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EVOLUTIVE SYSTEMS FOR CALIBRATION

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Abstract. *In some complex sensing machines, such as the feedback system of a robot, a camera, a digitising device, etc., the accuracy of the measurement not only depends on the repeatability of the sensors, but also on the geometry of the machine itself [3]. We present here a novel method for machine parameter estimation (calibration) based on evolutionary computing/genetic algorithms. This method has been successfully applied to the calibration of a special purpose 3D digitizer, in which we could reduce the average machine error in a factor of 10 by using G.A [1]. This work has been carried out within the scope of the BRITE/EURAM III project "Computer Integrated System for Shoe Last manufacturing", CRAFT BE-S2 3411*

1 REPEATABILITY vs. ACCURACY

When we build a certain machine, the repeatability of its sensors can be very high. For example, state of the art ordinary angular encoders can provide linearity and repeatability within few seconds of arc. However we cannot have such accuracy in the mechanical processes used to build the real geometry of the machine due to unavoidable tolerances in part building and assembling, with reasonable manufacturing prices [6]. Sometimes, as it is the case of complex sensors, it is not important to have certain mechanical measurements in the geometry, but *to know* the geometry. For example, in case of a robot, it is not important to have 100 or 101 mm of distance between two consecutive joints, but we really need to know this distance very accurately if we want to calculate the target position of the robot based on our encoder readings. The encoder reading could give us a theoretical repeatability of 0.01 mm in 100 mm distance, but we need to know if it is really 100 or 101 mm to calculate the target position within the 0.01 mm range [4].

For simple machines, the calibration can be a simple and straightforward process. However, when the sensor output is calculated from non-linear functions involving both the raw sensor readings and the sensor geometry, the estimation of machine parameters is not so simple. There has been a great amount of work carried out to perform the calibration of robots and cameras, and some special models have been designed and successfully applied. However, these models are very specific and cannot be used if the sensor to calibrate is not a robot or a camera. [2].

2 CALIBRATION AND GA/EC

In a more general way, the calibration of a sensor can be defined as the process of defining a suitable mathematical model for its behaviour, as well as setting the proper values to the parameters in this model.

However, with traditional approaches, we have two problems:

- The mathematical model for the sensor must be kept as simple as possible, because the complexity of the problem grows exponentially with the number of parameters to estimate.
- Good calibration reference patterns must be known. The error in these reference models must be lower than the accuracy to achieve.

Genetic Algorithms / Evolutionary Computing can help us in the development of calibration strategies for different machines, as they can deal with minimisation problems for non-linear multivariable functions where the number of free parameters is very high.

The process of calibration a machine, using GA/EC, consists then in five steps:

1. Build a mathematical model of the system, where both the sensor data and the system intrinsic parameters will be combined in a possibly non-linear output function. This will be a *one-way* function, which will take as some arguments the sensor data, and as some other arguments the machine parameters, providing as output real-world magnitudes.
2. Isolate the intrinsic and extrinsic machine parameters (joints distance and orientation, zero positions, etc. in case of a robot, focus length, lens distortion, etc. in case of a camera...) which we must calibrate. Assign initial values and range of possible values to every parameter.
3. Build a real-life pattern and reproduce/capture /digitise it with the machine. In our case, this will be a real hard-iron box, which we will digitise.
4. Define an energy function that can compare the real pattern with the output from function specified in step 1, given a certain configuration of the machine-estimated parameters.
5. Use GA/EC to optimise the energy function in step 4. Each chromosome will consist of a certain set of values for the intrinsic/extrinsic machine parameters.

3 THE 3D SHOE LAST DIGITIZER

To test this calibration process, a special 3D digitizer for Shoe Lasts (special wooden or plastic foot-like shapes which will be used to produce shoes by building the difference parts around it) has been developed. It is a mechanical device, where a special torus-like shape is used to measure by contact the shoe last. Once the position of the tool is known, the real 3D surface can be calculated by a special volumetric algorithm in post-process. The accuracy needed for the digitising must be below 0.1mm. Without calibration, it is not possible to have accuracy better than 1 mm. Santos [1].

