Geometric Modelling for Computer Integrated Road Construction

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VORWORT DES HERAUSGEBERS

Das Institut für Technologie und Management im Baubetrieb (früher: Maschinenwesen im Baubetrieb) beschäftigt sich seit 5 Jahren mit der Computer Integrated Road Construction (CIRC). Die Forschungs- und Entwicklungsarbeiten wurden in zwei europäischen Verbundprojekten durchgeführt. Das erste unter dem Titel "Computer Integrated Road Construction" (CIRC), das zweite unter dem Titel "OSYRIS ("Open System for Road Information Support"). Im ersten Projekt stand die GPS-gestützte Überwachung der Einbau- und Verdichtungsgeräte zur Qualitätssicherung im Mittelpunkt. Das zweite Projekt hat die Aufgabenstellung erweitert mit dem Ziel, die Planungsdaten direkt auf den Maschinen zu deren Steuerung - entweder automatisch oder über Informationen für den Bediener - zur Verfügung zu stellen und zu nutzen. Dafür wurde ein Straßenplanungs-Programm dergestalt modifiziert, daß daraus Vorgabedaten für die Einstellung der Maschinenparameter abgeleitet werden können. An Bord der Maschinen installierte Computer wurden entwickelt, die in der Lage sind, diese Informationen in Steuerungselemente umzuwandeln. Zur Datenübertragung wird sowohl GPS als auch eine bodengestützte "Robotic Total Station" mit der jeweiligen drahtlosen Datenfernübertragung verwendet. Das gleiche System wird auch verwendet, um die "As Built" Daten zu erfassen und im zentralen Computer niederzulegen. Diese Daten können sowohl kurzfristig zur Einbausteuerung als auch langfristig zur Planung der Unterhaltung verwendet werden. In beiden Projekten war es notwendig, das Objekt Straße mit seinen Einbauschichten (hier im wesentlichen die Asphaltschichten) so zu modellieren, daß die gesetzten Ziele der Datenkommunikation und der Einbaukontrolle erreicht werden können. Es gibt durchaus praktikable und moderne Instrumente, das Objekt Straße in Form von Längs- und Querprofilen und auch räumlichen CAD-Methoden zu beschreiben und die entsprechenden Daten für die Ausführung zur Verfügung zu stellen. Für CIRC und OSYRIS sind diese jedoch nicht ausreichend. Geht es hier doch darum, die Vorgabedaten direkt auf die Maschine zu übertragen, sie dort in Kleincomputern als Steuerbefehle abzubilden und entweder automatisch oder über MMI (Man-Machine Interfaces) zu nutzen. Hierfür ist eine Modellierung erforderlich, die über die Möglichkeiten gängiger Modellierungen hinausgeht. Das geforderte Modell muß Prozeßdaten verarbeiten können und die Kommunikation verschiedener Maschinen untereinander ermöglichen. Dieser Aufgabe stellte sich Herr Jaroslaw Jurasz und präsentiert die Ergebnisse in seiner Dissertation.

Im Hauptkapitel 4. wird ein digitales Umgebungsmodell präsentiert, das die Erfordernisse einer Computer Integrated Road Construction erfüllt. Rein geometrisch vorgegebene Ausgangsdaten werden dabei mit Maschinenparametern und der Prozeßkontrolle verknüpft. Die Vor- und Nachteile akzeptierter und verwendeter Geländemodelle werden dabei untersucht. Die Notwendigkeit einer neuen Modellierung wird herausgearbeitet. Dabei wird immer im Auge behalten, daß die Praxis des Straßenbaues genauso zu beachten ist, wie die Wirtschaftlichkeit der Datenverarbeitung, der Speicherplätze und der Rechenzeit der verwendeten Computer an Bord und im steuernden Büro.

Als Lösung wird die modifizierte Ribbon-Technologie vorgeschlagen, implementiert und in Praxistests auf der Baustelle verifiziert. Die besondere Leistung der vorgelegten Dissertation besteht darin, diese Technologie angepaßt zu haben und dabei die Vorgaben "so komplex wie nötig" (ohne Prozeßdaten zu verlieren) und "so einfach wie möglich" (um Rechnerkapazität und Zeit zu sparen) konsequent beachtet zu haben. Dabei werden immer die praktischen Erfordernisse beachtet, die darin bestehen, zu hinterfragen, was ist die Straße, was kann dort vorkommen, wie können diese Vorgaben in Programme umgesetzt werden, wie geht das Modell damit um, aus dem GPS resultierende Abweichungen von der Soll-Position zu verarbeiten?

Eine besondere Leistung in der vorgelegten Dissertation besteht auch darin, daß in dem vorgelegten Modell Vereinfachungen, die sich aus der Straßengeometrie ergeben, konsequent genutzt werden, um Rechenkapazität und Rechenzeit zu verringern. Das präsentierte Modell wird auch daraufhin ausgerichtet, daß es eine Kommunikation zwischen den einzelnen Einbaustellen (Maschinen) ermöglicht (Site Networking).

