensor	◕	●	●
Full-closed loop position control	●	●	●
Hybrid position control	○	◔	◔

Legend: the blacker the circle is the more often the principle is applied in the indicated range.

6. Error mitigation principles

6.1. *Error budgeting and mitigation principles*

Attainment of the highest accuracy motions and measurements is based on the reduction and avoidance of error sources, the correction of repeatable errors, and compensation of errors arising from measurable contributors. An example taxonomy of these mitigation strategies is shown in Table 3. The reduction and avoidance of errors is often accomplished by improving the underlying structure of the system – either by applying the structure and alignment principles of Section 4 to the design, or by refining the quality of individual components (e.g., producing more precise surfaces for assembly) to support these principles. Once the system is operational, errors are measured at different locations within the system's performance range (or volume) and these quantities can be used to adjust either the commanded position (machines and measuring instruments) or the reported position (measuring instruments) of the end effector, or other "point of interest."

Table 3
Error mitigation strategies.

Mitigation strategy	Principal methods	Examples
Error avoidance	Architecture modification	Replacement of over-constrained structure with kinematic support
Error reduction	Component-wise improvement	Lapping of an axis to improve straightness
Error correction	Steady-state offsets of known, stable errors	Measurement of straightness errors of an axis, with subsequent correction
Error compensation	Real time, model-based computation of offsets	Estimation of scale growth due to temperature, with subsequent compensation based on the measured temperature(s)

This technique presumes that the errors are temporally stable, and retain validity between the measurement of the errors and the subsequent application(s) of the error correction. The set of methods of obtaining and correcting error values is a rich field, and references to the main techniques will be given in the sections that follow. For errors that are not stable in time, compensation (as opposed to correction) of errors may be possible. This error compensation requires a model of both the time-varying quantity and the influence of this quantity on the "point of interest."

These error mitigation techniques are explored further in the sections that follow, but it is instructive to consider where in the design and use lifecycle the mitigation is performed. Error avoidance, linked to the system structure, occurs at the conceptual design stage while error reduction occurs during the detail design where final component selection is performed. Error correction is based on the machine model and errors measured when the system is operating in its final placement, while the error compensation addresses errors from real-time sources, such as a changing thermal environment. As an example of the difference between the final two techniques (correction vs compensation) – error correction may be used to improve the accuracy of a CMM based on measured geometric errors of the CMM structure, while the error compensation is based on the thermal environment at the time of measurement and the coefficients of thermal expansion for the workpiece and the CMM [174,222]. While both correction and compensation may be *applied* in real time, the compensation relies on information *collected* in real time, as opposed to a prior measurement.

As a reminder, this paper uses the term 'system' to refer to either a measuring instrument or machine tool. Also, the error of either the tool tip, stylus tip, retro-reflector, or illuminated (by laser or other light source) measurement location will be the measurand. For the purposes of calibration, it is the uncertainty with which the error of the system can be determined, rather than the errors themselves, which is of importance. Hence, this gives a view of the error as a measurand.

6.1.1. Error budgeting

In the design of a precision machine or instrument, an error budget is used to identify, classify, and quantify the influence of these errors on the desired output of the system. The budgeting of the errors during the design phase is similar to performing an uncertainty analysis where the influences on a measurand are determined. As a design tool, a well-thought-out budget provides quantitative justification for design choices that will limit the errors of the system. The utility of an error budget is directly related to the knowledge of the budget's creator, and the care with which influence quantities are identified and the sensitivity of the measurand. Examples of error budgets can be found in [199,204] and early investigation into the interaction between different components of the budgets[182] examines the underlying statistical assumptions in this budgeting. In [203] Torralba et al. describe an example of an error budget used in the design of a nano-positioning system showing the variety of different error contributors that must be considered, which include, for example, sensors resolution, linearity errors, alignment errors, and environmental influences.

