USE OF APPLIED EVOLUTIONARY COMPUTING TECHNIQUES IN INTERFEROMETRIC FRINGE FRACTION ESTIMATION

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Abstract: Classical interferometry employed visual phase difference estimation performed by human operators. Modern systems otherwise uses automated/computing image-processing deterministic algorithms for it, but the stochastic algorithms designated as "Evolutionary Computing" should be explored. This work proposes simple and fast implementation approach showing comparative results towards previous automated methods used in Inmetro.

Keywords: Optical Metrology, Interferometry, Evolutionary Computing

1. INTRODUCTION

One of the greatest uncertainty contributions in length measurements by interferometric methods of small step heights or gauge-blocks is still due to estimative of phase differences between interferometric fringe patterns in two or more regions that give the main component for length calibration. Following hints of metrological expert staffs is known that a trained operator can unequivocally distinguish at worst noisy cases steps of approx. 5% for phase differences between two different continuous sinusoidal interferometric patterns. That particular contribution to the global measurement uncertainty budget is not meant to be easily ignored. Additionally, as this is not a length dependent contribution, its weight grows proportionally for smaller length steps in comparison with other length dependent components as modifications in air refractive index or thermal expansion of artifacts.

2. OBJECTIVE

This work aims to present the use of some evolutionary computing methods and techniques to perform specific fringe image processing. An additional issue is presented in a form of discussion about some uncertainty boundaries in these methods as applied to metrological activities.

3. METHODS OF PHASE ESTIMATION

Some interferometer types use a phase stepping approach to get phase information (see an example in ref. [1]). That method implies in taking a previously defined number of "snapshots" of interferometric image patterns, displaced in controlled form of distinct and homogeneous length steps over the regions of interest (ROI) of artifacts to be measured. If the behavior of displacement system is fairly linear that approach has a big accuracy, and if it is judiciously designed a lot of information can be clearly extracted from all surface of both local and global length variations. As seen in reference [1] a 5 % non-linearity causes systematic phase errors amounting until 1 % of a fringe, when using a four-step Carré algorithm.

Otherwise there are some interferometer types that are not properly designed to follow this "phase-step" approach. For these cases the only way to get the fraction fringe information is by processing the image pattern as a whole. As for an example of a kind of simpler interferometer see Fig. 1, depicting its manual schematic inner cut. This interferometer is still currently been used in interferometric calibration length services and has been recently adapted a digital camera as quick as possible to get the fringe image and process it to achieve an estimation of length deviation in gauge-blocks for industry and scientific community. In comparison with this system a new-automated interferometer is seen in Fig. 2.

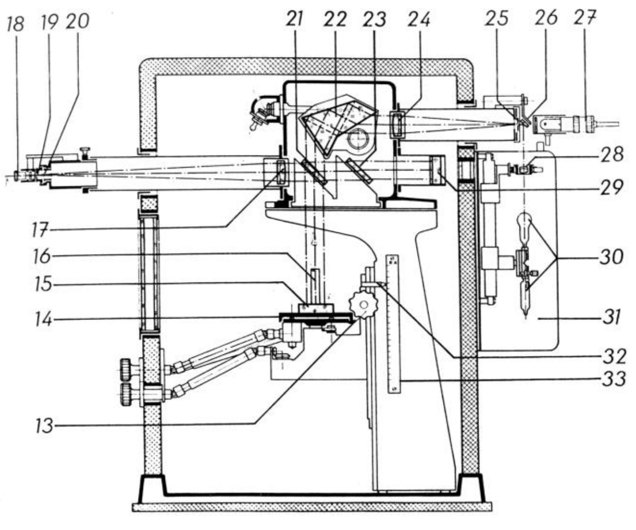

Fig 1 - Inner schematic description of an older manual/visual Michelson/Twymann-Green interferometer (build by Jena-Zeiss)