Die Arbeit beschränkt sich nicht nur darauf, die neuen Modellierungskonzepte zu präsentieren, sondern weist in ausgeführten Praxistests nach, daß die Modellierung und zugehörigen Datenübertragungstechniken funktionieren. Die MMI werden dargestellt und in ihrer Funktionsweise beschrieben.

Fritz Gehbauer

VORWORT DES VERFASSERS

Die vorliegende Arbeit ist ein Ergebnis meiner fünfeinhalbjährigen Forschungs- und Entwicklungstätigkeit am Institut für Technologie und Management im Baubetrieb (TMB, bis 2001 Institut für Maschinenwesen im Baubetrieb) der Universität Karlsruhe (TH). An diesem Institut arbeitet unter der Führung von Herrn Professor Fritz Gehbauer ein interdisziplinäres Team zusammen, welches in der Lage ist, Lösungen für die vielfältigen Probleme moderner Baustellen zu erarbeiten.

Zu diesen Problemen gehört unter anderem der rechnergestützte Straßenbau, der in der vorliegenden Arbeit unter dem Schlagwort „Computer Integrated Road Construction“ (CIRC) ausführlich behandelt wird. Zwei Generationen von CIRC-Systemen wurden am TMB im Rahmen der europäischen Verbundforschungsprojekte CIRC und OSYRIS (Open System for Road Information Support) erfolgreich implementiert. Als Entwickler des CIRC-Bordsystems für die Straßenwalze und Leiter des TMB-OSYRIS-Entwicklungsteams habe ich hierbei Lösungen für den rechnergestützten Straßenbau erarbeitet und erfolgreich auf Baustellen getestet. Insbesondere haben mich dabei die mathematischen und informationstechnischen Grundlagen solcher Systeme interessiert, die im folgenden vertieft und untersucht werden. Darüber hinaus wurden neue Ansätze und Algorithmen entwickelt, die sich dank Flexibilität und Leistungsfähigkeit besonders für die Vernetzung des Maschinenverbandes eignen.

Ohne die Unterstützung vieler Menschen wäre die Dissertation in dieser Form nie zustande gekommen. Mein besonderer Dank gilt an erster Stelle Herrn Professor Fritz Gehbauer, für die Möglichkeit, auf diesem faszinierendem Gebiet zu arbeiten und für die mir gewährte Freiheit bei der Ausführung dieser Arbeit. Sehr herzlich möchte ich mich bei meiner Korreferentin, Frau Professor Maria Hennes und Herrn Dr. Norbert Rösch bedanken, für die fruchtbaren Diskussionen, guten Fragen und wertvollen Anregungen, insbesondere zur 3D-Genauigkeitsanalyse sowie für die kritische Durchsicht des Manuskripts.

Die CIRC-Implementation ist eine Teamleistung. Ich bin allen Teammitgliedern am TMB und Projektpartnern sehr dankbar für ihre Beteiligung und Feedback. Besondere Unterstützung erhielt ich von meiner Ehefrau und Arbeitspartnerin Dr. Agata Ligier und meinem Freund und Kollegen Johannes Fliedner, der mich in diese Thematik einführte. Ich schätzte sehr die anspruchsvollen Fragen von François

Peyret vom französischem Laboratoire Central des Ponts et Chaussées, der das CIRC Projekt initiiert hatte. Herrn Alfons Horn von der Firma Moba bin ich für den inspirierenden Gedankenaustausch sehr dankbar.

Da die kleine CIRC-Gesellschaft sehr international geprägt ist, habe ich mich entschieden, die Arbeit in englischer Sprache zu verfassen.

Jarek Jurasz Karlsruhe, im Februar 2003

GEOMETRISCHE MODELLIERUNG FÜR DEN RECHNERINTEGRIERTEN STRAßENBAU - AUSFÜHRLICHE ZUSAMMENFASSUNG

Schlagworte: Bänder, Baumaschinensteuerung, Bordrechner, Digitales Geländemodell, Digitales Umgebungsmodell, Annäherung des Straßenentwurfs, Entwurfsübertragung, Flächendeckende dynamische Verdichtungskontrolle, Hermitesches Spline, Nivellierung, Rechnergestützter Bau und Straßenbau, Rechnerintegrierter Bau und Straßenbau, Straßenmodell, Ribbons, Tensorprodukt-Fläche.

KAPITEL 1. EINFÜHRUNG

Heutzutage werden Baumaschinen immer häufiger mit EDV-Systemen ausgestattet, die das Bedienpersonal unterstützen und aufwendige Kontroll- und Dokumentationsaufgaben übernehmen. Ihre Anwendung ist dank der jüngsten Fortschritte der Positionierungstechnologie und mobiler EDV möglich. Vor allem der Straßen- und Erdbau bietet ein vielversprechendes Anwendungsfeld durch sich wiederholende und klar definierte Aufgaben. Gerade hier spielt die kontinuierliche Qualitätskontrolle eine große Rolle. Besonders in den neuen Vertragsmodellen, wie z. B. funktionelle Verträge oder Build-Own-Operate wünschen die Benutzer, sehr aktiv an der Qualitätskontrolle teilzunehmen. Hohe zusätzliche Kosten, sowie die beschränkte Funktionalität und niedrige Robustheit sind Faktoren, die den Fortschritt der Bord-EDV Technologie bremsen.

