

Gernot Hoffmann
Computer Vision
Documents for Students

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Graphics Collection

September 15 / 2005

Please print everything as grayscale and
replace at least these pages by color prints:

Covi-Lab: 15, 16

Covi-Bild: 16, 18, 19, 20,35, 38

Computer Vision Project No.

Project Title

First Name, Family Name

Matrikel No.

Studying P+D or TM

Date

Check by G.Hoffmann

Comments

Project No.1

Image Processing

Take any private color photo which must contain at least one person with visible skin.

Scan the photo.

Print the original scan in original size and approximately in DIN A4 size.

Apply Image Processing with color correction and retouch.

Print the improved photo in original size and approximately in DIN A4 size.

Add informations about computer, scanner, programs, printer, other sources.

Discuss the procedures and the results (German or English).

Project No.2

Vector Graphics

Covi-Bild contains two vector graphics which are hand drawn: Figure 7.3 and 7.4

These drawings shall be replaced by computer graphics, using InDesign, Illustrator or CorelDraw.

Graphics format: EPS (Encapsulated PostScript),
Readable by PhotoShop, Pagemaker and any PostScript Viewer

Size: Approximately like original on DIN A4

Color: Black.

Disk: 1.4 MB floppy, no subdirectories

Analyze the graphics elements of all figures. Make a catalogue of elements.

Add informations about computer, programs, printers, other sources.

Discuss the procedures and the results.

Each student makes one page with one drawing of one figure.

Use title sheet and make a complete document.

Date of delivery:

Pass 1: not later than December 22

Pass 2: not later than Januar 15

Foreword

This lecture is based my personal work since 1995 with the help of several contributors:.

Photogrammetry: Dr.-Ing.K.Andresen (TU Braunschweig).

Electronics for the marionette (Teach-In of a robot by Showing the Motion), fundamental algorithms and programs for Image Processing: Dipl.-Ing. Ralph Scherge, who is since 1996 a member of the Hewlett Packard Company.

CAD- and Milling-Program HoCad: Dipl.-Ing Heinz Hinrichs.

Vector graphics system GrafProz: Dipl.-Ing. Jens Klüver .

Application of GrafProz for Engraving: Dipl.-Ing. Ralf Berger.

Identification of camera parameters for photogrammetry: Dipl.-Ing. Frank Meyeraan, Dipl.-Ing. Michael Habbe.

JPEG Compression: Hermann Hildebrandt.

3D-Scanner: Dipl.-Ing. Toni Gosling.

General laboratory maintenance and support: Wilhelm Kettwig.

ZEBRA is our Image Processing System.

ZEFIR is our open Computer Graphics System.

Desktop Publishing by PageMaker.

Some words are written in an unusual manner:

Coordinates	correct: co-ordinates
Color	american style, in English colour)
Scanline	correct: scan line

Gernot Hoffmann

September 1999 / 2000 / 2001 / 2002 / 2003 / 2004 / 2005

Contents of the Lecture Computer Vision

The actual lecture consists of a selection of the following contents

1. Graphics Representations
 - 1.1 Metaplanes and Pixels
 - 1.1.1 Metaplane
 - 1.1.2 Graphics Devices
 - 1.1.3 Screens
 - 1.1.4 Plotters
 - 1.1.5 Resumed
 - 1.2 Frames and Windows
 - 1.3 Workstation Transformations
 - 1.3.1 Frame to Screen Transformation
 - 1.3.2 Window to p-Pixel Transformation
 - 1.3.3 Window to q-Pixel Transformation
 - 1.3.4 Undistorted Mapping from Frame to Window
 - 1.3.5 Frame to Graphics Device Transformation
 - 1.3.5.1 Frame to Viewport Transformation
 - 1.3.5.2 Viewport to Frame Transformation
 - 1.3.6 Undistorted Mapping from Frame to Viewport
 - 1.3.7 Example
2. Basic Transformations
 - 2.1 Vectors and Matrices
 - 2.2 Coordinate Rotations
 - 2.3 Coordinate Translations
 - 2.4 Body Rotations
 - 2.5 Aligning a Body Axis
 - 2.6 Perspective Projection using an Orthogonal Image Plane
 - 2.7 Perspective Projection using a Tilted Image Plan
 - 2.8 Homogeneous Coordinates
 - 2.9 Perspective Mapping
 - 2.9.1 General Perspective Mapping
 - 2.9.2 Special Features of Perspective Mapping
 - 2.9.3 Camera Position and Orientation
3. Projections for Computer Graphics
 - 3.1 Perspective Projections
 - 3.1.1 General Perspective Projection using an Orthogonal Image Plane
 - 3.1.2 Perspective Projection for Undistorted Verticals using a Tilted Image Plane
 - 3.1.3 Perspective Projection for Undistorted Fronts using a Tilted Image Plane
 - 3.2 Parallel Projections
 - 3.2.1 General Parallel Projection using an Orthogonal Image Plane
 - 3.2.2 Isometric Parallel Projection using an Orthogonal Image Plane
 - 3.2.3 General Parallel Projection using a Tilt Image Plane
 - 3.2.4 Parallel Projection for Undistorted Fronts using a Tilted Image Plane
 - 3.3 Projection by Perspective Mapping

- 4. Methods for Photogrammetry
 - 4.1 Laboratory Situation
 - 4.2 Computation of Object Coordinates by Use of two Ideal Cameras
 - 4.3 Pragmatic Parameter Identification for Ideal Cameras
 - 4.4 Automatical Parameter Identification for one Ideal Camera
 - 4.5 Simultaneous Parameter Identification for two Ideal Cameras
 - 4.6 Simultaneous Parameter Identification for two Ideal Cameras by Use of Moveable Targets
 - 4.7 Parameter Scaling
 - 4.8 Minimization by the Method of Steepest Descent
 - 4.9 Improved Model for Non Ideal Cameras
 - 4.10 Parameter Identification for Non Ideal Cameras
 - 4.11 Computation of Object Coordinates by Use of two Non Ideal Cameras
 - 4.12 Parameter Identification for one Ideal Camera by Perspective Mapping