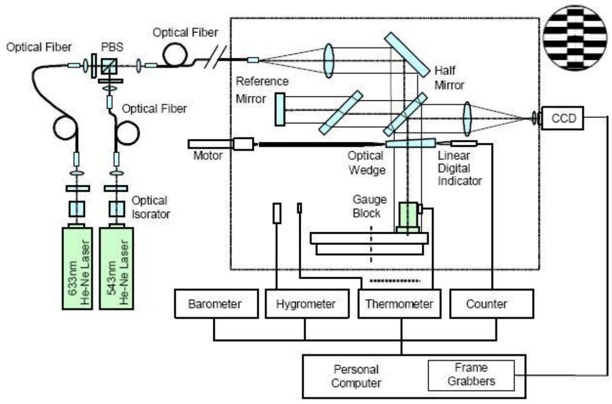

Fig 2 - Schematic description of a new automated Michelson interferometer system (reproduced from its manual by Mitutoyo Inc.). Just over the compound gauge-clock/platen it is positioned the subsystem (optical wedge + motor + linear digital indicator) that performs phase-stepping operations. An example of a circular fringe pattern obtained by CCD camera is presented on upper right part.

Previously to this work there was a lot of research developed before in Inmetro´s interferometry laboratory, aiming towards automated phase information results with best uncertainties, got from other type of a Zeiss interferometer (as can be seen in ref [11]). The algorithm used to get the fringe fraction then was a variant from random search in multipameter space, and was applied with excellent results.

The software that came with the purchase of the interferometer seen in Fig 2 (GBI) produces as some of its results a digitized fringe pattern and its calculated phase difference estimation. This work aims to compare this kind of estimation with results produced by alternative methods. As it is known all optical systems can carry some image noise along their subsystems, therefore it is advisable also to use some clever and immune–noise approaches as those presented in form of stochastic methods. One group of those (known as “Evolutionary Algorithms”) is biologically inspired on evolution processes.

3.1. Evolutionary Algorithms:

To produce the "evolution" of the "chromosomes" (or parameter vectors that comprise individuals of one population of size "n", each one representing also a distinct solution of an objective function) there are the following sub-steps:

3.1.1. Classification of Evolutionary Algorithms (EA):

Broadly speaking there are four main branches of EA as follows [4]:
a) Genetic Algorithms (GA);
b) Evolutionary Strategies (ES);
c) Evolutionary Programming (EP);
d) Genetic Programming (GP).

3.1.2. Parameters/Operation of a basic GA:

To produce the "evolution" of the "chromosomes" (or parameter vectors that comprise individuals of one population of size "n", each one representing also a distinct solution of an objective function) there are the following sub-steps:

3.1.2.1. Selection:

At the beginning we must define the kind of parameter vector that contains all information needed for description of our problem, initialize all individuals (each parameter vector) in a total population size and define the proportion/part of those that would suffer the stochastic modifications for each cycle. Normally their parameter values are chosen in randomized form within some constraints. There are a lot of kinds of selection rules used in GA. Many of them use a first fitness evaluation (see 3.1.2.3. below) to pick the best individuals as starting point to accelerate convergence. But for the first cycle the selection can be a pure randomized form or one of many mixed forms between fitness-like and random selection.

3.1.2.2. Recombination (crossover):

This kind of global variation operator emulates a pairwise exchanging of genetic material as in biological cell reproduction, and is based on taking a pair of parameter vectors (random or selected) and through some splicing method to exchange the selected part(s) of each "parent" considering each chromosome or parameter vector represented as a extended number chain in real or binary form, for example. There are many kinds of possible splices for this operator as those based on one or many points, use of binary or real/arithmetic representation, weighted and heuristic forms, etc. The probability of that exchange is normally maintained high through the whole calculation cycle (or at least in the first iterations at the beginning of search) aiming to explore a great number of possibilities in parameters space. A "multi-parent recombination" can be used to produce offspring using the best features from a greater range of individual "parents" or from only one pair.

3.1.2.3. Mutation:

It is based on the possibility to fine tuning each parameter of the chromosomes after the last pairwise recombination aiming to reach for a more exact solution. Normally it is defined as a small probability of changing a parameter bit or real number. In one individual seldom occurs more than one parameter mutation for each cycle, unless for some EC approaches, as the Evolutionary Programming for example, where the absence of a recombination operation also forces a rising in probability value and parameter range for mutations in each cycle to explore in a faster and broader way the parameters space.