Die erwähnte EDV-Technologie gehört zu dem allgemeinen Konzept des **rechnerintegrierten Bauens** (engl. Computer Integrated Construction, CIC), das als eine EDV-basierende Integration von Informationen aus Baumanagement, -Planung, -Entwurf und -Durchführung definiert werden kann. Im deutschsprachigem Raum spricht man dabei öfter von „Rechnergestützem Bau“, bzw. „Maschinensteuerung“. Diese Begriffe erfassen aber nicht das gesamte Integrationskonzept.

Der **rechnerintegrierte Straßenbau** (engl. Computer Integrated Road Construction, CIRC) ist eine Spezialisierung des CIC-Konzeptes, die dank der speziellen Geometrie und einfachen Struktur der Straße sehr vielversprechend ist. Die im Straßenbau anstehenden Aufgaben lassen sich **informationstechnisch besonderes gut beschreiben und automatisieren**.

So wie das geometrische Modell des Produkts in seinem Soll- und Ist-Zustand das wichtigste Integrationswerkzeug für CIC darstellt, ist auch die Modellierung der

Geometrie für die CIRC Anwendung entscheidend. Daher befaßt sich die vorliegende Arbeit mit den **geometrischen Modellierungsmethoden** im rechnerintegrierten Straßenbau. Das geometrische Modell ist dabei als **digitales Umgebungsmodell** (engl. Digital Environment Model, DEM) zu bezeichnen. Es wird auf dem Bordrechner der Maschine verwaltet und stellt ein Herzstück jeder CIRC Implementation dar. Ein DEM setzt sich aus Soll- und Ist-Zuständen zusammen, also aus dem Straßenentwurf, der durchzuführenden Arbeit der Maschine und ihrer Aufzeichnung. Im Falle, daß die erreichte Arbeit nicht aufgezeichnet wird, ist das DEM statisch und als Digitales Geländemodell (DGM) bekannt.

Die bisherige Forschung hat sich vor allem auf Problematik der Positionsbestimmung konzentriert. Weniger Aufmerksamkeit wurde dem Aspekt der Informationsmodellierung geschenkt. Als CIRC DEMs wurden bisher die gängigen Informationsmodelle der geographischen Informationssysteme (GIS) verwendet, vor allem Raster und Dreiecksvermaschungen (TINs), die einige Nachteile aufweisen. Vor allem wurde bisher die Genauigkeit und Flexibilität dieser Modelle im CIRC Kontext nicht untersucht.

Mit der zunehmenden Zahl und wachsenden Funktionalität der Unterstützung-Systeme spielt die Frage nach der Interoperabilität und Standardisierung eine bedeutende Rolle. Unterschiedliche Maschinen, z. B. Asphaltfertiger und Walzen mehrerer Hersteller müssen kooperieren, um die gemeinschaftliche Aufgabe erfolgreich ausführen zu können. Die Ausrüstung der einzelnen Maschine kann sich unterscheiden, jedoch benötigt man ein gemeinsames Datenmodell, um die Zusammenarbeit zu ermöglichen. Entwicklung eines solchen Datenmodells ist das Hauptziel dieser Arbeit. Im Hinblick auf dieses Ziel ist die Struktur der Dissertation aufgebaut. Im Kapitel 2. werden die grundlegenden CIRC Konzepte und bestehenden Systeme mit dem Schwerpunkt auf der geometrischen Modellierung dargestellt. Nach der Diskussion der geometrischen Natur der Straße im Kapitel 3. und bestehenden Modellierungsmethoden wird im Kapitel 4. ein neues, effizientes und flexibles DEM für CIRC eingeführt. Die Ergebnisse der Anwendung, Konvertierungsmethoden und Datenaustauschproblematik werden anschließend ausführlich diskutiert.

KAPITEL 2. CIRC KONZEPT

Um die zu modellierenden Informationen zu identifizieren wird im Kapitel 2. das grundlegende CIRC Konzept diskutiert. Die verwendeten Maschinen lassen sich in drei Gruppen unterteilen: Profilierungsmaschinen, Oberflächenbehandlungsmaschinen und Erdbaumaschinen. Dabei sollen auf einer Asphaltbaustelle die ersten zwei Gruppen, und auf einer Erdbaustelle unter Umständen alle Maschinengruppen im Verbund arbeiten. Darüber hinaus sind die Maschinentypen und deren Hersteller oft unterschiedlich. Diese Situation ist als eine **heterogene Baustelle** zu bezeichnen.

Danach werden typische CIRC Anwendungsfälle sowie der Stand der Technik präsentiert, und als Grundlage der funktionellen Analyse eines allgemeinen CIRC Systems benutzt. So läßt sich die zu verarbeitende Information identifizieren und klassifizieren. Um den Bauprozeß darstellen zu können, wird zuerst die Modellierung des Maschinenwerkzeuges angesprochen. Der Prozeß läßt sich mit Hilfe der an die Werkzeuggeometrie verbundenen Attribute, wie z. B. Temperatur, Schichtdicke usw. darstellen. Die Werkzeuggeometrie ergibt sich als eine stückweise geradlinige, möglicherweise variable Struktur. Um sie darstellen zu können, werden Koordinatensysteme der Baustelle und der Maschine, sowie deren Transformationen eingeführt.