The "Deterministic Approach", so named by Jim Bryan [19], presumes a cause-and-effect relationship between any error and its root cause, and identifies *apparent non-repeatability* as the consequence of our inability or unwillingness to determine the details of this relationship. An error budget will capture the limits of the ability (or willingness) to control influence factors that result in errors, and the magnitude of these errors. This lack of control need not be due to sloppiness on the part of the designer; there may be a range of environments in which the system is intended to perform that will necessarily produce errors in the system.

6.1.2. Error avoidance

The basis of error avoidance is to utilize suitable design practices so that errors are not "built into" the system. These principles are summarized in Section 4, as the overall structure and alignment of the system components is determined at the onset of the design phase. Examples of these techniques include utilizing kinematic mounting of components where possible, and selecting materials that provide appropriate response to expected (thermal, gravitational, inertial, clamping) loads. Another technique is the use of isolation to minimize adverse effects on the performance of the precision systems by reducing the transfer of internal and external heat, vibrations, pressure, and humidity to components of the system. One needs to analyze vibration transmissibility, for long-duration vibrations and short-duration shocks, from mechanics and acoustics as well as the heat flow to select and dimension passive and or active isolation techniques. Isolation on the system level can also be grouped into passive (placement of sensitive instruments far from disturbances) and active (building confined spaces like metrology rooms which have low transmissibility). Therefore, isolation can also be considered a technique for error reduction in some cases.

6.1.3. Error reduction

Once an overall design has been selected, the ability to produce this design for optimal performance will rely on reducing the errors of the system components and their assembly. Individual components may require additional processing to achieve the required geometric (or electronic, or flow) characteristics. This may include lapping or polishing of mechanical surfaces, shielding electronics, and smoothing or baffling flow channels for the most repeatable performance. One-time adjustments may also be considered part of error reduction, such as setting the physical perpendicularity of a system's motion axes. Finally, the design and implementation of the control system that accommodates and responds to the anticipated system loads and environmental conditions is fundamental in reducing errors in the system. These error reduction methods are addressed in detail in Section 5 which focuses on motion measurement and control.

6.1.4. Error correction

If the errors that exist can be measured – either directly through test equipment, or indirectly through the examination of a workpiece – it must be determined whether these errors are constant in time, or changing. Errors that are constant over time may be corrected, based on where the error occurs in the machining or measuring volume. Advances in computer processing power and speed and algorithm complexity now allow corrections of the system to be applied throughout the system volume (as opposed to individual axes), either based on a lookup table for each position, or the propagation of errors through a kinematic model of the system.

The ability to correct errors in a system depends directly on the stability of these errors over time, and on the uncertainty with which the errors can be measured. The first item – known as long-term repeatability – is of fundamental concern to all precision systems, as ultimately this will drive the precision limit of the system. The second item is of concern to those who perform instrument calibrations and write standards for system performance. In most system performance tests, the measurand is the error of the system when making a particular motion or measurement. The ability to accurately determine these errors has been addressed in International Organization for Standardization technical committees (ISO TC213 and ISO TC39/SC2) and is referred to as "test value uncertainty" [83,84]. The distinction with which we concern ourselves here is that the uncertainty in determining the error values must necessarily be less than the desired (or specified) performance of the system being evaluated. Error correction is a mature field, and the application of the correction of rigid body geometric errors, as well as predicted dynamic errors has evolved from early modeling [77] for three-axis machines to more complex five-axis machines [206]. Methods of error measurement are either direct measurements of geometric deviations of the system motion, or indirect inference based on cutting results or artifact measurement.

Additional techniques for identifying errors rely on reversal, where a stable (but imperfect) artifact is measured in multiple orientations and the errors of the artifact and the system are separated mathematically [8,51]. As observed in [55] the rate of change of the deviations in the artifact (i.e., the slope) can limit the ability of a reversal to effectively separate errors, as the separation is increasingly sensitive, in proportion to the artifact's slope, to the registration of the different artefact orientations.