3.1.2.3. Evaluation:

After the both last operations the offspring of chromosomes/individuals parents resulting must be fitness checked to select the more adapted ones. This is made by feeding the modified parameters for each chromosome in a predefined objective function that should furnish a fitness parameter (normally a real number) that can be used to "rank" the evolved chromosomes to the next cycle. In this stage the best performances can be preserved from further variations ("elitism", as it is called in literature) and the worst ones discarded. The replacement can be made directly from the offspring over the parents locally or taken in global and broader ranges over the whole population size.

A stopping condition can be stated by reaching a predefined number of cycles or when any of results got after the fitness evaluation (or from a good amount of fitness results from diverse individuals) pass some threshold. Normally the best of individuals in last evolved cycle represents the more adequate parameter set for stating the final result. But we can also check the degree of "genetic diversity" in all mutated population to get some figure of merit as an estimation of "robustness" for the result and/or the method itself. There is a lot of other perfecting and updating possibilities for this basic algorithm as for example the use of adaptive approaches, hybridizing with other stochastic or deterministic algorithms, use of restriction and boundaries criteria, analyses by Markov Chains, etc.

4. RESULTS

Aiming to compare estimations of phase results obtained from some measurements we used image files containing digitized fringe patterns (in steps of 256 intensity levels) obtained from a commercial operation software purchased together with an automated interferometer by Inmetro´s Interferometry Laboratory (GBPAK-PSI – from Gauge Block Interferometer build by Mitutoyo Inc.).

The standards measured in this kind of system were three gauge blocks of different sizes and top surface class, wrung to base platen of also excellent surface quality. Images obtained from fringe patterns for both surfaces were based on B&W sine-like 2D intensity illumination profiles seen from above of these mountings. The monochromatic light was produced by one of the stabilized HeNe lasers used as spectral sources and interferometer length standards of the system.

The main uncertainty constraint due to the stepping produced by this kind of equipment is reduced by maintaining a strict linearity control of the phase displacements, that are performed for example by moving one of the interferometer reflection planes, whether of reference mirror in a Michelson configuration or of the sustaining base for the artifacts been imaged, and in others (as for differences to the GBI´s original design see [8]) modifying the optical path in some of the interferometer branches. It is made in GBI by direct feedback actuation control of a linear motor for orthogonal displacement of a transparent wedge put in the optical path. That displacement must change in equal global values the phase for each point or pixel of image in homogeneous steps.

All images used as interferometric pattern sources were those extracted from "bmp"-files saved by previous measurements in GBI automated interferometer. Those have in their filename, together with the final length deviation and fringe fraction estimation. We extracted then from a real fringe pattern three numerical intensity vectors representing our linear 3-channels as data sources. Therefore, we had a good benchmark to check the consistence of the final results achieved.

Our proposed calculation approach followed a method derivative of Evolutionary Computation, as it is fit to handle some noisy and hard-to-model numerical optimization problems. For obtaining the phase information we need to take only one interferogram image and get three predefined linear sine intensity variations along these 1D parallel channels, corresponding to similar regions over two lateral plate surfaces and block upper surface, with their respective intensity profiles. Afterwards we compare and check the conformity of those patterns against various generic sine functions, with distinct parameters, until is achieved a best match of its objective function by least square methods for each channel. The phase difference retrieval is then simply get by comparing the phase of sine pattern of gauge block channel and the mean of phases obtained in both platen channels near the center point.

The EC method chosen as an alternative calculation mode to the well-established but slower methods was designed to follow a stochastic evolution as the standard GA, but it is based mainly in a high probability mutation operator applied on each parameter vectors of individuals in a population size (not a usual practice in orthodox GAs as seen before). The “crossover” operation was implemented only by probabilistically swapping a pair of similar parameters (as single chromosome “alleles”) between both parents, without any changing of their individual numeric values. Such variables were the same four parameters of a generic pure sine function, as used in the package “Matlab-GA” before mentioned, i.e., amplitude, offset, frequency and phase. Actually, in an intermediate point of software design it was decided to evolve only the last two parameters, i.e. frequency and phase, assuming that amplitude and offset parameters were always numerically close to similar values, that the automatic gain control of the GBI´s camera by software tries to maintain before all image captures. The vector parameters selected after a fitness calculation made by following a minimum least square evaluation, in a simple point-to-point intensity comparison with all pixel intensities along one direction (“channel”). The last parameter – the phase itself - was our principal aim and each run was performed thrice-like (from three predefined and differently chosen "channels"), because the final result that is used in length determination is the phase difference between the sine patterns on top gauge-block surface and those phases of two lower surfaces (taken as one mean sine phase from two base-“channels”).