KAPITEL 3. DIE INTERAKTION ZWISCHEN STRAßEN-CAD UND CIRC

Die geometrische Natur einer Straße wird in dem Prozeß des Straßenentwurfs bestimmt. Darüber hinaus kann der Entwurf direkt auf die Maschine übertragen werden. Folglich behandelt Kapitel 3. die Interaktion zwischen dem Straßen-CAD und CIRC. Wichtige Analogien können gezogen werden, da beide Prozesse auf EDV basieren und die gleichen Objekte darstellen müssen. Dabei ergibt sich das **kontinuierliche Modell der Straße**, auch dynamisches Querprofil genannt, als eine wichtige Voraussetzung für CIRC Anwendungen.

Darüber hinaus können Straßenkurven als Splines von Klothoiden und Straßenflächen als zu solchen Splines zugeordnete Regelflächen beschrieben werden. Da diese sich wegen der Rechenkomplexität für eine CIRC-Implementierung nicht direkt eignen, müssen praktische Entwurfsannäherungen entworfen werden. Heutzutage werden einfache Annäherungsmethoden angewandt, die auf dem gleichmäßigem Abtasten der Straßenkurven und Interpolation mit Polylinien bzw. Dreiecken beruhen. Dieses Verfahren ist analog zu der Absteckung der Höhenbezugslinie. Dabei wird der Approximationsfehler oft nicht berücksichtigt. Eine Genauigkeitsanalyse ergibt, daß bei vertikaler Krümmung oder Verwindung ein sehr dichtes Abtasten erforderlich ist, um ein hinreichend genaues, dreidimensionales Modell zu erhalten. Dies spricht auch für die Anwendung der rechnergestützten, dreidimensionalen Nivellierung, da eine solche Absteckung nicht wirtschaftlich ist.

Dank der durchgeführten Genauigkeitsanalyse können Abtastmethoden mit optimierter Genauigkeit entwickelt werden. Darüber hinaus werden neue, sehr genaue Annäherungsmethoden entworfen, die auf den **linkubischen Tensor-Produktflächen** beruhen. Diese können zur genauen Berechnung der krummlinigen Koordinaten angewandt werden und können teilweise das dynamische Querprofil ersetzen. Darüber hinaus werden bestehende Formate für den Entwurfstransfer auf ihre Eignung für die CIRC Anwendung untersucht.

KAPITEL 4. DAS DIGITALE UMGEBUNGSMODELL FÜR CIRC

Die Rechnerimplementation des digitalen CIRC-Umgebungsmodells wird in Kapitel 4. diskutiert. Ein vergleichender Überblick existierender Datenmodelle, die auf Rastern, Polylinien und Dreiecken basieren, zeigt deren beachtliche Nachteile, insbesondere für eine heterogene Baustelle. Aus diesem Grund wird ein neues, vektorielles Datenmodell eingeführt, das auf **diskreten Bändern** (engl. Ribbons) basiert. Es eröffnet eine allgemeine Struktur, um notwendige Informationen über Geometrie und Arbeitsprozesse auf der Straßenbaumaschine speichern und bearbeiten zu können. Dabei ist die Kompatibilität mit bestehenden Datenmodellen, vor allem mit Straßendatenbankstrukturen gegeben. Im Gegensatz zu den anderen erwähnten Modellen kann das Ribbonmodell sowohl eine komplexe Geometrie, als auch umfassende Prozeßdaten aufnehmen, bietet Maschinenunabhängigkeit und ermöglicht Maschinenkooperation. Es eignet sich für alle drei geforderten Maschinengruppen. Für zwei Gruppen wurde die Anwendung in mehreren Baustellentests erfolgreich bestätigt. Mit der erforderlichen Flexibilität und Leistung eignet sich das Ribbon-Datenmodell als eine universelle Darstellung der Umgebung im Straßenbau. Die Ribbon-Beschreibung wird als Teil des zukünftiges internationales Standards für Automatisierung im Erdbau diskutiert. Darüber hinaus kann sie für andere linienförmige Bauten, wie Gleise, Kanäle oder Tunnel angewandt werden.

ABSTRACT

Keywords: compaction control, Computer Integrated Construction and Road Construction, design approximation and transfer, Digital Terrain Model, Digital Environment Model, Hermite spline, levelling, machine control, on-board computer, ribbon, road model, tensor product surface.

Nowadays the construction machines are increasingly often equipped with the on-board IT systems, which support the operators and take over the difficult and cumbersome control and documentation chores. Application of such support systems is possible thanks to the recent advances in positioning technology and mobile IT, and is especially promising in civil engineering, e.g. road construction, where the machines perform well-defined, repeatable tasks. The emerging technology meets the needs of the users, who wish to exert active control of the quality, in particular with the new contract models, e.g. Build-Own-Operate. The additional costs, limited functionality and low robustness are the factors slowing down the progress of the on-board IT technology.

