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Error budget and uncertainty analysis of portable machines by mixed experimental and virtual techniques

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ABSTRACT

This paper analyzes the error sources of portable machines, which can move along large parts to perform machining operations and defines a mixed virtual-experimental model to quantify such errors. The method combines three different aspects of particular relevance in portable machines: a process force and machine stiffness model, a geometric error model and a machine and work piece inter-referencing error model. The combination of these models helps to control and define the effects of different errors in the virtual mobile machine, before a real prototype is built. An application to a particular portable machine is presented where error values are either simulated or experimentally obtained from a conventional three-axis milling machine where typical strategies of mobile machines are implemented and tested. The research shows that portable machines can be a solution for automatic and unattended machining operations with accuracy requirements below 0.1 mm.

1. Introduction: portable machines and error budget

There is a clear trend in some industrial sectors (e.g. shipbuilding industry, railroad, power plants etc.) to demand large but precise work pieces, thus machining units that meet these requirements are demanded. These enormous parts require not only manufacturing, but also maintenance and repairing operations, which usually involve also machining operations. From the manufacturing point of view, the present answer from industry is based on increasingly large machine tools, which present specific problems due to their size and a tendency to amplify conventional problems as thoroughly reported by Uriarte et al. [1]. Regarding the maintenance and operation works, they are usually performed in situ and employ bespoke solutions for each target part. As a result, these tailor-made machines are not standard "off-the-shelf" solutions and must be conceived and designed with the target part and operation in mind, presenting very low flexibility [2].

In search for alternatives to the conventional approach and specially looking for minimized energy consumption Neugebauer et al. [3] proposed mobile or portable machine tools as a sound alternative to both large and in situ machines, changing the "work piece inside the machine" concept and replacing it by "small machines onto large work pieces". That leads to the study and development of small portable machines that can move along large parts to perform the required operations.

These new machine models have found difficulties to enter the industrial world. Since these machines are very innovative, technicians are not confident about their true potential and how portable machines will eventually behave on site, under variable conditions and environments. Even if a portable machine is accepted as the optimum solution for a certain machining problem, difficulties also appear when designing a particular machine.

As a response, academia has started to study specific topics regarding portable machines. Allen et al. [2] established some optimum kinematic concepts for portable machines covering both parallel kinematic machines (PKM) and serial kinematic machines (SKM). Tunc [4] studied the dynamic issues of portable hexapod machines for mobile machining. Dave et al. [5] reviewed the usability of portable machines scaling up micro systems to the macro level. Neugebauer et al. [3] proved the energetic benefits of portable machines. Zulaika et al. [6] showed possible process improvements by means of a higher robustness of machine components and subsystems applicable in portable machines whereas keeping a high mobility [7]. Their capability for miniaturization [8], higher adaptivity, improved mutability and multi-functionality [9] have also been studied. Regarding the design of portable machines, different clamping solutions have been compared [10], and Olarra et al. [11] developed the self calibration, operation and control logic. As

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a result, the scientific literature presents outstanding contributions in portable machines: Parallel machines as in Allen et al. [12], Axinte et al. [13], and Yang et al. [14]; hybrid machines as in Möhring [15]; and even fully serial portable machines like those in Collado [16] and Eguia [17].

However, their overall capabilities have not been fully defined. On the other hand, the error budget methodology and the uncertainty analysis are useful tools to define the limits of a machine-process combination [18]. This methodology is essentially an analysis tool for the prediction and control of the total error of a machine system when accuracy is a relevant measurement of performance. This tool has been extensively used to study high precision systems as micro-milling machines and processes [19] or desktop size miniature machines [20]. This paper presents the error budget and uncertainty analysis of a particular multifunctional portable machine using the method outlined in Slocum [21], Hale [22], Walter et al. [23] and Soons [24]. The budget includes the most significant elements that affect the final accuracy of the work piece, i.e. the machine, the process, auxiliary equipment and the interactions between them [25].

The error budget concept requires application of a combinatorial rule to assess total error which is affected by a number of individual error components. Error levels are usually obtained experimentally and in laboratory conditions [19], which means that the machine needs to be operative before the analysis is performed, in other words, an ex post analysis is done. To maximize the benefits of the error budget tool it is useful to perform this analysis in early stages of the design process, even if that means that some error values have to be estimated. Thus, this methodology can introduce significant design improvements that could not be possible in later stages of the design due to high costs or technical aspects. This paper fully employs this method and uses virtualization techniques [26] to estimate individual error sources when no experimental data is available. In this way, designers can judge the error sources and improve those that have the highest effect on precision and accuracy, delivering an optimum machine design for a given application.

