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Kinematic Calibration of Parallel Kinematic Machines on the Example of the Hexapod of Simple Design

Dissertation

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Vorwort des Herausgebers

Seit über 15 Jahren wird ernsthaft und in Breite an der Realisierung und dem Einsatz von Parallelkinematik-Maschinen für die Fertigungstechnik gearbeitet.

Die zunächst großen Hoffnungen in das damit erwartete Potenzial an Steigerungsmöglichkeiten für Steifigkeit und damit auch Genauigkeit sowie Dynamik bei gleichzeitigen Aufwandssenkungen schlugen bald aufgrund ernüchternder Anwendungsresultate in Skepsis um. Neben unzulässigen Verabsolutierungen und unausgewogenen Konzepten erweisen sich insbesondere auch mangelhafte Anwendungsaufbereitungen als dafür verantwortliche Ursachen. Hierzu zählt – obwohl im Bereich der Roboteranwendungen seit Jahrzehnten behandelt – das nach wie vor unbefriedigend gelöste Problem der Kinematischen Kalibrierung.

In diesem Umfeld einer Vielzahl bereits durchgeführter und gegenwärtig in Arbeit befindlicher Untersuchungen mit einer Unmenge, teilweise unvollständig und widersprüchlich aussagefähiger, Veröffentlichungen liefert die vorliegende Arbeit von Herrn Szatmári einen wertvollen Beitrag zur Einordnung, Wertung, methodischen Begründung und algorithmischen Untersetzung sowie praktischen Durchführung der Kinematischen Kalibrierung von Parallelkinematiken unter den besonderen Bedingungen und Anforderungen eines Hexapod einfacher Bauart.

(1. Introduction)

Zunächst erfolgt in einer kurzen **Einführung** die Abgrenzung des Problembereiches und die Orientierung auf die sich aus den Besonderheiten des Konzeptes der einfachen Bauart ergebenden Schwerpunktsetzungen sowie eine Kurzansprache zu Zielstellung und Gliederung der Arbeit.

(2. State of the Art)

In dem folgenden Kapitel wird der themenrelevante **Stand der Technik** – bei all den, durch großen Umfang und geringe Aussagefähigkeit der Quellen, gegebenen Schwierigkeiten sowie den daraus resultierenden Unausgewogenheiten in der Detaillierungstiefe – letztlich treffend und aussagefähig dargestellt.

(2.1 The Calibration Task of the Parallel Kinematic Machines)

Die Darstellung wird mit einer einführenden Umschreibung und Problemcharakteristik der **Kalibrieraufgabe an parallelkinematischen Maschinen** eröffnet.

(2.2 Hexapod of Simple Design)

Danach folgt die Kennzeichnung des Konzeptes zum **Hexapod einfacher Bauart** und die sich daraus ergebenden Besonderheiten hinsichtlich Aufbau und Eigenschaften, womit später die Anwendungsbedingungen und –anforderungen des zu entwickelnden Kalibrierverfahrens begründet werden können.

(2.3 Techniques to Increase the Precision)

Ausführlich wird im Weiteren die Positioniergenauigkeit mit den Genauigkeitskenngrößen, der Grundgenauigkeit des betrachteten Hexapod und einer systematischen Analyse der Fehlerquellen sowie den **Möglichkeiten zur Genauigkeitsverbesserung** diskutiert.

(2.4 The Kinematic Calibration Problem)

Den Hauptteil des Kapitels umfassen – entsprechend dem Dissertationsthema – die Darstellungen, Systematisierungen und Bewertungen zu Methoden, Aufwand und Anforderungen der Kalibrierung, womit bereits ein wesentlicher Beitrag zur systematischen und objektiven Einordnung der Vielzahl unterschiedlichster Ansätze zur Lösung des **kinematischen Kalibrierproblems** geliefert wird.

(2.5 Calibration Methods)

Als Grundlage zur systematischen Charakteristik der Kalibriermethoden werden die Merkmale: Zustand des Messobjektes, Erzeugung der Messwerte, Messwertverarbeitung, Gestaltung der Zielfunktion und Charakter des Suchverfahrens definiert und aussagefähig zur Einteilung und Zuordnung der existierenden Verfahren benutzt.

(2.6 The Calibration Outlay)

Wichtige und bislang vielfach überhaupt nicht betrachtete oder zumindest vernachlässigte Aussagen liefert die erarbeitete Systematik für die Einordnung und Bewertung zum **Aufwand der Kalibrierung**.

(2.7 Demands on the Calibration)

Ebenso bedeutsam ist die Einordnung der Unmenge publizierter Verfahren unter den dafür aufgestellten Kriterien und Gesichtspunkten zu den **Anforderungen an die Kalibrierung** sowie die vergleichende Bewertung der Verfahren mit unterschiedlich gewichteten technischen und wirtschaftlichen Aspekten.

(2.8 Deficits)

Mit dieser Systematik gelingt es, unter ganzheitlicher Betrachtung Schwerpunkte für die spezifischen Anwendungssituationen zur Verfahrensbeurteilung herauszuarbeiten und für das spezifische Arbeitsfeld **Defizite** im Stand der Technik abzuleiten.

(3. Proposed Objectives)
In dem anschließenden Kurzkapitel wird die **Zielstellung** der Arbeit mit den dafür existierenden Randbedingungen formuliert und eine schematische Übersicht zu den Hauptschritten des Vorgehens gegeben.

(4. Kinematic Calibration)
Das folgende Kapitel untersucht und erarbeitet ausführlich die Grundlagen und zu lösenden Teilprobleme für die **Kinematische Kalibrierung** und kann sowohl hinsichtlich Umfang und Inhalt als auch der darin enthaltenen und für die Problematik neuen und wertvollen Anteile als Kernkapitel der Arbeit angesehen werden.
(4.1 The Calibration Problem)
Zunächst wird das **Kalibrierproblem** erläutert und systematisch in die Teilaufgaben der Problemkreise von realer Struktur, Parameteridentifikation und Messmodell mit kinematischem Modell, Messsystem und Messung zerlegt und es werden untersetzend deren Bestandteile und Bezüge dargestellt.
(4.2 Model Based Measurement)
Anschließend werden die Grundlagen für die **modellbasierte Messung** behandelt. Dazu wird das Kalibriermodell, welches neben dem kinematischen Modell mit seinen unbekannten Geometrieparametern auch das Messsystem und Messverfahren abbildet, erläutert sowie das Prinzip der Simulation von Genauigkeitsmessungen beschrieben, welches einen wesentlichen Bestandteil des entwickelten Kalibrieransatzes darstellt.
(4.3 Measuring Procedure)
Ein weiterer Abschnitt befasst sich mit dem **Messverfahren**. Hier wird, ausgehend von den Anforderungen an das Messsystem, begründet, dass der Double–Ball–Bar (DBB) am besten dem Konzept der einfachen Bauart gerecht wird. Ausführlich werden Aufbau, Eigenschaften und Anwendung des DBB beschrieben, wobei die Untersuchungen zu den Varianten der Datenerfassung, wie statische Messung von Einzelwerten im Vergleich zu kontinuierlicher Messung entlang einer Messbahn bei unterschiedlichen Bahngeschwindigkeiten, wesentliche Ergebnisse für die Qualifizierung der Messbedingungen liefern.
(4.4 Planning the Measuring Path)
Mit der im Weiteren behandelten **Planung der Messbahn** wird ein für die wirksame Kalibrierung ganz wesentlicher und in vielen Veröffentlichun-

gen bisher vernachlässigter Aspekt aufgegriffen und gezeigt, dass die Identifizierbarkeit der Parameter maßgeblich auch von der Wahl der Messbahn abhängt. Als Grundlage für die Festlegung der Messbahn wird dazu systematisch die Sensitivität und Orthogonalität der Parameter im Arbeits– bzw. Messraum untersucht. Insbesondere die Betrachtungen zur Orthogonalitätsanalyse liefern einen wichtigen Beitrag und veranschaulichen sehr deutlich den Einfluss der Messbahn und des Bezugssystems der kinematischen Parameter auf die Orthogonalität. Die aus der Sensitivitäts– und Orthogonalitätsanalyse gewonnenen Erkenntnisse werden schließlich unter Berücksichtigung der von Messsystem (DBB) und Messwertaufbereitung (FFT) bestimmten Randbedingungen in einem Ansatz zur Optimierung der Messbahn zusammengeführt. Im Ergebnis lässt sich unter Ausnutzung aller 6 Freiheitsgrade eine – für die Anwendbarkeit der FFT notwendig – in sich geschlossene Bahn angeben, die – durch den Einsatz des DBB bedingt – auf einer Halbkugeloberfläche und zur Sicherstellung größtmöglicher Sensitivität in der Nähe der maximalen Wirkung der Parameterfehler verläuft, wobei deren Orientierungsverlauf unter Anwendung genetischer Algorithmen hinsichtlich maximaler Orthogonalität der Parameterfehler optimiert wird.

(4.5 Processing the Measurement Data)

Im nächsten Abschnitt werden zum Verfahrensschritt der **Messdatenverarbeitung** Möglichkeiten zur Glättung und Kompression der mit dem DBB über der Messbahn in großem Umfange erfassbaren Messdaten untersucht. Über den Vergleich von Kompressionsrate und Approximationsgenauigkeit verschiedener Verfahren wird die FFT als am besten geeignet begründet und vertieft hinsichtlich der geometrischen Interpretierbarkeit und der optimalen Anzahl von Fourierkoeffizienten untersucht.

(4.6 Parameter Identification)

Mit der **Parameteridentifikation** wird schließlich der letzte Schritt des Kalibrierverfahrens behandelt. Nach Ansprache der charakteristischen Optimierungsprobleme konzentriert sich der Abschnitt auf die Erschließung des Potenzials genetischer Algorithmen für die Identifikation der Kalibrierparameter. Hier werden ganz wesentliche Beiträge ur Effizienzsteigerung und Problemanpassung durch gezielte Modifikation der genetischen Algorithmen geliefert. Dies betrifft zum Einen die Einführung wirksamer Operatoren zur Bildung neuer Generationen, wobei mit der "Mittelwert–funktion" bessere Konvergenz und Lösungsraumabdeckung erreichbar sind und die "Gruppierungsfunktion" durch Zusammenfassung sehr ähnlicher Lösungen die Reduzierung der Populationsgröße ermöglicht. Zum Anderen liefern die Untersuchungen zum Einfluss der Zielfunktionsgestaltung auf das Optimierungsergebnis die Aussage, dass insbesondere hinsichtlich der Genauigkeitsbegrenzung durch Messrauschen das Kriterium "minimales Fehlermaximum" besser geeignet ist, als das üblicher Weise verwendete "Fehlerquadratminimum". Schließlich liefern die Untersuchungen zum Konvergenzverhalten, durch Variation von Populationsgröße und Generationenanzahl, wichtige Aussagen für die Aufwandsminimierung bei der praktischen Anwendung des Identifikationsverfahrens.

(4.7 Workflow of the Calibration)

Abschließend wird der Ablauf der Kalibrierung schematisch zusammengefasst und übersichtlich als modellbasierter Kalibrierungsprozess im Zusammenspiel von experimenteller Messwertgenerierung am realen Hexapod und simulationsgestützter Parameteridentifikation am erweiterten kinematischen Modell dargestellt.

(5. Implementation of the Procedure and Experimental Results)

Das Kapitel behandelt die konkrete **Umsetzung des Verfahrens und experimentelle Ergebnisse** aus der beispielhaften Anwendung am Hexapod einfacher Bauart. An dieser Stelle wurde konsequent auf alle Beschreibungen zu Equipment, Randbedingungen, Vorgehensweisen, Algorithmen und dgl. verzichtet, da dies vollständig im vorangegangenen Kapitel dargestellt wurde. Obwohl die Darstellungen daher im Verhältnis zum Gesamtumfang der Arbeit einen sehr geringen Raum einnehmen, sind sowohl die erhaltenen Ergebnisse eindrucksvoll und überzeugend als auch die zu ihrer Gewinnung zu leistende Arbeit hinsichtlich Qualität und Quantität höchst beachtlich einzuschätzen.

(5.1 Applying the Measuring Path for the Hexapod "Felix")

Unter Anwendung der für die Berücksichtigung von Sensitivität und Ortogonalität der Fehlerwirkungen sowie der Berücksichtigung der Messbedingungen entwickelten Vorgehensweise erfolgte zunächst die konkrete **Ermittlung der Messbahn für den Hexapod "Felix"**.

(5.2 Measurements, Results)

Die auf dieser im Positions– und Neigungsverlauf optimierten Messbahn vor und nach der Kalibrierung erhaltenen **Messergebnisse** belegen eindrucksvoll Wirksamkeit und Potenziale des entwickelten Kalibrierverfahrens, insbesondere wenn zudem der Vergleich mit den simulierten Werten herangezogen wird.

(5.3 Accuracy Evaluation)

Der **Genauigkeitsnachweis** und damit die praktische Bewertung des Kalibrierverfahrens erfolgt repräsentativ für den gesamten Arbeitsraum des Hexapoden. Mit dem dazu benutzten Kreistest für mehrere, weit auseinander liegende Mittelpunktskoordinaten, extreme Durchmesser und alle drei Ebenenlage wurde ein Testumfang zum Nachweis des Kalibrierergebnisses realisiert, der weit über die bisher publizierten Umfänge hinausgeht und eine für den gesamten Arbeitsraum repräsentative Bewertung ermöglicht.

(5.4 Limits of the Accuracy Correction)
Einen besonders wichtigen und arbeitsintensiven Beitrag stellt die abschließende Untersuchung zu den im Kalibrierverfahren begründeten **Grenzen der Genauigkeitskorrektur** dar. Mit besonderem Aufwand, z.B. 10000 simulierten Messungen, sind dabei die wertvollen Untersuchungen zur Übertragungsfunktion zwischen den kinematischen Fehlerparametern und den Bahnabweichungen verbunden. Hiermit gelingt die Abschätzung der verbleibenden Parameterfehler anhand der messbaren Restfehler über der Messbahn.

(6. Summary and Perspectives)
In einem abschließenden Kapitel werden **Zusammenfassung und Ausblick** zum Themenbereich der Arbeit gegeben, wobei die systematische Charakterisierung relevanter Problemstellung besonders hervorhebenswert ist.

Prof. Dr.-Ing. habil. Knut Großmann Dresden, den 18.09.2007

Vorwort

Das Schreiben einer Dissertation erstreckt sich über mehrere Jahre in denen man immer wieder mit zahlreichen Fragen konfrontiert wird, während man in seinem manchmal zu warmen Büro sitzt und über die Lösung dieser sinniert. Häufig hilft dann ein klärendes Gespräch mit netten Kollegen, die man mehr oder minder zufällig an der Kaffeemaschine trifft, die als eine der besten Wissensmanagementlösungen gilt. Das wurde sogar automatisiert, wir haben täglich gespannt auf die "...hmmm, jetzt gibt's lecker Kaffee" – Meldung gewartet (siehe auch: |Pawlow, 1905|).

So habe auch ich meine orange–farbige Tasse genommen und bin vor dem bisweilen lauten Krach des Kompressors von Thomas geflüchtet um eine Tasse Kaffee zu trinken und als "Strafe" einen unerlässlichen, präzisen Strich von Holger in die Kaffeeliste zu bekommen. Die Belohnung dagegen waren recht oft konstruktive Gespräche, aber auch die "fachbeitragsfreien" freitags Nachmittagsrunden, wo die endlose Kreativität von Jens und Lars nur durch Michael oder Holger K. überboten werden konnte, haben zur Fertigstellung dieser Arbeit beigetragen.

Besonders möchte ich mich bei meinem Doktorvater **Prof. Dr.–Ing. habil. Knut Großmann**, Direktor des Institutes für Werkzeugmaschinen und Steuerungstechnik der TU Dresden, bedanken für die sehr spannenden aber auch arbeitsreichen letzten Jahre , für die umfassende Betreuung der Arbeit und die Vermittlung neuer Sicht– und Denkweisen. Dank gebührt ihm auch für den gesetzten Maßstab an Qualität und Genauigkeit, der jede DIN–Norm übertrifft und den gezeigten Weg in die Systematik, was sich nicht nur fachlich aber auch im Alltag als nützlich erwies. Außerdem wurde durch ihn die Aufnahme meines Themas in das DFG Schwerpunktprogramm (SPP 1099) "Fertigungsmaschinen mit Parallelkinematiken" ermöglicht. Dank bekunden möchte ich folglich ebenso der Deutschen Forschungsgemeinschaft für die Unterstützung.

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Ganz besonders danke ich meinen Eltern für ihre unerschütterliche Unterstützung. Nachdem diese ihre Frage: "Und, wann bist du endlich fertig mit diesen parallelen Dingen?" letztendlich aufgegeben hatten, wurde ich tatsächlich fertig.

Ein herzlicher Dank geht auch an meine Freundin Jana, die mich trotz 'Promotionsphase' ausgehalten hat.

Schließlich geht eine Aufmunterung an meine Schwester Tünde, die sich mit unaussprechbaren Sachen in Physik quält und in der letzten Phase der Promotion kämpft: "Manche von euch denken, sie *werden* nicht kämpfen. Und manche, sie *können* nicht kämpfen. Das behaupten alle. Bis sie da draussen sind..." (Proximo, Gladiator)

Dresden, 16. Oktober 2007 Szabolcs Szatmári

*”Wenn mehrere Wahrheiten einleuchtend sind
und sich unbedingt widersprechen,
bleibt dir nichts anderes übrig,
als deine Sprache zu wechseln.”*

Antoine de Saint-Exupéry,
’Die Stadt in der Wüste’

Abstract

The aim of using parallel kinematic motion systems as an alternative of conventional machine tools for precision machining has raised the demands made on the accuracy of identification of the geometric parameters that are necessary for the kinematic transformation of the motion variables. The accuracy of a parallel manipulator is not only dependent upon an accurate control of its actuators but also upon a good knowledge of its geometrical characteristics. As the platform's controller determines the length of the actuators according to the nominal model, the resulted pose of the platform is inaccurate. One way to enhance platform accuracy is by kinematic calibration, a process by which the actual kinematic parameters are identified and then implemented to modify the kinematic model used by the controller.

The first and most general valuation criterion for the actual calibration approaches is the relative improvement of the motion accuracy, eclipsing the other aspects to pay for it. The calibration outlay has been underestimated or even neglected for a long time. The scientific value of the calibration procedure is not only in direct proportion to the achieved accuracy, but also to the calibration effort. These demands become particularly stringent in case of the calibration of hexapods of the so–called simple design.

The objectives of the here proposed new calibration procedure are based on the deficits mentioned above under the special requirements due to the circumstances of the simple design–concept. The main goals of the procedure can be summarized in obtaining the basics for an automated kinematic calibration procedure which works efficiently, quickly, effectively and possibly low–cost, all–in–one economically applied to the parallel kinematic machines. The problem will be approached systematically and taking step by step the necessary conclusions and measurements through: Systematical analysis of the workspace to determine the optimal measuring procedure, measurements with automated data acquisition and evaluation, simulated measurements based on the kinematic model of the structure and identifying the kinematic parameters using efficient optimization algorithms.

The presented calibration has been successfully implemented and tested on the hexapod of simple design 'Felix' available at the IWM. The obtained results encourage the application of the procedure to other hexapod structures.

Contents

Symbols and Abbreviations

Symbols

Scalar quantities

A_n	$--$	amplitude of the n–th Fourier wave
a, b	$--$	real and imaginary share of the Fourier coefficient
B	rad	latitude angle (modified Euler angle)
$cond$	$--$	condition number (of a matrix)
D	rad	drill (twist) angle (modified Euler angle)
i, k, l	$--$	index
L	rad	longitude angle (modified Euler angle)
l_i	mm	lengths of the strut i
$l_{i\ act}$	mm	actual lengths of the strut i
$l_{i\ nom}$	mm	nominal lengths of the strut i
n, N	$--$	number of kinematic parameters
$o_{k,l}$	$--$	orthogonality between parameter k and l
P_i	$--$	the i–th kinematic parameter
q	mm	position of the strut
q_i	mm	ideal position of the strut i
r	mm	distance between the two balls of the DBB
R	mm	radius
t	$--$	path parameter
Δl	mm	length offset of the strut
Δr_i	mm	simulated measurement with the Double–Ball–Bar
ϵ	mm	error (deviation)
λ	$--$	singular value
φ	rad	virtual angle between kinematic parameter vectors
φ_n	rad	phase shift of the n–th Fourier wave

Vectorial quantities

Vectorial quantities in this work are in ***bold text*** *marked. Further the 3D–vectors are notated with minuscule, co–ordinate systems and matrices are typed in upper case. The corresponding base co–ordinate system can appear as index on the top left side of the letter.*

$\mathbf{b_i}$	mm	position of the base joint i
$\mathbf{C}$	$--$	Fourier coefficient
$\mathbf{G}$	mm, rad	base co–ordinate system
$\mathbf{G}^*$	mm, rad	simplified base co–ordinate system
$\mathbf{G_{act}}$	mm, rad	actual position of the base co–ordinate system
$\mathbf{G_{nom}}$	mm, rad	nominal position of the base co–ordinate system
${}^P\mathbf{h}_i$	mm	spacial position of the platform joint i expressed in the platform co–ordinate system
${}^G\mathbf{h}_i$	mm	spacial location of the platform joint i expressed in the base co–ordinate system
${}^G\mathbf{h_7}$	mm	position of the moving ball of the DBB
$\mathbf{H}$	mm, rad	co–ordinate system of the joints on the moving platform
$\mathbf{j}_i$	mm, rad	column i of the Jacobian matrix
$\mathbf{J}$	$--$	Jacobian matrix
$\mathbf{J}_{cal}$	$--$	Jacobian matrix of the calibration problem
$\mathbf{J}_k$	$--$	kinematic Jacobian matrix
$\mathbf{J}_e$	$--$	Euler angles Jacobian matrix
${}^G\mathbf{l}_i$	mm	space vector from base– to platform joint i
$\mathbf{M}_0$	mm, rad	position of the fixed ball of the DBB
$\mathbf{O}$	$--$	orthogonality matrix
${}^G\mathbf{o}_P$	mm	origin of the co–ordinate system **P** expressed in **G**
$\mathbf{P}$	mm, rad	platform co–ordinate system
$\mathbf{P}^*$	mm, rad	simplified platform co–ordinate system
$\mathbf{p_i}$	mm	position of the platform joints
$\mathbf{P_{act}}$	mm, rad	actual position of the platform co–ordinate system
$\mathbf{P_{nom}}$	mm, rad	nominal position of the platform co–ordinate system
${}^G\mathbf{P}$	mm, rad	platform co–ordinate system expressed in **G**
$\mathbf{q}$	mm	vector of the actuator values
$d\mathbf{q}$	mm	modification of the actuator vector

$\mathbf{q}_k$	mm	actuator values on the k–th iteration step
${}^G\mathbf{R}_P$	rad	rotation matrix of the co–ordinate system $\mathbf{P}$ expressed in $\mathbf{G}$
${}^G\mathbf{s}_i$	mm	spacial position of the base joint i expressed in the base co–ordinate system
${}^G\mathbf{s}_7$	mm	position of the fixed ball of the DBB
$\mathbf{S}$	mm, rad	co–ordinate system of the base joints
$\mathbf{V}, \mathbf{S}, \mathbf{U}$	$--$	matrices of the singular value decomposition
$\underline{\mathbf{v}}$	mm	position of the mounting point of the moved DBB–ball
$\mathbf{x}$	mm, rad	Cartesian pose of the platform
$\mathbf{x}_0$	mm, rad	initial value of the platform pose
$d\mathbf{x}$	mm, rad	modification of the platform pose
$\mathbf{x}^*$	mm, rad	approximation of the Cartesian platform pose
$\mathbf{x}$	mm	vector of the error parameters
$\mathbf{x}^*$	mm	simplified vector of the error parameters
$\mathbf{x}_{Hi}$	mm	position deviation of the platform joints
$\mathbf{x}_{Si}$	mm	position deviation of the base joints
$\mathbf{x}_{li}$	mm	length offset of the struts
$\mathbf{X}_{ideal}$	mm	ideal measurement set
$\mathbf{X}_{real}$	mm	real measurement set
$\Delta\mathbf{b}$	mm	position deviation of the base joints
$\Delta\mathbf{b}_{x,y,z}$	mm	position deviation of the base joints along X, Y, Z axes
$\Delta\mathbf{b}_{r,t}$	mm	position deviation of the base joints along radial and tangential direction to the base circle
$\Delta\mathbf{p}$	mm	position deviation of the platform joints
$\Delta\mathbf{p}_{x,y,z}$	mm	position deviation of the platform joints along X, Y, Z axes
$\Delta\mathbf{p}_{r,t}$	mm	position deviation of the platform joints along radial and tangential direction to the platform circle
$\Delta\mathbf{l}$	mm	length offset of the struts
$\Delta\mathbf{r}$	mm	length offset of the Double–Ball–Bar
$\Delta\mathbf{x}_k$	mm, rad	correction of the actuator values on the k–th iteration
$\mathbf{w}_0$	mm	location vector of the fixed ball of the DBB
$\hat{\Theta}$	mm	set of the kinematic parameters

Abbreviations

3D	three dimensional
AP	pose accuracy
CAD	Computer Aided Design
CNC	Computerized Numerical Control
CW	clockwise
CCW	counter–clockwise
D	diameter
DBB	Double–Ball–Bar
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
DOF	Degrees of Freedom
ES	Evolutionary Strategies
EP	Evolutionary Programming
F	radial deviation
FFT	Fast Fourier Transformation
G	circular deviation
GA	Genetic Algorithm
GP	Genetic Programming
H	hysteresis
IK	inverse kinematic transformation
IR	industrial robot
ISO	International Organization for Standardization
IWM	Institute of Machine Tools and Control Engineering
LCS	Learning Classifier Systems
M	midpoint of the hemisphere
NC	Numerical Control
PC	Personal Computer
PKM	Parallel Kinematic Machine
RP	pose repeatability
QC10	Quick Check 10 Renishaw DBB-System
SME	Small and Medium Enterprise
TCP	Tool Center Point
U–joint	universal joint

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1 Introduction

Controlling the motion accuracy of a parallel kinematic machine in practice is still a scientific challenge although extensive research work has been done in this field so far [Mer99]. Among the generally accepted benefits displayed by parallel kinematic machines are a favorite stiffness-mass ratio, the comparatively simple generation of motions in up to six degrees of freedom (DOF) and modest requirements made on production and assembly through the availability of correction methods [Gro99, Gro00c, Gro01a]. Here especially the hexapods have to be mentioned and as a result of their dexterity in complex motion, similar platforms have been used as flight simulators, manipulators and recently as CNC milling machines [Zhu98]. Important especially in case of this last application, where a high accuracy is required, is the fact that the structure enables to compensate the inaccuracies of the construction through the 6 DOF control of the six legs [Cha02, Gro99, Gro02f, Kha99, Mer00]. However, the industrial exploitation of these advantages is only possible if the desired precision is achieved reliably and efficiently. Efficient kinematic calibration procedures and intelligent approaches to counterbalance further errors are consequently of vital importance, in particular for a hexapod of the so–called simple design [Gro00a]. The strategic aims of this concept developed at the *Institute of Machine Tools and Control Engineering (IWM)* of the *Technische Universität Dresden* are:

- making possible a wide range of applications for machining and handling through structural flexibility and technological adaptability [Gro00c, Gro01a],
- minimizing the realization outlay through simple, robust mechanical solutions using thereby low–cost standard components as far as possible,
- optimum use of control techniques to improve the principally worse basics and initial values of motion accuracy.

In order to fit the concept, the calibration of the hexapod of the simple design obviously has to meet high demands concerning minimum outlay, feasibility and efficiency [Gro01b, Gro02e, Gro02f]. The latter together with the characteristics mentioned above lead to the following decisions about the selection, layout and design of a suitable calibration procedure:

- use of a simple measuring instrument with only one setup (if possible) to generate the measured values from the motion space,
- analysis of the measured values to suppress measurement noise and outliers using data filtering,
- using a kinematic model of the structure to make computer simulation of the measurements.

These demands will guide us further through planning the strategies for measuring and identification of the kinematic parameters like assembly errors and manufacturing tolerances. Other influences, like the non-geometric share of the motion errors (as elastic or thermal influences), are not considered here, they are supposed to be previously model-based corrected using control-integrated, structure-based models as the result of a previous research at the IWM [Kau06].

Considering the simple design-concept, the goal of this work consists in obtaining the basics for an automated calibration procedure which works efficiently, quickly, effectively and possibly low-cost, all-in-one economically applied to PKMs, in particularly hexapods, especially those of simple design. Here the six motion DOFs of the hexapod are used for correction, through the functionality of the controller. Special emphasis is laid on the following points:

- systematical analysis to generate an optimal measuring procedure customized for the given device
- automated measurements with the Double-Ball-Bar (DBB) along an optimized path
- identifying the kinematic parameters by using optimization algorithms like genetic algorithms (GA) finally proving the results on a hexapod structure available at the IWM

Working out these points, this document is guided as following:

Chapter 2 handles the State of the Art of the calibration, defining the problem, analyzing and discussing the actual calibration approaches found in the literature with their strengths and weaknesses.

Chapter 3 is phrasing the objectives of this work, limitations and proposed procedure of the calibration.

Chapter 4 presents the substance of the calibration, describing a systematical approach to the problem, splitting down the calibration in their sub-problems and elaborating a new method which embraces the merits and overcomes the shortages of the actual calibration approaches. Analysis of the sensitivity and orthogonality of the parameters are made to optimize the measuring path and the acquired data are prepared for the identification with genetic algorithms. Here the GA's are customized for quick and robust solution to the problem.

Chapter 5 handles the implementation of the algorithm on a hexapod structure available at the IWM. Experimental measurements are done and the results are verified under in standards specified circumstances to obtain a better reference in comparison with other manufacturing machines.

Chapter 6 presents the summary and perspectives of the work and open possibilities for further research in this area.

2 State of the Art

2.1 The Calibration Task of the Parallel Kinematic Machines

The aim of using parallel kinematic motion systems as an alternative of conventional machine tools for precision machining has raised demands made on the accuracy of identification of the geometric parameters which are necessary for the kinematic transformation of the motion variables. Therefore, researchers have been intensely working on the development and advancement of suitable compensation methods since the middle of the 90s [Mer99, Mer00]. Most of the works done and published by now deal with the analysis and calibration of particular (specialized) kinematic structures [Den04]. There are, however, no general statements on tested fundamental methodical and algorithmic processes which can also be transferred to other parallel kinematic structures and which can be used as a framework for an automated operating sequence.

So far an efficient calibration algorithm is still a challenge for the parallel kinematics. Developing an algorithm is a complex task. Conflicts with problems, like choosing the measuring instruments and strategy, data acquisition and processing the measured values and elaborating an appropriate procedure, able to find the range of the calibration offsets [Mer02, Mer05].

An essential drawback of calibration is the great number of kinematic parameters which are to be identified and also the principally worst conditioning of the calibration problem [Den04]. If the input data are discrete measured values of poses in the workspace, this not only generates inevitable measurement inaccuracies (measurement noise) but also other influences (errors) that are not caused by deviations of the kinematic parameters. Unless these errors are eliminated from the measured data, the obtainable calibration accuracy remains limited [Gro04]. These demands become particularly stringent in case of the calibration of hexapods of the so–called simple design [Gro01b].