The mentioned construction support technology belongs to a general concept of **Computer Integrated Construction** (CIC), which can be expressed as the IT-enabled integration of management, planning, design, construction, and operation information. The geometrical model of the product in its designed and actual form is the most important integration tool.

This work is focused on the geometric modelling methods used in **Computer Integrated Road Construction** (CIRC), which is a particularly promising CIC specialisation. The designed road, the machine missions and work achieved by the machines are the elements of the **Digital Environment Model**, which needs to be managed on-board. Until now little research attention has been paid to the information modelling aspect of CIRC. Common GIS geometric models have been applied, for example raster or **triangular irregular networks** (TINs). Accuracy and interoperatbility of these models in the CIRC context have not been studied. As standardisation efforts are currently initiated, both issues are of major importance. The work presents basic CIRC concepts, concentrating on geometrically based entities, discusses modelling methods currently in use and presents a novel, efficient and flexible environment modelling method for CIRC application. The results of its application, conversion methods and data exchange issues are discussed extensively.

The dissertation is structured as follows. In order to identify information to be modelled, the basic CIRC concept is discussed in Chapter 2. The state of the art of existing systems is presented, and serves as a basis for the functional analysis of the generic CIRC system. This allows to establish the terminology used further on. The core concepts of coordinate systems, tool geometry, as well as position definition and process attributes are discussed.

Modelling of the road geometry is crucial to any CIRC application. The road design process defines the road geometry for CIRC directly, by design transfer, and indirectly, by road's geometrical nature. For this reason Chapter 3. is devoted to the interaction between the road design and CIRC. Important analogies can be drawn, as both processes are IT-based and need to model the same objects. **Continuous road model** is an important prerequisite for CIRC. The road curves and surfaces resulting from current road design methodology can be described as **clothoid splines** and associated **ruled surfaces**. As they are not directly suitable for CIRC implementation, practical design approximation methods have to be sought. As of today, the simple methods based on sampling and polyline interpolation, analogous to the setting-out procedure, are used with no guarantees on approximation accuracy. To fill this gap, several 3D modelling methods are studied. The accuracy estimates and sampling methods with guaranteed worst-case accuracy are given. New methods based on the **lincubic tensor product surfaces** are derived and prove particularly advantageous. The applicability of existing design exchange standards for CIRC is discussed.

The computer implementation of the CIRC digital environment models is discussed in Chapter 4. Existing data models show considerable drawbacks, especially for the **heterogeneous worksite**. To circumvent this situation a novel **ribbon data model** is introduced. It provides a general structure to store efficiently all geometrical and process information on a road construction machine, yet is compatible with all data models in current use. As opposed to the other mentioned models, the ribbon model can accommodate complex geometry and comprehensive physical process attributes, offers machine independence and enables inter-machine co-operation. It can be applied for all three required machine groups, and as of today it has been successfully verified for the two of them in several full-scale tests. Ribbon model offers the flexibility and the performance required for the universal on-board representation of the environment in road construction. Presented approach is discussed as a possible part of a new ISO standard for data controlled earth-moving operation.

CONTENTS

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ABBREVIATIONS

nD – n-dimensional ($n = 1,2,3$)

ACD – Asphalt Compaction Documentation

ACV – Asphalt Compaction Value

ACW – Achieved Work CIF Format

B-O-O – Build-Own-Operate

B-O-T – Build Operate Transfer

BSS – Board Sub-System

CAD - Computer Aided Design

CAES – Computer Aided Earthmoving System

CAGD – Computer Aided Geometric Design

CAM – Computer Aided Manufacturing

CAN – Controller Area Network

CANopen – CAN-based higher layer protocol

CESIS – Construction Equipment Support Information System

CIC – Computer Integrated Construction

CIF – CIRC Interchange Format

CIM – Computer Integrated Manufacturing

CIRC – Computer Integrated Road Construction

CIRC project – European research and development project “Computer Integrated Road Construction”

CIRCOM – A CIRC project implementation for compactors

CIRPAV – A CIRC project implementation for pavers

COM – Component Object Model (Microsoft)

CPU – Central Processing Unit

DEM – Digital Environment Model

DG – Differential Geometry

DGM – Digital Terrain Model (Ger. Digitalles Geländemodell)

DOF – Degree Of Freedom

DTM – Digital Terrain Model

DXF – Drawing eXchange Format

EDI – Electronic Data Interchange

ETRS – European Terrestrial Reference System

FDVK – Dynamic Compaction Control (Ger. Flächendeckende Dynamische VerdichtungsKontrolle)

