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Artifact-based calibration and performance verification of the MScMS-II

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Abstract

Large scale measuring systems, i.e. measuring systems characterized by a measurement volume from some meters up to some hundreds of meters, are gaining importance in industry to check large parts or track the position of automated vehicles. In contrast with classical monolithic measuring systems, modern large scale measuring systems are constituted by constellations of sensors able to track the position of objects by triangulation or trilateration. This new design allows a greater system flexibility, scalability, and portability, together with a general reduction of costs. The MScMS-II is a large scale measuring system based on infrared triangulation. It has been designed to guarantee the maximum flexibility and reconfigurability, so every set-up procedure has been reduced as much as possible, so that its deployment and calibration requires a short time. However, its accuracy could benefit of a more complete volumetric calibration through the definition of a model of the volumetric error to be compensated.
This work continues the one proposed at the CAT2012 conference [1]. An artifact has been developed which is constituted by a series of infrared reflective spheres, thus being well visible by the MScMS-II system. It has been calibrated with a ~1 µm uncertainty. It carries two series of balls. A pair of spheres with a reciprocal distance equal to 800 mm can be used for system calibration. A series of couples of balls with reciprocal distances equal to 200, 400, 600, 800, and 1000 mm respectively can be adopted for performance verification similarly to what is suggested in the ISO 10360 series of standards for CMMs. Experimental results are proposed for the calibration and performance verification procedure of the MScMS-II system.

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1. Introductioni

Large Scale Dimensional Metrology [2, 3] deals with all those 3D measurement tasks which involve a large measurement volume (from some meters up to some hundreds of meters). Application of these systems are more and more often found in industry, e.g. for the geometric control of large products (aerospace industry, large machine tool manufacturing), and to locate and track the position of robots or automated vehicles within large environments.

Traditional Large Scale Measuring Systems are simply larger version of classical coordinate measuring systems, e.g. large Coordinate Measuring Machines. However, the improvements in optics and laser systems have given rise to a new generation of Large Scale Measuring Systems, which instead of being monolithic measuring machines are constituted by smaller devices, able to locate the objects within the measurement volume usually by means of triangulation or trilateration. Several instruments of this kind are already available (laser trackers, laser radars, digital photogrammetry systems, indoor GPS). These instruments are usually

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cheaper than traditional measuring systems of similar size, and more portable, flexible and scalable.

The Mobile Spatial coordinate Measuring Machine System – II (MScMS-II) [4] is a large-scale measuring system based on (at present six) infrared cameras which take images of one or more infrared targets. The position of the target(s) within the measurement volume can then be identified by means of triangulation. A mobile measuring probe has been developed which can measure points on the surface of any object by contact. Compared to other large scale measuring systems, the MScMS-II shows advantages in portability, flexibility, handiness, scalability, and cost. The MScMS-II has in fact been developed to guarantee a system which can be easily relocated and set-up with a simple and lean procedure.

MScMS-II main drawback is its accuracy, which can be evaluated in the order of 1 mm in a measurement volume equal to 2 X 2 X 2 m [4]. This performance is influenced by both random errors, which cannot be corrected, and systematic errors, which are due to an imperfect determination of the system calibration parameters and to other not corrected aberrations, like camera lens distortion, and can be compensated if known. Therefore, the knowledge of a model of the systematic (volumetric) error can lead to an improvement of the system performance.

In a previous work [1], to which the reader can refer for a complete discussion about calibration and self-calibration, a test has been conducted on the use of an uncalibrated artifact for the self-calibration of the MScMS-II. However, the results indicated that most of the volumetric error present in the system was linked to the lack of traceability of the system itself: the residual volumetric error was quite small, but the measurement result on a reference calibrated artifact where systematically smaller than the calibrated value. Therefore, the self-calibration procedure proposed in that work has been slightly modified, in order to support the use of a calibrated artifact instead. Coherently, a calibrated artifact has been designed, which carries a couple of balls separated by about 800 mm, the distance between the balls having been calibrated with micrometric accuracy. The artifact carries as well six more balls. The distances between a reference ball and the other balls has been calibrated, so that it is possible to use the calibrated artifact for the performance verification (and evaluation) of the MScMS-II in a way similar to the one proposed by the ISO 10360-2 standard [5] for cartesian CMM. This paper proposes the design of the new calibrated artifact, the methodology developed to exploit it, and the first results about its effectiveness on the performance of the MScMS-II.

