CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Modelling and traceability for computationally-intensive precision engineering and metrology

J.M. Linares (1)[a,*], G. Goch (1)[b], A. Forbes[c], J.M. Sprauel[a],
A. Clément (1)[d], F. Haertig[e], W. Gao (1)[f]

[a] Aix Marseille Univ, CNRS, ISM, Marseille, France
[b] University of North Carolina, 9201 University City Blvd, Charlotte, NC, United States
[c] National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom
[d] Dassault Systèmes, France
[e] Department of Coordinate Metrology, Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
[f] Tohoku University, Japan

ARTICLE INFO

Keywords:
Geometric modelling
Error
Computational accuracy

ABSTRACT

In contrast to measurements of the dimensions of machined parts realized by machine tools and characterized by CMMs, software results are not fully traceable and certified. Indeed, a computer is not a perfect machine and binary encoding of real numbers leads to rounding of successive intermediate calculations that may lead to globally false results. This is the case for poor implementations and poorly conditioned algorithms. Therefore, accurate geometric modelling and implementations will be detailed. Based on the works of National Metrology Institutes, the problem of software traceability will also be discussed. Some prospects for this complex task will finally be suggested.

1. Introduction

Humanity is facing very big challenges such as global warming, depletion of natural resources, and sustainable development, for example. At the same time, the business world tries to improve industrial competitiveness accounting for these environmental constraints. Most industrialized countries have thus launched development programs to answer these challenges (USA: Advanced Manufacturing, Manufacturing renaissance, National Network for Manufacturing Innovation, India: Make in India, Japan: Innovation 25 program, China: Intelligent Manufacturing, Made in China 2025, European countries: Horizon 2020, Factories of the Future, Industry 4.0 . . .). All these programs are based on the development of computerization and networking in industrial systems. This is the convergence of the physical and virtual worlds to Cyberspace. The German National Academy of Science and Engineering defines this evolution as a 4th generation industrial revolution based on Cyber-Physical Systems (CPS) [84,122,143,172]. In this new environment, information technology (IT) will allow decision makers to do more over time to improve product quality and customisation, productivity and customer satisfaction. This global expansion of the use of computers in industry brings to the forefront the need for traceability and certification of industrial software. Scientific calculations have indeed become central issues in design, manufacturing, precision engineering and metrology software. The fundamental binary code together with all basic arithmetic operations were developed by Leibniz in 1697 [123]. The principle of modern programmable computers was first proposed by Alan Turing in his 1937 paper: “On Computable Numbers with an Application to the Entscheidungsproblem” [167]. The Turing machine is the first universal programmable computer. It invented the concepts of programming and program. The construction of Pilot ACE (Automatic Computing Engine) based on Turing’s designs was completed by the National Physical Laboratory in the early 1950’s. In 1946, the first architecture of electronic computers was proposed: the ENIAC (Electronic Numerical Integrator and Computer, using the vacuum tube technology. Fig. 1 shows a picture of this computer. The second generation of computers was based on the invention of the transistor in 1947. Despite the use of transistors and printed circuits, the computers were still bulky and only used by universities, governments and large companies. The third generation of computers (around 1959) was based on electronic chips. In 1971, Intel revealed the first commercial microprocessor, the 4004. It did not achieve more than 60,000 operations per second. Today, standard desktop computers have a much bigger processing capacity (for example, an Intel Core 2 Duo processor at 2.4 GHz can execute around 2 billion operations per second). Microprocessors include most of the computing components (except for the clock and the memory) on a single chip. The computer is now the daily companion of people both at the office and in private life. For the average user, the computer remains however a black box that just provides results from the data that were entered. These outcomes are generally

---

[*] Corresponding author.
E-mail address: jean-marc.linares@univ-amu.fr (J.M. Linares).

https://doi.org/10.1016/j.cirp.2018.05.003

Please cite this article in press as: Linares JM, et al. Modelling and traceability for computationally-intensive precision engineering and metrology. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.05.003

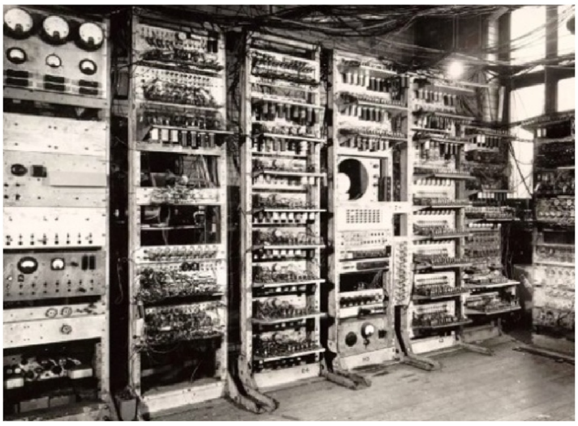

Fig. 1. ENIAC (Electronic Numerical Integrator and Computer) [95].

considered above any suspicion. For future industrial systems, based on cybernetics, will the results supplied by computers be really traceable and validated numerically? To answer this question, technological incidents could be reconsidered that have happened in recent history and had a computer error as source.