GIS – Geographical Information System

GPS – Global Positioning System

GSS – Ground Sub-System

IAI – International Alliance for Interoperability

IFC – Industry Foundation Classes

ISO – International Organisation for Standardisation

IT – Information Technology

LAN – Local Area Network

MMI – Man-Machine Interface

MultiCIRCOM – extension of CIRCOM for multiple compactors

NIAM – Nijssen's Information Analysis Method

NSI – Non-Self Intersecting

OKSTRA – Objektkatalog für das Straßen- und Verkehrswesen

OLE – Object Linking and Embedding

OPC – OLE for Process Control

OSYRIS – European research and development project “Open System for Road Information Support”

PDM/EDM – Product/Engineering Data Management

PPP – Public-Private Partnership

PSS – Positioning Sub-System

RMS – Root Mean Square (Error)

RTS – Robotic Total Station

SADT – Structured Analysis and Design Technique

SIS – Site Information System

STS – Statistic CIF Format

STEP – ISO Standard 10303 for the Exchange of Product Model Data

TCP/IP – Transmission Control Protocol/Internet Protocol – a common family of protocols comprising today's Internet

TIN – Triangular Irregular Network

TMB – Institut für Technologie und Management im Baubetrieb (Institute for Technology and Management in Construction), formerly Institut für Maschinenwesen im Baubetrieb at the University of Karlsruhe

WGS-84 – World Geodetic System 1984

WSI – Worksite Information CIF Format

XML – eXtensible Markup Language

COMMON SYMBOLS

A – clothoid parameter

α – arc angle

$\mathbf{C}(t)$, $\mathbf{C}$ – parametric curve in $\mathbb{R}^2$ or $\mathbb{R}^3$

$\mathbf{C}^n$ – class of n-times continuously differentiable functions

χ – roll (cross slope) angle

Δl – sampling distance

δ – material density

ε – approximation error

ε_{len} – length error, difference between arc length and chord length with polyline approximation

ε_{orth} – orthogonal error, maximum distance between arc and chord with polyline approximation

$\mathbf{G}^n$ – class of n-th order geometrically continuous parametric curves

h – height, grade

H – radius of vertical curvature (Ger. Halbmesser)

$H_i^3(u)$ – i-th ($i = 0, 1, 2, 3$) cubic Hermite polynomial

φ – machine heading (yaw), tangential angle of a curve

$\mathbf{J}$ – Jacobian matrix

K, κ – curvature

L, l – curve length, distance

λ – pitch (long slope) angle

$\mathbf{n}$ – normal vector

o – offset coefficient

θ – layer thickness

$\mathbf{p}$ – position vector

$\mathbf{R}$ – rotation matrix

R, r – radius of horizontal curvature

$\mathbb{R}^n$ – Cartesian n-space

s (cursive) - scalar

s_C – tangent of the cross slope

s_L – tangent of the long slope

t – time, curve parameter

τ – torsion

u – curvilinear abscissa (in longitudinal direction)

unit($\mathbf{x}$) – a unit normalisation of a vector $\mathbf{x}$

v – speed of a curve or machine

$\mathbf{v}$ (bold) – vector in $\mathbb{R}^2$ or $\mathbb{R}^3$ with components v_x, v_y etc.

w – curvilinear ordinate (in lateral direction)

W – road width

$\dot{x}_t$ (dot) – a derivative of x with respect to t (t omitted when clear from the context)

$\hat{x}$ (hat) – an approximation of x

$\|\mathbf{x}\|$ – Euclidean norm of vector $\mathbf{x}$

x – Cartesian abscissa

y – Cartesian ordinate

z – height (grade)

z_{Pos}, z_{Des} (subscript) – an actual (as measured by positioning sensor) and designed value of a variable z

1. Introduction

1.1. CONTEXT

Nowadays the construction machines are increasingly often equipped with the on-board computers, which support the operator and take over the difficult and cumbersome control and documentation chores [Peyret 00] [Thurner 01]. Their application is especially promising in civil engineering, especially road construction, where the machines perform **repeatable and well-defined tasks** [Peyret 99]. Also users wish to participate more actively in the quality control, especially in new contract models, e.g. B-O-O (Build-Own-Operate) or B-O-T (Build-Operate-Transfer). Thanks to advances in positioning technology and on-board computing, and following the need of the users, the on-board IT plays increasing role on the modern road construction site.

The terms *construction automation* (Ger. Bauautomatisierung), *machine control* or *guidance* (Ger. Baumaschinensteuerung [Resnik, Bill 00]), *digital quality assurance* (Ger. digitale Qualitätssicherung [Thurner 01]), *worksite management* or *support systems* are used to describe the systems mentioned above. However, they seem too limited to grasp the issue as a whole. The general term adopted in this work is **Computer Integrated Road Construction** (CIRC) [Peyret, Philippe 92], derived from the established concept of **Computer Integrated Construction** (CIC) [Sanvido, Medeiros 90] [Jung, Gibson 99]. The core concept of CIC is the comparison between the design (target state, Ger. Soll-Zustand) and the results of construction execution (as-built state, Ger. Ist-Zustand) in an IT system. CIRC can be defined as an emerging interdisciplinary field, combining traditional road construction with the advances of information technology, real-time positioning and machine control, in order to automatically capture the road construction process and allow for online comparison with the designed road. The goal is to build better roads, and to build them in more conscious way. The focal point of each CIRC application, and also one of this work, is an **on-board computer**[1], central unit combining the road design with the work results.