2.2 Hexapod of Simple Design

A typically parallel kinematics construction is the Gough platform [Gou57, Gou62] which consists of six variable–length legs connected at one end to a fixed base by U–joints and at the other end to a movable plate by ball–joints [Mer00, Zhu98]. This six–leg–construction (hexapod) offers high force/torque capability and high rigidity to the structure [Mer00].

In some papers is, although, considered that a hexapod is a mix of parallel and serial structures. [Wil00] stipulates that, although, a hexapod is globally parallel, the architecture is serial where you can find the greatest number of mechanical pieces, in-between articulations.

As a result of their dexterity in complex motion, similar platforms have been used as flight simulators, manipulators and recently as CNC milling machines [Zhu98]. Important especially in case of this last application, where an effectual accuracy is required, is the fact that the structure enables to compensate the inaccuracies of the construction through the 6 DOF control of the six legs [Cha02, Gro99, Gro01a, Gro02a, Kha99, Mer00, Kau06]. This possibility is new compared to the 3 DOF mechanisms (tripods) and means a milestone for future industrial applications [Gro02b, Gro02c, Neu98, Neu00, Wec98b].

The above mentioned features can be exploited as accuracy benefits with proper use of the controller facilities. That means there is no absolute need of a high–end geometrical structure to obtain the desired accuracy, but a simple construction can be intelligently programmed, doing the same operations with a sufficient precision for the desired application. This *simple design* construction would cover the application–field between conventional machine tools and universal robots.

When speaking about hexapod, beside the accuracy another important point of view is the economical aspect. An ample description of the topic and about the hexapod of simple design developed at the IWM (Fig. 2.1) can be found in [Gro00a, Kau06].

Here is also mentioned that the efforts to obtain the desired accuracy of the machine have to be invested in two levels: the mechanical construction and the control technique. For the motion control a kinematic model is required which builds a virtual image of the physical structure. From this point of view the following approaches can be defined:

- Executing accurately the mechanical components so that a simple model will be sufficient to guarantee the required motion accuracy. This approach charges primarily the construction efforts and spares the performance of the control computer.
- The kinematic model on the control system is extended in order to handle the complex behavior of a rudimentary mechanical construction. Here the efforts are focused on the controller, charging the computer performance, on the other hand spares the construction efforts of the mechanical structure.

Both variants have their benefits and drawbacks, but neither of them presents a completely stand–alone fulfilling of the nowadays requirements, especially applied in the SMEs. A possible solution can be seen more in cleverly combining these approaches [Kau06]. Analyzing the problem for more machines, especially in case of quantity production, the advantages of a simple mechanical construction can be generally admitted by transferring the already developed control software to the new structures.

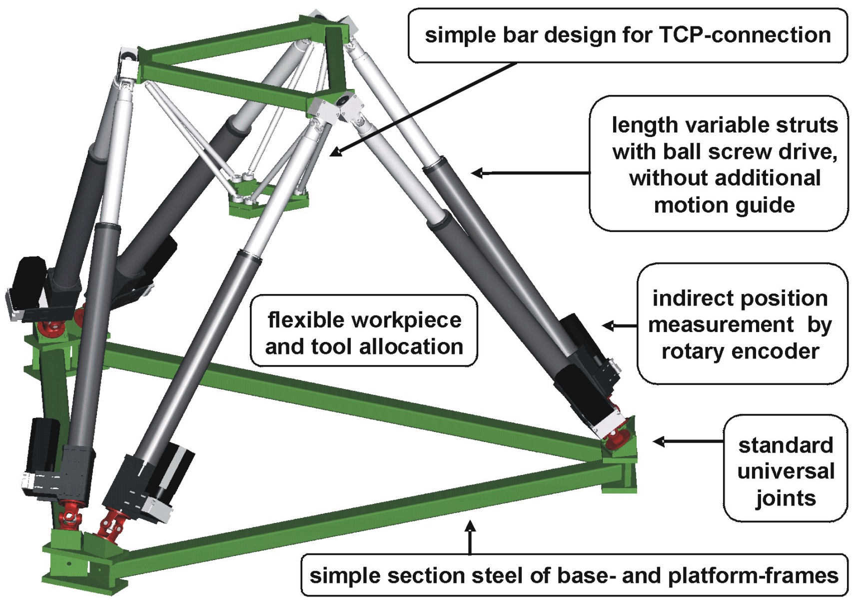


Fig. 2.1: *Hexapod of simple design*

2.2.1 Construction and Features

Designing a manipulator in the low–cost area begins with minimizing the realization outlay of the mechanical structure. The concept of the hexapod of simple design means to reduce as far as possible the mechanical effort invested in constructing a parallel manipulator. The goal of this concept is to develop a robust, low-cost, simple construction accessible to use in the small and medium enterprises [Gro01a, Gro01b]. The motto of the concept can be defined as following: *"The machine has to be as good as the work piece requires. – More accurate machines are mainly most expensive"* [Wec01].

The construction of the hexapod of simple design is based on choosing as far as possible standard components like universal joints, simple section steel of the platforms, struts without additional motion guide and simple position measurement systems as rotary encoders. Fig. 2.1 demonstrates the essential features of the simple design concept of the hexapod 'Felix' which has been developed for various applications at the IWM [Gro00a, Gro01b].

2.2.2 Main Characteristics

The hexapod 'Felix' is a 6 DOF – fully parallel kinematic machine, based on the construction of a Gough–platform [Gou57, Gou62, Mer00]. It has been designed using 6 length variable struts which link the base frame to the platform frame (Fig. 2.2). For more details of the construction see also [DPMA00, Gro00a, Gro01b, Kau06].

The base joints and the moving joints are situated each in a plain of a circle with a 1500 mm and 600 mm radius respectively. The traversing range of the struts, which hence the distance connecting a set of base and moving joints, is situated between 1533.0 mm and 2513.0 mm absolute length [Gro00a]. The origin of the strut co–ordinate system is defined by an absolute length of the struts of 2000.0 mm. According to this, the relative motion of the struts can be measured between –467 mm and +513 mm. The origin of the global co–ordinate system will be in the center of the moving platform, defined in the pose where the struts are at null – approximately in the middle of the workspace of the hexapod (Fig. 2.3).

Fig. 2.2: *Hexapod 'Felix' at the IWM, Dresden*

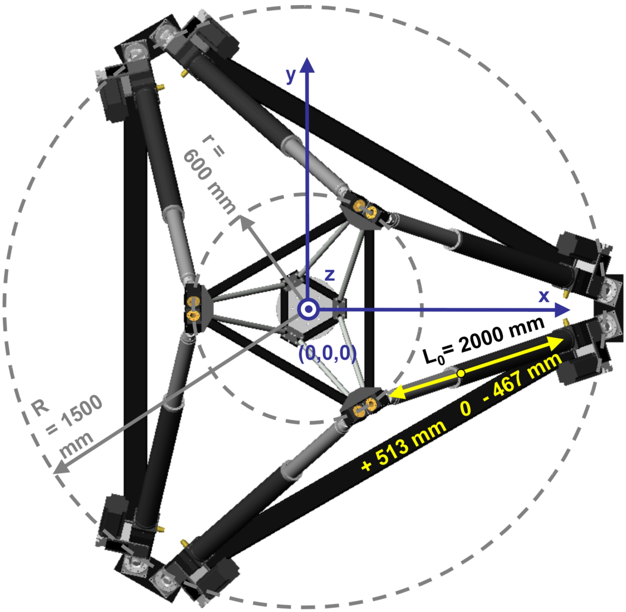


Fig. 2.3: *Main characteristics of the hexapod 'Felix'*

2.2.3 Position Accuracy

2.2.3.1 Performance Criteria

Accuracy control is made usually for the final acceptance of a machine or for their periodic verification. To ensure a high accuracy of the machine, various measurement systems and processes have been created and standards governing machine tool acceptance tests have been published, summarized in [Ble06]. Here is related that the methods of machine acceptance can be mainly broken down into direct and indirect processes to recognize the properties of the machine:

- **Indirect examination of machine accuracy**

  The machine tool is tested by manufacturing sample workpieces with defined geometric characteristics. The conclusions about machine accuracy will be drawn on the basis of deviations between the required and actual geometries. Due to the error overlap, a clear attribution of deviations in the geometry of the sample workpiece to the individual properties of the machine is not trivial. Hence, indirect processes will be more used for final functional tests to determine the accuracy of the machine and therefore preferable used in acceptance tests. For more detailed examinations the direct processes are rather used.

- **Direct determination of machine properties**

  The direct determination of the properties of a machine tool allows the identification of error sources. Parameters are determined directly on the machine with the help of measuring instruments. Tests of customized criteria and arbitrarily degrees of freedom can be carried out to respond to more demanding accuracy requirements. The results may be processed further in various ways, depending on the kinematic structure.

Robot manufacturers, as an industry standard, publish the repeatability of each machine. These specifications are determined by performing stringent experiments in accordance with [ISO9283]. This international standard depicts the performance criteria and related testing methods to determine performance characteristics of manipulating industrial robots. Here are described methods of specifying and testing the following performance characteristics of manipulating industrial robots:

- pose accuracy and pose repeatability
- multi–directional pose accuracy variation

- distance accuracy and distance repeatability
- position stabilization time
- position overshoot
- drift of pose characteristics
- exchangeability
- path accuracy and path repeatability
- path accuracy on reorientation
- cornering deviations
- path velocity characteristics
- minimum posing time
- static compliance
- weaving deviations

This International Standard does not specify which of the above mentioned performance characteristics are to be chosen for testing a particular robot. The tests described here are primarily intended for developing and verifying individual robot specifications, but can also be used for such purposes as prototype testing, type testing or acceptance testing.

To compare performance characteristics between different robots, the following parameters have to be the same: test cube sizes, test loads, test velocities, test paths, test cycles and environmental conditions [ISO9283]. This international standard can be applied to all manipulating industrial robots as defined in [ISO8373]. However, for the purpose of this standard, the term *"robot"* means manipulating industrial robot.

The most important accuracy relevant properties mentioned above in the case of a parallel manipulator are mainly considered the:

- **pose accuracy (AP):** Difference between a command pose and the mean of the attained poses when visiting the command pose from the same direction.
- **pose repeatability (RP):** Closeness of agreement among the attained poses for the same command pose repeated from the same direction.
- **path accuracy:** Difference between a command path and its attained path.
- **path repeatability:** Closeness of the agreement between multiple attained paths for the same command path.

The test equipments and metrology methods of operation for robot performance evaluation are summarized amongst others in [ISO13309]. The metrology approaches as presented in the ISO technical report, are:

- Positioning test probe methods
- Path comparison methods
- Trilateration methods
- Polar coordinate measuring methods
- Triangulation method
- Optical tracking methods
- Inertial measuring methods
- Cartesian coordinate measuring methods
- Path drawing methods

The presence of such a wide range of metrology solutions suggests that industry has still to settle on any single method [Con00]. Each offers a slightly different approach to a similar problem, therefore the most appropriate solution is subjected to the parameters each individual process requires [Con00].

A broad–applied precision test of machine tools is the circular test with the Double–Ball–Bar. The manufacturers, which produce the DBB [Ren], base their tests on the [ISO230] reports. Here are five available views of the accuracy presented:

G (CCW) – Circular deviation by counter-clockwise measurement
G (CW) – Circular deviation by clockwise measurement
F (CCW) – Radial deviation by counter-clockwise measurement
F (CW) – Radial deviation by clockwise measurement
H – Hysteresis

The mentioned tests will be used to determine the accuracy of the manipulator in the actual case of the hexapod of simple design.

2.2.3.2 Position Accuracy of the Hexapod of Simple Design

The mechanical parts of a construction such as a hexapod have more or less tolerances in manufacturing and assembling. This is generally valid for mechanical structures, but especially stringent in case of the parallel manipulators, particularly in case of the simple design hexapod [Gro00a].

The simple mechanical construction of the hexapod involves a principally worse basic and initial values of the motion accuracy [Gro01a, Gro01b]. One possible accuracy test is presented by [Kau06] (Fig. 2.4) where bi-directional repeated measurement results have been made with the laser interferometer along X and Y axes of the basic structure, through the middle of the workspace (origin). Against the poor motion accuracy the hexapod possesses a very good repeatability of the measurements. As the error influences have a systematic character, they can be principally corrected through the controller facilities.

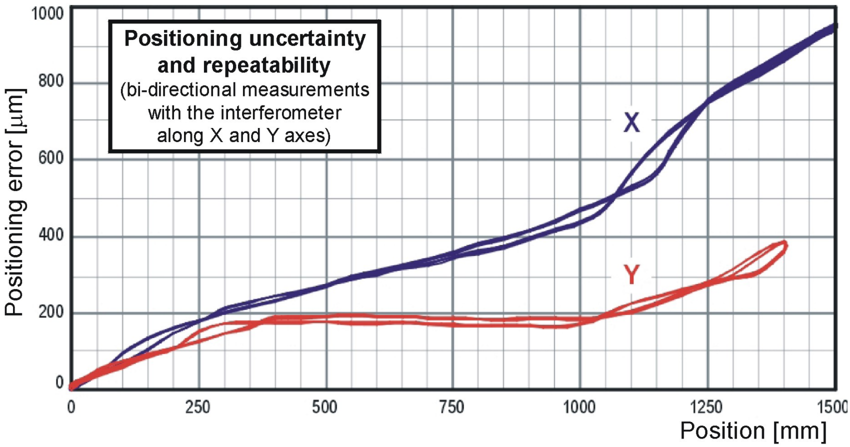


Fig. 2.4: *Positioning uncertainty and repeatability of the hexapod of simple design [Kau06]*

Analyzing the accuracy of the hexapod measured along circles with 300 mm radius in the middle of the workspace on orthogonal planes, the measurements can be observed in Fig. 2.5. Extensive measurements to estimate the positioning uncertainty of the hexapod 'Felix' using the DBB will be presented later in Chapter 6.

2.2.3.3 Error Sources

There are a huge amount of error sources which affect the accuracy of the hexapod. They have to be investigated in order to know their influence and the method to correct them. A possibly organized view of these influences

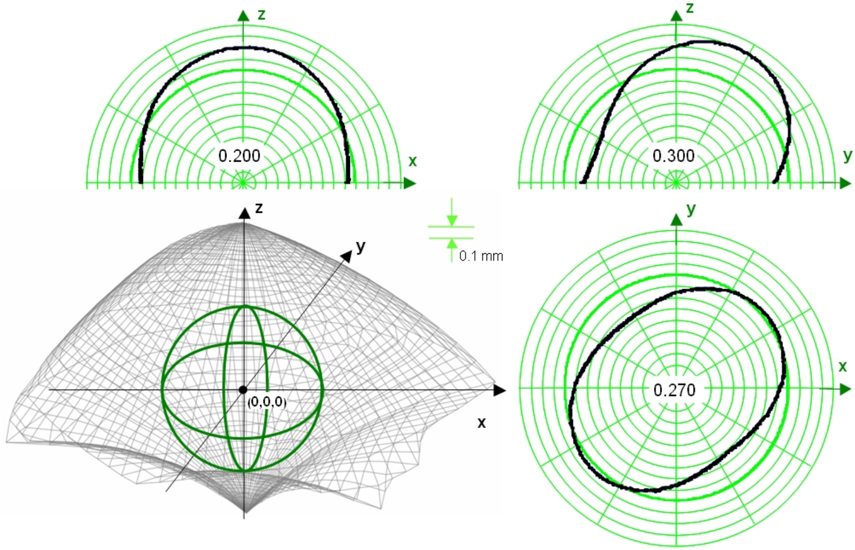


***Fig. 2.5**: Circular deviation measured with the DBB (R=300 mm)*

offers [Con00] analyzing the reasons which act on the overall accuracy and originate the errors (Fig. 2.6).

Considering the location, where the errors occur, and complementing the sorting proposal made by [Beh00], the following main error sources can be mentioned:

- **Errors in the joints and the drives**

  Errors in the joints and drives are probably the essential errors which characterize the parallel kinematics. These errors can achieve dimensions of several millimeters, especially valid in the case of large constructions. They are important firstly due to the higher number of joints relative to the serial structures and can arise due to:

  - *Manufacturing and assembly errors:* the real position of the joints is unknown due to uncertainties in manufacturing the parts and the assembly tolerances
  - *Backlash:* position uncertainty due to the internal clearance of the joints
  - *Reversal errors:* occurs with the reversal of the stress in joints

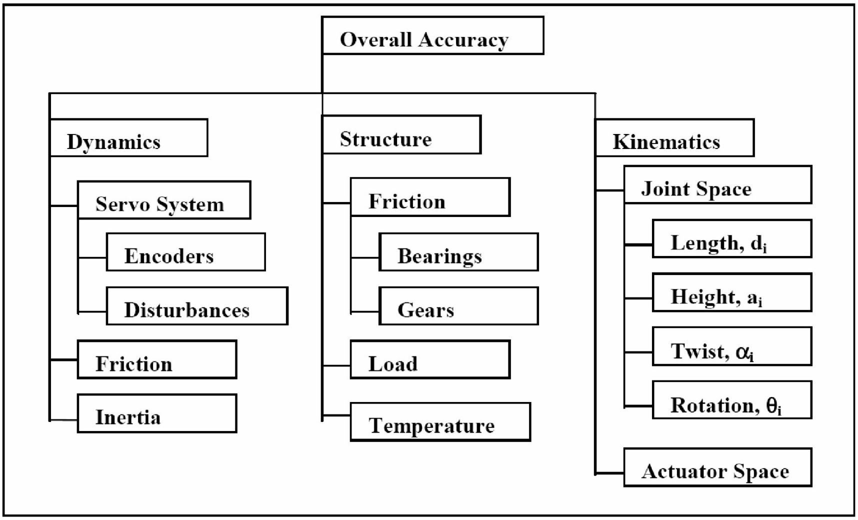


Fig. 2.6: *Error tree [Con00]*

- *Eccentricities:* deviations of the motion from the center of the joint
- *Elasticity:* own weight and forces during the application change the location of the joints
- *Transmission errors:* between the drives and the actuators
- *Friction:* the friction cause undesirable forces and phenomena (e.g. stick–slip)
- *Wear:* the quality deterioration during the use of the joints affects their precision
- *Heating:* thermal effects act on the position and dimension of the joints

- **Errors in the actuators**

  In the same manner as in the joints, the actuator's errors are dominantly important while they occur directly where the motion is originated (e.g. in the struts). The errors in the struts can average tenths but only up to some millimeters due to the mainly large construction design of the structure and can be generated by:

  - *Manufacturing and assembly errors:* position errors due to uncertainties in manufacturing and assembly tolerances of the actuator components
  - *Parallelism:* deviation from the parallelism of the actuator's components
  - *Orthogonality:* deviation from orthogonality of the actuator's components
  - *Elasticity:* own weight and process forces deform the actuators

- **Errors of the end–effector**

  The main problem of the end–effector is that even small error influences act directly on the precision of the manufactured workpiece or on the measuring instrument. The magnitudes of these errors are heavily dependent on the tool installed and have to be newly measured or determined by tool change. Fundamentally, it can be observed deviations derived from:

  - *TCP–determination:* uncertainty of determining the TCP due to the difficulty of a direct measurement mostly in a point without a physical representation
  - *Model deviation:* differences between the TCP location in the model and the real structure
  - *Adjustment and calibration:* due to incomplete adjustment (e.g. of the TCP–offset) or residual kinematic calibration errors

- **Errors from the encoders and sensors**

  Due to these errors the encoders and sensors provide the controller with false position information of the actuators. Hence, the controller undertakes false steps to correct a non–existent error, causing an invalid positioning of the machine. With the ever–developing industrial standards and the improvement of the quality of the encoders and sensors, these errors are decreasingly significant. They come mainly from:

  - *Adjustment and calibration:* uncertainty on adjusting and calibrating the encoders and sensors related to the manufacturer
  - *Error on defining the null position:* systematic offset to the desired null position
  - *Resolution:* rounding errors due to the resolution of the encoder

- *Standard deviation:* uncertainty of the position information given by the encoders and sensors
- *Eccentricities:* position deviations of the center point of a circular encoder from their nominal value
- *Concentricity:* radial deviation from the nominal value of a circular encoder
- *Force influences:* external forces can false the acquired dimensional value of the encoder or sensor

- **Controller errors**

  The loop controller is responsible for managing the position of the actuators through controlling the activities of the drives. It has permanently to correct and maintain the position information especially during a programmed motion of the structure. The nowadays high-performance controllers afford a very accurate control of a given position, although the problem is aggravated by a high–velocity motion of the drives due to the limited bandwidth of the control frequency. The magnitude of the controller errors depends on:

  - *Model of the robot:* there are differences between the model used in the controller and the real structure: on one hand, the kinematic model contains simplifications and on the other hand, the model parameters are not known exactly
  - *Transformations:* errors transforming (interpreting) the signal from the encoders and sensors
  - *Position control:* positioning accuracy of the controller which involves a position uncertainty of the physical structure
  - *Accuracy of the interpolation:* interpolation errors between path poses
  - *Rounding errors:* numerical errors in the controller
  - *Incremental error:* position errors due to rounding to the next incremental step
  - *Contouring (cornering) error:* dynamic path tracking problem expressed in motion errors as path deviation between actual and desired position due to the axis delay times over a bounded frequency bandwidth

- **Errors during the application**

  The positioning accuracy of the manipulator is further dependent on the influences during the application process. These are hardly to be anticipated because of the high variety of the industrial purpose and environment the manipulator has to face to. The structure has to overcome undesired effects due to:

  - *Elasticity:* elastic deformations of the structure due to forces during the application
  - *Load ratio:* errors due to pose specific forces of the manipulated load
  - *Environmental influences:* positioning uncertainties due to external influences e.g. vibration, temperature change of the environment

- **Errors due to the programming**

  Further negative influences on the accuracy are the errors due to the programming. These are mostly accidentally originated from the human operator and can derive from programming:

  - *On-line:* manual inaccuracies
  - *Off-line:* robot model, environmental model, definition of the base co-ordinate system

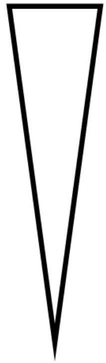
With experiments claimed by [Beh00], the relevance on the position accuracy of the influences from above can be sorted as presented in Tab. 2.1.

Inaccuracies due to the tool and work piece model can be eliminated with proper use of TCP and base offset corrections. The major systematic error sources, hence, can be generally considered as following:

◦ **Lengths offset of the struts** due to origin offset of the indirect measuring system, pitch error of the ball spindle, pose–dependent back–twist of the ball spindle – discussed by [Kau06]

◦ **Position deviation of the base and platform joints** from their nominal values due to construction and assembly tolerances

The other effects are considered less relevant, they cause either minor position deviations or have a less systematic character, hence difficult to compensate – they have to be considered by the assembly and by start–up – not considered deeply in the actual work. A constructive measure to

Error influences on:	Relevance hierarchy
• Work piece • Tool • Errors on defining the null position of the joints • Lengths or angular errors of the actuators • Thermal errors • Backlash, elasticity, and eccentricity of the joints • Elasticity of the actuators • Resolution of the measuring system	

Tab. 2.1*: Relevance hierarchy of the error sources [Beh00]*

reduce the joint clearance is proposed by [Lij04]. For detailed information on correction of thermal and elastic errors refer [Schö00, Kau06].

2.2.4 Consequences

[Wil00] claims that any parallel mechanism is not linear and not isotropic. That has influences on the error propagation, as described there:

- At one workspace point the error can yield negligible impact and at another can have a significant influence
- Between two points the error amplification shall not evolve linearly
- The prediction law is complex, so one axis inaccuracy can be attenuated and another can be amplified
- The error addition is hardly predictable, thus it is often impossible to order them in a significant hierarchy

Working with the hexapod of simple design implies the following consequences to be analyzed:

- **Complex kinematic model**

  The required improvement in precision will be done by exploiting the controller functionality to apply structure–based correction models.

This aspect of the error correction is nearly discussed in [Gro99, Gro00b, Gro01a, Gro02a, Kau06].

- **Complex error compensation algorithm**

  The resulting geometrical imprecision of the structure due to the worse properties of the basic parts must be determined after the assembly.

2.3 Techniques to Increase the Precision

To improve the motion accuracy of the hexapod, different techniques based on complex algorithms can be applied. They vary mainly through the behavior during the industrial application. From this point of view following approaches can be mentioned:

- Continuous compensation of the influences of non–kinematic parameters
- One-shot correction of the kinematic parameters in the control model

2.3.1 Compensation of non–kinematic Effects

The effects of the non–kinematic parameters have to be considered all over the motion in each point of the trajectory. Here can be mentioned as an example the elastic and thermal behavior. To consider these behaviors, two concepts can be found in the literature:

- Minimizing the undesired influence
- Correction of the induced errors

Examples of the measures taken against, the thermal and elastic influences can be seen in Tab. 2.2 and will be discussed below.

2.3.1.1 Minimizing the Influence of Thermal Effects on the Real Structure

Thermal errors are an important source of decreased volumetric accuracy of the parallel manipulator. The major starting place of the thermal drift is the thermal expansion of the struts due to heat generated in the ball screw drives [Wec00].

measures taken \ load	Thermal effects	Elastic effects
Minimizing the undesired influence (on the real structure)	- Conditioning cell (climate room) - Cooling with fluids - Using thermally invariant materials	- Designing a very rigid structure - Restricted motion (limits of the velocity and acceleration)
Correction of the errors (on the control system)	Model based correction (thermal model)	Model based correction (elastic model)

Tab. 2.2: *Measures taken against non–kinematic influences*

Another important source of the thermal errors is the drift of the joints due to thermal expansion of the base frame or the moving platform. The moving platform is mainly thermally exposed by the heat generated by the industrial process or the spindle bearings, whereas the base frame is mainly influenced by the changes of the ambient temperature [Wec00].

One measure to reduce the thermal load is that the robot and all the measurement devices have to be mounted inside of a thermal insulated box, in which the temperatures are monitored and controlled [Faz06]. The temperatures are acquired using temperature sensors placed in order to monitor all the involved parts: robot, measuring device, work piece, ambient air. Another special measure to reduce the thermal influences is proposed by [Wec00], where the frame of the robot is thermally regulated through pipes flooded with cooled fluid. A thermally constant behavior of the robot can be obtained with using thermally invariant materials especially on the encoders as proposed by [Wec00].

Further literature about the influence and correction of the thermal effects can be found as follows in [Gro99, Hei00b, Jun00, Kau06, Mai93, Neu02b, Pri00, Pri02], but this list is not exhaustive.

2.3.1.2 Minimizing the Influence of Elastic Effects on the Real Structure

Elastic deformations result from the limited stiffness of the kinematics, when it is loaded with a force. Related to [Pri02], the main force categories, which act on the parallel manipulators and cause the most elastic deformations, are:

- **Weight forces**

  The weight of the tool platform leads to elastic deformations of the real machine due to the flexibility in the machine kinematics. The gravitation forces in parallel kinematics have a particular adverse effect because of non-constant stiffness in the workspace.

- **Machining forces**

  High process forces are the reason for drive errors due to a low disturbance stiffness of the drives (Fig. 2.7). A low stiffness of the machine kinematics results in higher positioning errors due to deformations.

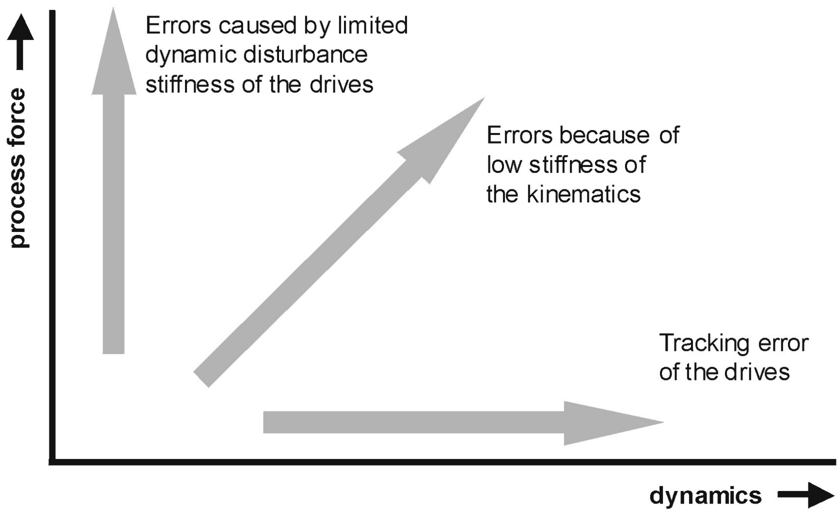


Fig. 2.7: *Reasons for positioning errors depending on the manufacturing process [Pri02]*

- **Inertial forces**

  Inertial forces caused by accelerated motion lead to deformations resulting in considerable errors.

To minimize the elastic influences, rigidity aspects of the structure have to be considered already by designing the robot. For a given parallel manipulator, other elements have to be added which increase the stiffness of the structure, although the subsequent stiffening of the kinematics is often impossible to find and - because of the lightweight construction - it has its limits [Pri02]. Another proposal suggests to limit the dynamical load of the robot with low speed and low acceleration motions [Wei02]. Further authors, who consider measures to minimize the elastic influence, are (without the claim of an exhaustive list) for example: [Meg98, Pri02, Wec00, Wei02].

2.3.1.3 Model Based Correction of the Errors

For the model based correction of the errors the controller facility will be used. Here, the accuracy-relevant behavior of the structure has to be considered to choose the suitable correction model. [Kau06] summarizes different aspects about the behavior models, as seen in Fig. 2.8.

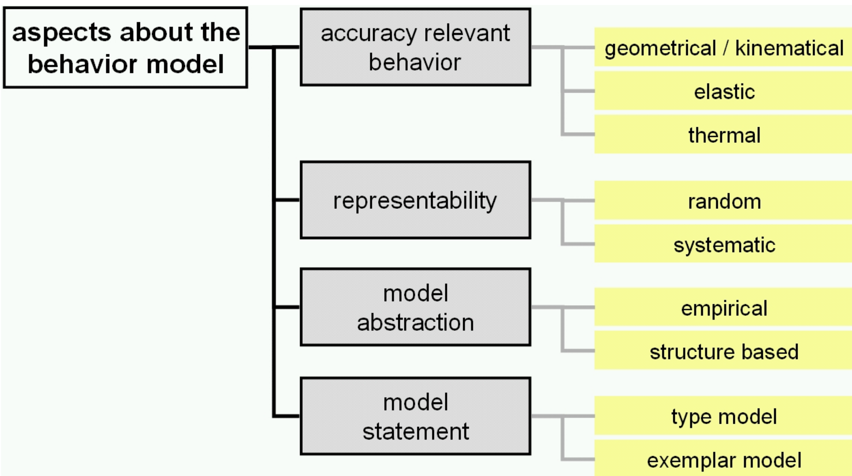


***Fig. 2.8**: Aspects about the behavior model [Kau06]*

Here the following considerations have to be mentioned [Kau06]:

- The manufacturing accuracy of a work piece will be affected only from **geometrical errors at the end-effector**. Hence, relevant are just that error shares which cause a deviation at the end-effector at all.
- Furthermore relevant are only the error contingents which can be corrected with **economically justifiable outlay**. Therefore will be considered here only the static and quasistatic behavior.