- 5. Color Science
 - 5.1 Physical Colors
 - 5.3 CIE (1931) Color Space
 - 5.4 CIELab Color Space
 - 5.4 RGB Color Space
 - 5.5 HLS Color Spaces
 - 5.6 Coding Colors
 - 5.6.1 Indexed Color
 - 5.6.2 True Color
 - 5.6.3 High Color
 - 5.6.4 Conversion of True Color to Indexed Color
 - 5.6.5 Construction of Palettes and Interpolation
 - 5.7 CMYK Color Spaces
 - 5.8 Color Management
 - 5.8.1 Principles
 - 5.8.2 Monitor Calibration
 - 5.8.3 Printer Calibration

- 6. Image Processing
 - 6.1 Introduction
 - 6.2 Geometry
 - 6.3 Segmentation
 - 6.4 Color
 - 6.4.1 HLS Mode and Contrast
 - 6.4.2 RGB Mode
 - 6.4.3 CIELab Mode
 - 6.5 Light Effects
 - 6.6 Filtering
 - 6.6.1 Standard Filters
 - 6.6.2 Contour Filters
 - 6.6.3 Anti Aliasing Filters
 - 6.7 Retouch
 - 6.8 Distortion (Morphing)

- 6.9 Dithering and Halftoning
 - 6.9.1 Hilbert-Peano and Floyd-Steinberg Dithering
 - 6.9.2 Halftoning
- 6.10 Compression
 - 6.10.1 Runlength and LZW Compression
 - 6.10.2 JPEG Compression

- 7. Vector Graphics
 - 7.1 Introduction into PostScript
 - 7.1.1 Bézier Polynomials
 - 7.1.2 Clipping

- 8. Vector Geometry
 - 8.1 Normal Vectors and Visibility
 - 8.2 Coordinate Systems
 - 8.2.1 Cartesian Coordinates
 - 8.2.2 Cylinder Coordinates
 - 8.2.3 Sphere Coordinates
 - 8.3 Basic Surface Elements
 - 8.3.1 Cube
 - 8.3.2 Sphere
 - 8.3.3 Double Elliptic Cone
 - 8.4 Picking Line Segments

- 9. Wireframes and Rendering
 - 9.1 Wireframes
 - 9.2 Rendering
 - 9.2.1 Introduction
 - 9.2.2 Line Algorithms
 - 9.2.3 Z-Buffer Algorithm
 - 9.2.4 Scanline Algorithm

- 10. Light, Reflection and Textures
 - 10.1 Light models
 - 10.2 Reflection
 - 10.3 Shadows
 - 10.4 Textures

- 11. Multi-Body Scenes (mostly deleted)
 - 11.1 Short explanation

- 12. 2D-Scanning
 - 12.1 Practical hints

- 13. 3D-Scanning
 - 13.1 Scanning by Photogrammetry
 - 13.2 Scanning by Laser-Scanner

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Graphics by ZEFIR, Image Processing by ZEBRA, Pages by PageMaker

270 [Test Page for all Color Printers: Web Version, not for printing](#)

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kB Basic Principles for Computer Graphics and Mechanics

60	Bubbles - my first Computer Graphic (1969)
200	Bezier Polynomials
160	Draw a Circle through three Points in 3D
120	Circle a Square
73	Drawing arbitrary Lines by Pixels
160	Ellipse through four Points by Perspective Mapping
234	Euler Angles, Rotation Matrices and Projections
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600	Sphere Tessellation by Icosahedron Subdivision
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50	Balanced Palettes, designed in CieLab for Maps and the Web
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672	Quaternions for Computer Graphics and Mechanics
60	Solution for a Quadratic Equation - not as simple as expected
174	Visually Balanced Random Points in a Square
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lampe08032005.pdf	150	Student's Project: Daylight-Photo-Lamp
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tribus-2000.pdf	550	Display-System TriBus 2000 (German)

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random22122001.pdf	439	Noise Generator with Adjustable Spectrum and Constant Variance (German)
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loewe290800.pdf	39	Lion, Sculpture. New natural Background
loewe04012001.pdf	47	Lion, Sculpture. African Background
virtual290800.pdf	42	Trivial Virtual. Sculpture. Artificial Light for Image Processing
gilga290800.pdf	54	Gilgamesch, Paintings. Color Correction

Brochures **kB** **Made by PageMaker**

mabiprosp.pdf	300	MABi Prospekt .. Institut für Maschinen- und Anlagenbau (German)
mabifalter.pdf	300	MABi Faltblatt ... Institut für Maschinen- und Anlagenbau (German)
hocolor08122004.pdf	405	HoffmannColor ... Advertising Brochure, Example for a CMYK PDF (German)

Utilities

kB Download by right Mouseclick and rename *.Txt to *.Exe

cleantmp.txt	8	CleanTmp.Exe ...deletes all temporary files, use in Autoexec.Bat
pm65link.txt	13	PM65Link.Exe ...lists all Links for all PageMaker Files in one Folder
vesainfo.txt	16	VesalInfo.Exeanalyzes the VBE Status of Graphics Cards
hofrida.txt	128	HoFrida.ExeNyquist Diagrams for Filters; System Identific.(German)

Test

kB Communication Test

test.pdf	000	Communication Test: Rettet die Raucher
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Lectures

kB Material for Students (Password for Org, Intro, Lab, Bild)

pip05.pdf	3700	Internet Programming. Lecture Textbook, 61 Pages, many Images
diplom+master.pdf	60	Subjects for Diploma/Master Theses and Projects
compvis14052002.pdf	1100	What is Computer Vision ? Introduction into my Lecture
covi-org.pdf	50	Organization
covi-intro.pdf	400	References, Tables, Formulas
covi-lab.pdf	1100	Laboratory Exercises, Practicals
covi-bild.pdf	3300	Graphics Collection

 **Cover Page**

TEACH-IN OF A ROBOT BY SHOWING THE MOTION

Gernot Hoffmann

ICIP, Lausanne 1996

ABSTRACT

A computer controlled life size marionette, which is equipped with 12 mechanical degrees of freedom, can be taught to move by a human dancer. The person carries a rucksack with four flashing infrared light emitting diodes, which are strobed by radio transmission. Two CCD-cameras observe the motions. The generalized coordinates of the dancer are computed by use of the images of the light sources and filtered by several methods. When the same music is played, the marionette shows the choreographical motions of the dancer. The delays of the servo-systems are taken into account and the playback speed is synchronized by correlation control.