1.2. PREVIOUS WORK

The year 1992 can be called the advent year of CIRC with the article "Towards Computer Integrated Road Construction" [Peyret, Philippe 92]. Initially many researches recognised the precise and robust positioning as the most important prerequisite in realising the CIRC concept [Beliveau 96]. Advances in positioning technology [Frank 98], most importantly the of availability of precise GPS [Peyret et al. 97] and laser technology [Gorham 94], gave rise to the first research implementation of the CIRC concept for compactors: MACC [Froumentin, Peyret 96], [Li et al. 96] and pavers: [Legentil, Martineau 93], RoadRobot [Gonçalves et al. 96]. Further progress included the implementation of testing facilities for civil engineering positioning devices [Peyret 98] and application of data fusion technique for multi-sensor positioning systems with improved precision and robustness towards sensor failures, most importantly GPS shadow phases [Bonnifait et al. 97] [Bouvet et al. 01]. This gave rise to the second generation of the CIRC systems: CIRCOM and CIRPAV [Circ Web] [Pampagnin et al. 98a] [Pampagnin et al. 98b] [Peyret 00] [Peyret et al. 00a] developed in a European project CIRC[2], Asphalt Compaction Documentation System ACD by Geodynamik [Thurner 98] or Compaction Tracking System CTS-I [Li et al. 96] and CTS-II [Oloufa 01]. New laser positioning devices [Baum et al. 98] [Bouvet et al. 00] were applied in 3D levelling systems for pavers and graders. The 3D earthmoving support systems were introduced in order to optimise mass transfer [Kim et al. 00]. The understanding of the process aspects together with measurement and control methods has been developed intensively. We can mention especially the work on estimation and optimisation of compaction [Thurner 98] [Bomag Web] [Kröber et al. 01] [Floss 01] and pre-

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[1] Or microcontroller, depending on the IT technology used.

[2] European project CIRC: Computer Integrated Road Construction (Brite-EuRam III No. BE-96-3039) 1997-2000. To avoid ambiguity with the CIRC concept, the term "CIRC project" is used to denote this initiative, in frame of which two particular implementations of the CIRC concept (CIRCOM for compactors and CIRPAV for pavers) have been developed.

compaction [Monecke et al. 97, 98, 99]. The attempts for fully automatic road construction have been undertaken with RoadRobot [Gonçalves et al. 96] and AutoPave [Krishnamurthy et al. 98]. Automatic operation is especially promising in the landfill applications [Kunighalli et al. 95]. Thanks to the advances in the wireless technologies [Garza, Howitt 98], the information exchange in the team of machines could be introduced, for example in MultiCIRCOM [Peyret et al. 00b].

A major outcome of the CIRC project was the conclusion that advanced positioning and instrumentation are necessary, but not sufficient for a successful CIRC implementation. More general aspects: digital environment modelling, data exchange issues, Man-Machine Interfaces (MMI) etc. start to play deciding role. So far, considerably less research has been devoted to these issues.

The system developed in the European project OSYRIS[3] (Open System for Road Information Support) [OSYRIS Web] [Ligier et al. 01] [Jurasz et al. 02] can be mentioned as a third generation CIRC application. The advances include worksite-wide information exchange (site networking) using open interfaces, high configurability and modularity including low-cost positioning configurations [Jurasz, Kley 02], advanced functionality, including an asphalt cooling model and new compaction estimation methods [Delclos et al. 01].

With the increasing number and extending functionality of support systems in existence, the problems of interoperability and standardisation become increasingly important. Differently equipped machines from several vendors will have to co-operate in order to perform the common task. Depending on the kind of machine, the level of provided on-board support may be different, yet common data models are needed in order to enable the co-operation. This is especially important in perspective of the standardisation attempts [Peyret, Miyatake 01] [Peyret 02].

The broader idea of Computer Integrated Construction has been studied quite extensively [Reinschmidt et al. 91] [Teicholz, Fischer 94]. The problems in successful introduction lie in information modelling aspects and economical overheads [Elzarka 01]. Application of the CIC concept to civil engineering is especially promising

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[3] European project OSYRIS: Open System for Road Information Support (Growth No. GRD1-1999-10815), 2000-2003.

[Peyret 99] due to well defined and repetitive nature of the civil engineering tasks. Also economical analyses are encouraging [Hoffmann 01] [Seungwoo 02].

1.3. CONTRIBUTIONS

The author has been participating for over five years in research and development of two generations of CIRC systems within the projects CIRC and OSYRIS. As a development team leader at the Institut für Technologie und Management im Baubetrieb (TMB, Institute for Technology and Management in Construction)[4], he was extensively dealing with the following problems:

- development of efficient and robust on-board computer software and hardware,
- digital representation of the road construction process, especially geometric aspects and mathematical foundations of CIRC,
- interaction between the road design and a CIRC system,
- wireless site networking.
- human interaction, Man-Machine Interfaces (MMI),
- ensuring the credibility and integrity of results.