The elastic and thermal effects cause deformations of the components and act as geometrical errors at the end-effector (Fig. 2.9). Consequently, a suitable construction of the correction models and their parameters have to be considered and applied [Kau06].

The correction of elastic and thermally induced shares of the motion error of the hexapod 'Felix' has been made on the basis of structure models. This requires the development of models for the calculation of current–state deformations with adequate accuracy and, moreover, their integration into the control system to update states at an adequate velocity [Kau06]. It is

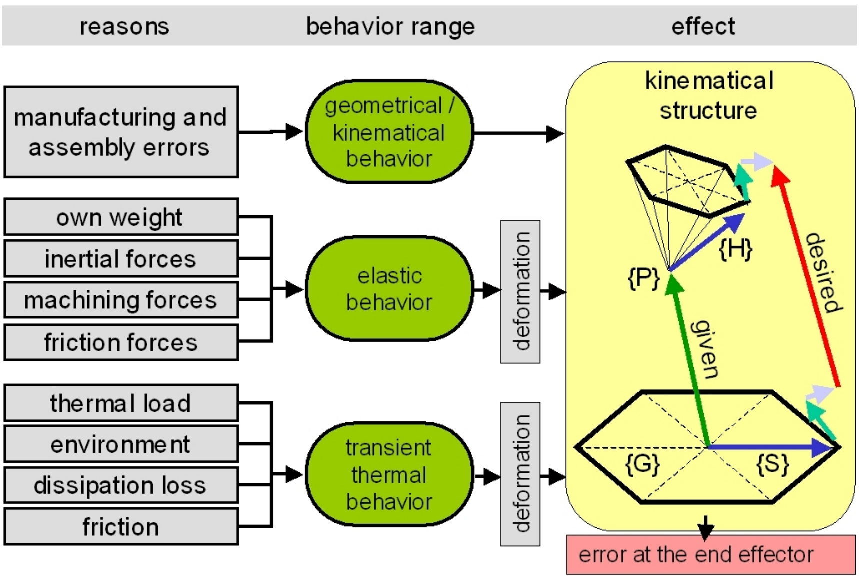


Fig. 2.9: Accuracy relevant behavior range [Kau06]

the aim that the principal solution is largely independent of the specific character of the used particular control and which essentially fits the *'simplicity concept'* also in this respect, i.e. no costly additional requirements – e.g. concerning hardware, implementation, qualification etc.

The correction concept developed at the IWM departs from the assumption that each parallel kinematic motion is reasonably preceded by a motion check of the kinematic transformation – at least for the collision conditions – and that the considered error influences are systematic. Having these conditions, the correction concept can basically be implemented outside the NC kernel and before processing starts. The concept is open to various users, flexible and non–time–critical. Within the frame of this concept, the elastic and thermal errors have been deeply analyzed and model–based corrected by [Kau06], as an important prerequisite for the calibration. The sequence of the model–based corrections of the non–kinematical influences and the placement of the calibration can be seen in the flowchart presented in the Fig. 2.10.

2.3.1.4 Limits and Consequences Correcting the non–kinematic Errors

The enhancement of the motion accuracy using model based corrections is basically limited from the point of view of the correction principle and economical aspects. The main reasons of these limits have been analyzed and presented by [Kau06] as following:

- The accuracy–relevant behavior of the machine *can not* be completely modeled. There is always a residual error of the model, hence principally the correction can be only approximated (Fig. 2.11)
- The determination and application of the correction is staggered in time (delayed)
- Bounded resources on the control and computer technique
- The model based correction demands suitable adjusting axis
- The acceptable outlay on designing, implementing and parameterizing the models is restricted from an economical point of view

From these considerations there are always residual positioning errors caused by uncorrected thermal and elastic influences. In case of the hexapod 'Felix', the correction of the thermal errors averages 50–70% of the initial value [Kau06]. It is again difficult to make a general statement of the residual elastic influence due to the complex character of the problem and strong dependencies on the position and load of the manipulator.

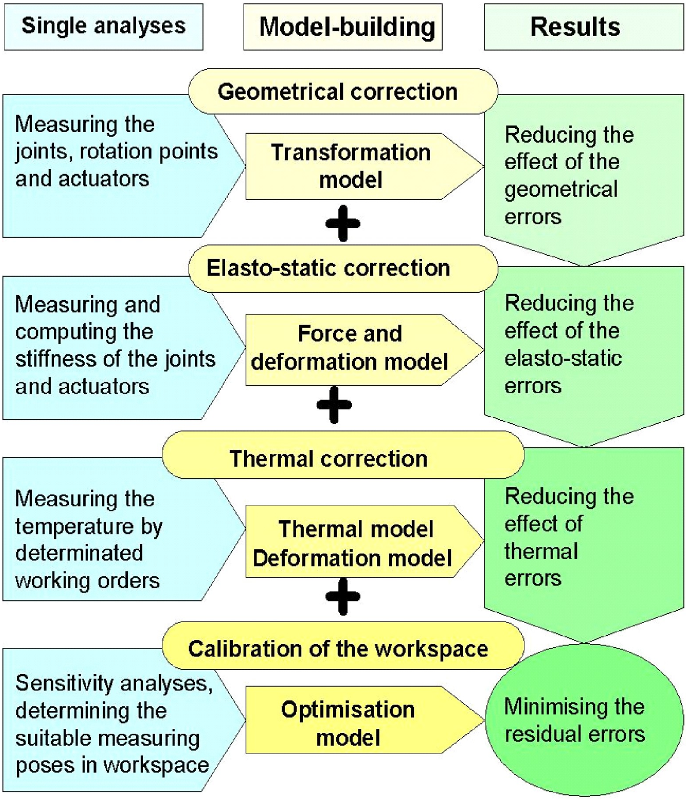


Fig. 2.10: *Model based correction of the motion accuracy*

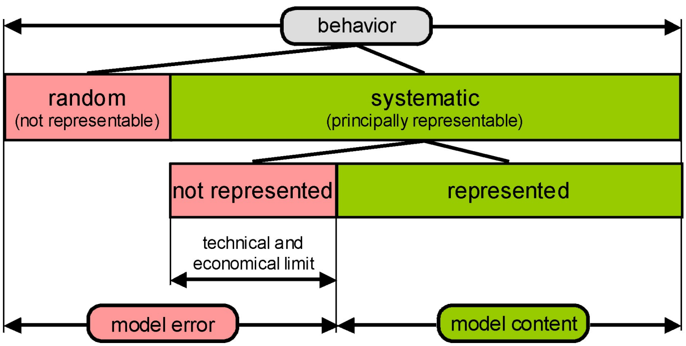


Fig. 2.11: *Representable behavior and rating [Kau06]*

The uncorrected non–kinematic effects cause residual positioning error of the manipulator and determine the uncertainty of correcting the kinematic parameters.

2.3.2 Correction of the Kinematic Errors

Principally, the kinematic errors can be handled in a correction, implemented once after the assembly of the manipulator, before the first practical application. The kinematic errors can be distinguished into repeatable and random errors [Meg98]:

- **Systematic errors** are errors which numerical value and sign are constant for a given manipulator configuration. An example of a systematic error is an assembly error.
- **Random errors** are errors which numerical value or sign changes unpredictably. At each manipulator configuration, the exact magnitude and direction of random errors cannot be uniquely determined, but only specified over a range of values. Random errors cannot be compensated using classical techniques. An example of a random error is the error which occurs due to backlash of an actuator gear train.

Classical kinematic correction methods can only deal with systematic errors, as already observed by [Meg98].

The quasistationary pose errors are mainly caused by the systematic influences of the differences between the parameters which are used for the kinematic transformation in the control system and the real parameters which are effective in the machine (e.g. actual value of the joint's position). There are several different approaches which can be used to determine the kinematic parameters of PKMs [Wav98]:

- measuring the geometry of the machine components directly: this is not always practical to do, particularly for large frame components (e.g. the joint locations for the machine) due to the virtual character of the reference points
- measuring errors in the relative motion of machine components (e.g. strut angles): installing the measuring system is not always obvious
- measurement of all errors in the platform pose can be obtained for a number of different locations and orientations throughout the work volume (Space Error Compensation)

- arbitrary performance evaluation tests (e.g. conventional Ballbar tests) can be used to estimate kinematic parameters through indirect measurements using a best–fit linear combination of parametric error shapes

Identification methods (kinematic calibration) consist in calculating the values of parameters which characterize the machine, so that the model represents the real machine instead of the nominal one. The controller has a better knowledge of the real dimensions of the kinematics, consequently is more accurate [Fra06a].

2.4 The Kinematic Calibration Problem

"Calibration of parallel robots poses an important problem. This is the price to pay for the good performance of parallel robots." [Mer00].

The accuracy of a parallel manipulator is not only dependent upon an accurate control of its actuators but also upon a good knowledge of its geometrical characteristics. According to the fabrication tolerances, many factors will play a role in the final accuracy of the robot. [Mas93] has shown that up to 132 parameters will be necessary to describe the geometrical features of a Gough platform. However, by a careful design these parameters may be reduced to the set of coordinates of the joint centers (36 parameters) and link offsets (6 parameters). The calibration of parallel manipulators remains an open question, as some papers have addressed this issue [Mer99, Mer02, Roth87, Pri04, Bey04]. The degradation in accuracy is mainly due to manufacturing tolerances used to construct the platform, manifested as deviations between the nominal kinematic parameters of the platform model and the actual parameters. Since the platform's controller has determined the length of the actuators according to the nominal model, the resulted pose of the platform is inaccurate. One way to enhance platform accuracy is by kinematic calibration, a process by which the actual kinematic parameters are identified and then used to modify the kinematic model used by the controller. For active degrees of freedom (actuated joints) the kinematic model in the controller can be adjusted to the given machine geometry [Ble04]. The passive degrees of freedom (passive joints), which are decisive for processing, have to be adjusted to the nominal position as well as possible. Thus, the controller will use a more accurate model and as a result the accuracy of the platform will be improved. The process of calibration basically consists of the following steps [Ble04]:

- Measurement of the actual position of the TCP at the desired positions
- Calculation of adapted kinematic parameters or adjustment values from the measured deviations
- Implementation of the calculated parameters in the control or adjustment of the structure according to the values obtained

2.5 Calibration Methods

One of the difficulties of using parallel kinematic machine tools in industrial applications is the lack of automated calibration methods which would enable a simple and quick calibration in manufacturing environment [Ble04]. The study of the calibration methods of parallel robots has become increasingly important during the last years. This is shown by the rising number of papers published on the topic and various approaches were tried by researchers. Some of them have extended our knowledge about particular aspects of the subject; however numerous topics still has remained open. A systematic approach of the problem is still very modest; a narrow circle of scientists, like [Mer99, Roth87, Pri04, Bey04], tried to order the topic, without offering a complete solution. [Schö00] sorts the calibration approaches into the following two main categories:

- **External calibration**

  An external measuring system is used to get additional information about the manipulator;

- **Self calibration**

  For the measurement are used exclusively the own internal sensors of the manipulator. Related to [Schö00], the following methods can be used to perform a self calibration:

  - *Measuring passive joints*

    Contrary to serial structures, the parallel kinematics possesses always passive joints. Here a transducer can be mostly attached or permanently installed [Wam95]. Advantage of the method is that no external construction is needed and the calibration can be repeated arbitrarily by demand.

– *Use the redundant actuators as transducer*

Redundant actuators mean to increase the workspace and to eliminate singularities or backlash. They can provide useful measuring data for the calibration []Chiu04. The here mentioned redundant actuator can be interpreted also as mechanical or optical sensors or ultrasonic transducers.

– *Reduction of the structure*

Through mechanical fixation of two struts [Dan98], the overall DOF of the structure will be reduced to one. Three of the four resident struts will be therewith redundant and can be used to acquire additional data (measurement). The obtained accuracy improvement is although limited to a multiple of the measuring noise due to the narrowed measurements in a sub–space of the hexapod. Another problem and imprecision source can be met associated with the mechanical fixation of the struts.

On the other hand the calibration methods can be seen from the point of view of the solving direction of kinematic problem. Principally can be defined the calibration through the:

- Inverse kinematic of the manipulator
- Forward kinematic problem

2.5.1 Inverse Kinematic Calibration

The inverse kinematic transformation is needed to compute the actuator's position from a given Cartesian pose of the TCP. For the hexapod of simple design 'Felix', the inverse kinematic transformation has been described and solved by [Kau06] as presented below, departing from the simplified model seen in Fig. 2.12.

The base co–ordinate system **G** builds the reference frame of the platform pose ${}^{G}\mathbf{P}$. The parameters of the kinematical model are the location of the moving joints ${}^{P}\mathbf{h}_i$ in the moving platform and the location of the base joints ${}^{G}\mathbf{s}_i$ in the base platform. A vectorial representation of the relation between the pose ${}^{G}\mathbf{o}_P$ and the position of the actuator (length of the strut) ${}^{G}\mathbf{l}_i$ can be expressed as:

$$ {}^{G}\mathbf{o}_P + {}^{G}\mathbf{h}_i - {}^{G}\mathbf{l}_i - {}^{G}\mathbf{s}_i = \mathbf{0}\ . \tag{2.1} $$

where: ${}^{G}\mathbf{h}_i$ is the location of the moving joints in the base platform.

From here, the length of the strut for a given pose is:

$$ {}^{G}\mathbf{l}_i = {}^{G}\mathbf{o}_P + {}^{G}\mathbf{h}_i - {}^{G}\mathbf{s}_i \ . \tag{2.2}$$

To express the location of the moving joints in the relative coordinates of the mobile platform $\mathbf{P}$, the ${}^{G}\mathbf{h}_i$ have to be transformed using the rotation matrix ${}^{G}\mathbf{R}_P$:

$$ {}^{G}\mathbf{l}_i = {}^{G}\mathbf{o}_P + \left({}^{G}\mathbf{R}_P \cdot {}^{P}\mathbf{h}_i\right) - {}^{G}\mathbf{s}_i \ . \tag{2.3}$$

The inverse kinematic transformation expresses the absolute value of the strut's lengths as function of the pose of the mobile platform ${}^{G}\mathbf{o}_P$ and the known design parameters ${}^{P}\mathbf{h}_i$ and ${}^{G}\mathbf{s}_i$ as follow:

$$\begin{aligned} l_i &= \left|{}^{G}\mathbf{l}_i\right| \\ &= \left|{}^{G}\mathbf{o}_P + \left({}^{G}\mathbf{R}_P \cdot {}^{P}\mathbf{h}_i\right) - {}^{G}\mathbf{s}_i\right| \ . \end{aligned} \tag{2.4}$$

An extensive analysis and solution of the inverse kinematic problem for the hexapod 'Felix' can be found in [Kau06].

Many calibration methods based on inverse kinematics are proposed because of the analytically solvable equations, although, this approach may not be optimal due to the small measurable workspace and the need of computing separately the kinematic parameters of individual links [Mar04]. Moreover, as [Eco06] observes, for redundant PKMs the equation system associated to the transformation from user-space to machine–space coordinates (from Cartesian pose to the actuator position) is over–determined,

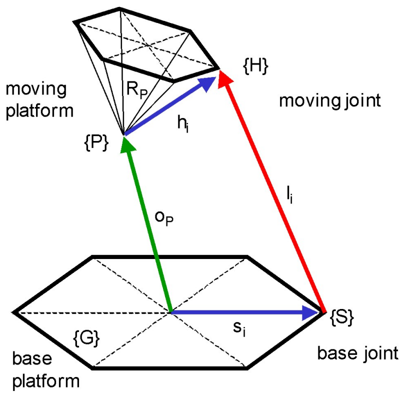


Fig. 2.12: *Simple kinematic model of the hexapod 'Felix' [Kau06]*

hence the inverse transformation has no solution in the case of non–ideal parameters. Thus, this transformation cannot be used as is for the calibration – relates [Eco06].

2.5.2 Forward Kinematic Calibration

Considering the disadvantages of the calibration through the inverse kinematics problem, researchers have been working on methods based on forward kinematics. These approaches involve the use of an external measuring device to obtain the position and orientation of the moving platform.

The forward kinematic transformation is the counter piece of the inverse transformation and is needed to obtain the TCP pose for the given position of the actuators (lengths of the 6 struts). This is needed – between others – for simulations, error analysis and the calibration. The forward kinematic problem commonly can *not be solved* with symbolic computations as a closed analytical form in case of the parallel kinematic machines. As indirect method can be used numerical approaches with successive approximations, solving iteratively the inverse kinematic transformation.

For the hexapod 'Felix' the forward kinematic problem has been solved using the Newton iteration algorithm and implemented by [Kau06]. The solution of the forward kinematics is approached here through linearization of the inverse kinematic transformation (IK) simplified described as:

$$\mathbf{q} = IK(\mathbf{x}) \ . \tag{2.5}$$

The Taylor expansion till the first term in the pose $\mathbf{x}^*$ (approximation for $\mathbf{x}$) gives us:

$$IK(\mathbf{x}) \approx IK(\mathbf{x}^*) + \frac{\partial}{\partial \mathbf{x}} IK(\mathbf{x}^*) \cdot (\mathbf{x} - \mathbf{x}^*) \ . \tag{2.6}$$

The linearization is realized with the partial differential of the inverse kinematic problem near the pose $\mathbf{x}^*$ and results in the inverse Jacobian matrix $\mathbf{J}(\mathbf{x}^*)^{-1}$:

$$\mathbf{J}(\mathbf{x}^*)^{-1} = \frac{\partial}{\partial \mathbf{x}} IK(\mathbf{x}^*) \ . \tag{2.7}$$

The direct Jacobian matrix is valid for a given pose of the hexapod and gives us a statement about how a modification at the actuators $d\mathbf{q}$ influences the pose modification $d\mathbf{x}$ on the moving platform:

$$d\mathbf{x} = \mathbf{J}(\mathbf{x}) \cdot d\mathbf{q} \ . \tag{2.8}$$

As the obtaining of the Jacobian matrix directly is a difficult problem [Mer00], it will be computed indirectly from the expression of the inverse kinematic Jacobian matrix.

The inverse Jacobian matrix expresses the problem from the opposite direction, what kind of $d\mathbf{x}$ pose modification at the moving platform demands a $d\mathbf{q}$ modification at the actuators:

$$d\mathbf{q} = \mathbf{J}(\mathbf{x})^{-1} \cdot d\mathbf{x} \,. \tag{2.9}$$

[Mer00] describes two different ways to obtain the inverse Jacobian matrix:

- The first possibility is to use the matrix relating the *generalized velocities* of the end–effector to the articular velocities. This matrix will be called the *kinematic Jacobian* matrix $\mathbf{J}_k$. It is not a Jacobian matrix in the strict mathematical sense of the term, while there has no representation of the orientation of a rigid body, the derivative of which - with respect to time - corresponds to the rigid body angular velocities.
- The second possibility for defining the inverse Jacobian matrix – having chosen a representation of the orientation – is to use the matrix relating the end–effector Cartesian velocities and the derivatives of the orientation representations to the articular velocities. If the chosen orientation representations for the end–effector are the Euler angles, we will obtain a matrix $\mathbf{J}_e$ called the *Euler angles Jacobian* matrix.

Having the inverse Jacobian matrix, the inverse kinematic transformation can be formulated as follow:

$$IK(\mathbf{x}) \approx IK(\mathbf{x}^*) + \mathbf{J}\left(\mathbf{x}^*\right)^{-1} \cdot \left(\mathbf{x} - \mathbf{x}^*\right) \,. \tag{2.10}$$

From here can be obtained $\mathbf{x}$:

$$\mathbf{x} \approx \mathbf{x}^* + \mathbf{J}\left(\mathbf{x}^*\right) \cdot \left[IK(\mathbf{x}) - IK(\mathbf{x}^*)\right] \,. \tag{2.11}$$

The iteration steps to obtain the forward kinematic transformation are summarized by [Kau06]:

$$\begin{aligned} \mathbf{x}_0 &= \mathbf{x}^* \quad , \\ \mathbf{q}_k &= IK(\mathbf{x}_k) \quad , \\ \Delta\mathbf{x}_k &= \mathbf{J}(\mathbf{x}_k) \cdot (\mathbf{q} - \mathbf{q}_k) \quad , \\ \mathbf{x}_{k+1} &= \mathbf{x}_k + \Delta\mathbf{x}_k \,. \end{aligned} \tag{2.12}$$

More about the implementation of the procedure in case of the hexapod of simple design 'Felix' can be found in [Kau06].

2.5.3 Overview of the Calibration Procedures

An overview of the calibration procedures can be meaningful defined and structured as seen in Fig. 2.13.

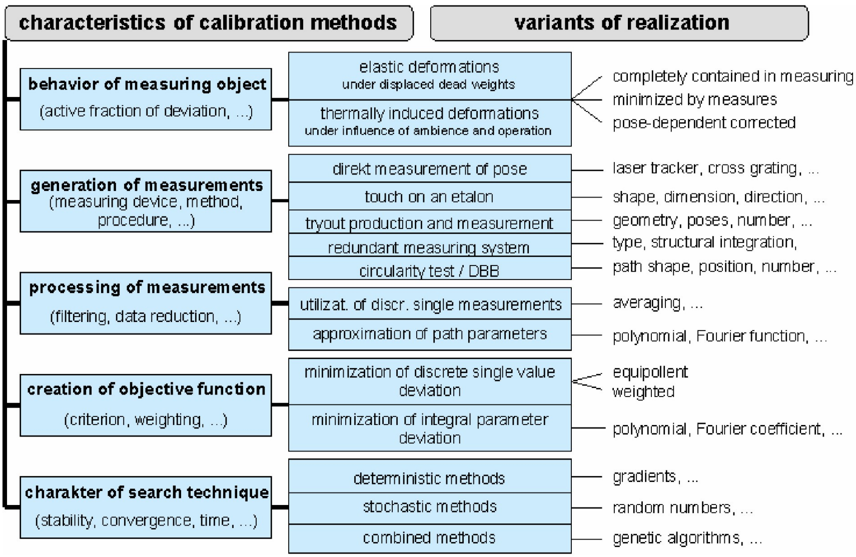


Fig. 2.13: Characteristics of the calibration methods

The actual calibration approaches of the parallel kinematic machines found in the literature can be sorted into the mentioned categories from the point of view of:

- Behavior of the measuring object
- Generating the measuring path
- Processing the measuring data
- Defining the cost function
- Character of the calibration procedure

2.5.3.1 Behavior of the Measuring Object

Most of the authors neglect partially or completely to analyze the behavior of the measured structure, which involves an increased uncertainty of the obtained measuring data. As seen in the chapter 2.3.1.3, the correction of the influences due to thermal and elastic behavior of the measured object – in actual case the hexapod – means an important prerequisite for the calibration. Especially for an efficient enhancement of the accuracy these effects have to be considered using compensations or special measures to decrease the error influence. Some researchers have applied special methods on:

- compensating thermally induced deformations

  [Jyw03, Wav98, Wec00, Hei00b]

- considering elastic deformations

  [Pri02, Wec00, Meg98, Eco06]

- special measures (e.g. using special materials)

  [Wec00, Faz06]

2.5.3.2 Generating the Measurement Path

In order to evaluate the accuracy of the machine various performance criteria are required, as already presented in the chapter 2.2.3. The measurements can be prepared by:

- **Touching an etalon** [Beh00, Gon00, Bri06]

  Within this method a previously carefully prepared etalon will be touched and the real positioning data of the hexapod is compared with the desired position. The deviation values are considered as measuring data and will be used as input information for the calibration. An example of this method is presented in the Fig. 2.14 (left hand side) by [Bri06] where a special developed probing system is used to effectuate measurements on a 3D ball plate.

- **Executing a test workpiece** [Alt04, Pri02]

  The measurement data can be acquired through manufacturing of a real workpiece and measuring its characteristics. Fig. 2.14 (right hand side) presents measurements from a milling task from a classical 3D–milling application test piece [Alt04].

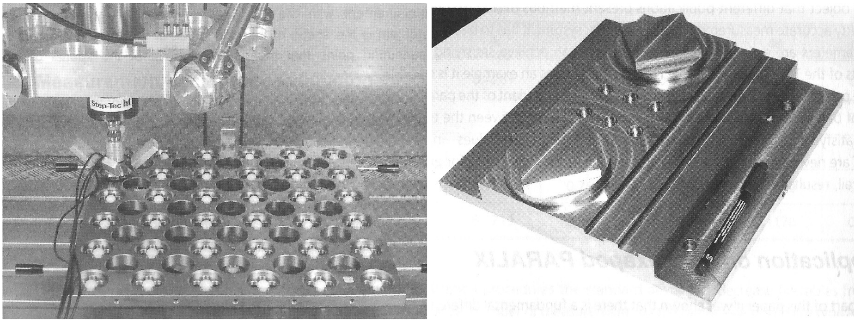


Fig. 2.14: *Measuring a ball plate [Bri06] (left) and executing a test workpiece [Alt04] (right)*

Other methods consider the system measurements performed by:

- **Using a redundant measuring system** [Alt04, Bai03, Bau06, Bey02, Ble01, Ble04, Cha02, Dan98, Dan99, Dan02, Fas02, Hei00a, Jyw03, Kha99, Kos98, Mar02, Pat00, Rau01, Rau04, Ren03, Ren04, Ren05, Ryu01a, Wam95, Wav98, Wec00, Zhu97, Zhu98, Zhu00, Zou]

  A redundant measuring system means to obtain additional positioning data of the construction components like struts or joints. An example of a special set-up for a laser measurement of the relative position error of a strut is presented by [Wav98] as seen in Fig. 2.15. The redundantly obtained positioning data will be compared with those obtained from the integrated sensors and used for computing the corrections.

- **Measuring with the Double–Ball–Bar** [Chi02, Den04, Fas02, Hei03, Iha00, Mar04, Ota00, Ryu01, Tak02]

  Although, this measuring instrument is very simple and can measure just 1 DOF, there is an increasing number of authors which employ it for calibration exploiting the facilities in obtaining quick and robust measurements. The measurement is made between the center points of two balls: one fixed to the machine frame and another to the moving platform or instead the tool (Fig. 2.16).

2.5.3.3 Processing the Measuring Data

The measuring data are acquired through:

- **Discrete single measurements** [Alt04, Beh00, Bey02, Ble01, Ble04, Bri06, Cha02, Chi02, Den04, Fas02, Fra06, Gon00, Hei00a, Hei03, Jyw03, Kha99, Kos98, Mar04, Ota00, Pri02, Rau01, Rau04, Ren03, Ryu01, Ryu01a, Wam95, Wav98, Wec00, Zhu97, Zhu98, Zhu00, Zou]

  The measuring data are considered to be a set of discrete deviations between the ideal and real poses while repositioning the machine and it is measured in 1...6 DOF. In Fig. 2.17 a DBB measurement of given discrete points can be seen presented by [Fra06].

- **Approximation of path parameters** [Iha00, Tak02]

  Instead of discrete points the measuring data can be processed as compressed information of the measuring path with approximation of the path parameters. In this case, we can speak about a so–called integral measurement, where the accuracy information of the machine is supported in a transformed and compressed form. As an example for the measurements with the DBB, the machine properties will be estimated from the character of the circular deviations detected relative to an ideal circle, observing the shape of the real measurement.

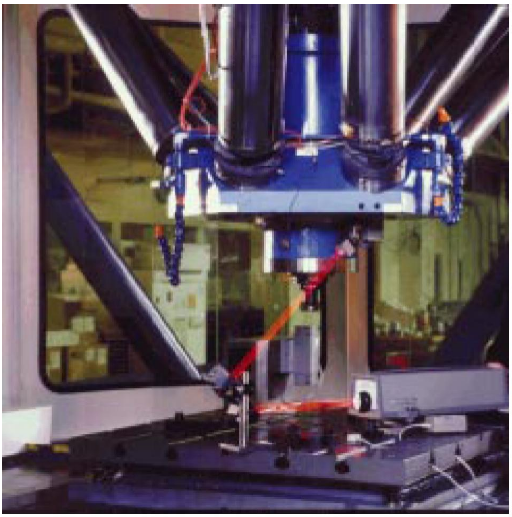


Fig. 2.15: *Special set-up to measure the relative strut lengths error [Wav98]*

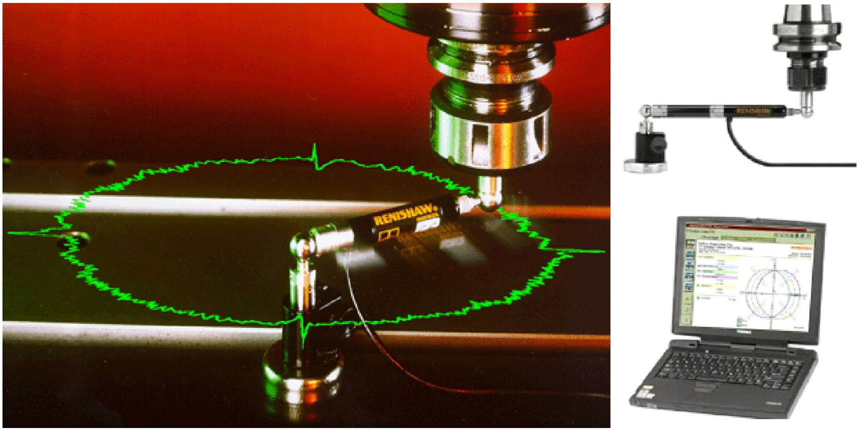


Fig. 2.16: *Double-Ball-Bar [Ren]*

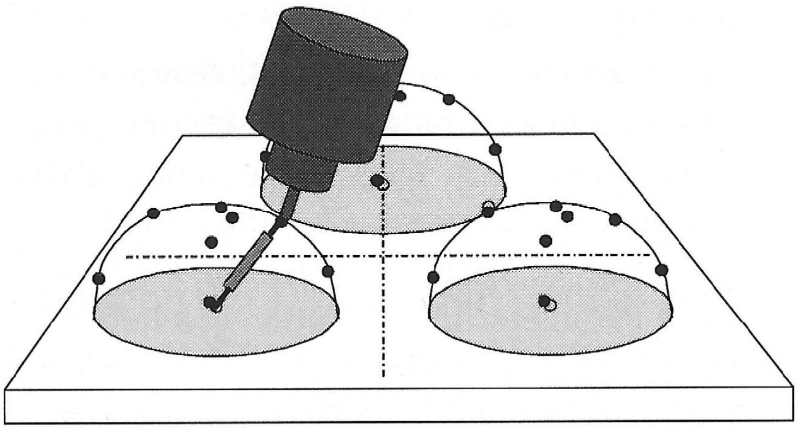


Fig. 2.17: *Measuring with the DBB in discrete poses [Fra06]*

2.5.3.4 Defining the Cost (Target) Function

Analogously to the obtained measuring data, the cost function of the optimization will be defined with:

- **Minimizing the deviations of discrete values** [Alt04, Beh00, Bey02, Ble01, Ble04, Bri06, Cha02, Chi02, Den04, Fas02, Gon00, Hei00a, Hei03, Jyw03, Kha99, Kos98, Mar04, Ota00, Pri02, Rau01, Rau04, Ryu01, Wam95, Wav98, Wec00, Zhu97, Zhu98, Zhu00, Zou]

  The calibration will be made by reducing the deviations between the measured discrete points.