The research shows the relative importance of different error sources in portable machines. It also proves that portable machines are useful machines for operations which require accuracies below 0.06 mm.

2. The target portable machine

State of the art developments favor parallel kinematic machines (PKMs) since they show higher stiffness-weight ratios than serial kinematic machines SKM [27,28]. A high stiffness-weight ratio is very interesting when miniaturizing machine tools. However, PKM machines do show some disadvantages. First of all, they require a complex design process focused on the optimization of the kinematics and the location of linkages, actuators and degrees of freedom, and the scientific literature is very prolific in papers in this regard. Besides this, their stiffness and overall performance is extremely pose-dependant, lacking homogeneity in the workspace and showing great differences in stiffness in the different directions in space [29]. These are the reasons behind some intense research activity in the optimization of stiffness behavior of parallel kinematic solutions, as can be seen in the work by Zhongzhe Chi et al. [30] and Hyunpyo et al. [31].

Therefore, if serial kinematics is to be competitive as structural solution for portable machines, it needs to show higher stiffness-weight ratios in the different axes. The machine analyzed in this research is a five-axis, miniature milling machine based on a serial kinematic architecture. This machine is a research platform where authors have worked to enhance the capabilities of SKM. Its design,

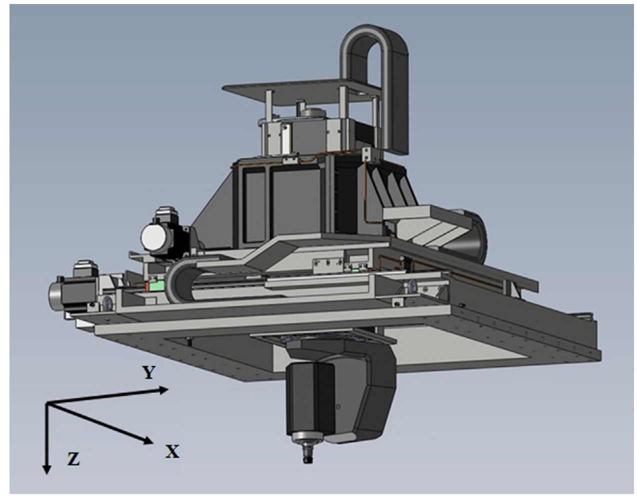

Fig. 1. Concept design of the portable machine studied.

the manufacturing process it performs and its breakthroughs have been reported in Ref. [17], where the machine was compared with a long list of existing alternatives with advantage. Owing to this, this machine model should be considered as a platform that explores and extends the limits of SKM. In this context, the error budget of the machine is significant and meaningful about the practical limits of the use of SKM.

Compared with other state-of-the-art machines, this portable machine can perform both mid-duty milling and drilling operations in a five axis configuration. However, it has been designed to perform essentially finishing operations, maintenance and repairing welding seams within the vacuum vessel of the International Thermonuclear Experimental Reactor (ITER). In operation, the work piece is most of the times much larger than the machine and once the rotation axes have been employed to adapt to the contour of the machine, the machining operations can usually be performed as three-axis operations. Due to these considerations, this paper performs the error budget of the machine in a three-axis configuration. To enable this, three stacked linear axes are included, which carry a two axis rotary-head holding the spindle, in a compact machine envelope of $1200 \times 1200 \times 1200$ mm. The work volume of the machine is $340 \times 300 \times 220$ mm with A and C axes ranging from -40° to 100° and 0–420°, respectively. Therefore, it is essentially a 3 + 2 axis milling system for large parts. Finally, both for machining operations and self-referencing tasks, the portable machine is intended to work with small geometric features that fit inside its work volume. An in depth analysis of the machine can be found in Ref. [17].

3. Estimates of individual errors

The main purpose of the research is to evaluate the use of portable machines and determine machining accuracy by including several error sources as described by Lamikiz et al. [32]. Nevertheless, errors have to be critically analyzed to decide whether they are relevant in portable machines or not. From all the studied errors, thermal errors are very seldom relevant in portable machines, since they operate in very short periods of time over large parts to perform usually small machining operations inside a small work volume in comparison with the whole part. Usually feed drives and tools are stopped most of the time, a time mostly devoted to clamp, translate and reference the machine. As a consequence, heat generation and power consumption occur in a small fraction of total time while the part represents a massive heat sink.