1. COMPUTER CONTROLLED MARIONETTE

The life size marionette Fig.1 consists of an aluminium skeleton with different textile costumes and heads. She moves vertically by 9 high speed string winches, can turn about the z-axis and move in the horizontal plane in an area of 1.5m x 1.5m.

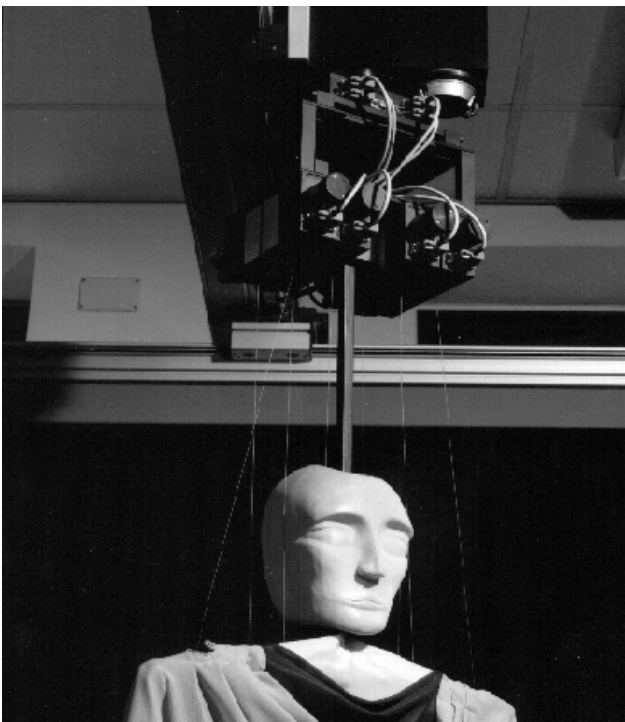


Fig.1 Computer controlled marionette

Two floodlights track the puppet automatically. The altogether 16 degrees of freedom are electrically driven. 5 personal computers, 1 signalprocessor and 2 microcomputers for the horizontal axes are combined in a realtime network.

The dynamics of the servomechanisms were identified and described by behaviouristic models which include the main features like time constants, time delays, small signal bandwidths, limited acceleration and speed [1].

The marionette dances also fully automatically to any kind of music in real time with no prior knowledge. This project is finished and the results were published [2], [3]. The automatic motions consist of bundles of oscillations, which are synchronized with respect to a twelve-dimensional rhythm pattern, computed by the Fourier-Time-Transformation FTT [2], [4], which is quite different to the standard FFT. Thus they include no intellectual or arbitrary elements and it is some need to teach the machinery directly the choreographical part.

Obviously motion to music cannot be taught using a step by step method. The marionette is a trainer for experiments with man machine interfaces which accept human habits. Probably in some years robots will learn smooth and fast trajectories by looking at their master, e.g. for painting, avoiding obstacles or handling heavy loads by multiwire cranes where the operator shows the angles and directions by a platform in his hands.

2. VIDEO MOTOGRAPHY

The term "video motography" is used here for the threedimensional on line measurement of single light sources by use of two video CCD-cameras. The cameras deliver 50 half images per second each, odd and even rows alternating, where the actual half image includes the information of the preceding half image in an adjacent row. Because of the very short video frame time of 20ms it is not reasonable to extract the coordinates from the natural video image. Instead of this attempt, the moving person is equipped with four light emitting infrared diodes (LEDs). In each video frame only one LED flashes for a very short time. The EX-TRAC system by *Wente/Thiedig* [5] computes the column and row numbers of the brightest pixel by hardware for both cameras. Result is a sequence of two pairs of pixel coordinates for LED1, LED2 and so on. Gathering four LEDs needs 80ms. The object space coordinates are computed by methods of photogrammetry, developed by the author and students [6],[7]. The application of EX-TRAC was initiated by a suggestion of *Baum* [8], who had also contributed to other projects of - as he says - On-line-Motografie [9]. The EX-TRAC station was originally connected to the LEDs by cables. To enable free motions the wireless "Motography Rucksack" has been developed..

3. MOTOGRAPHY RUCKSACK

The Rucksack Fig.2 is equipped with four high power infrared LEDs, type OD-100 [10], mounted on a square on adjustable rods. The power is typically 600mW (3A) and max. 1300mW (10A) for short pulses. The half intensity beam angle is $\pm 55^\circ$ from the radiation axis, which is here vertical.