This digitizer does not directly provide the 3D data from the shapes, but rather the toolpath of the contacting torus-like part. To get the real 3D shape, we need to make a CAM operation, called *erosion*, which is the inverse from a normal CAM CNC toolpath calculation. The mathematical model for the calibration process, consists then of the parameters of the machine to calibrate, and the parameters of the patterns. This model now has 6 parameters to estimate. The energy function used for this calibration system can be calculated as the square difference between the toolpath, estimated from the encoder readings, and the theoretical, computer generated one. To perform this comparison, we have to perform a matching between one digitised point and one point in

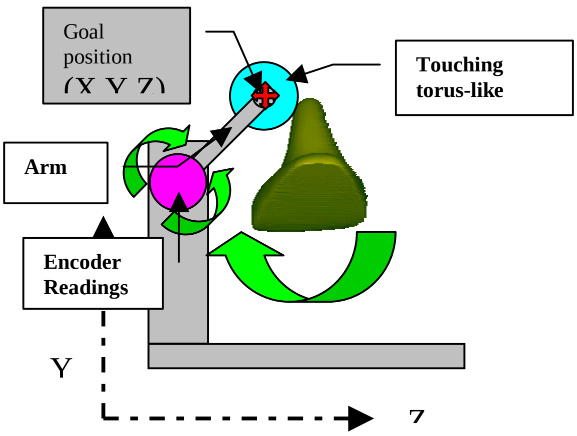

Figure 1: Digitizer mechanism

the theoretical toolpath.

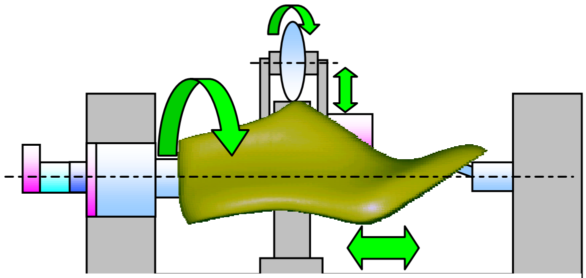

Figure 2: Lateral view

The mathematical model for the digitizer

The digitising process involves two steps:

For every instant, j:

1. Calculate of the x,y,z position of the tool at instant j.
1. Use the rotational position of the part at instant j to calculate the real toolpath, which will be represented in polar co-ordinates (R,δ). We will use polar co-ordinates to easily calculate the difference between the real and the theoretical toolpath as we will see later on this document.

The digitizer has an input system which consists of 3 incremental encoder devices, s0,s1,s2. For every encoder, we have two mathematical functions, which are Ψ(si), Δ(si,j).

Ψ(si) is the reference position for encoder i, while Δ(si,j) is the incremental position based on that reference at instant j. For encoders s0 and s1, the reference position is an angle (which is marked on a certain track of the encoder disk). For encoder s2, it is a fixed point in space (which is pressed by a switch). Mathematical systems based on encoders usually have a very good repeatability for the zero position (in the arc-second or micron range depending whether it is angular or linear) and a very good linearity on the Δ readings. However, because of mechanical problems when mounting the devices, it is very difficult to know accurately this zero position.

The X position of the device is very easy to calculate, as it can be computed as Xj=Ψ(s2)+Δ(s2,j). Although we do not know where Ψ(s2) is exactly, it would not make any difference on the shape of the part to be digitised, only on its position. We will then consider the first digitised point as having an X co-ordinate of 0. In that case, we will calculate Xj=Δ(s2,j)-Δ(s2,0).

The Z and Y positions are much more difficult, because they involve three unknown parameters, which are the zero position of encoder s1, as well as the distance between the axis where s0 and s1 are placed and the distance between s0 and the target position.

Once X,Y,Z have been calculated, we can calculate the polar co-ordinates (R,α), using Ψ(s0), Δ(s0).

The parameters to estimate for the digitizer will be: *Ψ(s0), Ψ(s1), L, Xr*

4 A MATHEMATICAL MODEL FOR THE PATTERNS

To perform the calibration, we do not really need to calculate the real 3D shape the digitizer would output after the volumetric *erosion* algorithm, but rather calculate the CAM toolpath from the patterns, as we would then save a lot of calculus power.

The theoretical toolpath for the patterns was calculated, and two parts with the same shape were built using hard iron to prevent deformations when touched by the tool. However, when getting to the calibration process, a problem arisen: although the shape of the parts was exactly the same as the shape of the ideal parts, when they were clamped in the digitizer, these parts were not exactly aligned. Once again, mechanical problems prevented us from getting a perfect part centring. If we calculated the difference between the theoretical toolpath and the estimated one, these toolpaths had to be aligned.

This misalignment introduced two new parameters in the calibration process, which were *offsetz* and *offsety*, These two parameters were not related with the machine itself, but rather with the calibration patterns. These are *extrinsic* parameters Not having perfect calibration patterns, can be a must in certain situations. If we can describe the position of the points in these patterns with a model, we can add its free parameters to the calibration process.