6.1.5. Error compensation

For errors that are determined to be changing in time, this may be due to a causal relationship between the errors and internal (velocity) or external (temperature) influences to the system. This relationship must be captured using a model of the system. A simple lumped model might be used to estimate the linear expansion of a system component with changes in temperature, but a more sophisticated model may have multiple temperature sensors, and attempt to capture non-linear distortions based on the gradients within the component [88]. Because of the complex structure and the large number of components in precision systems, the modeling of these systems is often not possible due to the interactions between the various influence factors. The distinction between error correction based on a classic "look-up table" and error compensation based on a sophisticated dynamic model of the system may seem arbitrary, as both methods rely on a model. However, we will use error correction to refer to removing the influence of system errors determined *a priori*, while error compensation is the application of corrections based on transient factors, such as loads or temperatures that are determined in real time. An example of the application of compensation applied in a machining context can be found in Bleys et al. [10], where a model of an electro discharge machining (EDM) milling process is used to predict tool wear. In this case the influence quantity that is measured is the electric pulse sent to the EDM tool. The corrections may be calculated based on the measurement of influence factors such as temperature, or based on the use of a metrology loop that is independent of the system's motion control, as summarized in Donmez et al. [41,82,145].

6.2. Small range systems

Small range machines often are relatively massive when compared to the workpieces produced or measured. The end effectors used with high-precision metrology "frames" can generally only accommodate small deviations in the motion of the system, and thus the movement of the tool or sensor must be accomplished with precision, although this movement is not used in the sensing of the system position. Thus, the moving system is quite precise, with a metrology loop that is nested inside the system, yielding even greater precision.

The main focus of these systems is often in the design and control stages, as the underlying accuracy of the components and their arrangement will drive the magnitude and type of errors that occur. Thus, the strategies of error avoidance and error reduction play a greater role in small systems. In very small systems, the damping of the moving components is harder to control without introducing hysteresis, and often special techniques must be used. One example of this is shown in Fig. 26, where Eddy current dampers are used to provide damping without friction effects [56]. Eddy currents caused by moving a conductive plate, in a magnetic field in an opposite polarity, generate a repulsive force proportional to the velocity, and therefore achieve damping effects.

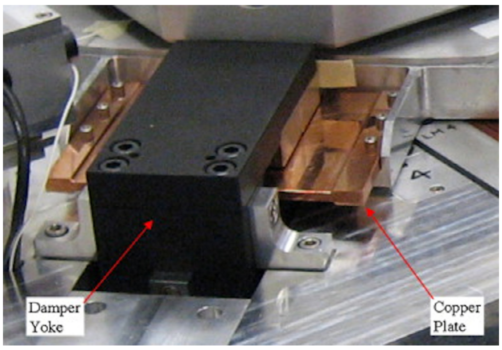

Fig. 26. Eddy current damper.[56]

As explained in Section 4 another technique utilized throughout precision machine design, but more frequently in smaller machines, is symmetry. This may be three- or four-fold symmetry depending on other design decisions that are made. An example of this is the molecular measuring machine [106].

Because of the small range of these systems, gradients in temperature across the range tend to be small, and the compensation of errors due to external influences is rarely needed. The correction of measurable errors is accomplished using traditional techniques, based on the assumption that these errors are unchanging.

6.3. Medium range systems

The vast majority of industrial manufacturing and measuring equipment fall in the category of medium range systems. Precision design principles have been applied to these systems, and the errors of these systems have been studied extensively and are well known. Recent developments frequently focus on adaptions of these systems to perform at greater speed (for example), requiring additional correction and compensation as the underlying precision design principles are violated. For medium size systems, all aspects of error mitigation are utilized. Examples for machine tools include [12,108], and [206].

For this scale of machines, the opportunity of active error reduction [174] is often used; this is a form of error compensation, where information about the current system state is used to make real-time corrections to the system output. One class of effective compensation devices is piezoelectric transducers. This mechatronic approach – to control various undesired behaviors in machine tools – is explored in Neugebauer et al. [146]. Examples of mechatronic applications include PZT-based axial vibration compensation unit, active hydrostatic, magnetic, and aerostatic guide systems and active spindle bearing systems, as mentioned in Section 5. PZT-based axial vibration compensation unit for ball screw drive systems, shown in Fig. 27, is attached between the ball screw nut and the carriage, where the bandwidth of the feed drive is inadequate to eliminate vibrations.