For a complete description of the MScMS-II, please refer to the paper by Galetto *et al.* [4]

2. MScMS-II calibration

The problem of calibration can be considered as the problem of correctly turning the sensor outputs into the measurement results. If calibration is perfect, then no volumetric error model is required. However, because the model for calibration usually assumes sensors are perfect, usually some residual volumetric is present, and a correction is required. Therefore, to understand completely the MScMS-II calibration, some hint on the conversion of the camera output into the Cartesian coordinates of the point is required.

2.1. MScMS volumetric error model

Two steps compose the mathematics that turns the cameras output into the corrected coordinates of the sampled points. The first step is the so called "localization algorithm". The localization algorithm is well defined in the literature concerning photogrammetry [6, 7]. Its complete description goes beyond the aims of the present work; here it is sufficient to remember that to apply the localization algorithm a series of parameters, summarized for every camera by the projection 3 x 4 real matrices $\mathbf{P}_i$, have to be defined. The application of the localization algorithm turns the camera output into the cartesian coordinates of the point $\mathbf{x}=\left[x, y, z\right]^{\mathrm{T}}$. An incorrect definition of these parameters leads to a distortion in this conversion, i.e. a volumetric error. Then the definition of the camera projection matrices can be considered as a "first order error model", which can then take into account part of the volumetric error. In practice, every error which would be generated by an incorrectly calibrated but optically perfect camera is considered by this first error model.

However, usually the localization algorithm does not take into account optics aberrations and other similar errors which go beyond a perfect system. To describe the volumetric error generated by these defects, a "second order error model" is required. In general, the output of the first order error model is a vector of Cartesian coordinates. Any function $\tilde{\mathbf{x}} = f\left(\mathbf{x}\right)$ can be in principle considered as a possible "second order volumetric error model", which can correct the residual volumetric error after the first order model has been correctly evaluated and the localization algorithm applied. The choice of the correct model can be suggested by the actual kind of sensors and optics adopted, but probably it would be easier to empirically choose the model among generic (polynomial, linear, spline) models, which are easier to manage.

2.2. Model parameters estimate

When a calibration procedure is adopted, turning the measurement results of the calibrated artifact into the parameters of the volumetric error model is most often straightforward. Ordinary Least Squares or similar techniques may be applied. This is possible because "supervised learning" is adopted. In self-calibration one deals with "unsupervised learning" instead, thus requiring more complex approaches.

Kruth et al. [8] supposes that the artifact is perfectly rigid, so that the distances between couples of points are constant. The application of this concept is particularly simple in the considered case: for the MScMS-II a ball-bar, can be adopted; therefore, it should be sufficient to verify that the length of the artifact is constant in every view. The general principles for this self-calibration are then the following:

1. Measure the artifact in several views;
2. define a volumetric error model which guarantees the length of the artifact is constant every view.

However, this is not sufficient to guarantee the traceability of the measurement. In fact, a simple degenerate solution could satisfy this criterion: $\tilde{\mathbf{x}} = \mathbf{0}$. With this solution, the artifact length is perfectly constant, but this is not, of course, an acceptable solution. Therefore, Kruth et al. introduced the need of a reference measurement performed on an artifact of known length. The original objective function introduced by Kruth et al. was then

$$\min_{\mathbf{a}} \left[\sum_{j=1}^{m-1} \left(d_j(\mathbf{a}) - d_{j+1}(\mathbf{a}) \right)^2 + \sum_{j=1}^{r} \left(d_j^m(\mathbf{a}) - d_j^R \right)^2 \right] \quad (1)$$

where m is the number of views, r is the number of measurement of the reference artifact, $\mathbf{a}$ is a vector of parameters on which the first and second order error model depend, $d_j(\mathbf{a})$ is the measured length of the uncalibrated artifact in the j^{th} view, $d_j^m(\mathbf{a})$ is the j^{th} measurement result of the calibrated artifact, d_j^R is the reference length of the calibrated artifact, and r is the number of measurements of the calibrated artifact. As apparent, due to the compensation of the measurement, every measured length depends on $\mathbf{a}$.