The objective function to be minimized is based on comparing through a sum of least square differences the intensity numerical profile of fringe images of one of channels analysed with the intensities model of an ideal sine function as showed in equation below.

$$I(j,c) = m(c) + ms(c) + \left(\frac{M(c) - m(c)}{2}\right) x \sin\left[2\pi\left(f(i,c)\left(\frac{j - 0.5N}{N}\right) + \Phi(i,c)\right)\right] \quad (1)$$

The parameters are listed as below:

-- j is an linear index for each “pixel” along one of 3 channels;

-- I(j,c) is the intensity of pixel “j” in each channel “c”;

-- m(c) is the lower intensity for all pixels of one linear channel “c”;

-- ms(c) is the offset of mean sine value in each channel “c”;

-- M(c) is the higher intensity for all pixels of one linear channel “c”;

-- N is the total amount of pixels in each channel (it is the same number for all three channels);

-- f(i,c) is the spatial frequency inside each channel “c”, as one of two distinct parameters of each chromosome “i”;

-- Φ(i,c) is the phase of sine in the middle pixel of each channel “c”, as one of two distinct parameters of each chromosome “i”.

Distinctly from ref [9] it was not tried in this work a parameterization of the fringe patterns following any 2-D n-grade polynomial approximation, for reasons of simplicity of algorithm (and absence of closed fringes in 1-D paths).

A global use of "crossover recombination" in any of its normal numeric forms was initially ruled out because of its potential disruptive effects over the search, getting out of potential good branches in search space, and also for simplicity/speed in the calculation itself. In last version of algorithm the only kind of recombination employed was implemented by swapping the two main description sine parameters - phase and frequency - without changing the values themselves. Because of that limitation we raise the mutation overall probability, aiming to explore earlier a greater extension of search space. Along one run that recombination probability is gradually reduced to minimize a greater spreading of best results.

Beyond these features there was additionally a understanding that, due to the cyclic nature of phase parameter representation, a "module based" description of this parameter could be strongly incompatible with a linear evolution using regular crossover as a main tool to explore the space parameter, because a simple real numeric phase description can have its first significant digits seldom modified by normal crossover operations.

To avoid any bias effects produced by starting from pseudo-random numbers to compute the variables chosen as bases for randomized mutation operations it was employed a widespread and common metrological practice. It consisted in taking a set or a series of different and independent calculation cycles (been here considered similarly as independent measurements) for a same fringe pattern. Afterwards their obtained standard mean deviation of the ensemble of phase results must be included as the software repeatability component (type A) in the final uncertainty budget for final phase differences determination. By this way we maintain a fair conformity of this method with good practices recommended by metrological community [10].

We took 100 or 256 “N” cycles of the algorithm for each result, and the final phase result is their average value, with standard deviation taken as type “A” repeatability component for uncertainty. And some results of an EC approach are listed in the table below:

Table 1. EC results in phase difference due to fraction fringe of some distinct image files (taken in distinct times) coming from 3 steel gauge-block measurements performed by GBI.

Phase (GBPAK)	Phase (EC)	S / √N	N(cycles)
200 mm (Frank 3692)			
0,684	0,6677	0,0023	256
	0,6705	0,0036	100
0,925	0,8852	0,0022	256
	0,8845	0,0032	100
0,720	0,6933	0,0021	256
	0,6984	0,0032	100
0,788	0,7794	0,0021	256
	0,7743	0,0038	100
100 mm (Frank 3693)			
0,850	0,8357	0,0023	256
	0,8414	0,0037	100
0,433	0,4388	0,0023	256
	0,4411	0,0037	100
23,5 mm (Mitutoyo 939581)			
0,398	0,3866	0,0021	256
	0,3915	0,0034	100
0,411	0,4070	0,0021	256
	0,4107	0,0036	100

A population of 16 and 20 parameter vectors (corresponding to 256 and 100 cycles, respectively) was subjected to evolution as a whole in 64 and 100 iterations (bearing the same correspondence), with each offspring replacing its direct parent if the former one presents a better evaluation. The mutation step was stochastically performed immediately before it in all offspring (range was between –10 and +10 % of former value in both parameters) and before that there was defined a parameter swap probability used as a simplified “crossover” step.