Fig.2 Motography Rucksack, four LEDs on a square

Every 20ms during the vertical retrace of the video signal (1.3ms), the shutters of the cameras are open for 0.5ms. In this interval the one actual LED must be strobed. This is done in the sequence 1,2,3,4 by a quartz controlled counter in the rucksack. The next sequence cannot be triggered directly by the strobe No.1 from the ground station, because the delay of the radio frequency transmission, including the modulator and the receiver filters, is not neglectable: $\Delta T \approx 100\mu s$. Therefore the ground station strobe signal No.4 triggers a digital delay generator that produces a delay $T_d = (20ms - \Delta T_1)$, $\Delta T_1 \geq \Delta T$, which switches the transmitter modulator in advance while the shutter is open. This necessity results also from the fact, that between the ground strobe and the shutter closing a gap of only $90\mu s$ is available. If the shutter is opened longer, then he starts earlier, but the ground strobe is always fixed to the same point of time. No reliable informations about the timing of the whole system were available, therefore this part has been highly experimental. Other methods of synchronization with the ground station, like optical or acustical transmission, did not look promising. A direct *acustical* distance measurement, sometimes suggested, is quite hopeless because of the long wavelength of sound. The Rucksack electronics are supplied by a reliable lead battery and voltage regulators. The LEDs are flashed by constant current controllers with a settling time of only $2\mu s$ and the current 3A is delivered by the battery without voltage controller. The LEDs are mounted vertically, thus on large distances the camera views because of unfavourable radiation angles rather low intensities; nevertheless the signals are detected over more than 5m. The person can move in an area of $4m \times 4m$. The printed card boards are small, but the Rucksack is on purpose rather bulky: the dancing person should be reminded that fuzzy motions are not welcome - the sample rate for each set of four LEDs is only 12.5 Hz. The Rucksack electronics were developed by Scherge [11].

4. PHOTOGRAMMETRY

Fig.3 shows the scenery of photogrammetry: Compute the coordinates $\mathbf{x}=(x,y,z)^T$ of a point in the object space by using coordinates $\mathbf{r}=(r,0,t)^T$ in the *image plane*, delivered by two cameras. Objects near to the image plane are mapped with scalefactor one; the center is fixed to the *viewpoint* in the object space. The image plane is a part of the object space.

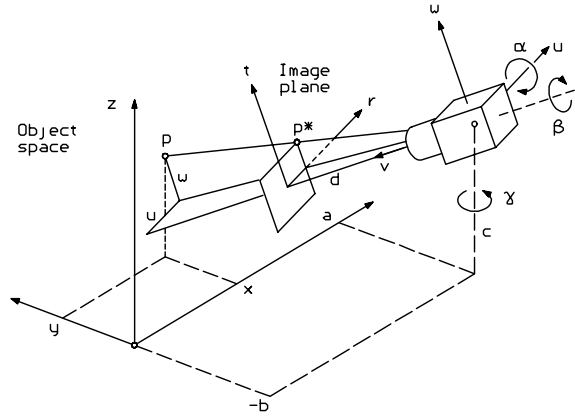


Fig.3 Photogrammetry, one of two cameras

The *image* is projected by the lens to the *picture* in the pixel plane and delivers pixel coordinates $\mathbf{R}=(R,0,T)^T$ for two cameras. The camera transformation is given by Eq.(4.1). The camera constant K has the unit pixel/m. R_0, T_0 are the pixel numbers near to the optical axis, a question which is discussed later. Dividing by the image distance d and introducing a new camera constant $L = K d$ results in Eq.(4.2), where d is merely a scalefactor which must *not* be known. L is in pixel only. No focal length or similar parameters must be determined.

$$\mathbf{r} = (R - R_0) / K; \quad \mathbf{t} = (T - T_0) / K \quad (4.1)$$

$$\mathbf{r} / d = (R - R_0) / L; \quad \mathbf{t} / d = (T - T_0) / L \quad (4.2)$$

The camera is rotated first about the yaw angle γ , then about the elevation angle α and finally about the roll angle β , according to the matrix \mathbf{C} , where c and s mean cosine and sine.

$$\mathbf{C} = \begin{pmatrix} c\beta c\gamma - s\alpha s\beta s\gamma & c\beta s\gamma + s\alpha s\beta c\gamma & -c\alpha s\beta \\ -c\alpha s\gamma & c\alpha c\gamma & s\alpha \\ s\beta c\gamma + s\alpha c\beta s\gamma & s\beta s\gamma - s\alpha c\beta c\gamma & c\alpha c\beta \end{pmatrix} \quad (4.3)$$

The perspective projection is given in coordinates u, v, w :

$$\mathbf{r} = d u / v; \quad \mathbf{t} = d w / v \quad (4.4)$$

By use of the matrix \mathbf{C} and the camera position $\mathbf{a}=(a,b,c)^T$, this can be written down in a homogeneous formulation:

$$\mathbf{A} = \begin{pmatrix} -1 & r/d & 0 \\ 0 & t/d & -1 \end{pmatrix} \quad (4.5)$$

$$\mathbf{A} \mathbf{u} = \mathbf{0} \quad (4.6)$$

$$\mathbf{A} \mathbf{C} (\mathbf{x} - \mathbf{a}) = \mathbf{0} \quad (4.7)$$

This formulation is the base for the identification of camera parameters and the computation of object points as well. The author, not an expert in photogrammetry, did not find equivalent descriptions in recent books of Meisel [12] and Sasse [13].

The identification of camera parameters $\mathbf{p}=(a, b, c, \alpha, \beta, \gamma, L)^T$ is *here* explained for the method of individual calibration.

We use an arrangement of laboratory fixed $n=5$ LED-markers \mathbf{x}_i , and each matrix \mathbf{A}_i is filled with the image of the marker \mathbf{x}_i . The altogether 10 equations cannot be solved simultaneously, therefore the errors $\boldsymbol{\varepsilon}_i$ are introduced:

$$\mathbf{A}_i \mathbf{C}(\mathbf{x}_i - \mathbf{a}) = \boldsymbol{\varepsilon}_i; \dots \mathbf{A}_n \mathbf{C}(\mathbf{x}_n - \mathbf{a}) = \boldsymbol{\varepsilon}_n \quad (4.8)$$

We use then the *method of steepest descent* [14], which is slow but reliable, to minimize a scalar error function:

$$F = \sum_{i=1}^n \boldsymbol{\varepsilon}_i^T \boldsymbol{\varepsilon}_i \quad (4.9)$$

A weighting matrix could be used, if information is available.