In computing, an integer overflow is a condition that occurs when a mathematical operation produces a numerical value larger than the greatest number that can be represented by the set of bits (binary digits) of the implemented variable. Perhaps the best-known consequence of such an error is the self-destruction of the Ariane 5 rocket during its first launch on June 4th, 1996. The Inertial Reference System (IRS) of Ariane 5 was derived from that of Ariane 4 but the new launcher had high initial accelerations and a trajectory that resulted in horizontal velocities five times larger than those of the previous rocket. These high speeds were captured by the sensors of the inertial platform but exceeded the maximum value that could be processed by the navigation program. It resulted in an integer overflow exception in the IRS software and the shutdown of the computers caused by the conversion from a 64-bit real number to a 16-bit integer [125]. False flight data led than to erroneous corrections of the launcher trajectory and finally to the self-destruction of the rocket.

An intrinsic feature of numerical computing is that real numbers are represented in finite precision and this means nearly all real numbers have to be rounded to be represented. The accuracy of the rounding operation can have great influence on calculated results. In 1992, at Dhahran in Saudi Arabia, a Patriot battery failed to track and to destroy a Scud missile [64]. This incident was caused by a software problem in the system's weapon control computer due to an inaccurate calculation of time and consequently of the tracking trajectory. The precision of calculations of on-board computers often depends on the number of bits of its registers. Patriot's clock system was performing some arithmetic operations using a 24-bit fixed point register. This hardware limitation led to a drift between the times elapsed since last boot, as measured by the system's internal clock, and the real delays. Table 1 shows the evolution of this time drift (inaccuracy) and the estimated shift in the range gate that Patriot tracked.

Table 1
Precision of a computer's calculations.

Hours	Seconds	Calculed time (s)	Inaccuracy (s)	Shift in range gate (m)
0	0	0	0	0
1	3600	3599.9966	0.0034	7
8	28800	28799.9725	0.0275	55
20	72000	71999.9313	0.0648	137
48	172800	172799.8352	0.1648	330
72	259200	259199.7528	0.2472	494
100	360000	355999.6667	0.3433	687

After 100 h of monitoring, the elapsed time calculated by Patriot's clock system drifted by approximately 0.3 s. In connection with the speed of the tracked Scud rocket, the resulting error of the calculated interception point was estimated to be about 700 m. Patriot's battery therefore failed to destroy the missile. The size of the registers of current generation of computers is now at least 64 bits, permitting calculations with greater precision but rounding effects are still inevitable.

Can such problems arise in precision engineering and metrology? Whereas there is an infrastructure to provide traceability of dimensions of machined parts realized by machine tools and characterized by CMMs, the results of software calculation are usually not fully traceable and certified. Indeed, a computer is not a perfect machine and binary encoding of real numbers leads to rounding of successive intermediate calculations that may lead to globally false results for poorly constructed calculations. To understand these calculation limits, the second section of the paper will be dedicated to the intrinsic performances of computer hardware and software. False computation results are often due to poor software implementations and badly conditioned or numerically unstable algorithms. The third section of the paper will therefore deal with detailed smart implementations of geometric modelling. Based on the works of National Metrology Institutes, the problem of software certification and traceability will also be discussed in the fourth section. Some prospects about these different subjects will finally be suggested.

2. Intrinsic performances of computer hardware and software

As discussed in introduction, the hardware (number of bits, number of processors . . .) and software (conversion effects, rounding effects, cancellation effects . . .) of computers, have a great influence on the accuracy of the calculated results. These topics will therefore be discussed now. The logical structure and functional characteristics of computers are shown in Fig. 2. A computer is built around one or more microprocessors with each microprocessor have one or more cores. The processor (named CPU for Central Processing Unit) is an electronic circuit clocked at the rate of an internal clock. A processor has internal registers of a fixed number of bits(now usually 64 bits) used to encode and manipulate the processed values. Several processor clock pulses are generally necessary to perform an elementary action called an instruction. The indicator, Cycles Per Instruction (CPI), characterizes the mean number of clock cycles required to execute a basic instruction on a microprocessor. It is about four for most current microprocessors. The CPU power can thus be characterized by the number of instructions processed per second and is often expressed in units of millions of instructions per second (MIPS) and corresponds to the frequency of the processor divided by the CPI. The CPU includes one or several Arithmetic Logic Units (ALU) that provide the basic functions of arithmetic calculations and logical operations on integers, and a Floating-Point Unit (FPU) to

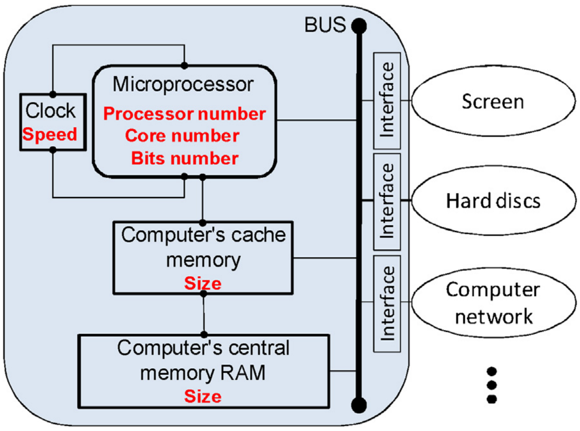

Fig. 2. Logical structure and functional characteristics of a computer.

Please cite this article in press as: Linares JM, et al. Modelling and traceability for computationally-intensive precision engineering and metrology. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.05.003