However, has it is been noted in a former work [1], the MScMS-II suffers of a relevant scale error. This has suggested to switch from a self-calibration procedure to a calibration procedure .In order to avoid the need of a complete redesign of the procedure, it is sufficient ot drop the first part of Eq. (1), in order to retain only the calibrated artifact related part of the optimization function. The final objective function is then

$$\min_{\mathbf{a}} \left[\sum_{j=1}^{r} \frac{\left(d_j^m(\mathbf{a}) - d_j^R \right)^2}{r} \right] \quad (2)$$

This is the objective function adopted in this work for the definition of the correct value of $\mathbf{a}$. The problem is essentially a non-linear least squares problem, to solve with classical least squares numerical algorithms.

2.3. Design of the experiment

We need to define how to obtain data to feed Eq. (2). When choosing how to sample the ball-bar to yield an accurate evaluation of the model, some general recommendations can be suggested:

3. The whole measuring volume of the MScMS-II should be covered;
4. Several different positions and orientations of the artifact should be considered in order to guarantee reversal [9].

The MScMS-II makes these requirements easy to fulfill. In fact, the MScMS-II is a very fast measuring system able to track the position of the artifact with a 50 Hz sampling rate. Therefore, the operator just needs to move the artifact in the measurement volume at a not too fast speed, so that the system is allowed to take a large number of measurements. The operator will also take care of randomly rotating the artifact while moving it, so that reversal in ensured. To cover the whole measurement volume, an adequate size of the uncalibrated artifact should be chosen.

2.4. Proposed artifact

The proposed artifact consists of a series of eight infrared retroreflective spheres fixed to an aluminium bar (Fig. 1). This artifact can be used as both calibration and verification artifact: a couple of "reference" balls, located at a nominal distance of 800 mm. form each other, serves for calibration. Among the reaming balls, the leftmost is considered as 0-ball. The set of 200, 400, 600, 800 and 1000 mm distances from this ball can be considered for performance evaluation/verification like in the ISO 10360-2 standard [5].

The manufactured artifact is shown in Fig. 2. It has been wrapped in black tape to reduce reflections. As Fig. 2 shows, its temperature can be easily measured by means of a contact thermometer. This artifact can be easily calibrated by means of a CMM: Table 1 reports the calibrated lengths and uncertainties. All uncertainties are lower than 3 μm, which can is adequate for the expected performance of the system (around 0.1 mm).

3. Methodology application and first results

To test the effectiveness of the model, an experimental campaign has been undertaken. This campaign consisted in taking three series of data. The first dataset consists in a series of 9207 samplings of the artifact shown in Fig. 2, considering only the "reference" couple of balls, covering a measurement volume of about 2 x 2 x 1 m. Taking these measurements required about a couple of minutes. This "initial" data will serve to feed a non-linear least square optimization algorithm

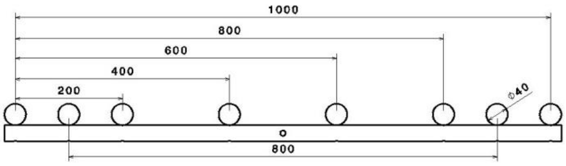

Fig. 1: Scheme of the proposed artifact.

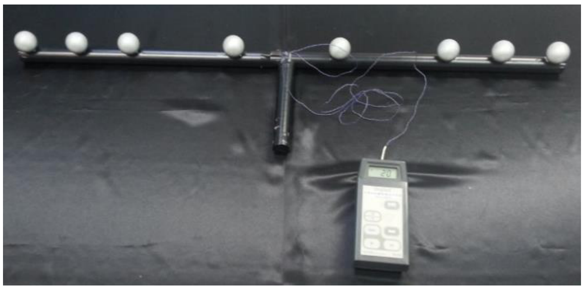

Fig. 2: Manufactured artifact.

Table 1: Calibration results for the manufactured artifact.

Nominal Distance [mm]	Calibrated distance [mm]	Expanded uncertainty [µm]	Coverage factor
200	200.432	1	2
400	400.328	1.4	2
600	600.818	1.3	2
800	800.968	1.9	2
1000	1001.030	2.1	2
800 (reference)	800.852	2.8	2

[10] which will solve problem in Eq. (2). Fig. 3 shows the schematically the artifact as it is moved through the measuring volume to cover it a completely as possible.