The computation of object points is based on two cameras, indicated by the upper index for the same point \mathbf{x} .

$$\mathbf{A}^1 \mathbf{C}^1 \mathbf{x} = \mathbf{A}^1 \mathbf{C}^1 \mathbf{a}^1; \mathbf{A}^2 \mathbf{C}^2 \mathbf{x} = \mathbf{A}^2 \mathbf{C}^2 \mathbf{a}^2 \quad (4.10)$$

This can be written down with block matrices, though it is not necessary for the practical computation.

$$\begin{pmatrix} \mathbf{A}^1 \mathbf{C}^1 \\ \mathbf{A}^2 \mathbf{C}^2 \end{pmatrix} \mathbf{x} = \begin{pmatrix} \mathbf{A}^1 & \mathbf{0} \\ \mathbf{0} & \mathbf{A}^2 \end{pmatrix} \begin{pmatrix} \mathbf{C}^1 \mathbf{a}^1 \\ \mathbf{C}^2 \mathbf{a}^2 \end{pmatrix} \quad (4.11)$$

$$\mathbf{M} \mathbf{x} = \mathbf{N} \mathbf{b} \quad (4.12)$$

This are four equations and three unknown coordinates \mathbf{x} . The matrix \mathbf{b} includes no image information. The best compromise is found by the well known *Gauss transformation* or *normal equation*, with the formal solution:

$$\mathbf{M}^T \mathbf{M} \mathbf{x} = \mathbf{M}^T \mathbf{N} \mathbf{b} \quad (4.13)$$

$$\mathbf{x} = (\mathbf{M}^T \mathbf{M})^{-1} \mathbf{M}^T \mathbf{N} \mathbf{b} \quad (4.14)$$

The system matrix is symmetric positive definite, thus the equations are solved by the *method of Cholesky* [15].

Now we consider an improved camera error model:

In Fig.4 the pixel plane has coordinates $\mathbf{F}=(F,0,H)^T$ instead of $\mathbf{R}=(R,0,T)^T$ and F_0, H_0 correspond to previous values R_0, T_0 . Because the viewline is not identical with the optical axis, the projection is oblique or tilt. The tilt angles δ, ε are correlated to offsets $\Delta f, \Delta h$ or $\Delta F = L \Delta f / d, \Delta H = L \Delta h / d$. The pixel plane is assumed mechanically orthogonal to the optical axis.

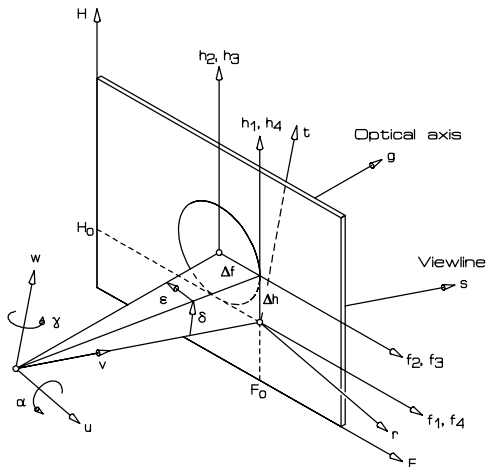


Fig. 4 Projection on a tilt pixel plane

The complete transformation, including the radial rectification by the orthogonal *Legendre polynomials* Q_i [16], is as follows:

$$f_1 / d = (F - F_0) / L; \quad h_1 / d = (H - H_0) / L \quad (4.15)$$

$$f_2 / d = f_1 / d - \Delta f / d = f_1 / d - \varepsilon; \quad h_2 / d = h_1 / d - \Delta h / d = h_1 / d + \delta$$

$$\rho = \sqrt{(f_2 / d)^2 + (h_2 / d)^2} / \rho_{\max} \quad (4.17)$$

$$Q_3 = (1/2)(5\rho^3 - 3\rho); \quad Q_5 = (1/8)(63\rho^5 - 70\rho^3 + 15\rho) \quad (4.18)$$

$$K_p = 1 + q_3 Q_3 / \rho + q_5 Q_5 / \rho \quad (4.19)$$

$$f_3 / d = K_p f_2 / d; \quad h_3 / d = K_p h_2 / d \quad (4.20)$$

$$f_4 / d = f_3 / d + \varepsilon; \quad h_4 / d = K_p h_3 / d - \delta \quad (4.21)$$

$$r / d = (f_4 / d) / (1 + (f_4 / d)\varepsilon - (h_4 / d)\delta) \quad (4.22)$$

$$t / d = (h_4 / d) / (1 + (f_4 / d)\varepsilon - (h_4 / d)\delta) \quad (4.23)$$

The background about the physics of radial distortion is based on [11] and *Regensburger* [17],[18], but *Legendre polynomials* are more suitable than non orthogonal polynomials or sine functions.

For many cases Q_5 alone would be sufficient. Then the parameters of the camera are $\mathbf{p}=(a, b, c, \alpha, \beta, \gamma, L, \delta, \varepsilon, q_5)^T$.

Eq.(4.22) is the linearized version of a projection on a tilt pixel plane. The complete transformation is available from the author. By this attempt we achieve a minimal number of significant parameters. Correlated parameters cannot be identified.

5. GENERALIZED COORDINATES

The coordinates of the moving person are represented by the position and the angles of the Rucksack: $x_0, y_0, z_0, \psi, \theta, \phi$. From \mathbf{x} to \mathbf{u} we rotate about the yaw angle ψ , then about the pitch angle θ and finally about the roll angle ϕ (similar to an aircraft).

The LEDs L_1, \dots, L_4 have body fixed coordinates $\mathbf{u}=(\pm b, \pm b, 0)^T$, but measured values in \mathbf{x} will not fit to a square. We introduce a set of generalized coordinates $\mathbf{q}=(x_0, y_0, z_0, \phi, \theta, \cos\Psi, \sin\Psi)^T$.