- **Minimization of integral parameter deviation** [Iha00, Tak02]

  The cost function is defined from the compressed path information of the integral measurements. The cost function in this case is largely independent of the number of measuring points captured by the measurement.

2.5.3.5 Character of the Calibration Procedure

The calibration procedure is carried out with:

- **Gradient-based methods** [Alt04, Beh00, Bey02, Ble01, Ble04, Cha02, Chi02, Den04, Fas02, Gon00, Hei00a, Hei03, Iha00, Jyw03, Kha99, Kos98, Mar04, Ota00, Pri02, Rau01, Rau04, Ryu01, Tak02, Wam95, Wav98, Wec00, Zhu97, Zhu98, Zhu00, Zou]

  The kinematic parameters are optimized using gradient–based techniques like the Quasi-Newton-method, Newton–Raphson–method, Levenberg–Marquardt–algorithm or others. Common to these procedures is the iterative observation and minimization of the error gradient departing from a given initial value of the desired parameters.

- **Neural networks** [Faz06, Kuh06]

  With neural networks the accuracy properties of the mechanical structure will be predicted based on teach-in transformations (error transmission) stored in the controller. This learning information has to be predetermined and it is obtained to analyze a large number of sample measurements.

- **Space Error Compensation** [Bri06]

  Space Error Compensation is mostly used by conventional machine tools or kinematics with 3 DOF or less. The method consists in interpolating the accuracy information stored in the controller. Contrarily to the neural networks, the error information is stored directly from fully measurements of the workspace using a grid of measuring points. Here is no need to know the error propagation function or the kinematic transformations of the structure. The procedure may be inefficient by more than 3 DOF where the stored information quantity raises exponentially.

- **Interval analysis** [Dan04a, Dan05a, Dan06b, Mer06, Pott05]

  This method breaks down the workspace into subspaces (intervals) considering that the subspace is safe if satisfy the accuracy requirements or is unsafe in the contrary case (Trust–Region–method). If the subspace is unsafe or no decision can be made due to singularities or computational (numerical) problems, the subspace will be iteratively further divided till a desired resolution of the workspace is obtained. This method can be used for optimizations or to evaluate the worst case accuracy of the manipulator [Mer06].

- **Statistical methods** [Pott04, Boy06, Alt04]

  Statistical methods use random simulated measurements to estimate the error propagation function from the kinematic parameters to the end–effector and to identify the probability of the unknown parameters.

- **Genetic algorithms** [Ble04]

  Genetic algorithms use a combined method to optimize (identify) the kinematic parameters. They are based on stochastic random background which will be cleverly directed to speed up the convergence [Gro03]. GA's are extremely robust to singularities or computational problems and increase the global character of the search algorithm. With the developing computer technique, the GA are expected to be progressively more used in the optimization problems with numerous parameters, like the calibration problem of the parallel kinematics.

2.6 The Calibration Outlay

The first and most general valuation variable for these different procedures is probably the relative improvement of the motion accuracy, eclipsing the other aspects to pay for it. The calibration effort has been underestimated or even been neglected for a long time. The scientific value of the calibration procedure is not only in direct proportion to the achieved accuracy, but also in the calibration effort. This outlay has to be analyzed, a possible systematical approach can be formulated as presented in Tab. 2.3.

sequence / effort	measuring system	measuring procedure	data evaluation	parameter identification
invested time	set up time	measuring time	computing speed	computing speed
arising expenses	• basic lay-out • additional components • measuring software	installation costs	providing evaluation software	providing identification software
required qualification	set up the measuring system	• planning the measuring path • operate measuring software	operate the data evaluation software	operate the identification software
achieved accuracy	resolution	extent of the measurement (nr. measuring points)	repress measuring noise	nature of the algorithm
practical applicability	• simplicity, robustness • generally applicable	user friendly	stand-alone / system integrated	automatic (control integrated) / manual

Tab. 2.3: *Outlay of the calibration*

To analyze the overall outlay of the calibration, the sum of all the component characteristics have to be considered. The overall performance of the procedure has to conform to the demands on the calibration for a specific application.

2.7 Demands on the Calibration

Further criteria of evaluation of the calibration approaches can be formulated if other issues, like *minimization of the total outlay*, *feasibility for practical applications* or *efficient automatability*, are added.

Fig. 2.18 shows possible resulting demands.

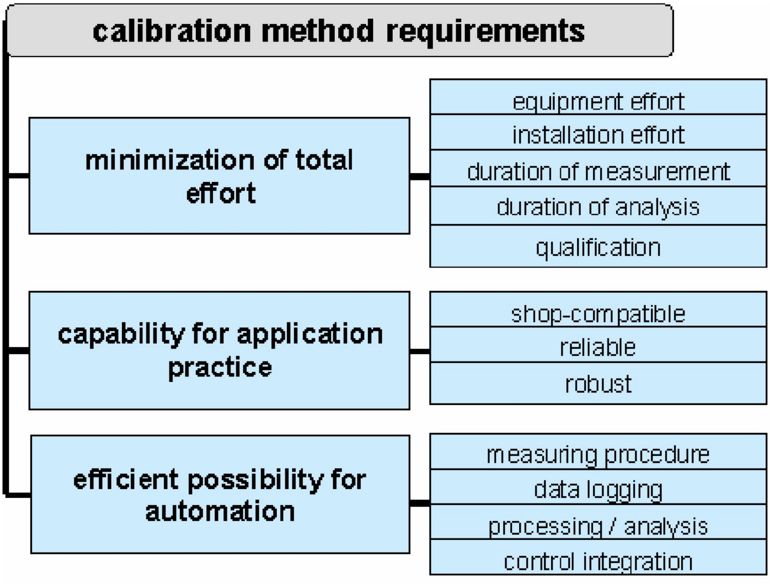


Fig. 2.18: *Demands on calibration*

Analyzing the actual calibration approaches, they can be sorted into the categories from above from the point of view of:

- **The total effort of calibration** (Tab. 2.4)
- **Capability for application practice** (Tab. 2.5)
- **Efficient possibility of automation** (Tab. 2.6)

An overall valuation of selected calibration approaches is presented in the Tab. 2.8. Here the following notations have been used, as can be seen in Tab. 2.7.

Cost of the measuring device		
low	middle	high
[Chi02, Den04, Hei03] [Iha00, Kha99, Mar04] [Ota00, Rau01, Ryu01] [Tak02, Wam95, Zhu93]	[Bey02, Bri06, Fas02] [Jyw03, Rau04, Zhu97] [Zou]	[Alt04, Beh00, Ble01] [Ble04, Cha02, Faz06] [Gon00, Hei00a, Kos98] [Pri02, Wav98, Wec00] [Zhu98, Zhu00]

Effort to install the measuring device		
easy	middle	complicated
[Ble01, Chi02, Den04] [Hei03, Mar04, Rau01] [Ryu01, Tak02, Zhu93]	[Alt04, Beh00, Bey02] [Cha02, Fas02, Hei00a] [Iha00, Jyw03, Kos98] [Ota00, Rau04, Wam95] [Wav98, Zhu98]	[Ble04, Bri06, Faz06] [Gon00, Kha99, Pri02] [Wec00, Zhu97, Zhu00] [Zou]

Duration of the measuring process		
short	middle	long
[Den04, Hei03, Jyw03] [Mar04, Rau01, Tak02] [Wav98, Zhu97, Zhu98]	[Alt04, Bey02, Ble04] [Cha02, Fas02, Faz06] [Hei00a, Kha99, Kos98] [Rau04, Wam95, Zhu93] [Zou]	[Beh00, Ble01, Bri06] [Chi02, Gon00, Iha00] [Ota00, Pri02, Ryu01] [Wec00, Zhu00]

Request of qualified personal		
low	middle	high
[Ble01, Den04, Hei00a] [Hei03, Mar04, Ota00] [Rau01, Tak02, Zhu93] [Zhu98]	[Alt04, Bey02, Ble04] [Chi02, Iha00, Jyw03] [Kos98, Rau04, Ryu01] [Wav98, Wec00, Zhu97] [Zou]	[Beh00, Bri06, Cha02] [Faz06, Gon00, Kha99] [Pri02, Wam95, Zhu00]

Tab. 2.4: *The total effort of calibration*

Robustness of the calibration		
poor	middle	high
[Beh00, Bri06, Den04] [Faz06, Gon00, Jyw03] [Kos98, Pri02, Wam95] [Zhu93, Zhu97, Zhu00] [Zou]	[Alt04, Bey02, Ble01] [Ble04, Cha02, Chi02] [Hei00a, Hei03, Iha00] [Ota00, Rau04, Ryu01] [Wav98, Zhu98]	[Den04, Kha99, Mar04] [Rau01, Tak02, Wec00]

Ability to generalize the procedure to other manipulator structures		
easy	middle	complicated
[Alt04, Chi02, Den04] [Hei00a, Kos98, Mar04] [Pri02, Rau01, Tak02] [Wav98, Zhu00]	[Beh00, Ble04, Bri06] [Cha02, Iha00, Ota00] [Rau04, Ryu01, Zhu93] [Zhu98, Zou]	[Bey02, Ble01, Faz06] [Gon00, Hei03, Jyw03] [Kha99, Wam95, Wec00] [Zhu97]

Expected improvement of the accuracy		
poor	middle	high
[Chi02, Jyw03, Ryu01] [Wam95, Wav98, Zhu93] [Zhu98, Zhu00]	[Beh00, Bri06, Cha02] [Fas02, Hei03, Iha00] [Kha99, Kos98, Mar04] [Ota00, Rau01, Tak02] [Wec00, Zhu97, Zou]	[Alt04, Bey02, Ble01] [Ble04, Den04, Faz06] [Gon00, Hei00a, Pri02] [Rau04]

Tab. 2.5: *Capability for application practice*

Ability to automate the measuring procedure		
easy	middle	complicated
[Alt04, Ble01, Den04] [Hei00a, Hei03, Kos98] [Mar04, Rau01, Tak02] [Wav98, Zhu97, Zhu98]	[Bey02, Ble04, Bri06] [Chi02, Fas02, Faz06] [Jyw03, Rau04, Zou] [Wec00]	[Beh00, Cha02, Den04] [Gon00, Iha00, Kha99] [Ota00, Pri02, Ryu01] [Wam95, Zhu93, Zhu00]

Ability to integrate the calibration into the controller of the machine		
easy	middle	complicated
[Alt04, Ble01, Mar04] [Rau01, Tak02, Wec00] [Zhu98]	[Ble04, Chi02, Faz06] [Den04, Hei00a, Hei03] [Jyw03, Kos98, Ota00] [Zou, Wav98]	[Beh00, Bey02, Bri06] [Cha02, Den04, Gon00] [Iha00, Kha99, Pri02] [Rau04, Ryu01, Wam95] [Zhu93, Zhu97, Zhu00]

Tab. 2.6*: Efficient possibility of automation*

Notation	**Technical performance**	**Economical aspect**
● ○ ○ (1/3)	Poor accuracy improvement or no measurements made	High–cost device / complicated measurements
● ● ○ (2/3)	Good accuracy approvement on certain areas, but not representing the entire workspace	Middle-cost device / effort on installing
● ● ● (3/3)	Good accuracy improvement in broad area of the workspace	Low-cost device / easy to install / short measuring time

Tab. 2.7*: Notations used for the overall valuation of the calibration approaches*

Calibration Approach	Technical Perform.	Economical Aspect	Overall valuation benchmark [%]		
			Not weighted	Technic. weighted	Economic. weighted
[Alt04]	●●●	●○○	70	80	50
[Beh00]	●●○	●○○	50	60	40
[Bey02]	●●●	●●○	80	90	80
[Ble01]	●●●	●○○	70	80	50
[Ble04]	●●●	●○○	70	80	50
[Bri06]	●●○	●●○	70	70	70
[Cha02]	●●○	●○○	50	60	40
[Chi02]	●○○	●●●	70	50	80
[Den04]	●●○	●●●	80	80	90
[Fas02]	●●○	●●○	70	70	70
[Faz06]	●●●	●○○	70	80	50
[Gon00]	●●●	●○○	70	80	50
[Hei00a]	●●●	●○○	70	80	50
[Hei03]	●●○	●●●	80	80	90
[Iha00]	●●○	●●●	80	80	90
[Jyw03]	●○○	●●○	50	40	60
[Kha99]	●●○	●●●	80	80	90
[Kos98]	●●○	●○○	50	60	40
[Mar04]	●●○	●●●	80	80	90
[Ota00]	●●○	●●●	80	80	90
[Pri02]	●●●	●○○	70	80	50
[Rau01]	●●○	●●●	80	80	90
[Rau04]	●●●	●●○	80	90	80
[Ryu01]	●○○	●●●	70	50	80
[Tak02]	●●○	●●●	80	80	90
[Wam95]	●○○	●●●	70	50	80
[Wav98]	●○○	●○○	30	30	30
[Wec00]	●●○	●○○	50	60	40
[Zhu93]	●○○	●●●	70	50	80
[Zhu97]	●●○	●●○	70	70	70
[Zhu98]	●○○	●○○	30	30	30
[Zhu00]	●○○	●○○	30	30	30
[Zou]	●●○	●●○	70	70	70

***Tab. 2.8**: Overall valuation of the calibration approaches*

The valuation has been carried out on the base of the demands on various concepts (Tab. 2.9):

- High demands on technical performance

  Technically weighted benchmark
- Low-cost (e.g. simple design)

  Economically weighted benchmark
- For general purpose

  Not weighted

Analyzed aspect	**Not weighted**	**Technically weighted**	**Economically weighted**
Technical performance	50 %	70 %	30 %
Economical aspect	50 %	30 %	70 %

Tab. 2.9: *Weighted performances*

From the analyzed overall valuation of the actual approaches seen in the Tab. 2.8 can be found a decision on choosing the suitable calibration procedure considering the different demands and goals:

- **High demands on technical performance**

  The following approaches can be considered for a high–end calibration (technically weighted benchmark > 80 %): [Alt04, Bey02, Ble01, Ble04, Faz06, Gon00, Hei00a, Pri02, Rau04]
- **Low-cost concept**

  For a calibration task, where the overall effort is limited by economical aspects (e.g. simple design concept), the following authors have developed the suitable concept (economically weighted benchmark > 80 %): [Chi02, Den04, Hei03, Iha00, Kha99, Mar04, Ota00, Rau01, Ryu01, Tak02, Wam95, Zhu93]

- **General purpose calibration**

  Some of the above mentioned calibration approaches can be used as well for multi–purpose mechanisms, particularly suitable are for this the proposals of the following authors (not weighted benchmark > 80 %): [Bey02, Den04, Hei03, Iha00, Kha99, Mar04, Ota00, Rau01, Rau04, Tak02]

A further valuation of the actual calibration approaches can be made by analyzing the desired applications on the hexapod 'Felix' at the IWM and formulating the advantages and drawbacks of the procedure to the given case. The deficits of the actual calibration procedures will be analyzed under considering the simple design concept and presented below.

2.8 Deficits

As seen in the analyzed literature, it is still hard to find a calibration approach which fits to the simple–design concept, their benefits are oriented mainly on well–defined application areas. Major disadvantages of the actual calibration approaches applied to the simple–design concept can be seen in the following points:

- **regard to non-kinematic influences**

  Analyzing the literature, it can be observed that a surprisingly reduced number of authors consider the active deformations of the manipulator structure (e.g. thermal or elastic deformations) before the calibration. Trying to obtain geometrical measuring data from non–geometrical deformations will certainly limit the parameter identification and causes that the calibration is valid just for the tested environment under certain conditions [Jyw03, Wav98, Wec00].

- **local measurements**

  Most of the researchers make measurements in discrete points and optimize the single deviations of these data. In this way the measuring noise is partially or fully neglected and could have drastically influence on the obtained accuracy of the machine as observed by [Rau01, Zhu93, Zhu97].

- **qualification of the identification methods**

  An other aspect to mention is the use of improper optimization methods to identify the kinematic parameters of the structure. It is well-known that for a huge amount of unknowns the deterministic methods cannot fully optimize a non-linear system of equations, observed by [Iha00, Mer00, Tak02, Wam95]. Even if the closed form solution exists, it is complex and difficult to work with. Usually only a partial (local) optimum is obtained which limits the achieved accuracy, demonstrated by [Osy02].

- **accuracy in the workspace**

  The good discussed results in accuracy refer mostly to a special part of the working area. This part is usually in the supposed middle of the manipulator's workspace and reflects an extremely reduced working volume. No information is available about the accuracy in the rest of the workspace, which is usually the larger part. The inaccuracy of the manipulator, when this moves in its work area, is generally fully neglected.

- **the economical aspect of the calibration**

  In spite that the obtained accuracy by some calibration approaches could be satisfying for the analyzed prototype, an industrial application wont be followed in the practice because their ineffectual economical aspect [Gro00c]. That means, the global effort on the calibration (e.g. the cost of the measuring system, invested time, etc.) is not justified for the planed application on the robot. This is especially valid in case of the applications in the small and medium enterprises (SME).

Even though numerous publications present different kinds of calibration procedures, the process of calibration is not yet fully understood. As [Alt04] recognized, it can be said that the dissatisfying accuracy of the PKM is still a problem and is one of the main barriers, preventing this machine concept from finding acceptance in practice. From an economical point of view, following the simple–design concept, beside the simple mechanical construction, obviously the correction and error compensation effort has to be situated in the low–cost area, too. That means, simple measuring system, possibly short time of the measuring process and parameter identification has to be in foreground by choosing the suitable calibration procedure [Gro04, Tak02].

The next chapter formulates the objectives of the actual work with the limitations and main steps of the proposed calibration procedure.

3 Proposed Objectives

3.1 Objectives

The objectives of this work are based on the deficits mentioned above under the special requirements due to the circumstances of the simple design–concept. Considering this concept, this work means to embrace the merits and overcome the shortages of the actual calibration approaches. Here the six motion DOFs of the hexapod are used for correction through the functionality of the controller. The main goal consists in:

Obtaining the basics for an automated kinematic calibration procedure which works efficiently, quickly, effectively and possibly low–cost, all–in–one economically applied to the parallel kinematics machines.

An exemplary measurement means to demonstrate the validity of the procedure it will be made on the simple design hexapod at the IWM.

3.2 Limitations

This work deals with 6 DOF parallel kinematics while permits to make – theoretically speaking – a fully kinematical correction of the 6 DOF error of the TCP. With this a transparent and easy–to–test calibration method will be guaranteed.

Because the stipulated economical aspect, the simple design construction is analyzed and the measurements are made on the hexapod developed at the IWM. The results and the main steps of the method can be easily applied to other parallel kinematics structures.

Following the demands on the calibration procedure from above, the limits and boundary conditions of this work can be formulated as follow:

- Non–kinematic shares of the error (e.g. elastic or thermal deformations) are not subject of this work. They are considered to be previously model–based corrected [Gro02a, Kau06]. The actual work presumes the efficiency of these methods and bases the further experiments on the already corrected measurement values.
- The kinematic calibration is based on simulations through an existing kinematical model of the structure [Gro00b, Gro01a, Gro02e, Gro02f, Kau06]. Numerical errors or inaccuracies of the computer model are neglected here.
- Random (not reproducible) errors of the physical structure (e.g. backlash of the joints, stick–and–slip in the struts) are considered only in the limits of the data acquisition during the measurements but not discussed deeply here. Generally they are considered not be able to be corrected at all [Mer06].

3.3 Procedure

This work presents a systematic approach of the calibration problem. The main concept of the calibration can be seen in the Fig. 3.1.

The objectives will be achieved by approaching the problem systematically and taking step by step the necessary measurements and conclusions respectively. Here the following points can be mentioned:

- Systematical analysis of the workspace to determine an optimal measuring procedure
- Measurements with automated data acquisition and evaluation
- Simulated measurements based on the kinematic model of the structure
- Identifying the kinematic parameters using efficient optimization algorithms

Considering the prerequisites presented in the chapter 2 (the concept of simple design, model based correcture of the non–geometrical error effects), the next chapter formulates the substance of the proposed objectives.

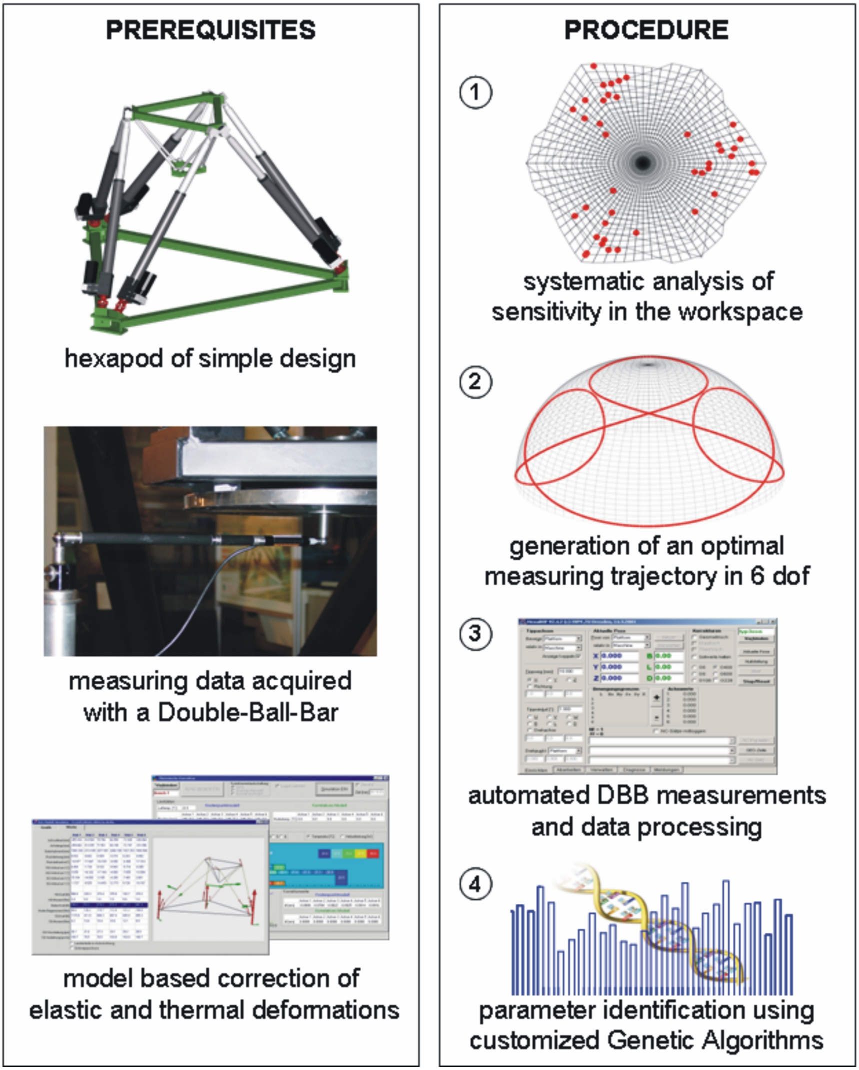


***Fig. 3.1**: Basics, objectives and procedure of the calibration*

4 Kinematic Calibration

In this chapter the calibration problem is discussed, a splitting down in sub–problems and a systematic way to solve the calibration will be proposed.

4.1 The Calibration Problem

4.1.1 The Role of the Kinematic Model in the Calibration Problem

In the literature the proposed calibration methods differ from each other regarding the use of the correction model. [Faz06] defines the following two methods to calibrate a given robot:

- **Model–based approaches**

  Here a corrected kinematic model or correction function has to be computed, establishing an analytical relationship between actuator co–ordinates and end–effector co–ordinates. This model has a given number of parameters directly or indirectly related to the geometry of the robot. In the calibration procedure these parameters are determined as a result of a numerical optimization of a properly defined error function.

- **Non–model–based approaches**

  In this case the relationship between actuator and end-effector co–ordinates is a pure numerical correspondence. This correspondence can be obtained either by using spline interpolation (Space Error Compensation) or by means of neural networks, without any physical knowledge on the possible causes of inaccuracy.

The non–model–based approaches use mainly a complete measurement of the working space with sophisticated measurements to create an exhaustive map of the pose error [Faz06]. The limits of using such measuring instruments due to the calibration outlay will be discussed later. Moreover, data provided by high–precision measurement devices (in particular interferometers) are strongly influenced by environmental perturbations, in particular temperature variations [Faz06].

The model–based approaches use for the calibration a kinematic model. The set of unknown parameter is estimated via measurements and a parameter identification algorithm. As [Boy06] describes, every part of these "ingredients" affects the result of the calibration. The kinematic model means mathematical transformations and includes the forward kinematic transformation and the inverse kinematic transformation. It represents the relation between the driven joint coordinates and the world coordinates of the manipulator.

The kinematic model has a central role in the control and correction of parallel kinematic machines (Fig. 4.1). It is implemented and used in the:

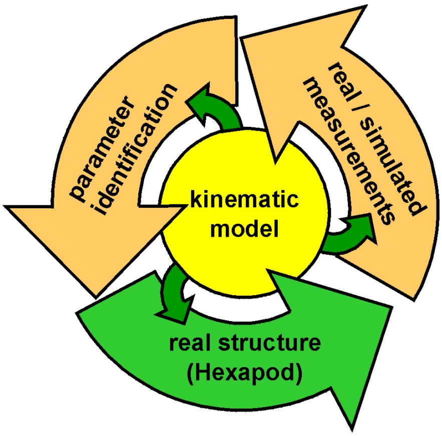


Fig. 4.1: *The role of the kinematic model in the calibration problem*

- **Controller of the real structure**

  The volumetric accuracy of the hexapod depends on how accurate the controller model describes the real kinematic behavior of the machine.

- **Simulated measurements**

  Simulated measurements can be processed through the kinematic model of the hexapod using the advantages of the computing speed of the nowadays technique and assuring a repeatably measurement without noise. The measurement is done as a difference between the pose computed for an ideal and a modified parameter set [Kau06].

- **Parameter identification**

  The identification of the kinematic parameters is realized using non–linear optimization procedures which base on the real measurements (kinematic model on the controller of the real structure) and on the simulated measurements (simulated parameter set on the kinematic model).

4.1.2 The Calibration and their Sub-Problems

In comparison with the serial kinematics, the kinematic parameters of a PKM have to be considered as an integral problem. Separate calibration of single parameters – commonly used by serial manipulators – is not possible [Boy06]. By now many different calibration methods and algorithms have been introduced, they vary in the number of measured degrees of freedom, the reachable measurement accuracy, the number of possible measurement poses, the complexity of the kinematic model and the method used to estimate the unknown parameters. Although a systematic approach of the problematic is still very poor.

The actual work means to find an order and a hierarchy structure of the calibration problem, to split up into sub–problems and to present a systematic way to approach the solution. Fig. 4.2 means to show a possible structure of a general calibration approach and to mark the interdependencies and influences of the chosen method/instrument on the global problem.

The model based measurement means to gain pose information of the real structure by using the measuring model and by obtaining the measuring data set as base for the parameter identification. From this meaning, the calibration problem can be split up into the following sub–problems:

- **The real structure**

  A detailed description of the real structure – in this case the hexapod of simple design – can be found in [Gro00a] and [Kau06], the key features have been already summarized in the chapter 2. The main properties can be seen here in the:

  - *Kinematic behavior* of the real structure: reducing the kinematic errors consists the subject of the actual work and is made through identifying the kinematic parameters.

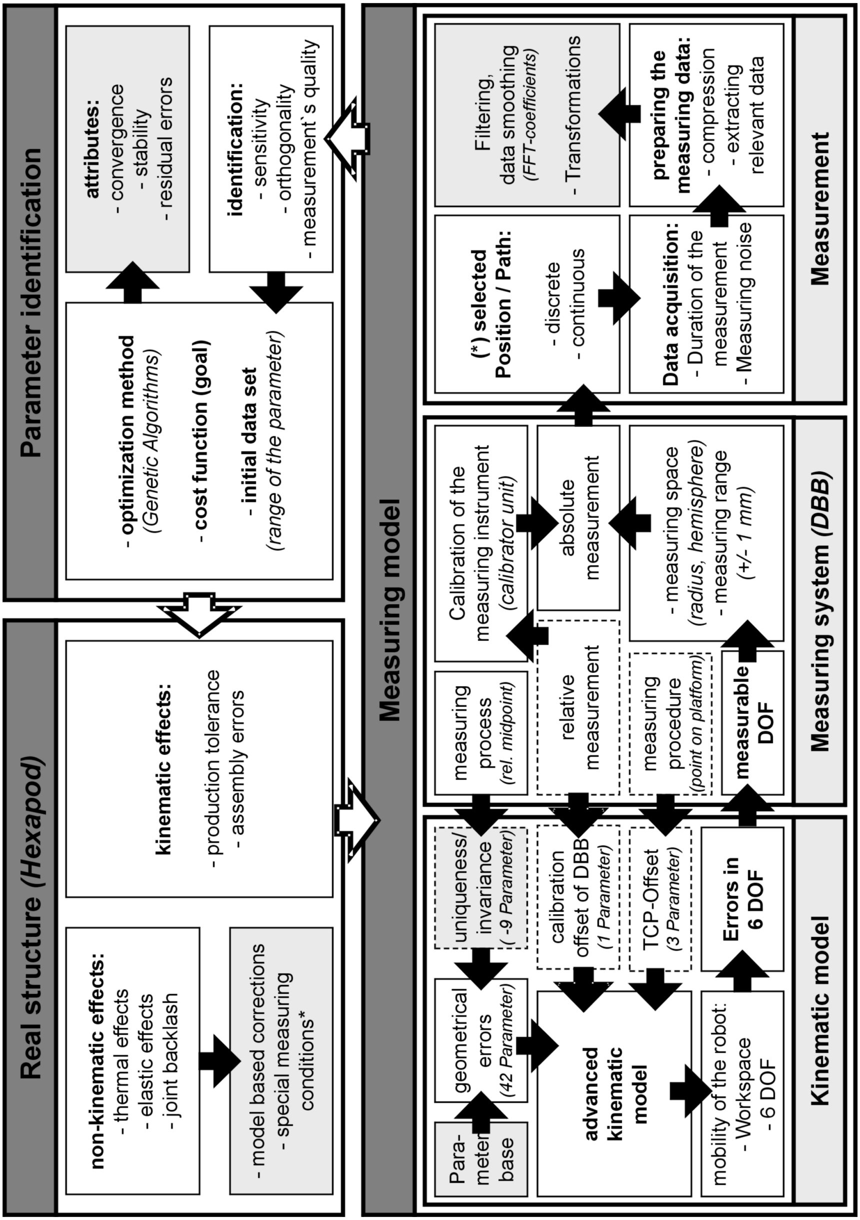


Fig. 4.2: The calibration problem

  - *Non–kinematic behavior:* the elastic and thermal effects have been widely model–based reduced by [Kau06].
  - *Residual non–kinematic effects:* they are shares of the errors not corrected due to limits of the technical outlay or from economical considerations. Special measuring conditions have to be applied to minimize these effects, they will be discussed in the chapter 4.3.4.