Another area of importance is the error reduction in medium size systems. As these systems are on the scale of human size, the control of the environment is of utmost importance. Small scale systems can, with the adequate materials selection, often be designed to operate in vacuum,

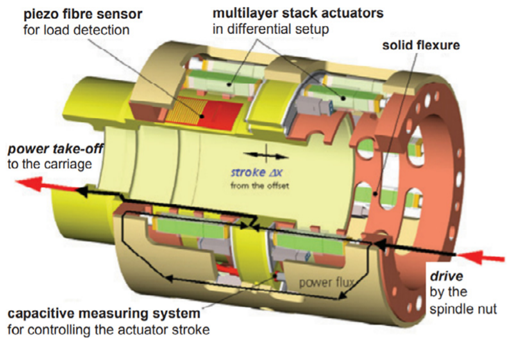

Fig. 27. Axial vibration compensation unit.[146]

while large scale systems rely more on the compensation of the environment than on environmental control. In addition to making the design insensitive to these variations as much as possible, designers also include control systems to minimize such variations. Lithography scanners are a significant example of this, since the entire machine enclosure is isolated from environmental disturbances such as vibrations and heat fluxes [22]. Another noteworthy example of such an effort, designing two forms of temperature control for a precision turning machine, is described in Donaldson et al. [40], the first was to reduce the temperature variations due to internal heat generation in machine spindle. A closed-flow water jacket was installed around the spindle motor. The spindle temperature was controlled within 50 mK using a simple proportional (P) controller with feedback from a thermistor. The second temperature control system was for the recirculating air flow around the machine. Fig. 28 shows the

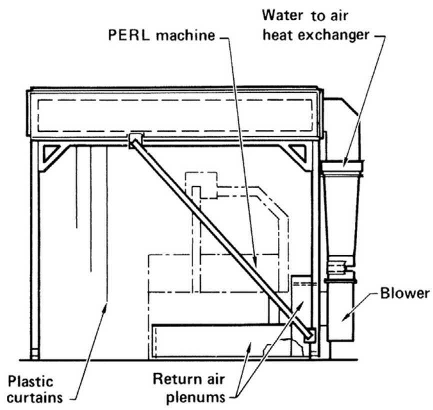

Fig. 28. Environmental enclosure for precision turning machine.[40]

schematic of this environmental enclosure. Temperature variations were controlled within 50 mK over periods of 6 h by chilled water heat exchanger using a PID controller with thermistor feedback.

In designing such temperature control systems, careful consideration of system disturbances is necessary. Chou and Debra [31] provided a detailed study of the control system development for environmental control for precision machine tools using oil shower as the temperature control medium. Oil temperature was controlled using chilled water flow through a heat exchanger. Temperatures of water and oil at the inlet and outlet of the heat exchanger were used in the controller. Fluctuations of the water and oil temperatures at the inlet were used to develop the disturbance models, which were used as feedforward control. Using a conventional PI controller with disturbance feedforward compensation, the oil temperature at the outlet was controlled within about 25 mK. Tonnellier et al. [202] report on reduction of temperature effects by applying nine control circuits to control temperature for their precision grinding machine used to grind segments of an extremely large telescope.

6.4. Large range systems

Large range systems experience errors that cannot be "designed out" or reduced by traditional methods. Only occasional examples of vibration isolation of precise components used for large scale applications can be found, for example in the LIGO, where a two-stage twelve-axis vibration isolation and positioning platform was developed to mount its interferometer's core optics operating in ultra-high vacuum [130]. Often the influences that result in errors are due to gradients in the environmental conditions due to the large volume of the system, and the self-weighing (gravitational) effects of large system structures and the workpieces themselves. The investigation of machine tools for large parts[207] closely examines both the requirements of the foundation for supporting large machines and workpieces, as well as pointing out the large magnitudes of thermo-mechanical errors. The conclusion of this work states "*These machines, due to their size, suffer of remarkable thermal and mechanical deformation issues.*"

One class of error compensation that has been investigated is determining the refractive index of air to compensate the laser-based measurements that are the foundation of many large-scale systems. This compensation [43] allows the compensation in real time of distances measured based on changing environmental conditions. The weakness in this strategy is that the index varies along the beam path, and the influence of the changing index must be integrated into the final compensation.