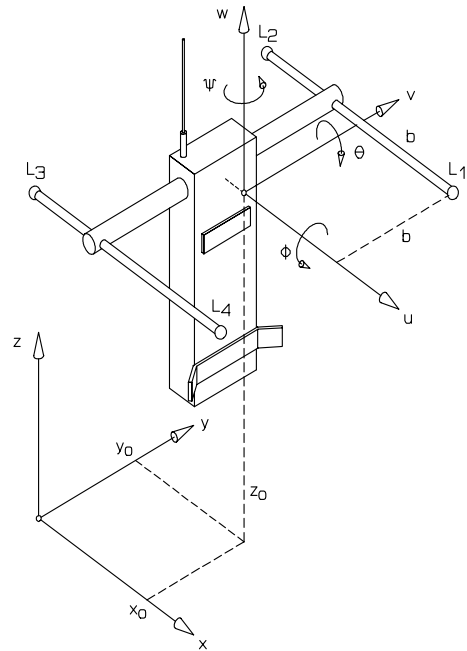


Fig. 5 Coordinates of the Rucksack

The angles ϕ and θ are assumed to be small, but the yaw angle is fully turning and represented by cosine and sine. By use of the *linearized* rotation matrix \mathbf{B} we get 4 sets of 3 equations. These are reassembled to 12 *linear* equations for 7 variables \mathbf{q} :

$$\mathbf{x}_i - \mathbf{x}_0 = \mathbf{B}^T \mathbf{u}_i \quad (5.1)$$

$$\mathbf{M} \mathbf{q} = \mathbf{m} \quad (5.2)$$

The measured values \mathbf{x}_i are stored in $\mathbf{m}=(x_1, y_1, z_1, \dots, x_4, y_4, z_4)^T$. Then the *Gauss transformation* is applied and the resulting system can be solved *analytically*:

$$\mathbf{x}_0 = \sum_{i=1}^4 \mathbf{x}_i / 4 \quad (5.3)$$

$$\Phi = (z_1 - z_4 + z_2 - z_3) / (4b) \quad (5.4)$$

$$\theta = (z_2 - z_1 + z_3 - z_4) / (4b) \quad (5.5)$$

$$\cos \psi = (x_1 - x_2 + x_4 - x_3 + y_2 - y_3 + y_1 - y_4) / (8b) \quad (5.6)$$

$$\sin \psi = (x_3 - x_2 + x_4 - x_1 + y_1 - y_2 + y_4 - y_3) / (8b) \quad (5.7)$$

The computed LED-square is shown on a screen in *realtime*.

6. FILTERING OF THE TRAJECTORY DATA

Sometimes one LED is shaded or several LEDs are invisible. One missing LED can be complemented. This is called *syntactic filtering*. Fig.6 shows that other manipulations on the data are necessary to prepare them off line for sending to the robot.

The trajectory must be smooth, this is a *semantic* information. Graph(B) shows linear bridging. Graph(C) shows lowpass filtering by a 21-stage FIR-filter [19] and a nonlinear compression of the working area.

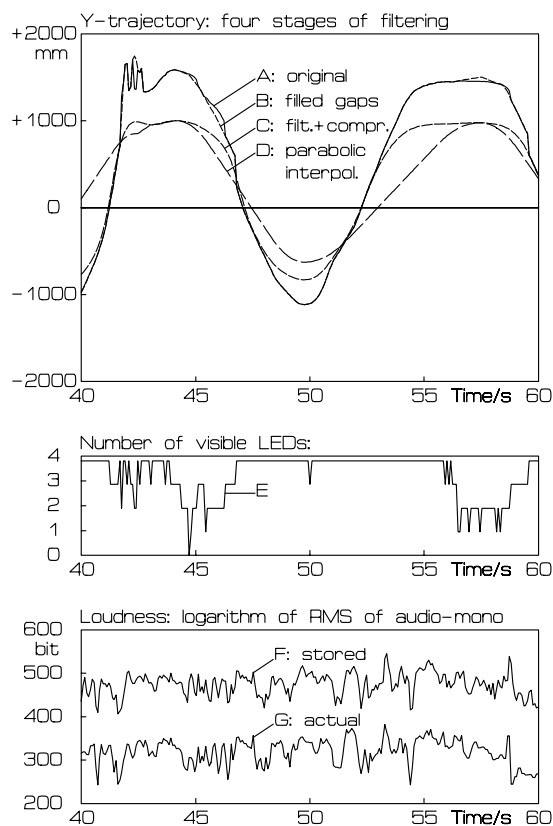


Fig.6 Several stages of digital filtering

For the application of teaching choreography there is a pragmatic aspect too: the dancing motion contains points of rest at musical climaxes, which must be reproduced during the playback by the robot exactly at the same time, even though the machinery is slower than the moving person. This problem is solved by *pragmatic filtering*: Minima and maxima of the trajectory are connected by parabolic interpolation, Graph(D). The ends are parabolic and in the middle the slope is constant with the maximal speed of the servosystem, which must be known. The mean time delay of each servosystem is taken into account by sending the data in advance.

Fig.6 (bottom) shows the speed control by correlation of stored and actual loudness of the music, sampled by $T=20\text{ms}$. Depending on the correlation, stored data are either doubled or skipped. Thus any speed variation of recorders is compensated.

CONCLUSIONS

The method of *Teach-In of a Robot by Showing the Motion* is not very accurate, mainly because of small elevation angles of the two cameras. More cameras would be helpful.

In further applications the LEDs must be fixed on irregular patterns on the moving object and the appropriate set of generalized coordinates must be treated fully *nonlinear*.

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- May 1996. Graphics by Gernot Hoffmann. Photos by Wilhelm Kettwig. The author thanks him and Ralph Scherge for their assistance.