The phase differences results got from a same gauge block seen in first column of Table 1 were due to changes in air ambient variables and block temperature itself for measurements made by GBI interferometer system. Those had affected directly air refractive index and block length each time. Therefore these changes necessarily showed themselves as modifications of their fringe fraction readings.

5. DISCUSSION

As a phase-shift designed instrument the automated interferometer (GBI) have as one of its main features the operation of taking and recording many phase-shifted interferograms for each instance of fringe pattern. As calculation algorithm the system employs one version of the Schwider-Hariharan´s algorithm (in [6] and [7]) that uses at least five equally displaced phase interferograms. That approach has as an advantage the production of a height map from all standard area, and the flatness information that it carries additionally can be used independently as a calibration itself. But, following the definition stated in the written standard describing the specification of gauge-blocks as length standards (ISO 3650), the length measurand for this kind of artifact is represented as the distance between only the central points of its two main parallel faces. Originally the first type of GBI coped with that definition by using only three aligned point sensors to get their phase information, and those were centered on the upper gauge surface and on two other regularly spaced parallel plate centers. Actually, in older interferometers it was used also only the same central gauge upper surface point and its local phase information was compared by visual estimation with the two equally displaced parallel points over a plate/base to whom it was wrung. Some geometrical considerations could be the cause for a maximal difference in 3 % between GBI and EC results (due to mainly in choosing slightly distinct face central points).

As a cross-checking between different automated approaches (still comparing with those values obtained in GBI for phase differences on each fringe pattern) it was tried a ready-made Genetic Algorithm package included in some recent versions of Matlab. All their many operational parameter possibilities were set manually in several distinct configurations initially by trial and error. A lot of combinations of these worked well together, giving acceptable results of phase difference between interferograms in both surfaces (plate and gauge-block). The problem is, as in many stochastic approaches, to choose an adequate calculation time or predefine a threshold until where we leave the package run to achieve good confidence margins for each final result. In many times an apparent but not correct premature convergence could show itself in a short amount of interactions. Sometimes it happened also that after some indefinite waiting time the fitness calculation for the objective function jumped from a stable but worse result (sometimes blatantly wrong) to a better one.

One of best results obtained from it is displayed below:

Gauge-Block => Steel block with 200 mm length (Frank 3692) over square steel platen:

Phase difference by previous GBI measurement: <u>**0.925**</u>

-- Numeric real parameters: Amplitude, Frequency, Phase, Offset (all constrained to positive and limited values)

-- Population = 100 vectors

-- Number of iterations = 100 (hard time limiting)

-- Operational parameters: stochastic mutation; stochastic uniform selection; heuristic crossover; 2-individuals elitism

The package was used thrice for one image, producing the 3 phase values corresponding to the 3 channels/ROI. The final phase difference $\Delta\phi$ was obtained as below:

ϕ_ch_1 = 0.29360;

ϕ_ch_2 = 0.22396;

ϕ_ch_3 = 0.27488;

$\Delta\phi$ (ϕ_ch_2 - (ϕ_ch_1 + ϕ_ch_3) / 2) = <u>**0.95582**</u>

(The difference seen above amounting to approx. 3 % far from previous GBI result was due probably to the fact that ROIs at “ch_2” in both cases were not equally centralized)

To an accurate achievement of phase result for each run it was additionally selected a package option that included a deterministic optimization for searching a best final fitness. In this case it was the "fminsearch" option that is based in a variant of simplex method to refine the group minimization.