The second dataset is similar, consisting of 9402 measurements of the artifact. This "check" data will serve to check that the model evaluated based on the initial data is good to compensate any measurement, and not adapted to the initial data.

Finally, a series of about 5000 measurements has been taken for each of the five calibrated lengths given by the five couples of balls. These measurements will serve to propose an evaluation of the system performance.

As mentioned in §2.1, the easiest way to define a second order volumetric error model is to choose it among general purpose fitting models. In the following, three structures for the second order error model will be

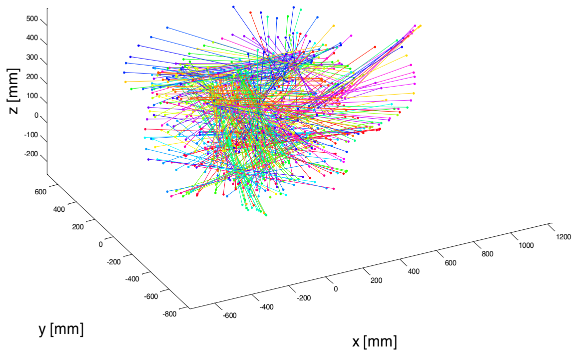

Fig. 3: Visualization of the artifact measurements in the first series of measurements.

considered: a polynomial model, a piecewise linear model, and piecewise spline model. Together with these models a "0" model will be considered, i.e. a model in which no second error correction is present but only the projection matrices parameters are adjusted.

3.1. Polynomial model

The polynomial model consists in a simple polynomial correction of the coordinate at which the point is measured, so the model can be written as

$$\begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix} = \begin{bmatrix} x + \sum_{i=0}^{g} \left(\beta_{ix,x} x^i + \beta_{ix,y} y^i + \beta_{ix,z} z^i \right) \\ y + \sum_{i=0}^{g} \left(\beta_{iy,x} x^i + \beta_{iy,y} y^i + \beta_{iy,z} z^i \right) \\ z + \sum_{i=0}^{g} \left(\beta_{iz,x} x^i + \beta_{iz,y} y^i + \beta_{iz,z} z^i \right) \end{bmatrix} \quad (3)$$

where the various β are optimization parameters and g is the polynomial degree (in this experience $g = 4$). In this case, the parameter vector **a** in Eq. (2) is constituted by $12n_c + 9g$ parameters, where n_c is the number of cameras constituting the MScMS-II.

3.2. Piecewise linear and spline model

In piecewise models a cubic grid of n_p x n_p x n_p points covering the measurement volume is defined (in this experience n_p = 5). For each point, a value of the volumetric correction which has to be applied at that coordinate is defined for x, y, z, so that there are $3n_p^3$ values of the correction. To obtain the correction value at any coordinate, the n_p^3 corrections at the defined points are interpolated either linearly (piecewise linear model) or by mean of a cubic spline (piecewise spline model). In this case, the parameter vector **a** in Eq. (2) is constituted by $12n_c + 3n_p^3$ optimization parameters.

3.3. Volumetric error compensation results

Table 2 reports the values of the average value and standard deviation of the residuals from the calibrated distance of the reference couple of balls. The column "optimization data" refers to the measurements that have been fed to the optimization algorithm to evaluate the parameters. The colum "check data" refers to the additional measurement which have been performed on the reference couple of balls. A high (absolute) value of the mean indicates the presence of some bias, while the standard deviation is related to the repeatability of the measurement. The row "no model" refers to the condition in which no optimization is performed, neither on the first or second order error model. The remaining four rows refer to the various error models considered.

Table 2: Calibration results.

model	Optimization data		Check data	
	mean	standard deviation	mean	standard deviation
no model	-11.08	11.1044	-4.4548	8.1370
0	-0.006	1.0054	-0.4130	1.6060
polynomial	0.001	1.0046	-0.4130	1.6036
linear	-0.001	0.7518	-0.3618	4.2353
spline	-0.001	0.6437	88.0815	295.0452