Tables

DIN Paper

DIN	x / mm	y / mm	Ratio	Area / m ²
A0	841.0	1189.0	1.4138	0.9999
A1	594.0	841.0	1.4158	0.4996
A2	420.0	594.0	1.4143	0.2494
A3	297.0	420.0	1.4141	0.1247
A4	210.0	297.0	1.4143	0.0624

Because of round-off errors the formats are not exactly matching:
4 x edgelenh DIN A4 is not equal to edgelenh DIN A0

Character size (point, pt)

DIN point	0.376055 mm	1m = 2659.185 DIN point
Postscript point	0.352777 mm = 1/72 Inch	1m = 2834.652 PS point
US point	0.351460 mm	1m = 2845.274 US point

Frame to screen

$$xw = xwA + (xf - xfA) \frac{xwE - xwA}{xfE - xfA}$$

$$yw = ywA + (yf - yfA) \frac{ywE - ywA}{yfE - yfA}$$

$$xf = xfA + (xw - xwA) \frac{xfE - xfA}{xwE - xwA}$$

$$yf = yfA + (yw - ywA) \frac{yfE - yfA}{ywE - ywA}$$

Window to p-pixel

$$xp = xpm \cdot xw$$

$$yp = ypm \cdot (1 - yw)$$

Window to q-pixel

$$xqm = xpm(xwE - xwA)$$

$$yqm = ypm(ywE - ywA)$$

$$xq = \frac{xw - xwA}{xwE - xwA} xqm$$

$$yq = \frac{ywE - yw}{ywE - ywA} yqm$$

$$xq = (xw - xwA) xpm$$

$$yq = (ywE - yw) ypm$$

Undistorted Frame to Window

$$\frac{x_fE - x_fA}{y_fE - y_fA} = (4/3) \frac{x_wE - x_wA}{y_wE - y_wA}$$

$$x_fE = x_fA + (4/3) \frac{x_wE - x_wA}{y_wE - y_wA} (y_fE - y_fA)$$

$$x_wE = x_wA + (3/4) \frac{x_fE - x_fA}{y_fE - y_fA} (y_wE - y_wA)$$

Frame to Viewport and Viewport to Frame

$$x_v = x_vA + (x_f - x_fA) \frac{x_vE - x_vA}{x_fE - x_fA}$$

$$y_v = y_vA + (y_f - y_fA) \frac{y_vE - y_vA}{y_fE - y_fA}$$

$$x_f = x_fA + (x_v - x_vA) \frac{x_fE - x_fA}{x_vE - x_vA}$$

$$y_f = y_fA + (y_v - y_vA) \frac{y_fE - y_fA}{y_vE - y_vA}$$

Undistorted Frame to Viewport

$$\frac{x_fE - x_fA}{y_fE - y_fA} = \frac{x_vE - x_vA}{y_vE - y_vA}$$

$$x_fE = x_fA + \frac{x_vE - x_vA}{y_vE - y_vA} (y_fE - y_fA)$$

$$x_vE = x_vA + \frac{x_fE - x_fA}{y_fE - y_fA} (y_vE - y_vA)$$

General rotation matrices

$$\mathbf{X}_{21} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

$$\mathbf{Y}_{21} = \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix}$$

$$\mathbf{Z}_{21} = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Camera rotation matrix

$$\mathbf{C}_{41} = \begin{bmatrix} \cos(\beta)\cos(\gamma) - \sin(\alpha)\sin(\beta)\sin(\gamma) & \cos(\beta)\sin(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) & -\cos(\alpha)\sin(\beta) \\ -\cos(\alpha)\sin(\gamma) & \cos(\alpha)\cos(\gamma) & \sin(\alpha) \\ \sin(\beta)\cos(\gamma) + \sin(\alpha)\cos(\beta)\sin(\gamma) & \sin(\beta)\sin(\gamma) - \sin(\alpha)\cos(\beta)\cos(\gamma) & \cos(\alpha)\cos(\beta) \end{bmatrix}$$

Camera rotation matrix with zero roll angle

$$\mathbf{D}_{41} = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\cos(\alpha)\sin(\gamma) & \cos(\alpha)\cos(\gamma) & \sin(\alpha) \\ \sin(\alpha)\sin(\gamma) & -\sin(\alpha)\cos(\gamma) & \cos(\alpha) \end{bmatrix}$$

Tilted image plane rotation matrix

$$\mathbf{T}_{41} = \begin{bmatrix} \cos(\varepsilon) & \cos(\delta)\sin(\varepsilon) & \sin(\delta)\sin(\varepsilon) \\ -\sin(\varepsilon) & \cos(\delta)\cos(\varepsilon) & \sin(\delta)\cos(\varepsilon) \\ 0 & -\sin(\delta) & \cos(\delta) \end{bmatrix}$$

Aircraft rotation matrix

$$\mathbf{A}_{41} = \begin{bmatrix} \cos(\theta)\cos(\psi) & \cos(\theta)\sin(\psi) & -\sin(\theta) \\ -\cos(\phi)\sin(\psi) + \sin(\phi)\sin(\theta)\cos(\psi) & \cos(\phi)\cos(\psi) + \sin(\phi)\sin(\theta)\sin(\psi) & \sin(\phi)\cos(\theta) \\ \sin(\phi)\sin(\psi) + \cos(\phi)\sin(\theta)\cos(\psi) & -\sin(\phi)\cos(\psi) + \cos(\phi)\sin(\theta)\sin(\psi) & \cos(\phi)\cos(\theta) \end{bmatrix}$$