One method proposed to reduce the uncertainty in the effective index of refraction of air along a given path is to measure the effective temperature along the beam path using an ultrasonic source, and infer the effective index of refraction at the laser wavelength. Work by Korpelainen and Lassila [105] and Pisani et al. [159] have shown this method can effectively reduce errors present in lumped-parameter models of the environmental temperature, both in the laboratory and outdoors (where many large scale measurements take place). One experimental setup is shown in Fig. 29.

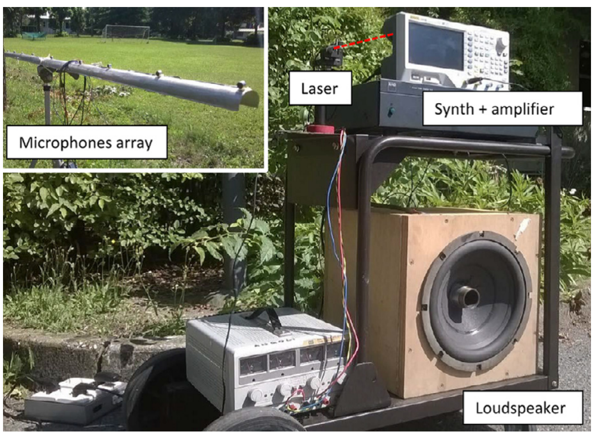

Fig. 29. Large-scale index of air estimation [159].

6.5. Discussion on error mitigation principles

When considering the scale of the precision system, the error mitigation strategies have different importance depending on the system scale. This is shown graphically in Table 4, giving a qualitative evaluation of the scalability of their implementation depending on the range of the system. While high-precision systems rely on all of the mitigation techniques, the overall trend is that small-range systems tend toward pure determinism, while large-range systems rely more on error correction and compensation due to the difficulty of controlling external influences to the system over large ranges/volumes. The systems that fall in the medium, or meso-scale, regime usually rely heavily on all of the error avoidance and correction techniques. This scale allows for components that are large enough to utilize the most precise manufacturing methods, such as diamond turning, but are small enough that uncontrolled gradients of material properties and environmental conditions are manageable in scope.

Table 4
Application and effectiveness of error mitigation strategies.

Error mitigation strategy	Small range systems	Medium range systems	Large range systems
Error Avoidance	●	◕	◔
Error Reduction	◕	●	◑
Error Correction	◑	●	◕
Error Compensation	◔	◑	●

Legend: the blacker the circle is the more applied the principle is in the indicated range.

New technologies are being explored in attempts to improve system performance (i.e., through the compensation of errors). Among these are the use of machine learning (ML) or artificial intelligence (AI), coupled with the large quantities of data that can now be collected during the machining or measuring process (big data). While these techniques have promise, and the enormous increase in computing power can support nearly arbitrarily complex models, there are risks in utilizing techniques that can extrapolate beyond known error states. Because many ML methods are purely data-driven, there is no way to ensure that accuracy is maintained in all machine states.

7. Conclusions

Precision design principles were reviewed and classified in three groups: structure and alignment principles; motion measurement and control principles, and error mitigation principles. Their applicability has been analyzed in order to establish their scalability or lack of it in small, medium and large range systems.

The first group, structure and alignment principles, includes principles concerning symmetry, kinematic design, Abbe principle, metrology frames, and thermal effects. In small range systems usually most of them are applied as it is the use of materials with low thermal expansion coefficient in their metrology frames. For precision medium range systems, the machine volume and the economical restrictions force that some of these systems renounce applying some of the structure and alignment principles in exchange for applying error correction or compensation techniques. In the case of large range systems, the thermal effects and the structure's own weight deformations may cause important loss of precision. The application of the structure and alignment principles for those systems is usually less frequent, and they usually resort to use error compensation techniques. However, when the need of precision is high and there are enough economical resources to afford it, there are also examples of high precision large-scale systems, especially in singular scientific facilities, that show very interesting applications of the mentioned precision design principles.