From the first row, it is apparent that if no error model is considered the measurements performed by the MScMS-II are both biased and scarcely repeatable. Now, consider the column "optimization data": this column suggests that any model is capable of correcting the bias. In fact, all the mean values are almost equal to zero. The standard deviation reduces significantly, too, indicating a repeatability improvement. However, this appearance could be explained by an "over-fitting" of the optimization data. To understand whether the calibration of the first and second order error model is effective, one should then consider the "check data" column, which is not affected by the optimization algorithm, and then will not be affected by over-fitting. This column suggests that bias is at least reduced by an order of magnitude (from approximately 4 mm to 0.4 mm). the repeatability improves as well of approximately an order of magnitude for the 0 and polynomial model. This does not apply to the spline model, which gives anomalous results. In fact, the spline model seem to be the best one when applied to the optimization data, and the worst when applied to the check data. This suggest that the spline model is very prone to over-fitting, and needs an improvement in robustness. By reducing the number of nodes, it could be possible to avoid over-fitting, but this could also neglect the expected advantages of the spline model. Anyway, one can conclude that the best performance is yielded when either the 0 or the polynomial model is applied.

3.4. Performance results

Now consider the third set of data that has been taken. These refer to the measurement of the couple of balls placed at a reciprocal nominal distance equal to 200, 400, 600, 800 and 1000 mm respectively. Fig.4 plots the residuals from the calibrated lengths for the various proposed models. Again, the 0 and polynomial models seem to be the best models, significantly improving the results available when no correction is applied, while the spline models yield inconsistent results. Fig.4 proposes an evaluation of the Maximum permissible error for the various models, as suggested in the ISO 10360-2 standard. The red lines graphically represent this performance in Fig.4. The green lines indicate the performance when no correction is applied. Please note that this performance evaluation does not neglect the probing error: in fact, the camera adopted do not give as output the a cloud of points on the surface of the sphere constituting the retroreflective target, but only the center of retroreflective target itself. Therefore, this performance correctly estimates the performance of the system considered as tracking system. However, the portable measuring probe has not been used in this performance evaluation, thus his influence is neglected.