Gyro rotation matrix

$$\mathbf{G}_{41} = \begin{bmatrix} \cos(\beta)\cos(\gamma) & \cos(\alpha)\sin(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) & \sin(\alpha)\sin(\gamma) - \cos(\alpha)\sin(\beta)\cos(\gamma) \\ \cos(\beta)\sin(\gamma) & \cos(\alpha)\cos(\gamma) - \sin(\alpha)\sin(\beta)\sin(\gamma) & \sin(\alpha)\cos(\gamma) + \cos(\alpha)\sin(\beta)\sin(\gamma) \\ \sin(\beta) & -\sin(\alpha)\cos(\beta) & \cos(\alpha)\cos(\beta) \end{bmatrix}$$

Mapping on tilted image plane

$$f = \frac{r / \cos(\varepsilon)}{1 - (r/d) \tan(\varepsilon) / \cos(\delta) + (t/d) \tan(\delta)}$$

$$h = \frac{t / \cos(\delta) - r \tan(\varepsilon) \tan(\delta)}{1 - (r/d) \tan(\varepsilon) / \cos(\delta) + (t/d) \tan(\delta)}$$

Perspective mapping

$$f = \frac{a_0 + \mathbf{a}^T \mathbf{x}}{1 + \mathbf{c}^T \mathbf{x}}$$

$$h = \frac{b_0 + \mathbf{b}^T \mathbf{x}}{1 + \mathbf{c}^T \mathbf{x}}$$

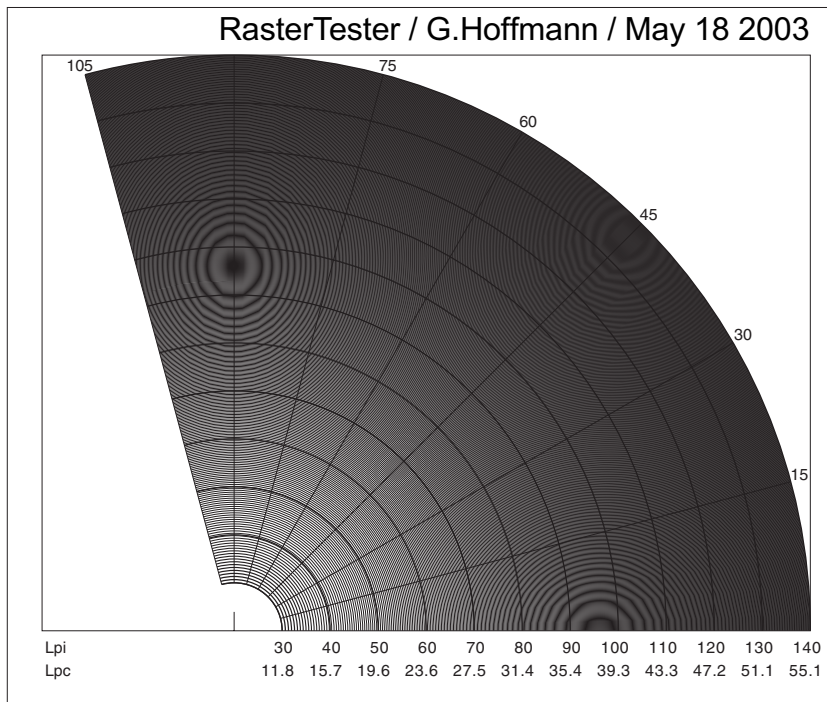
$$\mathbf{a}^T \mathbf{x}_i + \mathbf{0}^T \mathbf{x}_i - f_i \mathbf{c}^T \mathbf{x}_i + a_0 + 0 = f_i$$

$$\mathbf{0}^T \mathbf{x}_i + \mathbf{b}^T \mathbf{x}_i - h_i \mathbf{c}^T \mathbf{x}_i + 0 + b_0 = h_i$$

Raster Tester

Placeholder

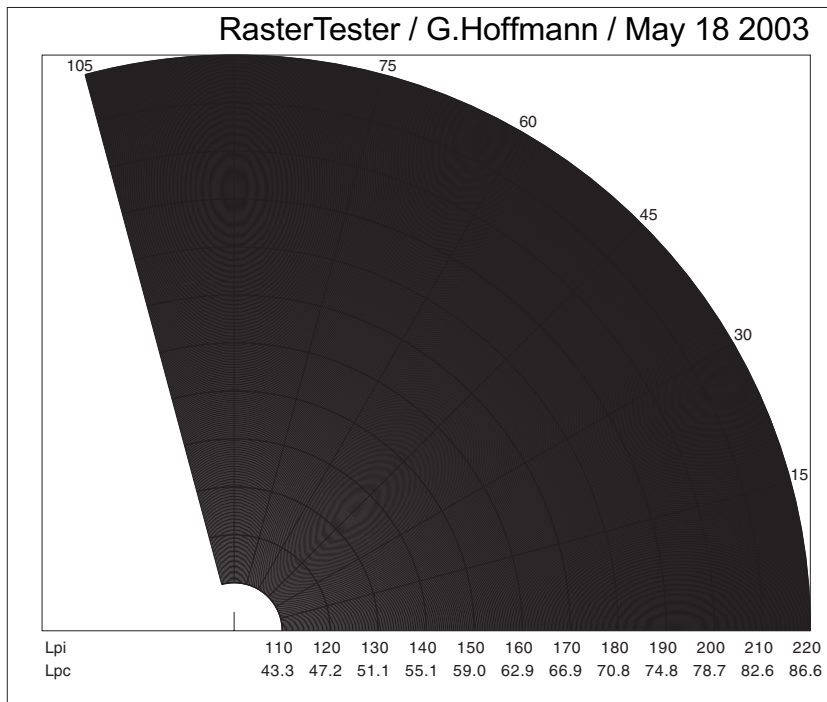
Raster Tester 30 - 140 Lpi



Raster Tester

Placeholder

Raster Tester 110 - 220 Lpi



Old links:

<http://www.fho-emden.de/~hoffmann/>

<http://www.fho-emden.de/~hoffmann/filename.pdf>

Please use since February 2013

New links:

<http://docs-hoffmann.de/>

<http://docs-hoffmann.de/filename.pdf>