- **Measuring model**

  The measuring model means to gain measurement data of the hexapod through real and simulated measurements to evaluate the accuracy of the structure, discussed in chapter 4.2. The main components are here the:

  - *Kinematic model:* is a simplified image of the real structure including only the relevant mathematical transformations and parameters of the hexapod of simple design. The geometric (kinematic) errors are transformed into 6 DOF pose deviations expressed in position and orientation uncertainties of the end–effector. Here the forward (direct) kinematic transformation of the manipulator will be used.
  - *Measuring system:* The choice of a measuring system has consequences on planning the measuring procedure, including additional parameters in the kinematic model and processing the measuring data. An adequate measuring instrument under the given circumstances can be seen in the Double–Ball–Bar, discussed in chapter 4.3.2.
  - *The measurement:* In order to prepare the measurement, systematic analysis of the manipulator's workspace have to be made under the conditions given by the Double–Ball–Bar. Suitable measuring path and measuring conditions have to be found as discussed in the chapter 4.4. Finally the measurement will be done and the obtained data are prepared for the parameter identification using data filtering and compression methods.

- **Parameter identification**

  The parameter identification happens on the base of the obtained measuring data through optimization procedures. A suitable optimization method for the problem must be found and a proper definition of the cost function has to be determined. The obtained quality of the parameter identification depends on:

– the character of the optimization procedure, discussed in the chapter 4.6.1.

– the convergence of the optimization method as presented in chapter 4.6.4.

– the character of the cost function and stability against measuring noise (including residual uncertainties due to uncorrected non–kinematic effects) as described in chapter 4.6.3

– the limitations due to the calibration outlay, analyzed in chapter 4.6.5.

4.2 Model Based Measurement

The measuring model, as kernel of the model based measurement includes the:

- Kinematic model
- Measuring system, and the
- Measuring procedure

These three components can be analyzed separately, although, a fully separation from each other is not always possible due to the strong interdependencies – e.g. the measurement depends on the chosen measuring instrument or the measuring system has impact on the kinematic model – as seen in Fig. 4.2.

4.2.1 Ideal and Extended Kinematic Model

For error analysis and amplification [Pott04] as well as for the calibration of PKMs it is needed to analyze the impact of geometrical errors which emerge on the TCP from manufacturing and assembly tolerances. An ideal kinematic model neglects the tolerance uncertainties of the components. To involve the effects of these errors, an extended kinematic model has been developed for hexapod 'Felix' at the IWM of TU Dresden by [Kau06] (Fig. 4.3).

The extended kinematic model means to establish the impact of the kinematic parameter including the geometrical errors/tolerances on the pose accuracy of the manipulator. This mathematical transformation set includes the forward and the inverse kinematic problem of the hexapod to

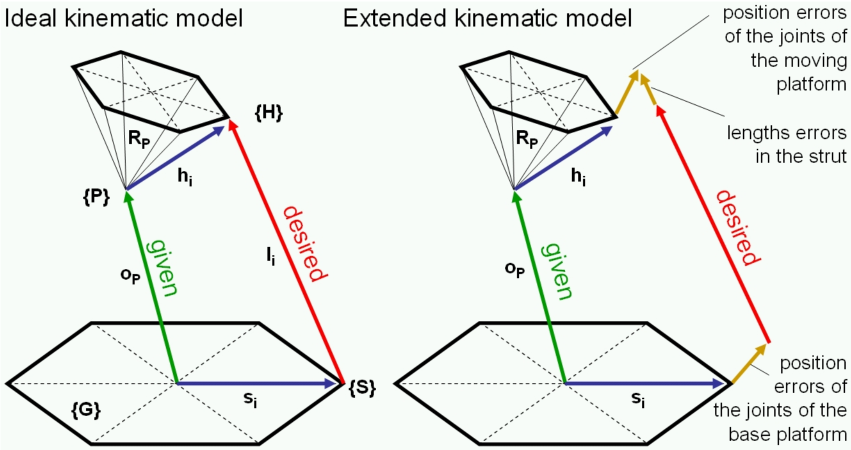


Fig. 4.3: Ideal and extended kinematic model of the hexapod 'Felix' [Kau06]

compute the relation between the error parameter of the hexapod and the errors measured on the TCP.

4.2.2 Error Parameters

As the elasto–static and thermal influences are considered already corrected [Kau06], the subject of this work is limited to the analysis of the geometric/kinematic error parameters of the hexapod. They are caused mostly by the manufacturing uncertainty and assembly tolerances of the physical structure [Gro00a]. The unknown parameters in case of a hexapod are derived from (see Fig. 4.4):

- **Kinematic structure**

  There are the standard kinematic error parameters of the hexapod, like the position uncertainty of the joints on the base (3 x 6 parameter) and the moving platform (another 3 x 6 parameter) and the lengths uncertainty (offset) of the struts (6 parameter), summing 42 unknowns.

- **Measuring procedure**

  Beside the standard kinematic parameters of the hexapod, there are other unknowns derived from the measuring technique (measuring procedure). As an example, in case of a measurement with the Double–Ball-Bar, the unknown are the offset of the measuring point on the moving platform (3 parameters). To assure a correct parameter estimation, these unknowns have to be determined at the same time with the kinematic parameters within the calibration procedure.

- **Measuring instrument**

  Other unknowns are result of choosing the measuring instrument. As the standard Double–Ball–Bar measures a relative deviation value, for an absolute measurement with the instrument the offset to the nominal length is needed (1 parameter). This offset can be directly measured by using a *calibration unit* [Ren]. If this is not available on the required length, the unknown parameter has to be additionally included in the parameter estimation procedure.

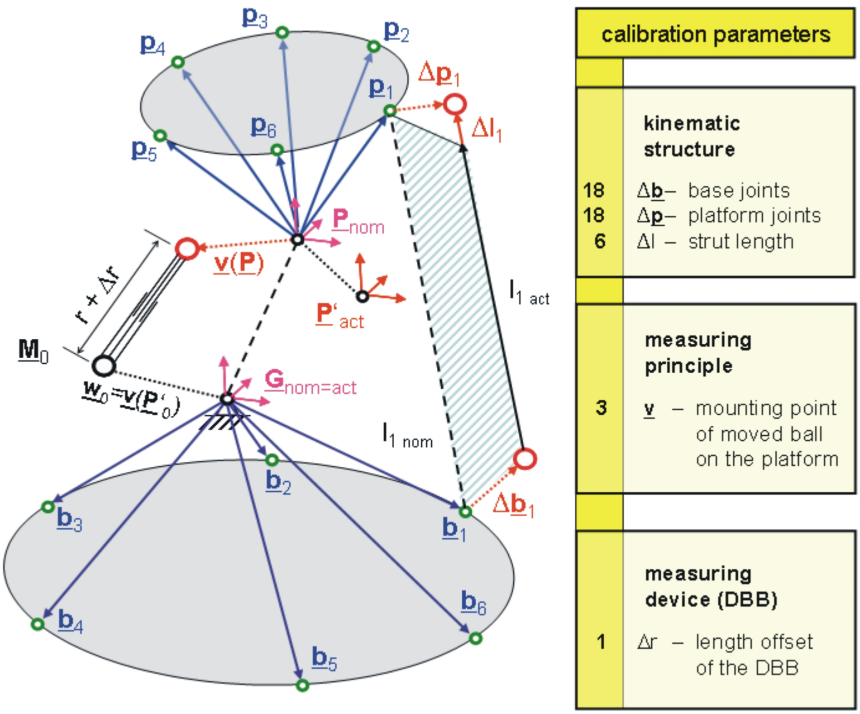


Fig. 4.4: Parameters of the calibration problem

The mentioned parameters are defined in the global co–ordinate system of the hexapod. The choice of the reference system has impact on the parameter identification, this alternative will be discussed later by analyzing the orthogonality of the parameters. Furthermore, the identification of these parameters is conditioned by the invariance of the measurement to the reference system of the kinematic parameters.

4.2.3 Invariance of the Kinematic Parameters

When speaking about invariance of the kinematic parameters in this work, it will be meant the uniqueness of the measurement at the end–effector to the kinematic parameters of the structure. With other words the following question is put:

Does a given set of kinematic parameters cause a unique measurement data set?

Or vice–versa:

Can be the kinematic parameters uniquely identified through a given measurement data set?

Especially this last question plays an important role in determining the identifiable parameters through the calibration. In case of the hexapod of simple design at IWM, the invariance has been discussed by [Mös06] considering measurements with the Double–Ball-Bar. As shown here, the statement of the problem depends on the kinematic configuration of the structure and the character of the processed measurements (e.g. measuring system and measuring procedure).

[Mös06] formulates and demonstrates a lemma departing from the following considerations:

Let be the standard kinematic parameters of the hexapod as the:

- position deviation of the joints on the base $\mathbf{Z}_{Si} \in \Re^3$
- position deviation of the joints on the moving platform $\mathbf{Z}_{Hi} \in \Re^3$
- lengths offset of the struts $\mathbf{Z}_{li} \in \Re$

where: i=1…6

This standard error set is summing 42 parameters, as discussed above, and comprised in a vector $\mathbf{Z} \in \Re^{42}$

Lemma: *Through the calibration of the hexapod of simple design using measurements with the Double–Ball–Bar, there are only 36 of 42 parameters identifiable.*

Proof: Let $\mathbf{G}^*$ be a simplified base coordinate system with origin in one of the base joints (e.g. S_1) and $\mathbf{P}^*$ a simplified platform coordinate system with origin in a platform joint (e.g. P_1) and let the struts be parallel to $\mathbf{G}$ respectively $\mathbf{P}$. Let $\mathbf{Z} \in \Re^{42}$ and $\mathbf{Z}^* \in \Re^{36}$ be the set of kinematic parameters which define one and the same hexapod, each in their own system. Through choosing $\mathbf{G}^*$ or $\mathbf{P}^*$, some elements of $\mathbf{Z}^*$ will be null). For $\mathbf{Y} \in \Re^6$ constant strut lengths [Mös06] has proved that in the poses $\mathbf{X} = g(\mathbf{Y}, \mathbf{Z})$ and $\mathbf{X}^* = g(\mathbf{Y}, \mathbf{Z}^*)$ is valid:

$$\mathbf{X} = \mathbf{X}^* + \begin{pmatrix} {}^G\mathbf{R}_P \cdot {}^P\mathbf{H}_l - {}^G\mathbf{S}_l \\ 0 \end{pmatrix} . \tag{4.1}$$

By the calibration the distance between $\mathbf{H}_7$ and $\mathbf{S}_7$ will be measured. [Mös06] has proved furthermore that:

$$\left|{}^G\mathbf{S}_7 - {}^G\mathbf{H}_7(\mathbf{X})\right| = \left|{}^{G^*}\mathbf{S}_7 - {}^{G^*}\mathbf{H}_7(\mathbf{X}^*)\right| . \tag{4.2}$$

That means that the measurements of both systems (both using 36 or 42 parameter) are the same. As the goal of the calibration is to determine from the measured data the set of kinematic parameters, in consequence through a measurement only 36 parameters can be identified.

The rest of 9 parameters, which can not be identified related to [Mös06], comes from:

- the position and orientation of an arbitrary situated simplified base coordinates system (6 parameters)
- the orientation of an arbitrary situated platform co–ordinates system (3 parameters)

A further, detailed appreciation of the number of identifiable parameters will be presented in chapter 4.4.2 with the orthogonality analysis of the kinematic parameters by using simulated measurements.

4.2.4 Simulation of the Position Accuracy

Measurements, using a conventional measuring instrument, acquire superposed effects of the kinematic errors of the real structure and non–kinematic behavior of the system including measuring noise. These effects cannot be separated by using a real measuring instrument or hit the economical limit of the measurement due to cost– and time–intensive complex procedures. Hence, the identification and analysis of the uncertainty sources could be very difficult or nearly impossible by using a conventional measuring system.

An alternative solution to the real measurement could be seen in simulations implying a kinematic model of the structure. The main idea of the simulated measurements is to create an environment where the repeatability of the measurement and obtaining the 'clean' measuring data set can be guaranteed.

The simulated measurement uses the kinematic transformations through a kinematic model. From one hand, the inverse kinematic transformation is computed for the ideal pose with the nominal kinematic parameters (Fig. 4.5).

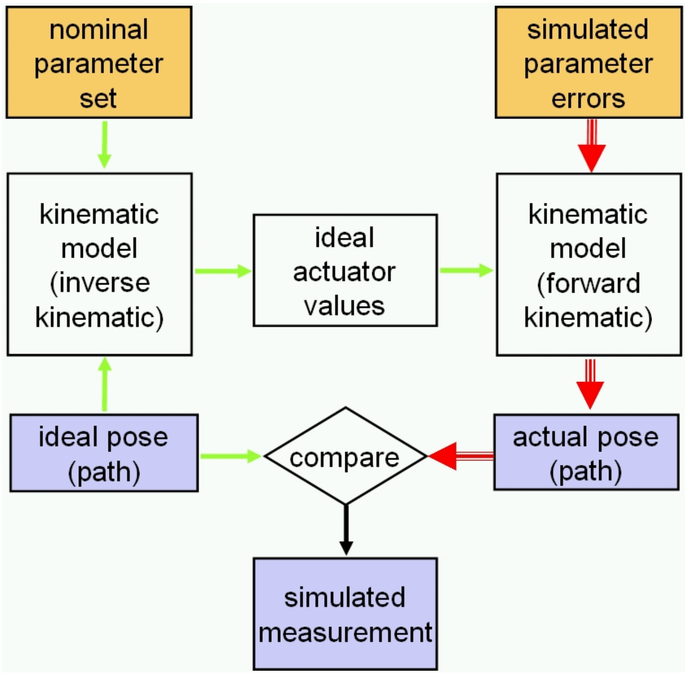


Fig. 4.5: *Simulated measurement*

On the other hand, the obtained ideal values of the actuators are re–transformed into pose information of the hexapod by using this time given deviation of the parameters (simulated parameter errors). The information obtained in this way is compared in 6 DOF with the appropriate ideal pose and their difference is considered to be a simulated pose measurement. The procedure can be repeated for a set of poses along a path.

The model based simulated measurement of the hexapod 'Felix' at the IWM ensures, beside obtaining the clean measuring data, the repeatability of the process, too. In this way the impact of pre–defined parameter errors can be arbitrarily analyzed separate from the undesirable effects and measuring uncertainty or measuring noise.

The software for the simulated measurement has been developed in MathCAD and has the following key features:

- Switch ON/OFF the compensation of the thermal effects (link to the thermal model)
- Switch ON/OFF the compensation of the elastic effects (link to the elastic model)
- Able to include the geometrical corrections from a previous measurement or estimation
- Repeatability of the experiments
- Arbitrary definition of the sampling rate by a measurement
- Speed of the measurement is incomparably faster as in the real case
- Measuring noise can be simulated but also completely neglected

4.3 Measuring Procedure

4.3.1 Demands on the Measuring System

It is of common knowledge that measurement results are never perfectly accurate. In practice the sources of systematic and random errors, which can affect the results of measurement, are numerous (even for the most careful operators). To describe this lack of perfection, the term *uncertainty* is used. Although the concept of uncertainty may be related to a *doubt*, in the real sense the knowledge of uncertainty implies increased confidence in the validity of results [Cen04, Gro06].

A rough distinction of the measurement methods can be drawn between one–dimensional and multi–dimensional measurement systems [Ble06]:

- **One–dimensional measurement system**

  One–dimensional measurement systems cover one degree of freedom. Well–known measurement systems include shaft encoders and linear scales working according to inductive, magnetic or photo–electric principles.

- **Multi–dimensional measurement system**

  Multi–dimensional measurement systems are combinations of conventional one–dimensional measuring instruments. The measurement uncertainty of the total measurement system is composed of the measurement uncertainties of the individual instruments. Hence, here the obtained measurement accuracy is always lower than by an one–dimensional system.

An example of the most used interferometric systems to perform one– and multi–dimensional measurements can be seen in Fig. 4.6.

Measurement of the complete pose (6 DOF) simplifies the identification process and requires fewer measuring points. But measuring just one coordinate is considerably simpler and causes less outlay of the measure-

***Fig. 4.6**: Example of one– and multi–dimensional laser measuring system [API07]*

ment (measuring and installation costs, personal qualification). Of course, the information density is significantly lower, therefore the identification process becomes more complex and more measuring points are necessary. Hence, the information level of a measurement must be compared with the required effort, the accuracy and the resolution of the measuring system. As well observed by [Den04], due to the interdependency of the calibration concept, an integrated view about the identification about the optimization of the measuring strategies is necessary.

Analogously to [Bey04], in the calibration mostly used measuring systems and their characteristics can be consolidated as seen in Tab. 4.1.

For sufficient accuracy of the machine tool, measurement systems are usually required to have measuring accuracy, which is one power of 10 higher, and resolution, which is two powers of 10 higher, according to [Ble06]. Here is also evaluated that a realistically aimed degree of accuracy of the machine tools is roughly $10\mu m$. Therefore, the measurement system should have a measurement accuracy of 1mm and a resolution of $0.1\mu m$ up to $0.5\mu m$, means the author.

measuring procedure	uncertainty [mm / °]	measuring principle	measuring time	Number of measurements needed to evaluate a pose	required qualification	providing and installation costs
Caliper	0,005 / 0,01	tactile / inductive	1/s	6	low	low
Theodolite	0,01 / --	optical	2/min	2	middle	middle
Ultrasonic measurement	0,2 / 0,5	acoustic	10/s	6	middle	middle
Cable winch	0,1 / --	optoelectronic	10/s	6	low	low
Double-Ball-Bar	0,001 / --	inductive	250/s	6	low	low
Interferometry	0,001 / --	optical	5000/s	2	high	high
Videometry	0,001 / --	optical	1/s	2	high	middle

Tab. 4.1: *Characteristics of the most used measuring systems*

Considering the simple design concept of the hexapod, the applicability criteria of the analyzed measuring systems can be embraced in the Tab. 4.2.

measuring system	resolution	providing and installation costs	required qualification	automat ability	robustness
Caliper	✓	✓	✓	✗	✓
Theodolite	✓	✗	✗	✓	✗
Ultrasonic measurement	✗	✓	✓	✓	✗
Cable winch	✗	✓	✓	✓	✓
Double-Ball-Bar	✓	✓	✓	✓	✓
Interferometry	✓	✗	✗	✓	✗
Videometry	✓	✓	✗	✓	✗

Tab. 4.2: *Applicability of the measuring systems to the simple design*

The measuring system, which fully fulfills the mentioned requirements, is the Double–Ball–Bar and it will be used further to gain the pose information needed for the calibration.

This list is sure not exhaustive, other authors have proposed customized measuring systems, prototypes which mean to measure a specified PKM under certain conditions [e.g. [Yua02, Bey02]. In the actual work it is considered that designing a prototype measuring instrument exceeds the measurement outlay of the simple design concept and will be not accepted here. For other circumstances the choice of the measuring instrument has to be reconsidered, although, the DBB permits very broad potentials in calibration, as mentioned by [Tak02] and [Fra06].

4.3.2 Double-Ball-Bar

The Double–Ball–Bar is a tactile lengths measuring system (Fig. 4.7). The measurement happens between the center points of two ball joints centered in magnetic cups with three–point holder (Fig. 4.8).

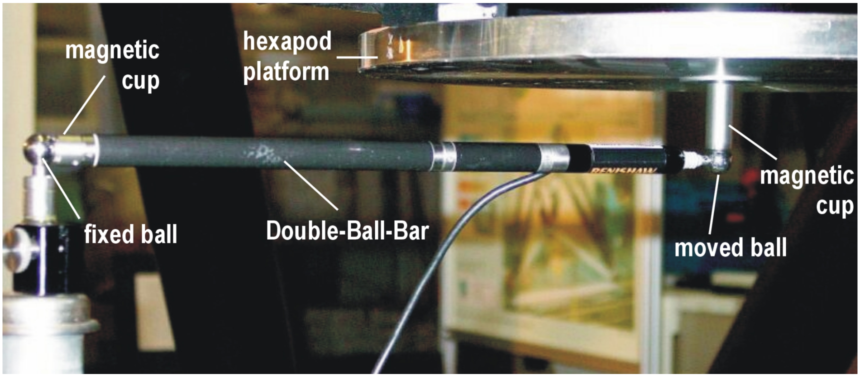


Fig. 4.7: *The the Double–Ball–Bar*

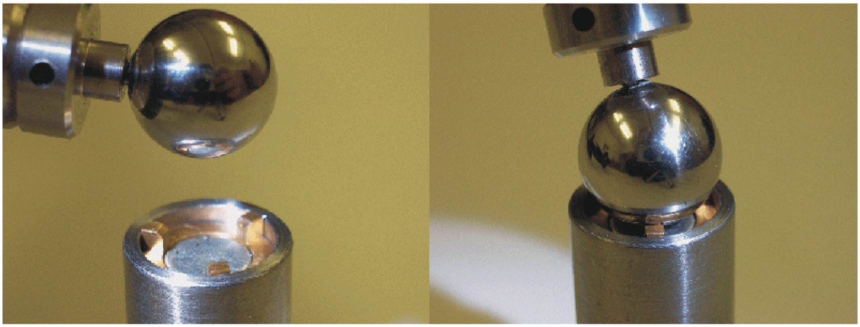


Fig. 4.8: *Magnetic cup with ball joint*

One of the magnetic cups is fixed (center mount) and gives the motion center of the instrument around a circle (or a sphere). The other magnetic cup at the opposite end will be connected to the machine (Fig. 4.9) – the radial difference between the both ball joints is measured.

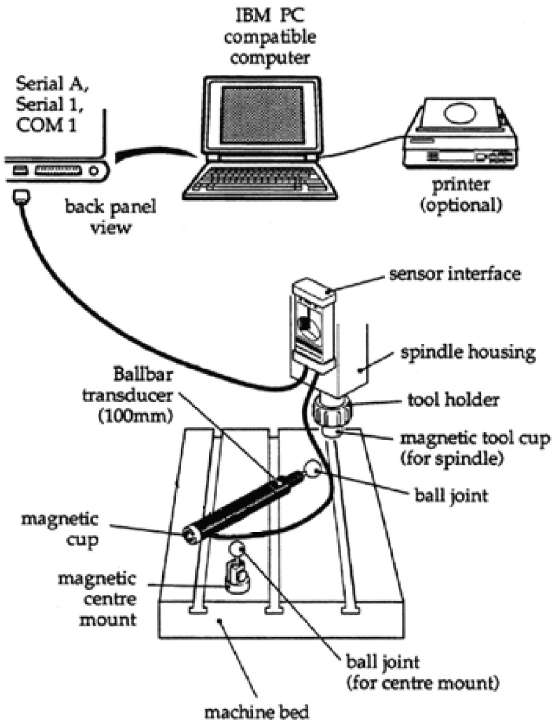


***Fig. 4.9**: Configuration of the Double-Ball-Bar system [Ren]*

The applied Double–Ball–Bar is a *QuickCheck QC10* produced by Renishaw. According to the producer the system specifications of the Ballbar transducer are presented in Tab. 4.3. Absolute radius can be measured by calibrating the measuring system (Fig. 4.10).

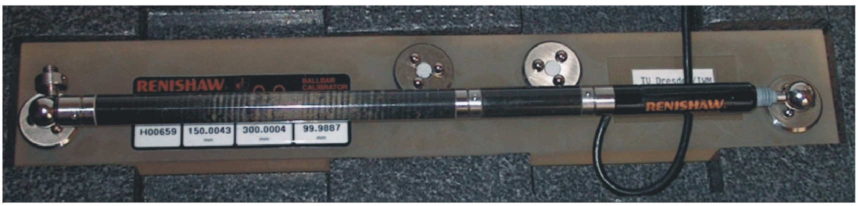


***Fig. 4.10**: Double–Ball–Bar and Zerodur © calibration unit*

Sample rate	250 samples/sec (maximum)
Nominal length	100 mm (between ball centers) 150, 300, 450 and 600 mm (with extension bar)
Stroke	-1.25 to +1.75 mm
Resolution	$0.1\mu m$
Measuring range	$\pm 1mm$
Accuracy	$\pm 0.5\mu m$ (at 20°C) $\pm(0.8\mu m + 0.4\%$ reading (0-40°C)

Tab. 4.3: *System specifications of the Double-Ball-Bar [Ren]*

The obtained accuracy is given by the summation of the relevant Calibrator accuracy presented in Tab. 4.4 and of the radial variation accuracy above.

To assure a suitable accuracy of the measurements under real circumstances, a very careful set–up of the Ballbar system is required.

Nominal length	**Tolerance**	**Calibration accuracy** (at 20°C)
100 mm	$\pm 50\mu m$	$\pm 1.0\mu m$
150 mm	$\pm 50\mu m$	$\pm 1.0\mu m$
300 mm	$\pm 50\mu m$	$\pm 1.5\mu m$

Tab. 4.4: *Calibration accuracy and nominal lengths of the Double–Ball–Bar [Ren]*

4.3.2.1 Setting up the Ballbar System

The Double–Ball–Bar system has to be set up very carefully, considering the following steps:

1. Load the magnetic tool cup into a suitable tool holder. Fit the tool holder to the spindle.
2. Move the machine to the co-ordinates where the center mount is to be located. The tool cup should be positioned that it has to be approximately 65 mm (2.5 inches) above the point on the machine bed where the center mount is to be located.
3. Slacken the knurled knob on the magnetic center mount to allow the ball joint to drop to the base of the center mount. Slide the center

mount under the tool cup. Visually align the center mount until it is directly underneath the tool cup in the spindle. Lift the ball joint up from the center mount until it snaps into the magnetic tool cup. Lightly tighten the knurled knob on the center mount to grip the ball joint (Fig. 4.11).

4. Define the current position of the machine as the origin (zero point) of the machine's axes (X, Y and Z).
5. Drive the machine to pull the tool cup up and away from the center mount ball joint, i.e. when calibrating the XY plane, drive the machine along its Z axis in the positive direction.
6. Move the machine toward the start point of the test (i.e. X 300.0, Y 0.0) and run the CNC–program to move along the defined circular path.

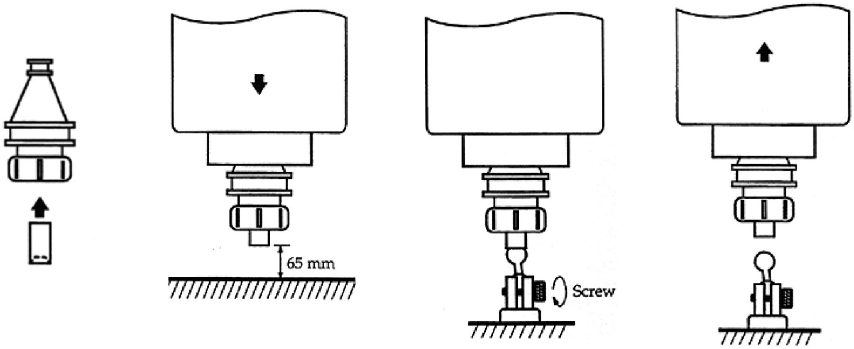


***Fig. 4.11**: Positioning the center mount on the machine [Ren]*

4.3.2.2 Limits and Consequences of Measuring with the Double–Ball–Bar

Measuring with the Double–Ball–Bar implies following limits and consequences to be considered:

- **incomplete pose measurement:** at a moment just a partial pose measurement, particularly one DOF (the length of the DBB) can be gained [Fra06]
- **the measuring direction** is constrained by the actual pose and the position of the center mount

- **relative position** of the center mount before and after calibration: after calibration a new position of the center mount (origin) has to be taken

Under the circumstances of these considerations a new measuring strategy has to be elaborated to capture the accuracy information of the manipulator.

4.3.3 Data Capture with the Double–Ball–Bar

The measurement with the Double-Ball-Bar has an integral character. That means, a completely set of measuring data has to be considered to evaluate the accuracy of the machine. Contrarily, a single measured value in 1 DOF contains very poor information about the accuracy behavior of the machine.

From the point of view of the work flow of a measurement, the measuring data can be captured using static measurements in a discrete number of points on a path or with continuous movement along the path.

4.3.3.1 Static Measurements

By static measurement the movement will be completely stopped at certain measuring points while data capture. There are principally three main steps while measuring one point:

1. Travel onto the desired pose
2. Wait to dying out (position stabilization)
3. Proceed the measurement

Advantages of this method are the clean tracking of the measured data and that the measurement is free from the dynamical effects of the moving structure. The number of the discrete points will be chosen high enough to assure the information content of the path. A numerical method, to determine the minimal number of measuring points on a curve, is proposed by [Lin96]. On it, departing from a defined path, there are placed a number of measuring points that define a cubic spline. The maximal deviation from the origin path is analyzed and compared to the goal accuracy of the measurement as follow:

1. Establish the data points to be measured on the curve
2. Calculate the angle between the two normal directions of the two neighboring data points
3. Compare the relationship between this angle and the preset angle
4. Drawing the cubic spline curve made up of the obtained measuring points
5. Comparing the distance errors in the normal directions of the curve made up from data points, to be measured with that of the curve made up of the obtained measuring points
6. Comparing the maximum distance in the normal direction with the preset allowance error value

Measurements on the hexapod of simple design 'Felix' proved that the hexapod has a good positioning repeatability relative to the reversal error of the structure (Fig. 4.12). A good repeatability means a low positioning uncertainty by measuring in one defined point approaching n–times from one and the same direction. Reversal errors occur by approaching the measuring point from other (e.g. opposite) directions.

The repeatability of the structure depends on the properties of the mechanical structure and the performance of the controller [Elb06].

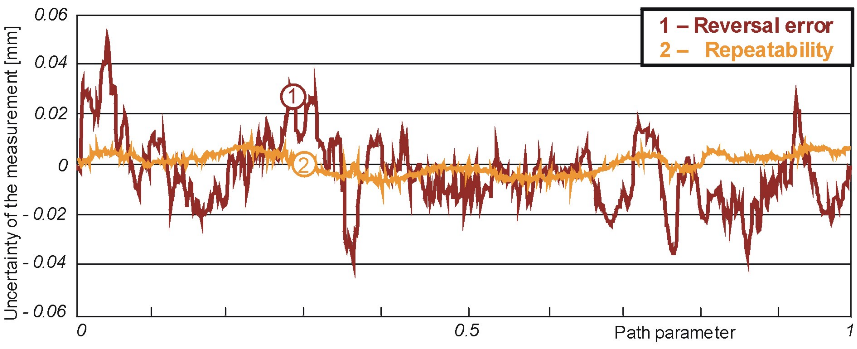


Fig. 4.12: *Reversal errors and the repeatability of the measurement*

An excellent repeatability encourages for a continues path measurement – without stop in each measuring point.

4.3.3.2 Continuous Measurement

The DBB permits a high rate data capture, therewith data capture without stopping in the measuring points. The measurement can be made continuously, decreasing drastically the measuring time. The motion of the machine has to be kept constant along the path and the use of an overshoot is advised (Fig. 4.13).