The second group of principles is focused on motion measurement and control. The main principles are the use of direct drives, frictionless bearings, non-contact direct sensors, the implementation of planar motion, and a full-closed loop position control. The selection of the drives depends on the travel range and desired accuracy. Although the solutions are varied, the implementation of direct drives is possible in every range, from very small ranges (<1 mm), where PZT are a common solution, to large systems, which use electromagnetic motors.

However, in medium to large range systems, the use of rotary motors is the most widespread solution because they are able to support heavier loads. Another precision principle is the use of frictionless bearings in order to achieve frictionless motion. For the implementation of this principle, there are different solutions depending on the range: while hinges are used in very-small-range systems, pneumatic and magnetic bearings are used in small-to-medium-range systems and hydrostatic worm and rack mechanisms, in large range systems. Planar motion is probably the principle that is more difficult to implement, since it not only affects the selection of the drives and sensors but also the whole structure design. For this reason, planar motion is more common in very small and small systems. For medium range a variation of planar motion can be found implemented in some ultra-high precision machine tools where two orthogonal linear axes are mounted on the same base independently (unstacked) so that *X-Z* motion is generated on the same plane [160]. On the other hand, recent advances in high precision optical sensors make the use of non-contact direct sensors a completely scalable principle. In very small machines capacitive sensors are commonly used, while in larger ranges, laser systems and optical scales are the most common solution, the latter can achieve ranges up to 100 m. The use of direct sensors facilitates the full-closed loop position control, which is also a scalable principle which is implemented in machines of every range. Specifically, in large range machines full-closed loop control can be combined with semi-closed control in a hybrid controller, in order to realize rapid control over a wide frequency bandwidth.

The third group of principles deals with error mitigation techniques. They are utilized in precision systems of every range, although they vary depending on the system scales. High-precision small range systems design is more deterministic and, thus, they rely on error avoidance. In medium and large ranges, a deterministic approach is more difficult to achieve, and, thus, they rely on error correction and compensation. Error budgeting is used for every range, especially in the design phase in order to identify, classify, and quantify the influence of these errors on the desired output of the system and can provide quantitative justification for design choices that will limit the errors of the system. The use of new technologies for error mitigation, such as machine learning and artificial intelligence are being explored in attempts to improve system performance. These new methods can predict the behavior of the machine, although their accuracy is not yet ensured, since there are risks related to the extrapolability of the results to all machine states.

Fig. 30 shows a graphical summary of these conclusions based on the analysis presented in Tables 1, 2 and 4. This information is of interest also to show the trends for future developments involving scales that are not envisaged today.

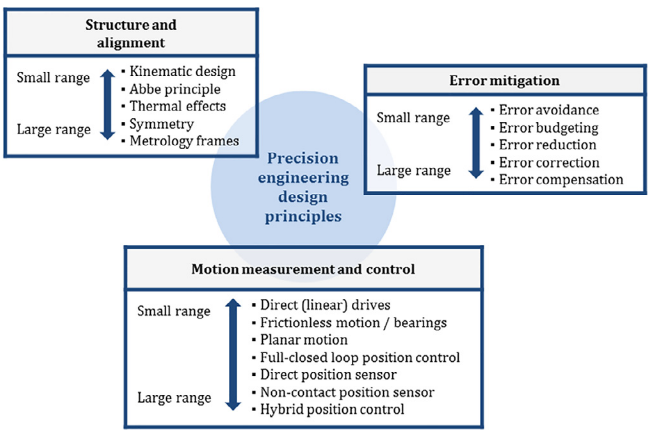

Fig. 30. Summary of precision engineering design principles applied to machines and instruments depending on its range.