The mathematical model for the calibration process, consists then of the parameters of the machine to calibrate, and the parameters of the patterns. This model, now has 6 parameters to estimate, which are**:** $\Psi(s_0)$, $\Psi(s_1)$, L, X_r offsetx, offsety**.**

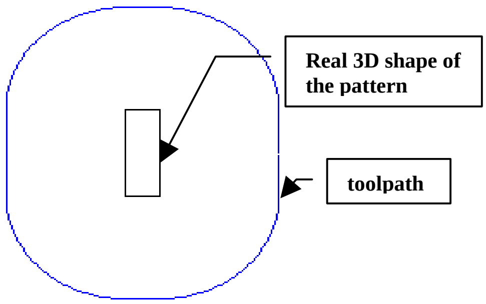

Figure 3: Pattern 1. A rectangle

5 THE EVOLUTIONARY PROCESS

Binary coding

To perform the calibration process, a simple genetic algorithm was used with binary coding of the parameters. Although we do not accurately know the exact values for the parameters, we can easily get a good approximation – especially for the length and offset -, and we can build a chromosome by putting the bits together.

A special calibration environment was created, where we could define the intervals and precision for the parameters. These intervals, although fixed for a certain test case, can be modified to improve the final results.

Genetic operators

We used two genetic operators: mutation and crossover. For the mutation operator, we made a bit flip at random with a certain probability. For the crossover operator, we selected a certain bit in the chain and perform a mix from both parents.

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We made a total replace from one generation to the other, with the following restrictions

1. The best solution was always kept
2. Both parents could not be the same
3. Two offspring could not be equal

6 THE ENERGY FUNCTION

The energy function used for this calibration system can be calculated as the square difference between the calculated toolpath and the theoretical one. To perform this comparison, we have to perform a matching between one digitised point and one point in the theoretical toolpath-

As we were using polar co-ordinates, the digitizer would give us a point in the form (R,δ)**.** We can also calculate the points in the theoretical toolpath in polar co-ordinates, in the form $(Rt,\delta t)$. If the number of points in the theoretical toolpath is much higher than the number of points in the digitizer readings, then we can match a point in the digitizer readings with the point in the theoretical toolpath which has the most similar δ.

The error associated with this matching would be the square difference in the radius of these points. This approach let us have a great number of points to compare. We have used 360 points per turn in the digitizer and 7200 points in the theoretical toolpath. Having 360 points to compare for a 6 free parameters estimation model, will ensure good results and even compensate for gaussian errors both in the pattern and in the readings. In fact, we were able to get a mean error below the sensor sensibility, which is even smaller than its repeatability.

The fitness function

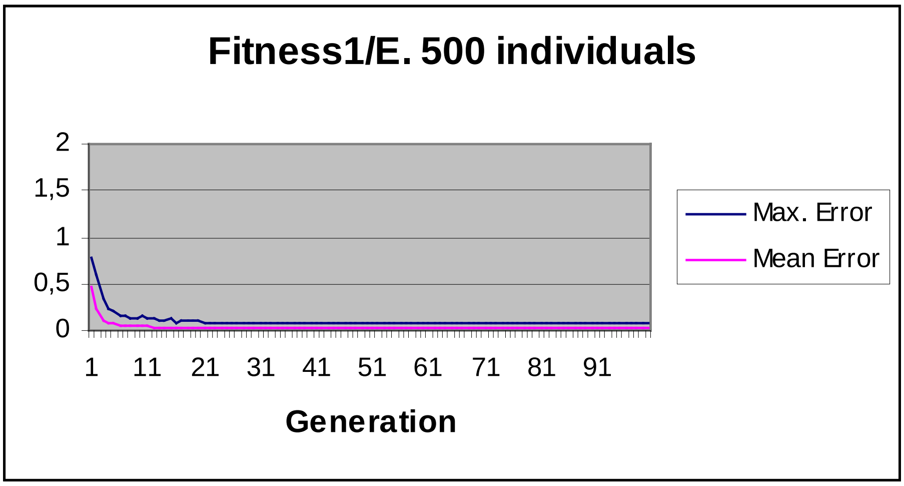
The energy function described in point 3.4 is not directly applicable for genetic computation, because the smallest value of this function corresponds to the highest fitness.

Several fitness functions have been used to tune the algorithm. We will describe the results with

$$f = \frac{1}{E}$$

6 RESULTS

With the digitizer model here presented, by using the 6 parameter estimation model, we could get an accuracy of 0.1 mm, with a repeatability of 0.02 mm in the sensor. This is a very good result if we compare it with the initial estimations, which were around 1 mm.



CONCLUSION

Machine calibration is a very important part of the design and manufacturing process. Good calibration functions can provide a means of simplifying both the underlying mechanics and the cost of the machines [6]. We have introduced a new method for performing machine calibration using G.A. This new method is more generalist than robot or camera calibration methods, as it is only based in *one-way* function estimation.

To test this method we built a special purpose 3D Digitizer and obtained a very important improvement in the accuracy of the device. We strongly believe that more research on the calibration/GA combination could be an important solution with complex systems where the number of parameters to estimate is large.

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