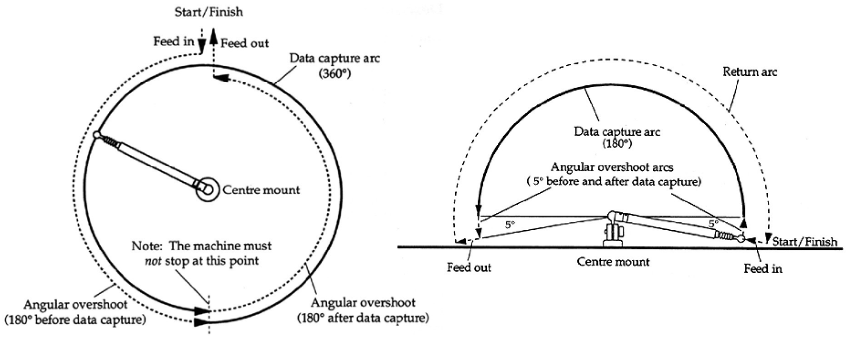


Fig. 4.13: *Data capture with the Double-Ball-Bar [Ren]*

To guarantee the correctness of the measured data respectively the synchronization between the data acquisition and the planed motion along the measuring path, the controller facility has to be used. The controller allows defining a constant velocity along the path and not depends from the number of the reference points [Kau06]. From the other side the measuring rate of the device (DBB) with 250 samples/sec is known [Ren]. In this way the synchronization between the measured data and the position of the end–effector along the path is assured.

By a continuous measurement some side effects due to the machine's movement have to be considered. Although, a full correction of these error influences is not subject of the actual work, these effects have to be avoided in the limits of obtaining a useful measurement data set. Fig. 4.14 and Tab. 4.5 shows how the measurement uncertainty depends on the travel speed of the platform.

On the one hand, a high–speed measurement is desired to reduce the measuring time. On the other hand the measuring uncertainty increases with the traveling velocity and cause inaccurate measurements. Optimal measuring velocity from these two points of view can be formulated as:

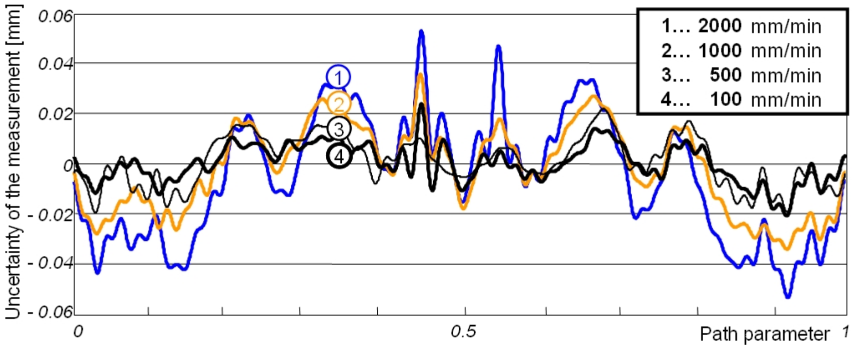


***Fig. 4.14**: The measurement speed vs. measuring uncertainty*

Measurement speed $[mm/min]$	2000	1000	500	100	0 (static measurements in discrete points)
Uncertainty of the measurement $[\mu m]$	54	36	22	22	15

***Tab. 4.5**: Measuring uncertainty due to the measurement speed*

- **Time–optimal solution:** high speed for a quick measurement
- **Minimum uncertainty of the measurement:** quasi–static motion (low speed)

A compromise between this two opponent aspects can be found by determining the maximum speed of the motion where the accuracy keeps at the feasible limits. The upper limit of the accuracy can be seen in the positioning repeatability of the structure ($10 - 15\mu m$), as discussed above. Therefore a suitable speed of the measurement (where the dynamical effects are reduced at minimum) for the hexapod 'Felix' can be seen with quasi–static motion by at most 500 mm/min path velocity.

In order to minimize the undesired effects during the continuous measurement, special measuring conditions have to be used.

4.3.4 Special Measuring Conditions

The measuring uncertainty is determined further by other influences which permanent correction is not subject of the actual work. Nevertheless, they have to be taken into consideration during the measuring procedure to minimize their effect on the measuring data. Here can be mentioned residual influences due to:

- Dynamical effects of the machine
- Inaccuracy of the control system
- Uncorrected elastic errors
- Backlash of the joints
- Stick–slip effects on the struts

To minimize the influence of these residual effects, the following conditions have to be applied during the measurement, as seen in the Tab. 4.6.

Residual error influences	**Adapted measures**
• Dynamical effects of the machine • Inaccuracy of the control system • Residual elastic errors	Static measurement or slow traveling speed during the continuous measurement
• Backlash of the joints • Stick-Slip effects	Mean value of forward/backward measurements

Tab. 4.6: *Influences of the residual errors and adapted measures*

4.4 Planning the Measuring Path

To determine the measuring path, a well–organized systematic analysis of the error effects is needed. It is necessary to properly select a trajectory off–line which:

- Stays inside the workspace of the hexapod
- Is compatible with the actuator extrema
- Stays inside the measuring range of the measuring device
- It gains the required accuracy information over the workspace

The first two conditions are verified by the controller system of the hexapod, the second two has to be determined by the user. Below it will be shown that measurements over an arbitrary chosen path do not consist enough information to use for a practical parameter identification.

When given a circular measurement with the DBB in an XY–plane without inclining the platform, experiments demonstrate that some geometrical parameters of the hexapod (e.g. value on the Z–coordinate of the base respectively platform joint) have no influence on the measurement (see Fig. 4.15).

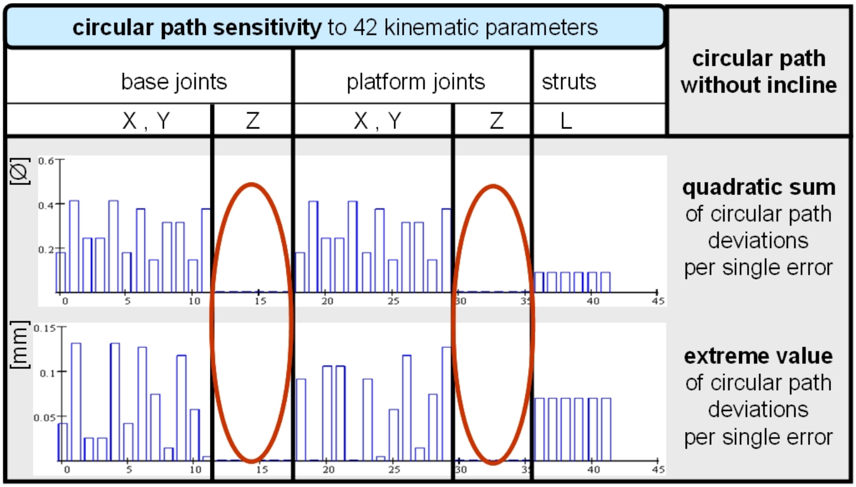


Fig. 4.15: *Effects of the kinematic parameters on a circular path without incline*

This phenomenon has been already analyzed in the literature by [Iha00] and observed by researcher like [Chi02, Fas02, Ota00]. The explanation is obvious: the measurement is made perpendicular to the direction of some parameters (in this case the Z–coordinate of the base joints). This fact shows us that such kind of measurement is not suitable for a kinematic calibration, because it cannot fully identify some of the geometrical parameters of the hexapod.

Fig. 4.16 shows that a plane measurement with non–perpendicular tool (platform with incline) permits the visualization of more kinematic parameters. It has to be mentioned, although, that the dimension of some of the observed values is quite low, the narrow differences to the measuring noise make difficult a clear–cut distinction between useful data and noise. Other researchers, confronted with the same problems, are e.g. [Iha00, Tak02].

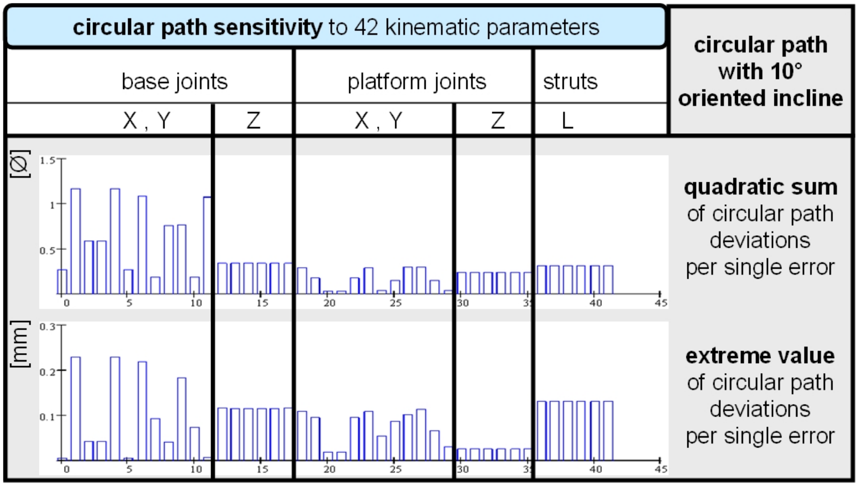


Fig. 4.16: Effect of the parameter on a circular path with a constant incline

For a sharp identification we need to obtain a 'better' set of measuring data. In order to get these data, a systematic approach to obtain a suitable measuring path will be analyzed. In the proposed method a two–step path optimization procedure is presented that is based on the:

- **Sensitivity analysis of the parameter in the workspace**

  Here the error propagation will be analyzed by the error parameters to the TCP.

- **Orthogonality analysis of the parameter**

  In this sense ortho-gonality means the independent effect of each parameter and it will be determined by comparing the sensitivities of all of the parameters.

4.4.1 Systematic Sensitivity Analysis Within the Workspace

The DBB does not permit only circulatory paths but any type of path on the surface of hemispheres, the degree of freedom while choosing a measurement path becomes obvious. This freedom can be deliberately used to increase the efficiency of the calibration procedure.

The construction of an 'ideal' measurement path for the use of the DBB has obviously a direct connection with the property of the kinematic system. This is in particular the sensitivity of the path deviations due to modified kinematic parameters which influences the cost function applied for the parameter identification. Important is here the significance of the criteria that are formulated to evaluate the path deviations, the design of the search technique, type, the parameterization and the control of the optimization procedure.

Determining an 'optimal' measuring path begins with finding the poses in the workspace where the TCP is most sensitive to the errors on the kinematic parameters. The most sensitive poses – where an elementary parameter maximal works – can be found with the following methods:

- **Statistical analysis of the error transmission**

  [Pott04] proposes a statistical method, where is assumed that the actual errors are Gaussian variables with a standard deviation proportional to their tolerance. While the changes in the parameters are small, the parameters are not correlated with each other and can be treated independently – relates the author. Thus, the total error is the sum of the single errors and an error propagation approach is used to calculate the variance of the TCP. This method is estimation-based and tolerates a broad spreading of the results.

- **Analyzing the Jacobian matrix and using iterative approximation methods**

  [Den04] claims a method where the influence of the kinematic parameters is analyzed through examining the Jacobian matrix of the manipulator. According to the author, the method allows the identification of singular and linear dependent parameters which will be eliminated from the calibration procedure, inasmuch can be seen more likely as an orthogonality consideration.

- **Nonlinear optimization procedures**

  Optimization procedures are a very robust tool in analyzing the effect of one or more parameters and the location in the workspace of their maximal propagation.

The actual work proposes a complete determination of the poses within the workspace which have the maximum sensitivity of the kinematic parameters measurable with the chosen measuring system. To find these poses nonlinear optimization, procedures are used with simulated measurements through the kinematic model of the hexapod. The effect of each prescribed elementary error is simulated and maximized (Fig. 4.17).

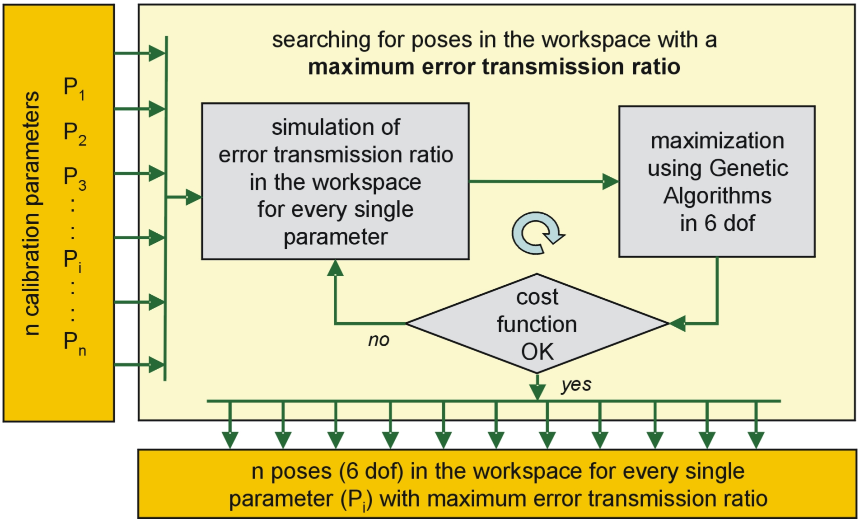


Fig. 4.17: *Searching for the most sensitive poses in the workspace*

The sensitive poses are searched in the 6 DOF workspace of the manipulator using genetic algorithms - the operation mode of the genetic algorithms will be presented later. In Fig. 4.18 a possibly found result of the poses can be seen within the workspace of the hexapod 'Felix'.

The orientation within the pose is defined by using the modified Euler angle B, L, D. The advantage of this convention is the better comprehensible illustration of the orientation angles through geographical representation as seen in Fig. 4.19.

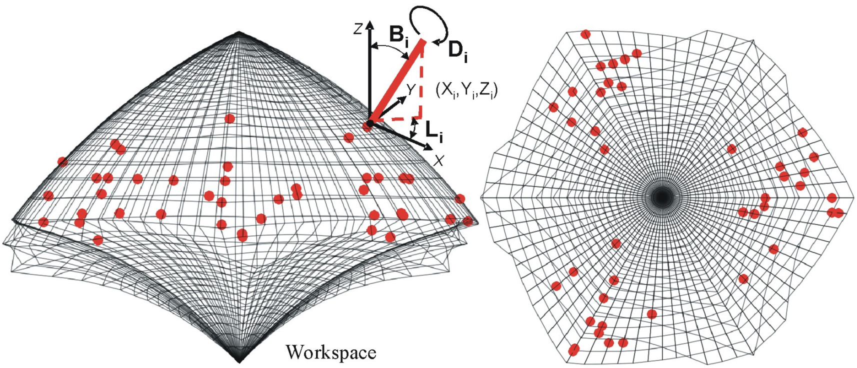


***Fig. 4.18**: Sensitivity analysis in the workspace*

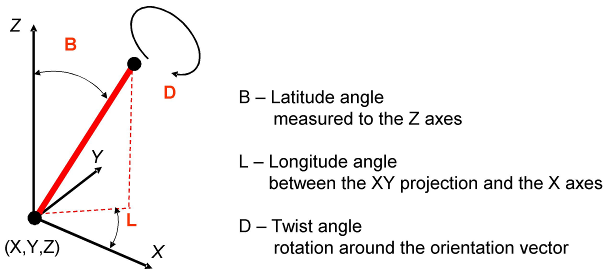


***Fig. 4.19**: Convention to represent the orientation through modified Euler angle*

It is observed that the most sensitive poses (measurable in the direction of the DBB) are symmetrically grouped – as expected – because of the symmetrical structure of the hexapod. In ideal case the measuring path should fit these tops, in practice, although, a fully ideal path through these determined poses can not be realized due to path planning problems like:

- **Constrains of the measuring instrument**

  The DBB has a constant nominal length; hence, the programmable path must be situated on a hemisphere within the manipulator's workspace.

- **Constraints from the measuring procedure**

  The path has to be continuously in order to guarantee an automatable measuring process.

- **Constraints from the controller of the hexapod**

  Steadiness and applicability of the velocity profile of the actuators has to be considered while planning the trajectory to obtain a smooth motion in order to prevent huge measuring noise due to undesirable dynamical behavior of the machine.

Applying these limitations, it is very difficult to generate automatically a path through the determined discrete poses in the workspace. A solution of the problem can be seen in approximating the poses with a path which fits as good as possible the regions where the most of the points are situated and effectuate an additional optimization step through the orientations along the path.

4.4.2 Orthogonality Analysis

The second optimization step is made by searching for the best possible orthogonality criterions of the parameters on the measuring path. Here the orientations (3 DOF) of the platform will be optimized along the measuring path on a hemispherical surface. Orthogonality means the independent effect of parameters and will be analyzed through the Jacobian matrix of the calibration problem (to not confound with the Jacobian of the kinematic transformation).

4.4.2.1 Jacobian Matrix of the Calibration

The calibration problem can be formulated as follows:

$$\mathbf{J}_{cal} \cdot \partial \mathbf{p} = \partial \mathbf{x} \; . \tag{4.3}$$

Where:

$\mathbf{J}_{cal}$ – the Jacobian matrix of the calibration problem
$\mathbf{p}$ – parameter set vector
$\mathbf{x}$ – measurement data set

$$\mathbf{J}_{cal} = \begin{bmatrix} \partial x_1/\partial p_1 & \partial x_1/\partial p_2 & \partial x_1/\partial p_3 & \ldots & \partial x_1/\partial p_n \\ \partial x_2/\partial p_1 & \partial x_2/\partial p_2 & \partial x_2/\partial p_3 & \ldots & \partial x_2/\partial p_n \\ \partial x_3/\partial p_1 & \partial x_3/\partial p_2 & \partial x_3/\partial p_3 & \ldots & \partial x_3/\partial p_n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \partial x_m/\partial p_1 & \partial x_m/\partial p_2 & \partial x_m/\partial p_3 & \ldots & \partial x_m/\partial p_n \end{bmatrix} \tag{4.4}$$

$$\text{with } \mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \vdots \\ p_n \end{bmatrix} \text{ and } \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{bmatrix}.$$

Each column of the Jacobian $\mathbf{J}_{cal}$ can be seen as a measurement with a parameter configuration set where only one of the parameters is different from zero ($p_n = 1$).

4.4.2.2 Orthogonality Matrix

To bear a physical meaning of its elements, the Jacobian matrix of the calibration can be normalized to represent the virtual angle between the effect of two parameters. The relation can be deduced from the equation of the scalar product of two vectors and results the orthogonality matrix $\mathbf{O} \in \Re^{m \times n}$ of the calibration problem:

$$o_{k,l} = \frac{|j_{cal}^{<k>} \cdot j_{cal}^{<l>}|}{|j_{cal}^{<k>}| \cdot |j_{cal}^{<l>}|} = \cos(\varphi_{k,l}) \; . \tag{4.5}$$

Where:

$k = 1 \cdots n$ and $l = 1 \cdots n$ with n= number of parameters

A "good" orthogonality between two certain parameters can be observed where the virtual angle between these is near to 90°, that means an independent impact on the measurement data. A "poor" orthogonality means respectively nearly parallel vectors, in this case the parameters are increasingly dependent (Fig. 4.20).

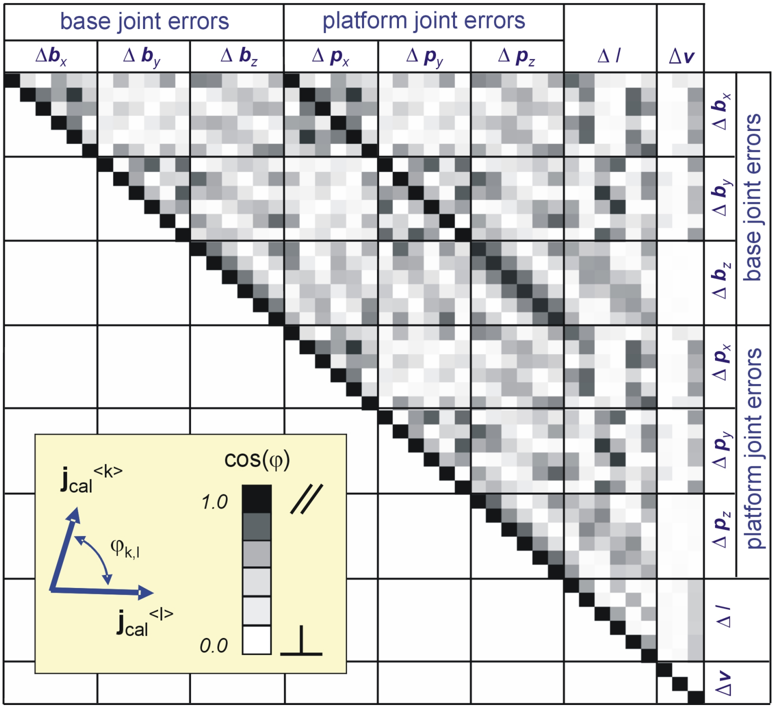


Fig. 4.20: *Orthogonality matrix to analyze the dependencies between parameters*

The notations used in the figure are:

Δb_x,Δb_y, Δb_z	– position deviation of the base joints on the base co–ordinate system from the nominal position
Δp_x,Δp_y, Δp_z	– position deviation of the moving (platform) joints on the platform co–ordinate system from the nominal position
Δl	– length offset of the 6 struts
Δv	– TCP–offset (x,y,z) in the platform co–ordinate system

In this sense the orthogonality matrix is symmetric to the main diagonal, for a better overview the bottom part will be fade out. The elements on the diagonal are the interdependencies between one and the same element (full interdependency). The interpretation of the orthogonality matrix can be seen in the Tab. 4.7.

Quality of the orthogonality factor	**Interdependency of the parameter**	**Physical inter-pretation**	**Value in the matrix**	**Color in the figure**
good	independent	$\varphi = 90^\circ$	$\cos\varphi = 0$	black
poor	dependent	$\varphi = 0^\circ$	$\cos\varphi = 1$	white

Tab. 4.7: *Interpretation of the orthogonality factor*

The elements of the orthogonality matrix depend on the measuring path (positions and orientations). A measurement along a random (not optimized) circular path involves an orthogonality matrix as seen in Fig. 4.21 (top side). On the bottom side of the figure is the orthogonality matrix of an optimized path, as described in the chapter 4.4.3.

4.4.2.3 Influence of the Parameter Co–ordinate System to the Orthogonality

The co–ordinate system, where the kinematic parameters are defined, has to be selected already by developing the kinematic model. Its impact on the parameter identification – although – will be seen first when the measuring procedure is known by analyzing the orthogonality of the parameter on the measuring path. If the measuring direction is near parallel with the direction of the pose error in the workspace of the specified parameter, the effect of this parameter can be comfortably measured (see also sensitivity analysis), a precondition to be identified. In contrary case an unfavorable measuring direction (co–ordinate definition) could cause a bad identification by the optimization. The influence of choosing the co–ordinate system can be analyzed also with computing and optimizing the orthogonality matrix under various conditions.

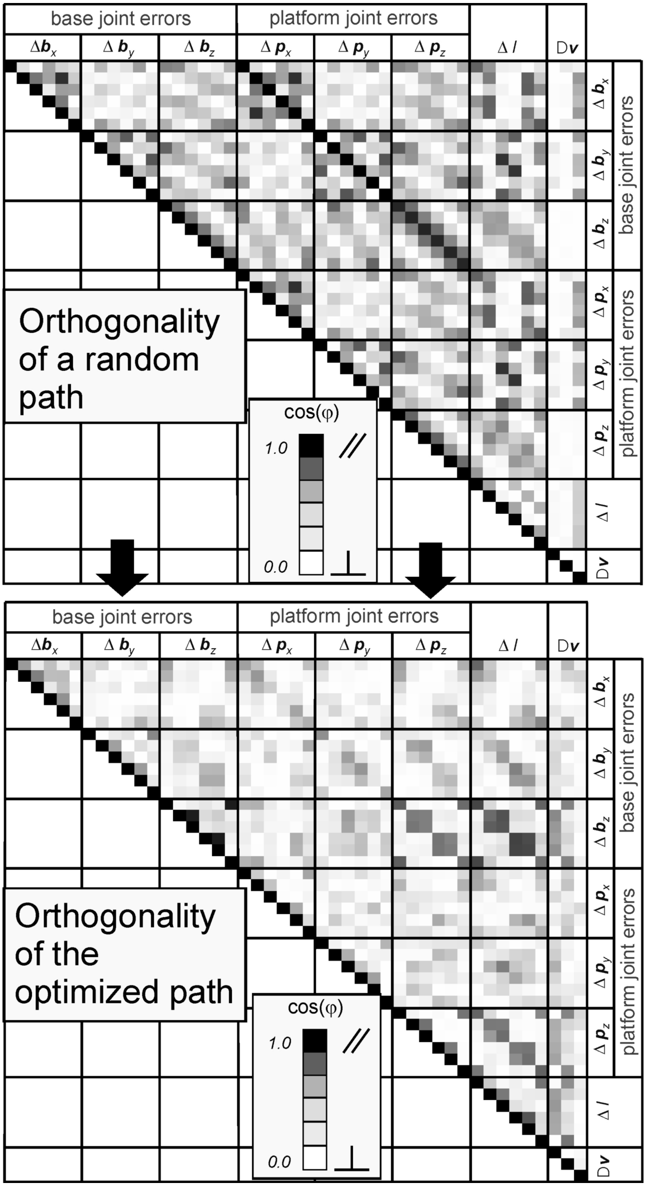


***Fig. 4.21**: Impact of the measuring path on the orthogonality*

A meaningful definition of the kinematic parameter can be seen in defining their work directions in cylindrical co–ordinates of the base and the moving platform respectively. This consideration comes from the symmetrical construction of the hexapod and attempts to obtain a symmetrical definition of the error effects, too.

With disclaim of an extensive systematic analysis in this work, finding a fully optimal frame to define the kinematic parameters could be subject of a further research analogously to other perspectives which will be presented in chapter 6.

The impact of the co–ordinate transformation on the orthogonality matrix is presented in Fig. 4.22. On the top of the figure the orthogonality matrix from the Cartesian definition of the kinematic parameters can be seen, on the bottom side the interdependencies (orthogonality matrix) of the parameters defined in a polar co–ordinate system as follows:

Δb_r – deviation of the base joints radial to the base circle
Δb_t – deviation of the base joints tangential to the base circle
Δb_z – deviation of the base joints along the Z–axes of the base

Δp_r – deviation of the platform joints radial to the platform circle
Δp_t – deviation of the platform joints tangential to the platform circle
Δp_z – deviation of the platform joints along the Z–axes of the moving platform

Δl – length offset of the 6 struts
Δv – TCP–offset (x,y,z) in the platform co–ordinate system

It can be easily observed by the last one that the worst-case dependencies of the parameters (black cells) are drastically reduced, therewith the number of the identifiable parameters has been increased.

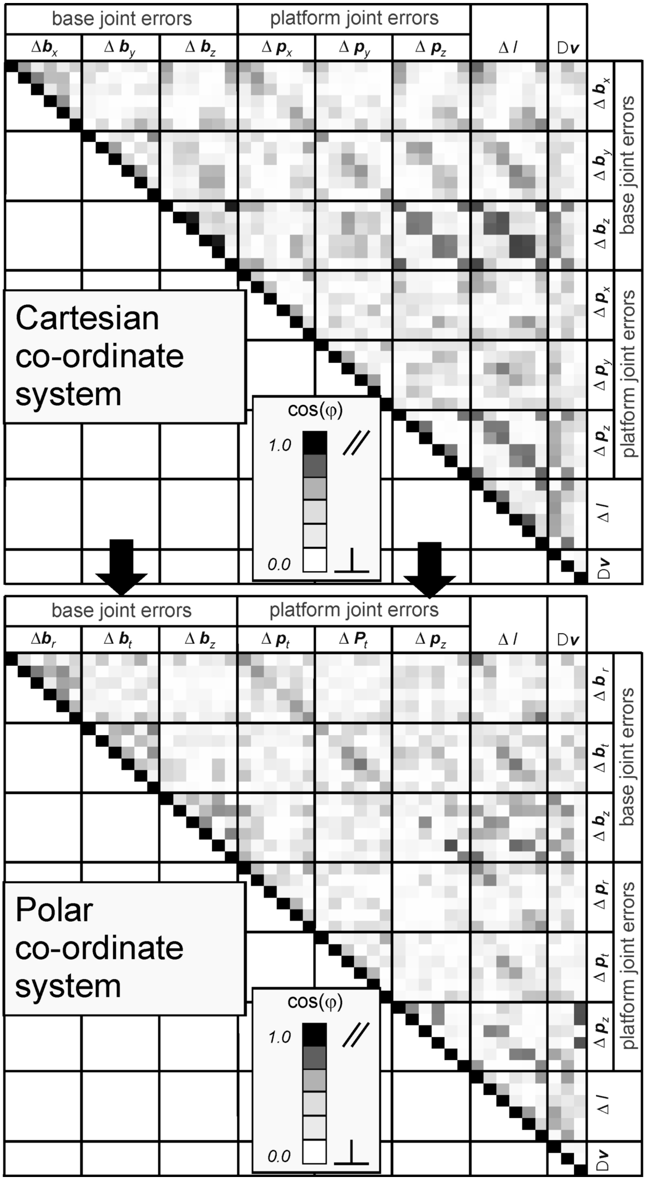


Fig. 4.22: *Influence of the parameter co-ordinate system*

4.4.2.4 Orthogonality of the Measuring Path

Departing from the orthogonality matrix, the goal of this section is to find a suitable measuring path which allows a further identification of the parameters. Orthogonality criterion can be defined here e.g. the condition number of the matrix [Fra06]. The condition number can be found from the singular value decomposition of the analyzed matrix (in the literature generally considered the Jacobian $\mathbf{J}_{cal} \in \Re^{m \times n}$:

$$\mathbf{J}_{cal} = \mathbf{V} \cdot \mathbf{S} \cdot \mathbf{U}^T \ . \tag{4.6}$$

where:

$$\mathbf{V} \in \Re^{m \times m} \ , \qquad \mathbf{S} \in \Re^{m \times n} \ , \qquad \mathbf{U} \in \Re^{n \times m}$$

$$\mathbf{S} = \begin{cases} 0 \rightarrow i \neq j \\ \lambda_i \rightarrow i = j \end{cases}$$

$$\text{with} \qquad \lambda_i \geq \lambda_{i+1}$$

The condition number gives us the scale between the maximum and minimum singular values:

$$cond = \frac{\lambda_{max}}{\lambda_{min}} = \frac{\lambda_1}{\lambda_n} \ . \tag{4.7}$$

This is considered mostly the measure of the ”goodness” of the orthogonality on the measuring path or points. A drawback of the condition number is that this gives no distinct physical representation of the worst case parameter - as would be desirable to evaluate the identifiability of the worst parameter.

A physical representation of the applicability of a specific measuring path can be seen in analyzing directly the dependency between two parameters in the orthogonality matrix **O** analyzed above. The number of the parameters, which can be identified with the calibration, can be obtained by calculating the *rank* of the Jacobian matrix. The rank gives us the number of non–zero elements of the diagonal matrix **S**. The difference to the whole number of elements represents the number of the parameters which can not be identified. Although, [Fra06] has shown that in spite of falling the condition number, the parameters can be still identified while measuring with the DBB.

4.4.3 Optimizing the Measuring Path

The construction of an 'ideal' measurement path for the use of the DBB has obviously a direct connection with the properties of the kinematic system – these are in particular the sensitivity of path deviations due to the modified kinematic parameters and their degree of orthogonality.

This section means to search for a measuring path, which includes sufficient information to identify all of the kinematic parameters mentioned above. The path optimization is made by determining suitable orientations (Fig. 4.21) in N nodes along the path.