In Table 2 below there are depicted some results using the same numeric intensity information from 3 lines of two of previously used fringe images (from a 100 mm gauge-block) gotten from GBI, and obtained after calculation using a free-software package called “Eureqa”, whose algorithm could be classified in the group of “Genetic Programming Algorithms” (see 3.3.1d) and used as additional benchmark:

Table 2. Results of differences in fractional fringe from “Eureqa” (GP package) performed thrice - one sine equation with phase information fitted for each channel - with some of its parameters

100 mm (Frank 3693)				
<u>GBI</u>	<u>Eureqa</u>	<u>Accuracy</u>	<u>Eval(10^8)</u>	<u>Duration</u>
0,850	***0,8443 (GP)***	0.10720	5.81108	16min42s
		0.11672	5.82980	17min10s
		0.11331	6.58463	17min03s
0,433	***0.4467 (GP)***	0.08797	10.2816	19min09s
		0.08074	9.20778	17min50s
		0.07687	10.4733	21min29s

That calculation method, instead of the two showed previously, was rather a kind of time intensive and therefore gave as final result a family of possible fitted sine equations with the best fit containing the phase information picked from each channel, represented by three lines for each result. Those results in a separate and independent step were used to calculate the difference in phase between block and the average base channel phases and depicted in bold in second column of Table 2. Other general parameters (chosen by the software itself and saved in a log file after finishing the calculations themselves) were the “Search Population” = 64 (like the “chromosome” number in GAs) and “Complexity” = 11. The last number represents the parameters or terms of fitted equations – rising mainly in dependence from time limit chosen to the end of analysis.

6. CONCLUSIONS

It was presented an alternative, simpler mode for calculating interferometric phase of some linear channels in interferometric patterns based on a tailored evolutionary method. The results showed a good enough comparative performance of the employed algorithm with other approaches, and its simplicity is such as that it can be easily inserted in custom softwares or as modules in pattern recognition suites operating in regular desktops or attached to any digital interferometric image capture systems.

As a suggestion for further explorations in these trends, it is known that in last two decades a lot of other kinds of stochastic methods and algorithms have been developed, And there are some that recently showed good numerical capabilities and performances, as for example those based in emulating the biological immune system as the CSA ("Clonal Selection Algorithms") or in reproduce a kind of macroscopic social spreading behavior as the PSO ("Particle Swarm Optimization"). Those can be further tried to compare performances by using "at-the-shelf" desktops and self-developed softwares, and using fringe pattern digitalized images as benchmarks as showed in this work.

REFERENCES

[1] J. E. Decker, R. Schödel, G. Bönsch, "Considerations for the evaluation of measurement uncertainty in interferometric gauge block calibration applying methods of phase step interferometry", Metrologia **41**, L11-L17, 2004.

[2] Z. Michalewicz, "Genetic Algorithms + Data Structures = Evaluation Program", Third Revised and Extended Edition, Springer Verlag, 1996.

[3] Z. Michalewicz and M. Michalewicz, "Evolutionary Computation Techniques and Their Applications", IEEE International Conference of Intelligent Processing Systems, Beijing, China, October 28-31, 1997.

[4] A. E. Eiben, J. E. Smith, "Introduction to Evolutionary Computing", Springer Verlag, 2003.

[5] D. Ashlock, K. M. Bryden, S. Corns, "On Taxonomy of Evolutionary Computation Problems", IEEE Congress on Evolutionary Computation, CEC 2004, 19-23 June, 2004.

[6] Hariharan, P., B. F. Oreb, and T. Eiju, "Digital Phase-Shifting Interferometry: A Simple Error-Compensating Phase Calculation Algorithm", Appl. Opt., 26, 2504 (1987).

[7] J. Schwider, R. Burow, K. E. Elssner, J. Grzanna, R. Spolaczyk, and K. Merkel, "Digital Wavefront Measuring Interferometry: Some Systematic Error Sources", Appl. Opt., 22, 3421 (1983).

[8] T. Narumi, S. Shutoh, T. Nakamura, J. Iida, M. Sawabe "Development of New Automatic Gauge Block Interferometer up to 250 mm", SPIE Conference on Recent Developments in Optical Gauge Block Metrology, San Diego, California, Vol. 3477, July, 1998.

[9] F. J. Cuevas, J. H. Sossa-Azuela, M. Servin, "A parametric method applied to phase recovery from a fringe pattern based on a genetic algorithm", Optics communication 203 213-223, 13, March, 2002;

[10] ISO, "Guide to the Expression of Uncertainty in Measurement," October 1993.

[11] A. Titov, I. Malinovsky, H. Belaïdi, R.S. França, C.A. Massone, "Precise interferometric length and phase change measurements based on reproducible wringing", Applied Optics, Vol.39, N4, pp. 526 – 538, 2000.