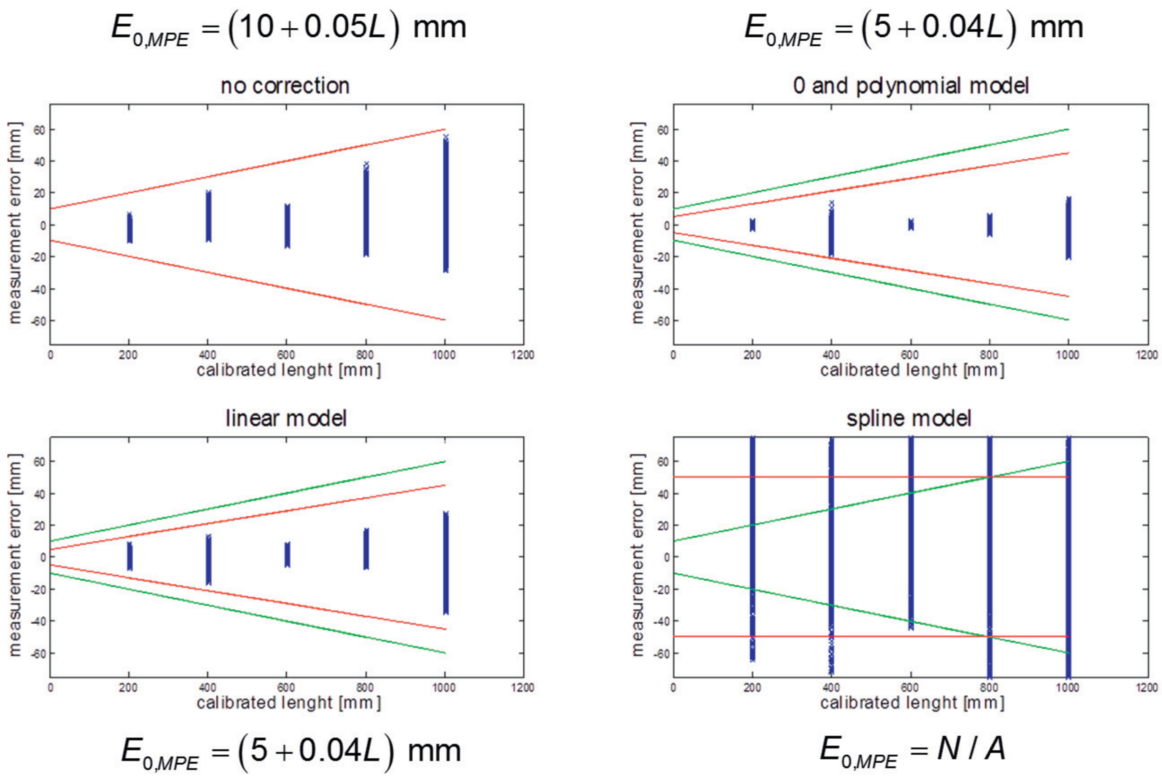

Fig. 4: Performance of the MScMS-II.

4. Conclusions

This work has proposed a model for the calibration and volumetric error compensation of the MScMS - II. The model differs from the classical volumetric error models and is specific for the MScMS-II, meaning that it considers the specific calibrations parameters that define the geometry of the MScMS-II. In particular, the proposed model is a two level one – the first one refines the calibration, the second one corrects residual errors.

To be able to apply the proposed calibration and volumetric error compensation model, a specific calibrated artifact has been designed, which can be applied both for calibration and performance verification. The artifact is constituted by a series of eight retroreflective balls whose reciprocal distances has been calibrated. A couple of these balls serves as reference distance for model parameters calibration. The remaining six balls define five calibrated distances, measuring which by means of the MScMS-II. It is possible to verify the performance of the MScMS-II itself. The artifact is handy to use and only few minutes are needed to take the measurements required for calibration/verification.

Finally, the MScMS-II has been experimentally calibrated and verified. The tests have shown that the proposed calibration procedure can significantly improve the MScMS-II performance. However, the error compensation model is not very effective at present. Most of the improvement is just due to the refinement of the projection matrices parameters in the first order error model, as proven by the effectiveness of the 0 model. More research is then required to understand whether the second order error model can bring some real improvement or not. Besides, a renewal of the MScMS-II hardware is scheduled, in order to improve its performance by adopting more performing cameras.

References

[1] M. Galetto, L. Mastrogiacomo, G. Moroni, and S. Petrò. Volumetric error compensation for the MScMS-II. In Xiangqian Jiang, Luc Mathieu, and Albert Weckenmann, editors, *Procedia CIRP*, volume 10, pages 98–104, Huddersfield, UK, 2013.

[2] W. T. Estler, K. L. Edmundson, G. N. Peggs, and D. H. Parker. Large-scale metrology - an update. *CIRP Annals - Manufacturing Technology*, 51(2):587 – 609, 2002.

[3] G. N. Peggs, P. G. Maropoulos, E. B. Hughes, A. B. Forbes, S. Robson, M. Ziebart, and B. Muralikrishnan. Recent developments in large-scale dimensional metrology. *Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture*, 223(6):571–595, 2009.

[4] Maurizio Galetto, Luca Mastrogiacomo, and Barbara Pralio. MScMS-II: an innovative IR-based indoor coordinate measuring system for large-scale metrology applications. *The International*

Journal of Advanced Manufacturing Technology, 52(1-4):291–302, 2011.

[5] International Organization for Standardization. ISO 10360-2: Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring linear dimensions, 2009.

[6] M. Franaszek, G.S. Cheok, and K.S. Saidi. Gauging the repeatability of 3-d imaging systems by sphere fitting. *IEEE Transactions on Instrumentation and Measurement*, 60(2):567–576, 2011.

[7] T. Luhmann, S. Robson, S. Kyle, and I. Hartley. *Close Range Photogrammetry, Principles, Methods and Applications*. Whittles Publishing, Caithness, UK, July 2006.

[8] J. P. Kruth, P. Vanherck, and L. De Jonge. Self-calibration method and software error correction for three-dimensional coordinate measuring machines using artefact measurements. *Measurement*, 14(2):157–167, December 1994.

[9] Chris J. Evans, Robert J. Hocken, and W. Tyler Estler. Self-calibration: Reversal, redundancy, error separation, and 'absolute testing'. *CIRP Annals - Manufacturing Technology*, 45(2):617–634, 1996.

[10] Thomas F. Coleman and Yuying Li. An interior trust region approach for nonlinear minimization subject to bounds. *SIAM Journal on Optimization*, 6(2):418–445, 1996.