One interesting property that was revealed in the study and classification of precision design principles across multiple scales is that these principles were – in general – most effective and appropriate in the medium-sized systems regime. These systems embody the vast majority of design and manufacturing activities, which prompts the following questions: *Are the design principles described in this and previous papers guided by the historical scale at which most manufacturing happens? If so, are there additional principles that will emerge as the boundaries to larger and smaller systems are explored? Does the specification method for allowable variations (*i.e.*, tolerancing) need to change for large and small systems to be more effective?* Perhaps this 'sweet spot' of systems that are considered medium size is simply an example of the well-known quote by Protagoras – "Man is the measure of all things."

The classical eleven precision engineering design principles established by McKeown [134] and updated by Schellekens et al. [176] have shown to keep being perfectly valid. They still cope with the advances presented by the last developments in designing precision systems. All of them have also shown to be scalable, although at different levels, as it has been presented in this paper.

As a general consideration for the future, design criteria based on environmental considerations, such us, decreasing the use of energy or taking into account the whole system lifecycle, will probably be more and more present in all the design processes, including precision systems.

In any case, structure and alignment principles remain the basis of a precise system design. As a vision for the future, advances in computer power and speed, parallel computing, cloud computing, and algorithm complexity as well as in computer-aided design and analysis methods and software will keep helping the designers to obtain a more precise forecast of the system structural, dynamical, and thermal behavior. From this point of view, appropriate digital twins may be a powerful tool in some phases of the design process. However, as was stated in Linares et al. [119] *"poor implementations and poorly conditioned algorithms may lead to rounding of successive intermediate calculations that may lead to globally false results"*. Therefore, it is important to validate those software and algorithms. It is assumed that the development of networks through the deployment of 5th Generation (5 G) fiber optic and wireless communications standards might speed up the analysis time. Nevertheless, essential obstacles remain such as the inaccessibility of the source codes for a detailed understanding. If techniques such as machine learning or artificial intelligence reach the desired reliability level and are fed and complemented with appropriate analytical and experimental methodologies, probably more and more error correction or compensation techniques will be applied in the future in order to obtain the desired accuracy to the disadvantage of systems designs that perfectly meet the structure and alignment principles albeit at a high economical or volumetric cost.

Inline measuring systems or integrated metrology in manufacturing systems will be more and more demanded in order to decrease the total production time. In that case, but also in every kind of precision systems, thermal variations and how the systems react to them will keep being one of the main challenges. To overcome it, different approaches will be possible in the future. Some examples: The development of new low thermal expansion coefficient materials or athermal designs (especially for small and medium range systems), the use of big data, machine learning, and artificial intelligence algorithms in order to monitor and predict the possible behavior of the system (especially for medium and large range systems), and the increase in the velocity of measuring and manufacturing processes in order to decrease their working time and minimize the influence of thermal variations (especially for large range systems).

Improvements in resolution, accuracy, and speed of sensors together with more and more advanced control systems are key factors for the advance of precision engineering in the coming years. Future trends in precision positioning systems include extending the motion range in micro positioning stages, improving dynamic performance of positioning systems by more sophisticated control algorithms, and extending the speed and bandwidth of these systems. To improve dynamic (tracking) performance of positioning systems via control algorithms, various sophisticated feedforward control algorithms were reported in recent literature. Zhong and Yao [223] modeled slow and fast dynamics of PZT driven stage due to nonlinear piezo effects and used Adaptive Robust Control algorithm to improve performance. Rotariu et al. [170] introduced adaptive Iterative Learning Control (ILC) to reduce systematic errors in performing same motion repetitively and Hu et al. [79] implemented Learning Adaptive Robust Control (LARC) on a magnetically levitated planar motion stage to extend the capability of learning controllers. Examples of the efforts to increase the speed and bandwidth of positioning systems can, for example, be found in Wu et al. [212] for high-acceleration point-to-point positioning in the presence of significant disturbance and excited vibration. Integration of more artificial intelligence tools and methods into positioning systems to predict and compensate for uncertain disturbances and improve system tracking accuracy at high speeds and high accelerations is expected in the near future. The optical frequency comb-based sensor technologies are also expected to play an important role in motion measurement and control [87].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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