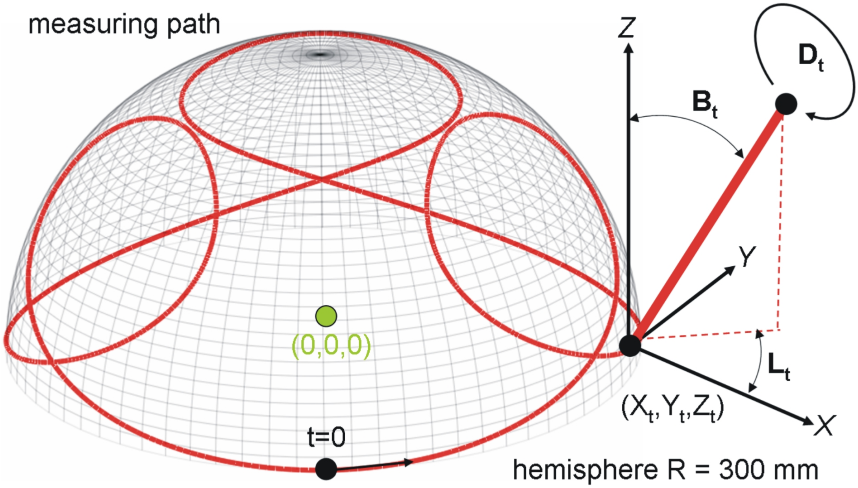


Fig. 4.23: *Measuring path on the hemisphere*

The optimization uses genetic algorithms (will be described later) where the goal (cost function) is to obtain the best from the worst–case orthogonalities between each two parameters:

$$max\,(\mathbf{O}_{k,l}) \rightarrow min, \qquad where \;\; k \neq l\;. \tag{4.8}$$

The obtained path is prepared for the measurement according to the following considerations:

- **Assuring a continuous motion along the path**

  The path will be interpolated between discrete points by using cubic splines to guarantee a continuous smooth measuring motion. The implementation of the obtained measuring path will be presented in the next chapter.

- **Assuring a constant velocity during the measurements**

  To guarantee the correctness of the measured data respectively the synchronization between the data acquisition and the planed motion along the measuring path, the controller facility is used. The controller allows defining a constant velocity along the path and it does not depend from the number of the nodes defining the path.

- **Checking the path for collisions**

  Collision problems have to be considered in advance by planning the measuring path. Especially vital is to prove the unrestricted motion between the moving platform and the measuring instrument according to the maximal mounting angle of the Double–Ball–Bar permitted by the magnetic cup.

4.5 Processing the Measuring Data

4.5.1 Data Smoothing and Compression Methods

During the measurement with the DBB, a huge amount of data is obtained due to the high sensitivity/tasting rate of the measuring system (250 samples/sec) [Ren]. To use these data efficiently and to extract the needed information for the calibration, a *data compression* is needed. That means, a suitable method is required to reduce the useful number of parameters without considerable lose of the path– and accuracy information.

Diverse approximation methods have been tested and compared for one and the same measurement along a 300 mm radius circle in a XY plane. Here can be mentioned the polynomial (Fig. 4.24 left hand side) and elliptical (Fig. 4.24 right hand side) approximations (scaled to 1) or decomposition in Fourier coefficients seen in Fig. 4.25.

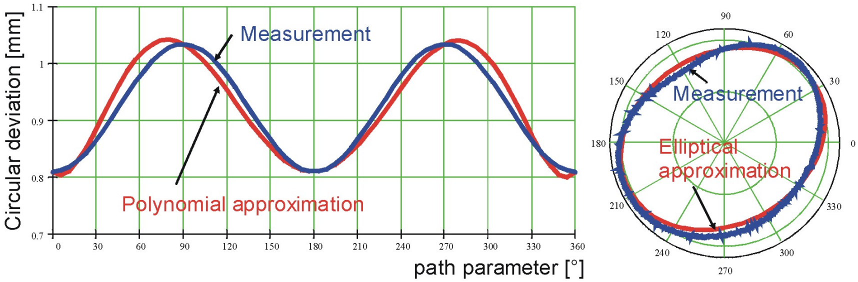


Fig. 4.24: *Polynomial (left hand side) and elliptical approximation (right hand side) of the measuring data*

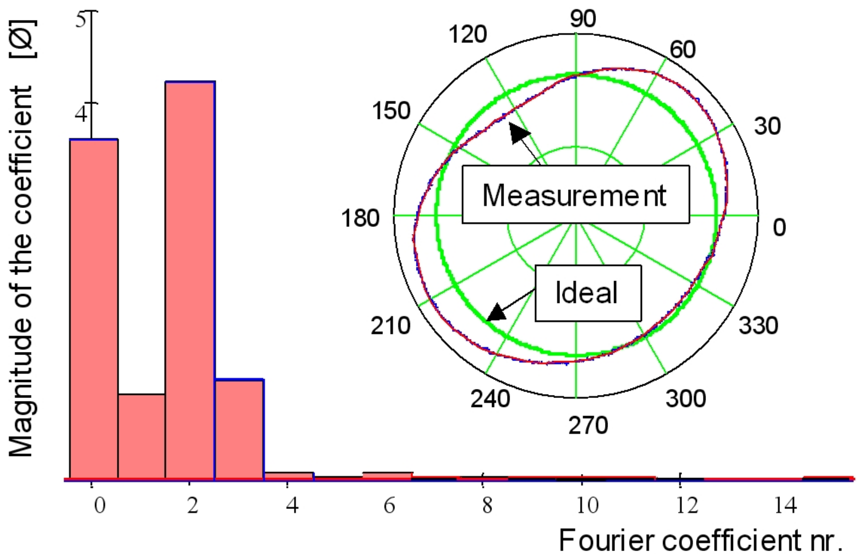


Fig. 4.25: *Fourier coefficients of the measuring data*

With these methods an overview of the obtained results can be seen in Tab. 4.8.

Approximation method	**Number of coefficients used for the approximation**	**Approximation error**
Elliptical approximation (for plane measurements only)	3	20 %
Polynomial approximation	12	25 %
Approximation with low–order Fourier coefficients	7	≤ 5 %

***Tab. 4.8**: Overview of the tested approximation methods*

The overall characteristics with advantages and drawbacks of the analyzed compression methods can be summarized as seen in the Tab. 4.9.

Approximation method	**Compression rate**	**Accuracy of the approximation**
Elliptical approximation (for plane measurements only)	high	very poor
Polynomial approximation	medium	medium
Approximation with low–order Fourier coefficients	very high	very good

***Tab. 4.9**: Overall characteristics of the approximation methods*

Considering the good compression rate of the approximation using Fourier coefficients and the very good obtainable accuracy of the approximation in the following measured data will be processed by using the fast Fourier transformation (FFT).

4.5.2 Data Smoothing Using FFT

An important characteristic by using the fast Fourier transformation is that the measuring noise is reflected in the high–level parameters. This can be explained with the fact that the measuring noise causes a high 'vibration rate' (frequency) in the measured data. Filtering out these parameters will drastically reduce the measuring noise. Here is another facility of using the Double–Ball–Bar, because this supports the Fourier–transformation thanks to the periodical character of the measurement. Through this, it permits the 'cleaning' of the measured data from noise without significant data lose.

From above results that the accuracy information is completely included in the low–level parameters, they are relevant to evaluate the position uncertainty of the hexapod [Tak02]. In Fig. 4.26 can be observed that the high–level FFT parameters, in case of a real measurement, are fundamentally smaller (nearly null) than the first values.

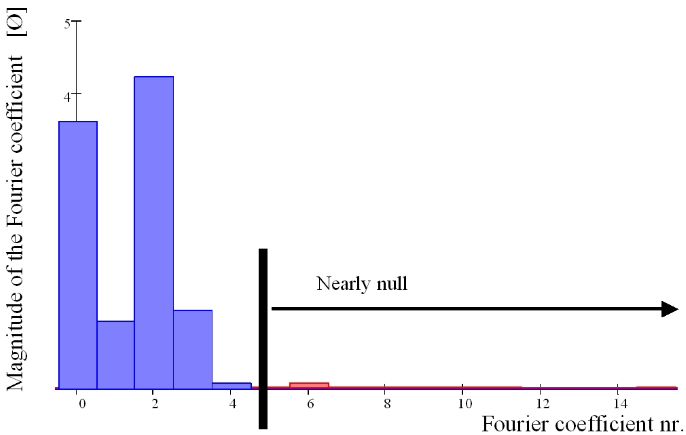


***Fig. 4.26**: Fourier coefficients for a circular measurement*

As a simulated investigation shows: from a measurement in 10.000 points just the first 4–5 parameters are significant and the rest of them represent less than 5 % of the maximum amplitude. This value, although, determined for a circular measurement, it depends further heavily from the character of the path and the dimension of the error effects.

The Fourier coefficients C_n bear a physical meaning of a circular measurement. Departing from the definition of the Fourier transformation [Wiki]:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(A_n cos(n\omega t - \varphi_n) \right) \ . \tag{4.9}$$

where:

$$A_n = \sqrt{a_n^2 + b_n^2} \tag{4.10}$$

is the amplitude in the point (a_n, b_n), particularly $A_0 = a_0/2$, and

$$\varphi_n = \begin{cases} \arctan\left(\frac{b_n}{a_n}\right) & , a_n \geq 0 \\ \arctan\left(\frac{b_n}{a_n}\right) + \pi & , a_n < 0 \end{cases}$$

is the phase shift which shows the quadrant of the point (a_n, b_n).

As seen in the Fig. 4.27 – departing from the definition of the Fourier transformation – each coefficient means the amplitude A_n and phase shift φ_n of the components

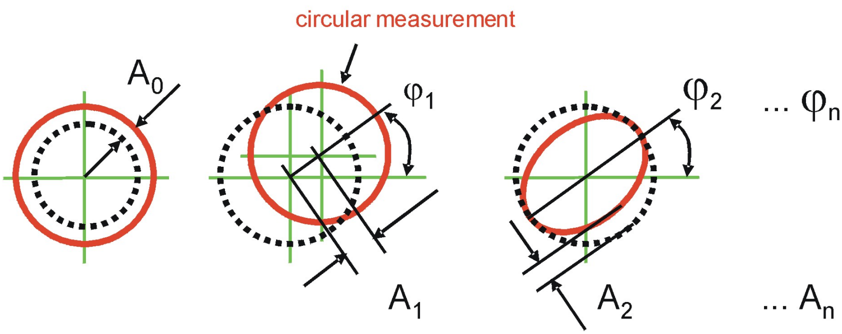


Fig. 4.27: *Physical meaning of the Fourier coefficients*

The notations used in Fig. 4.27 are:

A_0	– radius deviation of the base circle
A_1 , φ_1	– displacement of the center point
A_2 , φ_2	– ovality with a fixed center point
A_3 , φ_3	– tri–lob form of the measurement
A_4 , φ_4	– quadratic form of the measurement
A_n , φ_n	– magnitude and twist angle of the n-th component

Some examples of elementary errors and their influence on the Fourier coefficients can be seen in the Fig. 4.28. The analysis demonstrates further the physical meaning of the Fourier coefficients, encouraging to use them in compression and smoothing the measurements.

Another benefit property of the FFT is the computer–friendly algorithm which assures a very quick computation. Tests show that up to 100–200 time of the computing speed can be saved, compared with conventional smoothing algorithms.

4.5.3 Smoothing the Measuring Data

The choice of the adequate number of Fourier coefficients has an important role in preparing the data filtering. In the Fig. 4.29 a data smoothing has been analyzed by using different number of low–order coefficients. The three regions seen in the figure can be interpreted as following:

- **Region A**

  The number of Fourier coefficients is too low - the approximated path is far away from the desired smooth path.

- **Region B**

  It is met the right number of Fourier coefficients, the path is properly smoothed and the most part of measuring noise is eliminated.

- **Region C**

  Too many coefficients are used – no filtering effect will be made. The measuring noise remains as before, included in the data

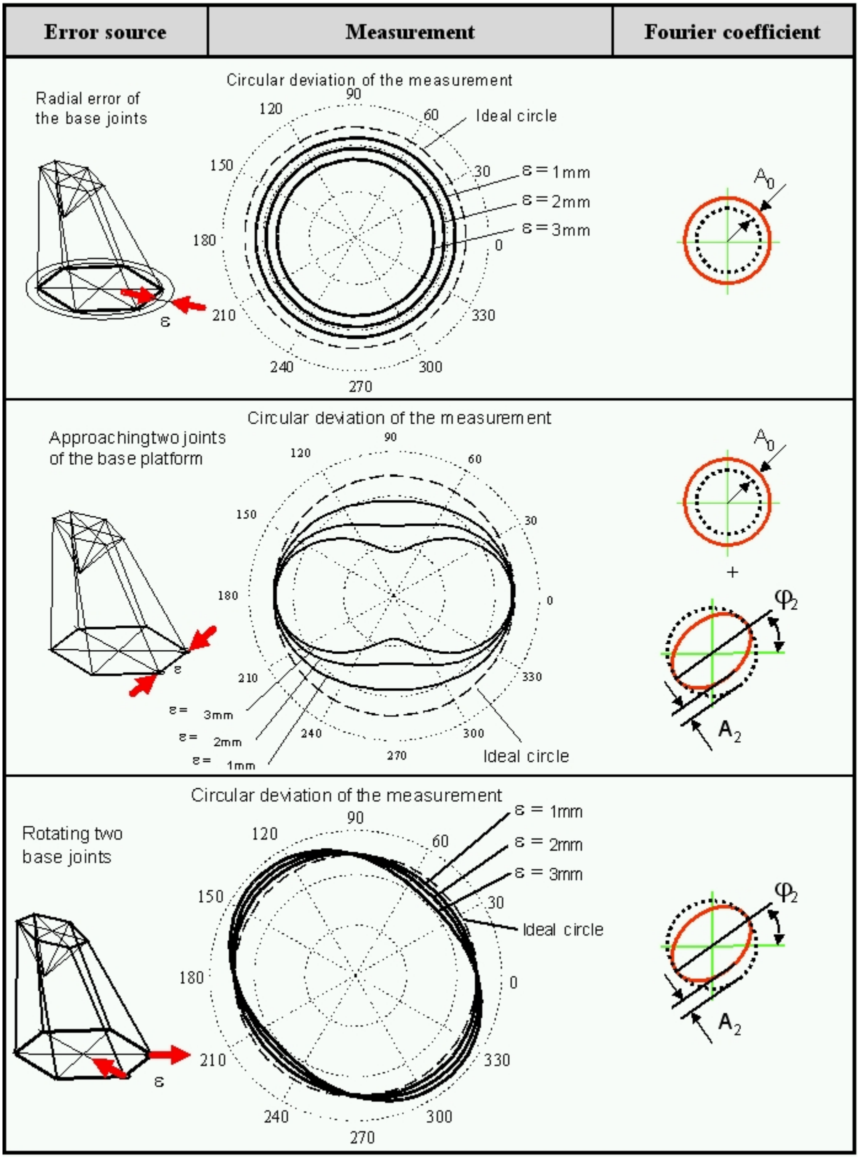


Fig. 4.28: *Error examples and their influence on the Fourier coefficients*

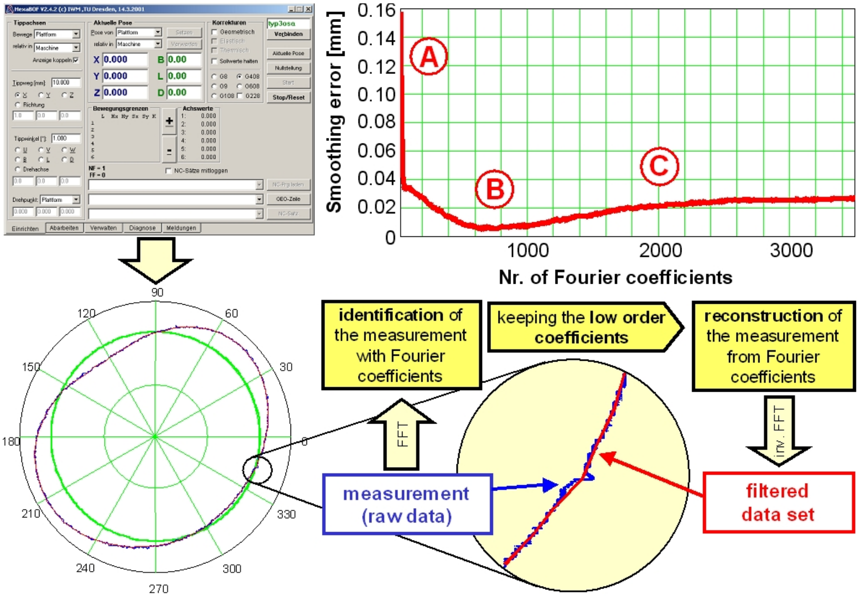


Fig. 4.29: *Data smoothing using FFT*

Because of the integral character of the FFT–analysis, this is robust related to the amount of the measuring points. That means, measurements in less points are as good as with high sampling rate. Here, although, a lower limit have to be respected to guarantee that the full path information is gained.

As the measurements are done, the measured data is smoothed and compressed; the obtained accuracy information is used for the identification of the kinematic parameters.

4.6 Parameter Identification

As the measuring data is acquired and processed, the final step in the calibration is the identification of the kinematic parameters on the basis of the prepared data. These parameters have to be estimated now by using different optimization techniques for minimizing the difference between the measured and simulated parameter sets. The most used methods are mainly gradient-based deterministic optimization algorithms, although, other considerations, as neuronal networks or statistic methods, have been tested, as already discussed in the chapter 2. The principal way to identify the parameters can be seen in the diagram presented in the Fig. 4.30.

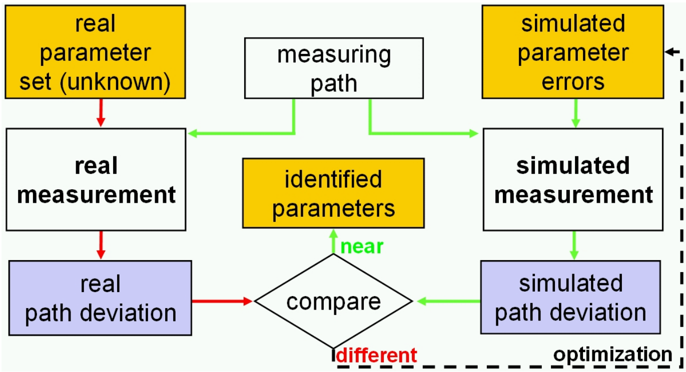


Fig. 4.30: *Parameter identification*

Firstly, a real measurement is made and than iteratively compared to the results of the simulated measurements as long as a satisfying approximation between the two measurements data sets is observed. If the stop criterion is achieved – the measured path is approximated by the simulated path – inevitably the source of the path deviation (the kinematic parameter set) has to be the same. So the kinematic parameters are now identified (estimated).

4.6.1 Optimization Methods

There exist more classical algorithms used to solve optimization problems. They are very effectual applied for smooth, low-rank functions (an example here are the broad–used gradient–methods). They use mostly the derivate of the target function to prognose the direction of the optima. The whole optimization process will be iteratively repeated till no more increase in the value is possible, so that the maximum is found.

The classical optimization approaches show, although, some disadvantages applied under certain circumstances:

- **The problem of the local optima**

Once a local optimum is found, these algorithms trend to 'stick' there, while no better solution exists in the near neighborhood.

- **The problem of the huge search space**

  The bigger the space, which contains the optimizing parameters; the worse will be the convergence to a solution. The ability of the algorithm to find an optimum trends to depend more and more on choosing the start values. An improper initial value could cause the impossibility to find an optimum.

- **The problem of the complex search space**

  By search space, which contains sharp tops or when no derivate of the target function can be found, the classical algorithms trend to jump to the very next random local optimum. Even a restart of the process has no guarantee of finding the global optimum.

The characteristics of the most used optimization procedures are resumed by [Bey04] as seen in Tab. 4.31.

optimization procedure	convergence	computing outlay	steadiness and remarks
Co-ordinates method	very low	n	stable, simply abort criterions
Gradient methods	linearly or worse	3n	very stable, bad conditioning can cause a premature abort
Newton method	quadratic	n^3	very susceptible to singularities, local convergence
Quasi-Newton method	linearly	n^2	not ever stable in case of singularities
Hook method	linearly or better	n^3	stable, singularities are nearly excluded, quick, local convergence
Gauss-Newton method	linearly or worse	n	singularities can not be excluded in spite of favorable iteration rules
Levenberg-Marquardt method	linearly	n	stable, quick, local convergence
Heuristic methods	extreme low	$n \ldots n^3$	global convergence, extremely robust, non-sensitive to noise
Genetic algorithms	low	$n \ldots n^3$	global convergence, very robust, non-sensitive to noise or singularities, considerably quicker as heuristic methods

Fig. 4.31: *Characteristics of the most used optimization procedures [Bey04]*

As already seen, by the calibration of the hexapod, the dimension of the optimization problem is to determine 45 kinematic parameters of the structure. The strongly nonlinear character of the problem causes a high risk of the optimization to run into a local convergence. To avoid this danger, heuristic methods or evolutionary algorithms (genetic optimization) have to be used. Especially this last one is considerably quicker in finding the solution without going into compromise on the very robust character against noise and singularities in the search space.

4.6.2 Evolutionary Algorithms

In the last years a new concept raised on the horizon of the optimization approaches: it's name is Evolutionary Algorithms (EA). This category contains more optimization procedures and was inspired from the biological evolutionary theory of Charles Darwin [May01, Osy02]. The Evolutionary Algorithms could be split into following classes [Wal97]:

- Genetic Algorithms (GA)
- Genetic Programming (GP)
- Learning Classifier Systems (LCS)
- Evolutionary Strategies (ES)
- Evolutionary Programming (EP)

4.6.2.1 Genetic Algorithms

A genetic algorithm approaches the problem by using the principles of natural selection [May01, Osy02, Wal97]. First, a number of solutions (*a population*) are created by setting the parameters randomly throughout the search space. From this population of solutions the worst are discarded and the best solutions are then 'bred' with each other by mixing the parameters (*genes*) from the most successful organisms, thus creating a new population. Additionally, every so often a gene will be slightly altered to produce a *mutation*. As in the real life, this type of continuous adaptation creates a very robust organism. The whole process continues through many *generations*, with the best genes being handed down to future generations [Osy02, Wal97].

Fig. 4.32 shows the schematic algorithm of the simple genetic algorithm. More information about the classical genetic algorithms can be found in the literature, numerous papers are already published in this direction [Gro03, May01, Osy02, Wal97].

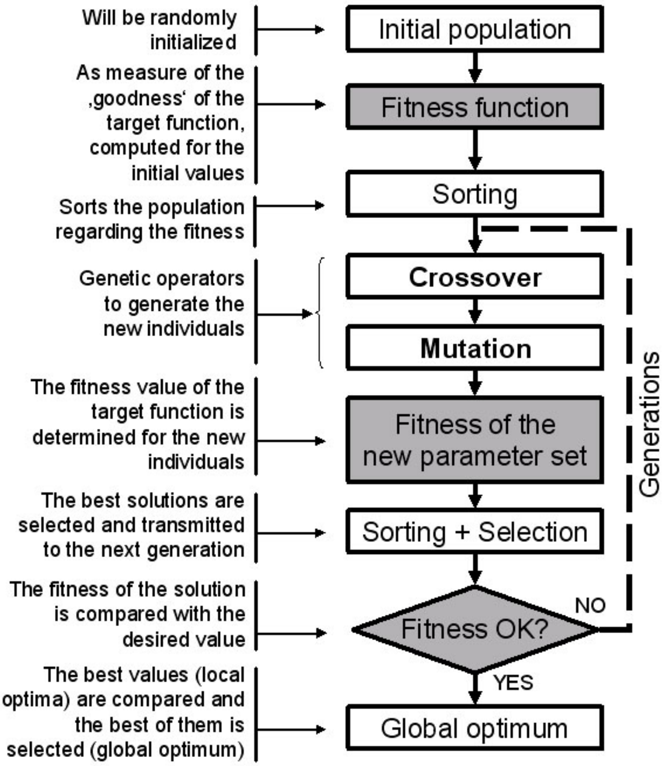


Fig. 4.32: *Schematic algorithm of the simple GA*

4.6.2.2 Genetic Algorithms Applied to the Parameter Identification

Against the classical optimization methods, the genetic algorithms have essential advantages on:

- **Converging to the global optimum**

  The genetic algorithms have more possible solutions incorporated in a parameter set, named '*population*'. In this way a bigger search space can be covered, improving the capability of the procedure to find the global maximum.

- **Continuity of the search space**

  This method needs no assumption about the availability of a search space without singular positions. Therefore, implementations on complex search spaces or on functions without differential solutions are also possible.

- **Defining the proper start values**

  Using a high number of populations can effectively cover a huge search space. No special start value is needed; an amount of initial values will be generated randomly.

- **Possibly parallel application**

  The genetic algorithm can be easily split into more parallel processes. So they can be run separately on different computers, reducing the computing time.

- **Robustness**

  his algorithm is robust against noisy or incorrect input data sets (see below the section "Cost function of the optimization" 4.6.3). No special measures or conditions to use the GA are required.

4.6.2.3 Modified Genetic Algorithms

To rise the efficiency of the optimization procedure of the parameter identification, the classical genetic algorithms were slightly modified, and customized for the purpose of obtaining a quickly convergent solution and a better overall accuracy of the identified parameters. Beside the classical genetic operators (*cross–over* and *mutation*), two new functions have been implemented and successfully tested:

1. **mean function**

   An average value is computed between the chromosomes of two selected individuals, which presents the following advantages applied to the genetic algorithms:

   - Results a very quick *convergence* of the solution if the parents have only slightly different chromosomes
   - Works as an additional *mutation* between parents with very different chromosomes, in this case new parameter information is created

2. **group function**

   The individuals with near properties (*genes*) are considered *neighbors* and will be grouped into a *colony.* The best individual (with the best fitness value) from them is selected, being the *"chief magistrate"* of the colony and will represent alone his colony in the next generation.

   The goal of the *group function* is to prevent a premature convergence of the optimization and can be seen as an "antipole" of the *mean function.* Against the *mean function*, the *group function* means to spread the solutions over the search space increasing the global character of the genetic algorithms.

The actual population is sorted by fitness and the best individuals are subject to both the conventional and the new genetic functions and will take part to rise the next generation. That guarantees the convergence of the function: no worse results are possible since the best individuals from the precedent generation are still "alive".

4.6.3 Cost Function of the Optimization

Beside the qualities of the optimization procedure presented above, the attributes of the used cost function have a significant impact on the parameter identification. To analyze this influence, several cost functions have been implemented and tested on robustness and achieved accuracy after the optimization. Meaningful was here the test of two approaches:

- **Least squares method**

  Compute the sum of the deviation's square in each measuring point along the path, this will be minimized:

  $$\sum (X_{real} - X_{ideal})^2 \rightarrow min \ . \tag{4.11}$$

  This is a broad-applied method of optimization procedures, although, some disadvantages can be observed, e.g. the result is dependent on the number of considered points.

- **Minimum error peak**

  Here the error peak of the measurement set (the maximal value) will be minimized:

  $$max\,(X_{real} - X_{ideal}) \rightarrow min \ . \tag{4.12}$$

Both functions give good results if applied to ideal measured data, but the robustness of the optimization has to be analyzed in case of measuring noise. Fig. 4.33 shows the influence of these cost functions on the robustness of the optimization, the results are compared with the situation when an artificial noise is added to the simulated measurements.

Most of the calibration procedures use the method of least squares in which the parameters are estimated in a way, that the sum of the squared residuals is minimized. This has for linear models a minimum variance and it is a good estimator of the motion quality. Hence, for the calibration of a hexapod – where the error transmission is nonlinear – these methods have to be reconsidered.

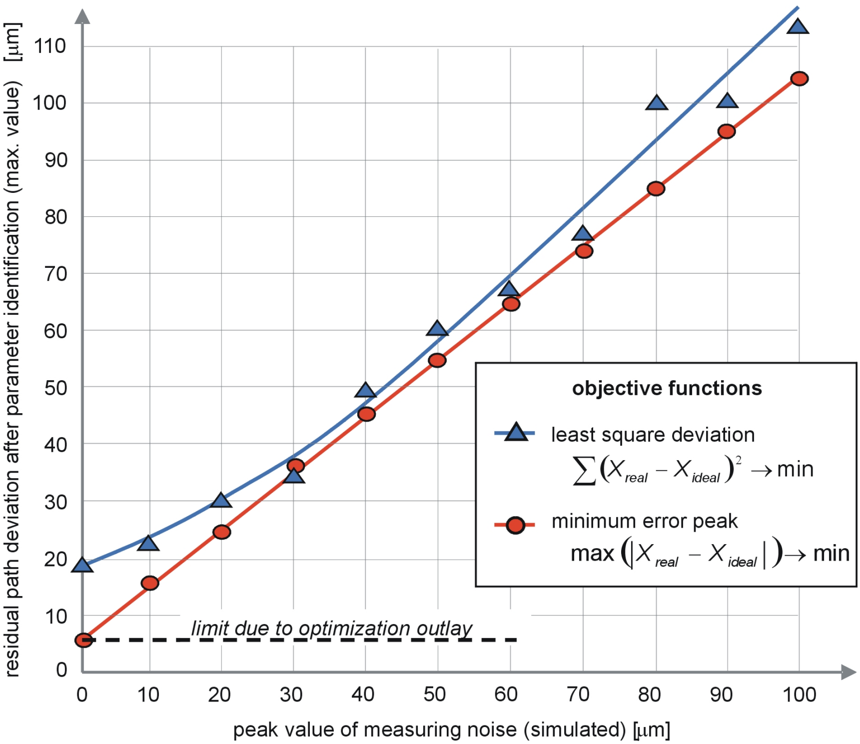


Fig. 4.33: *Robustness of the optimization procedure with different cost functions*

Against the robust character of the error peak function under influence of measuring noise the least squares deviation presents undesirable dispersion of the results and a significantly lower accuracy on the measuring path. The linear dependency of the residual path deviation by minimizing the error peak has the merit that this function will be used for the optimization and it will be implemented as fitness function of the genetic algorithms.

4.6.4 Convergence of the Optimization

The residual error of the target function is limited mostly due to the technical outlay of the optimization given by the constraints imposed by the concept of simple design. The outlay of the parameter identification can be evaluated with the convergence of the optimization procedure (Fig. 4.34). As can be easily observed in the figure, a low number of populations causes a quick convergence to a rough solution but an accurate result cannot be found. This problem is known in the literature as *"premature convergence"* [Liu00].

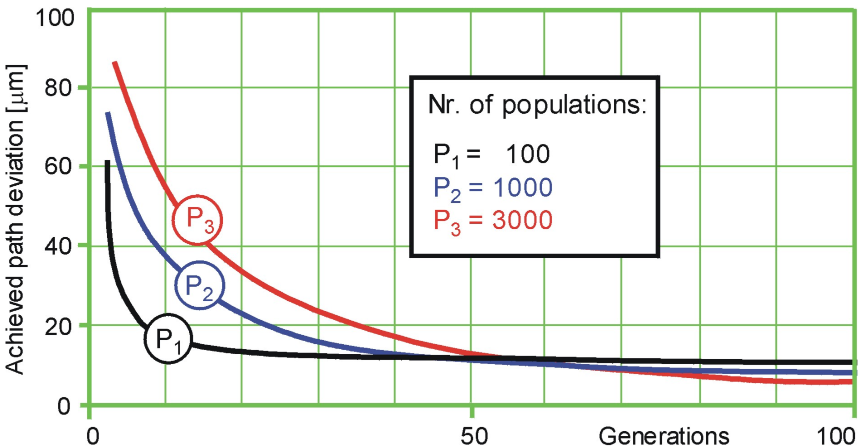


Fig. 4.34: *Convergence of the optimization with GA's*

Minimizing the calibration outlay means to reduce the time spent for the optimization, too. The optimization time can be roughly approximated as following:

$$T_{opt} = T_{Fitness} \cdot Nr_{Population} \cdot Nr_{Generations} \,. \tag{4.13}$$

where:

$T_{Fitness}$ = Computing time of the fitness function for one configuration ($individual$)

An absolute zero path deviation and with that an absolute parameter identification is not possible due to more reasons. One of them is the principal character of the genetic algorithms which converge very slowly to a solution - as price to pay for the global character of the optimization (aspiring to find the global optimum). Other limits and considerations will be discussed in the next chapter.

Best results of the parameter identification can be obtained, in our case; with a population number of 3000 individuals (parameter set) computed over 100 generations (Fig. 4.35).

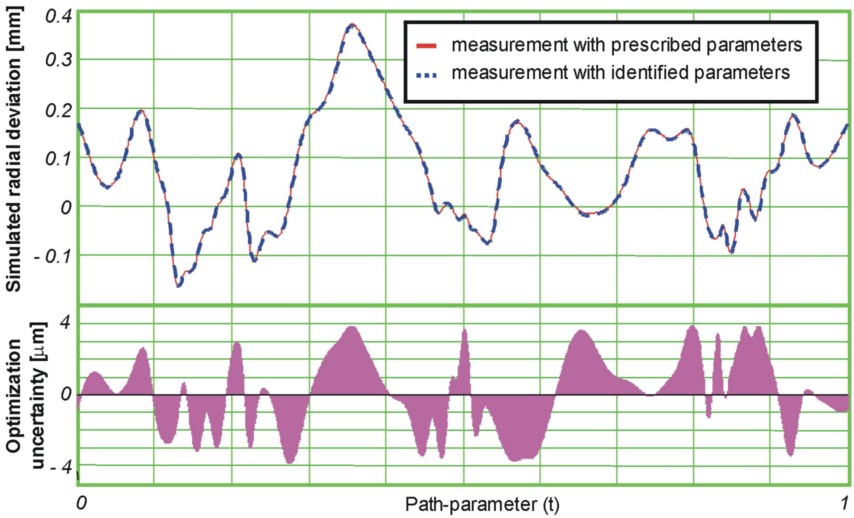


Fig. 4.35: *Uncertainty of the optimization procedure*

4.6.5 Admitted Effort on the Optimization

As the overall outlay of the calibration is limited due to the directives imposed by the concept of simple design, the effort of the parameter identification has to be kept within economical limits, too. The admitted effort of the parameter optimization considers mainly the optimization outlay spent to find a solution of the problem, and also the computing time. From the slow convergent character of the genetic algorithms is given a progressive slow–down of the accuracy improvement of the solution. Hence, waiting the optimization to find a high-accurate result may be economically inefficient and could compromise the applicability of the whole procedure in the industrial environment.

A possible way out can be seen in considering an admitted effort on optimization (Fig. 4.36) and break–down the procedure after reaching this limit. Further, the obtained results (kinematic parameters) can be handled as following:

- Accept the obtained uncertainty of the identified parameters if they are sufficient for the intended purpose (industrial application).
- Analyze the obtained uncertainty of the parameters and apply a second optimization step with a different, quicker convergent algorithm.

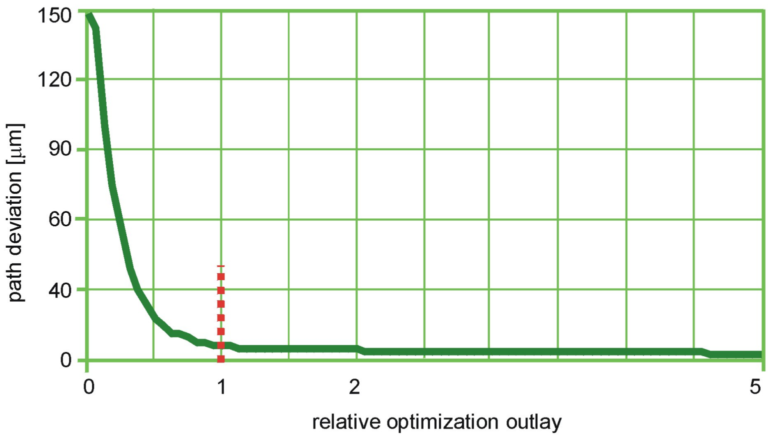


***Fig. 4.36**: Admitted effort on the optimization procedure*

Given the fact that the main dangers of the parameter identification have been presented in the chapter 4.6.1 and that now, after an optimization step the obtained result is inevitable closer to the global solution, a further optimization procedure has not to fulfill the previously imposed demands. Near the global optimum a quicker deterministic method can be implemented to finalize the optimization. The two-step combined optimization could be in this case:

- Genetic algorithms to obtain a rough global approximation of the solution
- Gradient based quick optimization methods on the neighborhood of the global solution

The residual parameter errors and their impact on the global accuracy of the hexapod will be analyzed in the chapter 5.

4.7 Workflow of the Calibration

As the elastic and thermally induced shares of the motion error can be corrected, the quasistationary pose errors are mainly caused by the systematic influences of the differences between the parameters, which are used for the kinematic transformation in the control system, and the real parameters, which are effective in the machine. These parameter deviations, which are unknown for the hexapod [Mer00], will be determined below during the geometric calibration on the basis of suitable measurement data.

Fig. 4.37 illustrates the overall simulation-based calibration process which has been developed and practically tested at the IWM. As shown in the figure, firstly, initial values are defined for the geometrical parameters. These values correspond to the ideal structure (no error) and are used to make the first measurement. During the measurement with the DBB, the model based corrections of the elastic [Gro01a] and the thermal [Gro02a] errors are active in the controller to filter out the mentioned effects [Kau06]. The measurement is made with low speed rate to minimize the dynamic effects. The obtained data are transformed with FFT and the low–order parameters are used as further reference for the inverse transformation.

Secondly, a simulation model is used to iteratively identify the above mentioned error peaks from the filtered measuring data. Random initial values of the geometric parameters (initialization of the genetic algorithms) are transformed to the end-effector (direct kinematics. Simulated measurement is made along the same given path (preliminarily optimized) and simulated measurement data are obtained. This will be handled like the real measurement and the two parameter sets are compared. The optimization is made with the customized genetic algorithms, repeated until the desired precision is obtained or till the limit of the optimization outlay is reached.

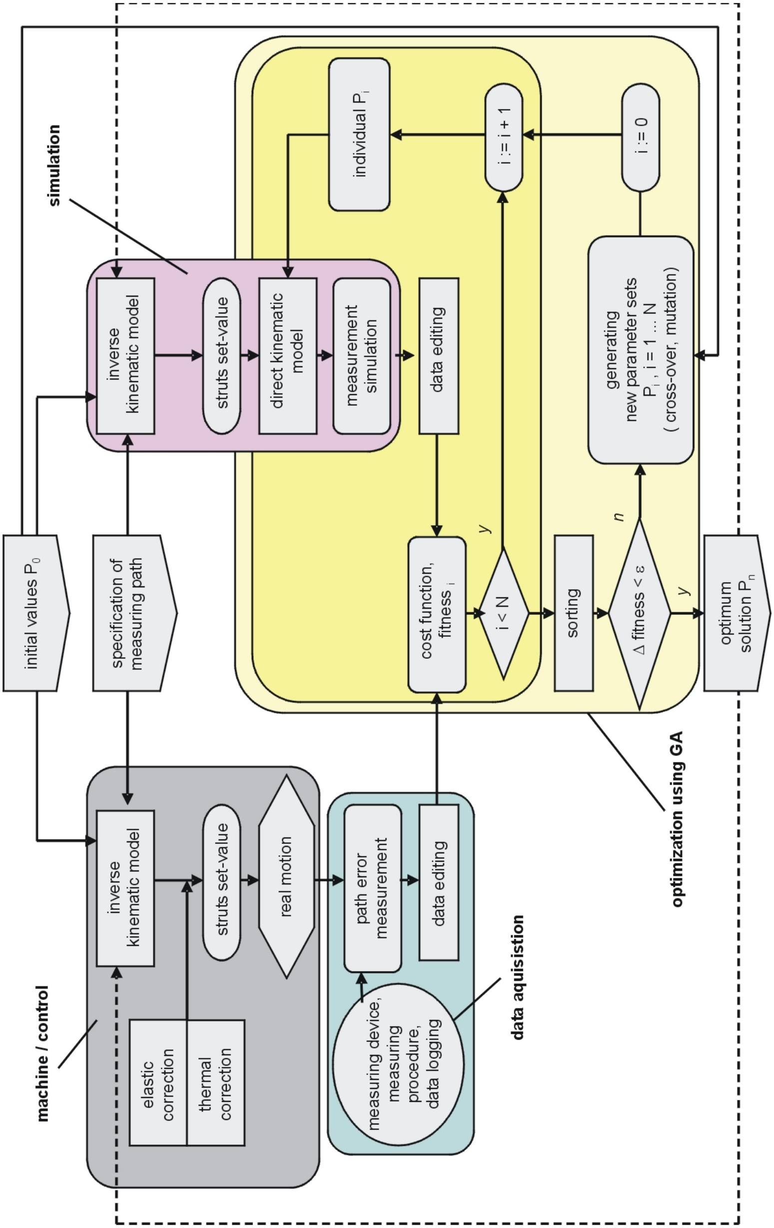


Fig. 4.37: Flowchart of the calibration

The implementation of the calibration procedure to the hexapod of simple design 'Felix' and results with numerical examples are presented in the next chapter.

5 Implementation of the Procedure and Experimental Results

The presented calibration procedure has been successfully implemented and tested on the hexapod of simple design 'Felix' available at the IWM. The kinematic calibration is principally valid to other hexapod structures, although, the kinematic specifications of the given structure have to be considered. These particularities of each structure come mainly from the dimensions and the shape of the platforms, and base frame and arrangement of the actuators. Furthermore, the location of the end–effector within the moving frame plays a deciding role, too. According to these details by implementing the calibration to a real machine, the following conditions have to be fulfilled:

- Availability of a kinematic model of the structure just like as implemented in the controller: in the case of the hexapod of simple design the available model has been developed by [Kau06]
- An appropriate worst–case measuring path: the path for the hexapod "Felix" has been computed departing from systematic analysis on the sensitivity and orthogonality of the kinematic parameters

Insofar, the kinematic calibration of a new designed structure begins with performing the measurements along the existing measuring path.

5.1 Applying the Measuring Path to the Hexapod 'Felix'

The determination of a proper measuring path is non time-critical, has not to fulfill real–time requirements. It can be computed once by designing the mechanical structure and it remains principally valid for arbitrarily calibrations in the future.

The worst–case measuring path for the hexapod of simple design has been determined by using optimizations with genetic algorithms as presented in chapter 4. Here the obtaining of a path with the worst-case sensitivity of the parameters and a sufficient orthogonality along the path is desired. It has been searched for suitable orientation angles B, L, D along the path, optimized in interpolation points as seen in Fig. 5.1.

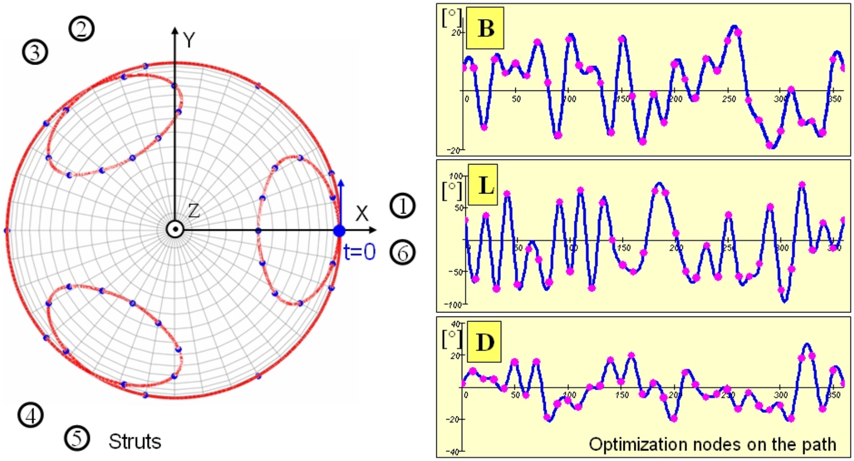


***Fig. 5.1**: The optimized measuring path for the hexapod 'Felix' at IWM*

The path is situated on a hemisphere within the workspace of the hexapod, with the center in the origin of the hexapod co–ordinate system (presented in chapter 2) having a radius of 300 mm.

5.2 Measurements and Results

The Renishaw [Ren] Double–Ball–Bar has been applied to measure the radius deviation along the determined measuring path before and after the calibration, as seen in Fig. 5.2.

Unlike the initial path deviation up to 0.7 mm, the calibrated structure measures an uncertainty of 0.170 mm along the same path. As the measurements are performed along the worst–case path, this involves that further measurements are expected to sit above the presented accuracy.

The good conformity of the real measurement with the previous simulations demonstrates that the potentials to eliminate the residual errors are hidden in a further correction of the non–kinematical parameters.

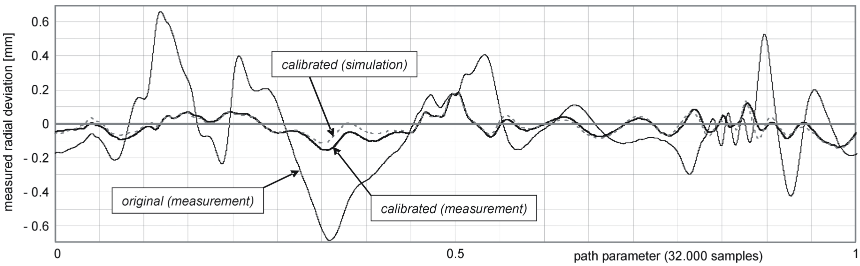


Fig. 5.2: *Measurements before and after the calibration along the optimized path*

5.3 Accuracy Evaluation

In the metrological identification of the positioning accuracy of conventional machine tools with serial layout of the kinematic structure it is usually assumed that the axis–specific kinematical errors are decoupled. In the more recent development of standards, the accuracy test is already taken into account an overlay of axis movements. If an overview of all errors at the TCP is desired, the six possible degrees of freedom have to be evaluated on the end–effector throughout the entire workspace of the machine tool [Ble04].

Hence, a complete evaluation of the workspace is not always possible due to the limits of the measuring system, sample measurements have to be made in subspace of the working area of the machine. In the actual work, the cross–validation of the effectuated calibration is performed with measurements on trajectories, different from those used for the calibration step. Exhaustive measurements have been made within the workspace under circumstances offered by [Ren].

In Fig. 5.3 are defined the regions over the workspace where the accuracy control is effectuated. In Fig. 5.4 circular measurements in these regions can be seen before and after the calibration over 300 mm radius circles, each in three perpendicular planes. The results are presented in Tab. 5.1.

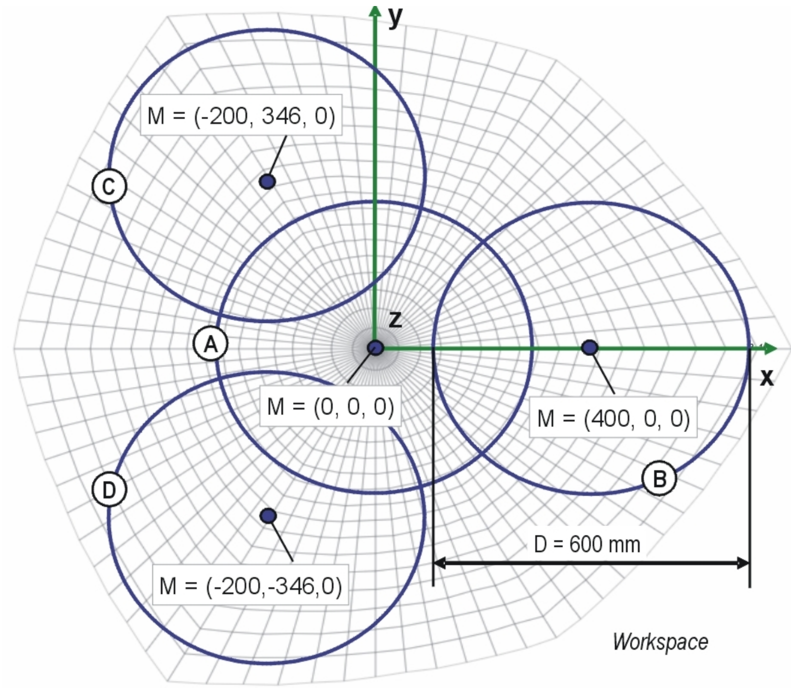


Fig. 5.3: *Accuracy control in the workspace of the hexapod*

5.4 Limits of the Accuracy Correction

5.4.1 Limits of the Calibration

It is generally admitted that a perfect error correction algorithm can not be achieved considered more points of view. As [Wil00] affirms, it would be necessary to define in each point an algorithm which chooses the optimized solution for:

- the most accurate hexapod
- the most rigid hexapod
- the fastest hexapod
- the lowest energy of torque requirements
- the most realistic leg lengths variation

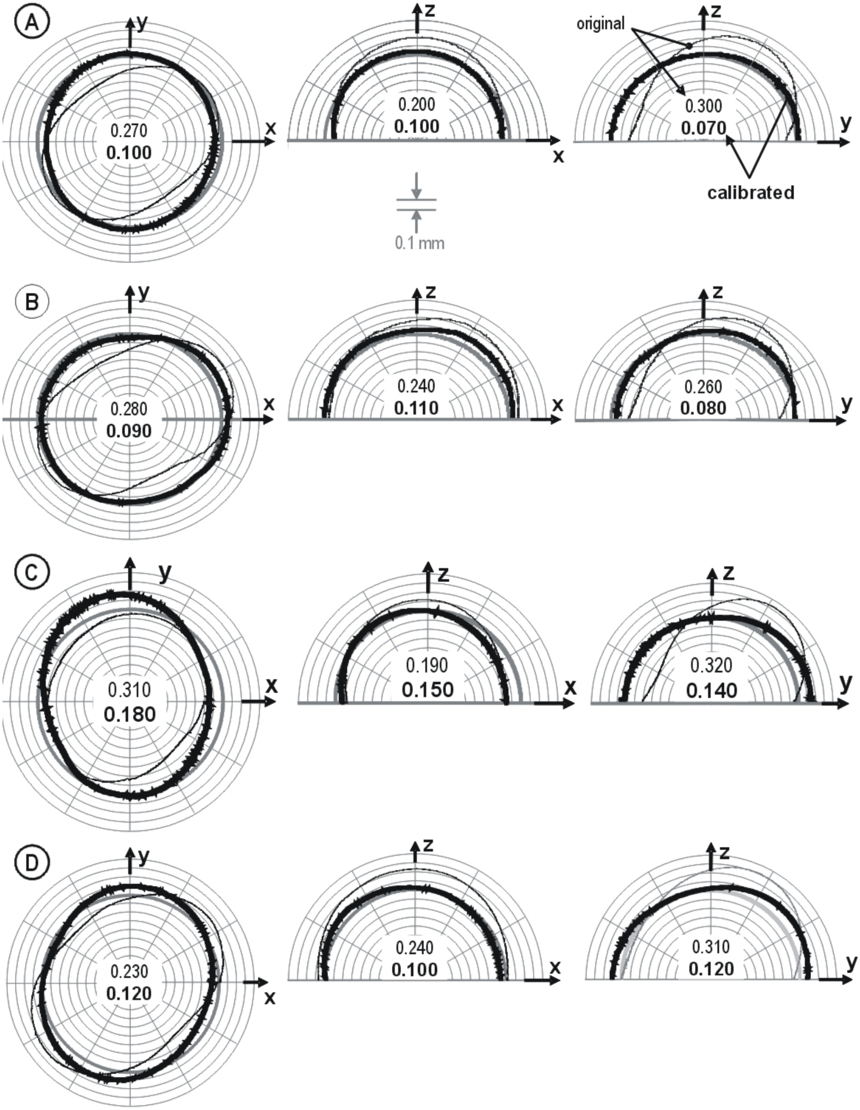


Fig. 5.4: *Measurements in the workspace of the hexapod*

Measurement in plane	Initial max circular deviation [mm]	Corrected max circular deviation [mm]
Region A, M=(0,0,0)		
XY	0.270	0.100
XZ	0.200	0.100
YZ	0.300	0.070
Region B, M=(400,0,0)		
XY	0.280	0.090
XZ	0.240	0.110
YZ	0.260	0.080
Region C, M=(-200,346,0)		
XY	0.310	0.180
XZ	0.190	0.150
YZ	0.320	0.140
Region D, M=(-200,-346,0)		
XY	0.230	0.120
XZ	0.240	0.100
YZ	0.310	0.120

Tab. 5.1*: Measurements in the workspace of the hexapod*

Considering just the point of view of the accuracy, there are still huge factors to be optimized. Given the fact that the attainable accuracy is principally limited because of the internal clearance of the universal joints (approximately 50 μm) and because of the existence of other residual errors, those were not object of the calibration in the examined hexapod structure of the simple design, the findings impressively confirm the calibration approach studied. At the same time, the remaining errors underline that there are still potentials for examinations which are subject of current and future research tasks at the IWM in Dresden.

5.4.2 Residual Parameter Errors

The residual parameter errors can be deduced from the residual path error with a study of the transmission factors from kinematic parameters to the path deviation. A deterministic deduction is difficult due to the complexity of the transmission composed from the sum of:

- **Kinematic transformation of the hexapod**

  In practice it is hardly possible to calculate analytically the kinematic transformations even for simple kinematics. The reason is that either the forward or the inverse transformation is involved in performing the simulated measurement. The forward kinematics problem of the hexapod can be solved only with complex numerical approximations.

- **Sensitivity of the measuring instrument**

  Considering that the Double–Ball–Bar can acquire only a single DOF measurement, the sensitivity of the DBB is a function of the measuring direction in the current pose.

- **Sensitivity of the determined measuring path**

  The actual calibration approach means to obtain a suitable path to perform the parameter identification, although, the integrality of the measuring path is limited from the constraints given by the measuring instrument, collision problems and the outlay demands of the calibration.

- **Residual errors of the non–kinematic effects**

  The measuring noise, but also the residual elastic and thermal influences will make the error transmission function more complex and unpredictable.

An evaluation of the error transmission can be made, although, by using statistical studies. Mathematically the estimated (identified) parameter sets are values which are calculated from the measuring data $\hat{\Theta} = \hat{\Theta}(X)$. It has to always be considered that an observation is a realization of a random variable [Alt04], therefore the estimated parameters are random variables as well. The random variables X have a particular distribution which can be described by a mean $<X>$ and a variance σ_X^2. If the variance σ_x^2 is known, the variance of the estimates can be calculated with a rule which is known as the propagation of the error, as observed by [Alt04]:

$$\sigma_{\Theta}^{2} = \sum_{i=1}^{N} \sigma_{X}^{2} \left(\frac{\partial \hat{\Theta}}{\partial \hat{X}_i} \right)^2 . \tag{5.1}$$

with notations used by [Alt04]:

N – the number of parameters
$\hat{\Theta}$ – set of the kinematic parameters
X – measured data

The same results can be obtained using the Monte Carlo simulation where numerous sets of random data with variance σ_X^2 are produced. Each data set is used for an estimation of the parameters leading to many realizations of random variables $\hat{\Theta}$. Variances of the estimates can be calculated from their distributions as follows:

1. a numerous set of random kinematic parameters is initiated
2. simulated measurements are done for each configuration
3. the deviation peak (target function of the calibration) on each path is observed and scaled to the mean value of the kinematical parameters of the actual parameter set
4. statistical analysis of these values are made

A great advantage in calibrating PKM is that the estimated values are known in advance quite accurately. For example, the position of a joint is known already from the drawings. As the expected mean value is already known, just the variances have to be determined.

Using the Monte Carlo simulation, by a sufficient large number of simulated measurements (Fig. 5.5) a mean transmission function is obtained (Fig. 5.6) which characterize the error propagation on the hexapod.

Departed from an uniform distribution of the given kinematic parameters (Fig. 5.6, left side), through the error propagation function, a normal distribution of the path errors is obtained (Fig. 5.6, right hand side).

Reversing the problem – e.g. the residual path deviation is known - the distribution of the kinematic parameters can be estimated. Herewith, the expected residual uncertainty of the parameter identification can be found.

In the case of the hexapod of simple design 'Felix', the initial and the residual uncertainties can be expressed as seen in Tab. 5.2.

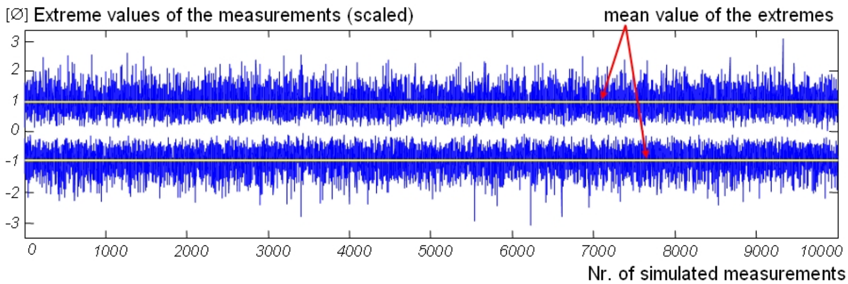


Fig. 5.5: *Monte Carlo simulation to determine the transmission function from the kinematic parameters to the path deviation*

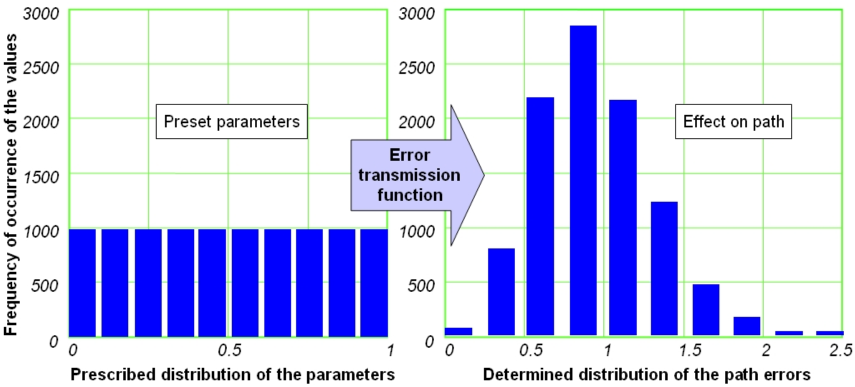


Fig. 5.6: *Distribution of the path errors as result of the Monte Carlo simulation*

	Measured un–certainty on the worst–case path	**Estimated mean uncertainty of the kinem. parameters**	**Estimated max. uncertainty of the kinem. parameters**
Initial (before calibration)	0.700 $[mm]$	0.700 $[mm]$	1.750 $[mm]$
Residual (after calibration)	0.170 $[mm]$	0.170 $[mm]$	0.425 $[mm]$

Tab. 5.2: *Uncertainties measured in the workspace of the hexapod 'Felix'*

A summary of the presented calibration procedure and perspectives for further measures taken to correct the residual errors are discussed in the next chapter.

6 Summary and Perspectives

6.1 Summary

The position accuracy of parallel kinematic machines depends on how accurate the controller model describes the real kinematic behavior of the machine. Some error sources can be minimized by proper mechanical design or special construction measures, others can be predicted and compensated by using an extended controller model. This work presents a new calibration concept to identify these model parameters and it has been developed at the Institute of Machine Tools and Control Engineering (IWM) at the Dresden University of Technology. It is a new approach to make a kinematic calibration of the simple design hexapod 'Felix' and supports the generalization of other parallel kinematics structures, too.

The calibration uses the measurement data from the Double–Ball–Bar moving along a hemispherical path. The accuracy of the hexapod is prior cleaned from elastic and thermal effects by running model-based correction algorithms on the CNC controller. The input data are cleaned from the measuring noise by using Fourier transformations. To identify the geometrical parameters of the hexapod, Genetic Algorithms are used as optimization procedure. The results obtained so far confirm a considerable improvement of the motion accuracy over the whole workspace.

Summarized advantages of the mentioned procedure are:

- Cost–effective solution by using low–cost measuring instruments (DBB)
- Short measuring time, the measurement happens continuously over the programmed path, no stops are needed in these points
- Short computing time thanks to the very effective optimization algorithm
- A considerably rise of the accuracy near to the limit with the tillage precision of the component parts

- The obtained accuracy is measured on a complex path over a significant share of the workspace
- The optimization algorithm supports the parameter identification of other hexapod structures

6.2 Perspectives

The following perspectives can be considered as subject of further research on the topic:

- **Finding the optimal measuring path with the Double–Ball–Bar customized for a given PK structure**

  The measuring path presented in this work allows us to gather data which will be used for the calibration. This measured data are sufficiently representative to identify most of the parameters, although, not yet perfect. An optimal path would be that drives through the most sensitive poses of each kinematic parameter. To find such a path and by the same time to maintain his continuous character, which can be measured by using the Double–Ball–Bar, makes place for further research.

- **Improvement of the calibration algorithm**

  Due to the empirical character of the function parameters of genetic algorithms, the calibration process can be further optimized to converge faster and quicker to the desired value. To handle the individual parameters of the process and to analyze and eventually improve the goal function presents the aim of further work.

- **Obtain a completely autonomous calibration procedure**

  The automation of the procedure plays an important role considering the practical applicability of the calibration for industrial use. This would increase the efficiency of the process and would permit to process the calibration without human intervention. Further research in this direction is a main topic at the IWM.

- **Implement the software tools in the control panel of the hexapod**

  Allowing the user to switch the calibration from the control panel would be a very comfortable solution which would reduce the requirements on qualification of the user. Therefore, the implementation of the software tools in the machine control device is needed. Creating the software will allow the next user to repeat spontaneously the calibration in order to improve or to check the accuracy of the device.

- **Assessment of the calibration algorithm through the complete measurement of the workspace**

  A complete measurement of the manipulators workspace is currently not possible due to the limits given by the measuring instrument and the economical aspect of the calibration outlay. More extensive measurements on 6 DOF would assure a wide–ranging assessment of the calibration procedure and the residual positioning uncertainty of the hexapod.

- **Generalize the calibration to other hexapod structures**

  This work has exemplarily proved the calibration of the hexapod of simple design at the IWM. The procedure is, although, applicable to other hexapods or other type of parallel robots. The presented algorithm supports a generalization, nevertheless, some particular properties of the analyzed structure have to be considered, such as:

  - The geometrical construction of the analyzed device
  - The possible error sources as result of the different tolerances of the component parts (parameters to be identified)
  - The presence of a kinematic model of the structure
  - Influences of other factors like thermal and elastic ones and their preliminary correction

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