Several of these issues have not been widely studied so far. Many basic, but important aspects of the CIRC implementation (e.g. terminology, tool modelling, coordinate systems, including curvilinear coordinates) require more precise definition and discussion. Little is known about the limitations and accuracy of the used geometric models (e.g. raster, triangular networks), especially in three dimensions. Interoperable, flexible, networking-friendly digital representations need to be sought. These problems are central to this work.

The primary contributions of the work described in this dissertation are:

- Mathematical foundation for CIRC implementation (Sect. 2.6-2.6.4), most importantly the approximation methods of the road design (Sect. 3.5) – numerical methods for efficient modelling of the three dimensional road surface and curvilinear coordinates with worst-case guarantee.
- A universal on-board description of the worksite, known as a *ribbon description* (Chapter 4.). Presented approach can be used to implement profiling and

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[4] Until 2001 IMB, Institut für Machinenwesen im Baubetrieb.

surfacing support systems and enables the co-operation of all types of machines used on the road construction site.

Other contributions are:

- state of the art study of existing CIRC systems (Sect. 2.4),
- functional analysis of a generic CIRC system (Sect. 2.5).
- definition of basic CIRC concepts,
- state of the art study of design exchange formats (Sect. 3.6).

1.4. OVERVIEW OF STRUCTURE

In order to identify information to be modelled, the basic CIRC concept is discussed in Chapter 2. The state of the art of existing systems is presented, and serves as a basis for the functional analysis of the generic CIRC system. This allows to establish the terminology used further on. The core concepts of coordinate systems, tool geometry, as well as position definition and process attributes are discussed.

Modelling of the road geometry is crucial to any CIRC application. The road design influences the functioning of CIRC systems directly, by design transfer, and indirectly, through road's geometrical nature. For this reason Chapter 3. is devoted to the interaction between the road design and CIRC. Important analogies can be drawn, as both processes are IT-based and need to model the same objects. Continuous road model, also known as dynamic cross section is an important prerequisite for CIRC. The road curves and surfaces resulting from current road design methodology are described using terms of Computer Aided Geometrical Design and Differential Geometry as clothoid splines and clothoid ruled surfaces. As they are not directly suitable for CIRC implementation, practical design approximation methods have to be sought. As of today, the simple methods analogous to setting-out procedure, based on sampling and polyline interpolation, are used with no guarantees on approximation accuracy. To fill this gap, several 3D modelling methods are studied. The accuracy estimates and sampling methods with guaranteed worst-case accuracy are given. New methods based on the lincubic tensor product surfaces are derived and prove particularly advantageous, allowing for correct interpolation between static cross sections and major reduction of the sampling point set. Further on the existing design exchange standards are surveyed and discussed.

The computer implementation of the CIRC digital environment models is discussed in Chapter 4. Existing data models show considerable drawbacks, especially for the heterogeneous worksite. To circumvent this situation a novel ribbon data model is introduced. It provides a universal structure to store efficiently all geometrical and process information on a road construction machine, yet is compatible with all data models in current use. The ribbon data model offers the flexibility and the performance required for the universal on-board representation of the environment in road construction. It can be applied for all three required machine groups, and as of today it has been successfully verified for two of them in several full-scale tests. As opposed to the other data models in use, the ribbon model can accommodate complex geometry and comprehensive physical process attributes, offers machine independence and enables inter-machine co-operation. Presented approach can be applied not only to roads, but also to other linear civil engineering structures, for example railways, canals or tunnels.

2. CIRC Concepts

2.1. OVERVIEW

In this chapter the basic concepts of CIRC are discussed, starting from the context and motivation. The selective state of the art survey of existing systems is presented, and serves as a basis for the functional analysis of the generic CIRC system. This allows to establish a common terminology used further on. Finally the core concepts of coordinate systems, tool geometry, as well as position definition and process attributes are discussed.

2.2. CIRC CONTEXT

2.2.1. INTERDISCIPLINARY NATURE

The Computer Integrated Road Construction is a wide interdisciplinary field, combining advances in several interconnected domains (Fig. 2-1.). The involved domains can be described in a more detailed, but non-exhaustive way with the following keywords:

- Information technology – data storage and exchange technologies, Computer Graphics and Geometry, Computer Aided Geometrical Design, Algorithm Theory, Network Theory, On-board computers, mobile and wireless applications, implementation techniques, hardware development, MMI aspects, robustness.
- Real-time positioning – positioning devices, especially GPS receivers and RTS[5], navigation systems, data fusion, Kalman filtering.
- Surveying and GIS (Geographical Information Systems) – positioning devices, coordinate systems, geographic/spatial modelling, handling and supervision in the field.
- Sensor, Automatic Control – positioning and process sensors, control algorithms, machine control.

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[5] Robotic Total Station, also known as tracking tacheometer.

- Road administration, Road CAD – client requirements, contractual aspects, establishment of procedures, geometry definition, Pavement Management Systems, Road Databases.
- Civil Engineering – process and management aspects, user requirements, procedures, economical requirements.
- Human Interaction – MMI aspects, ergonomy, personnel training, psychological aspects.

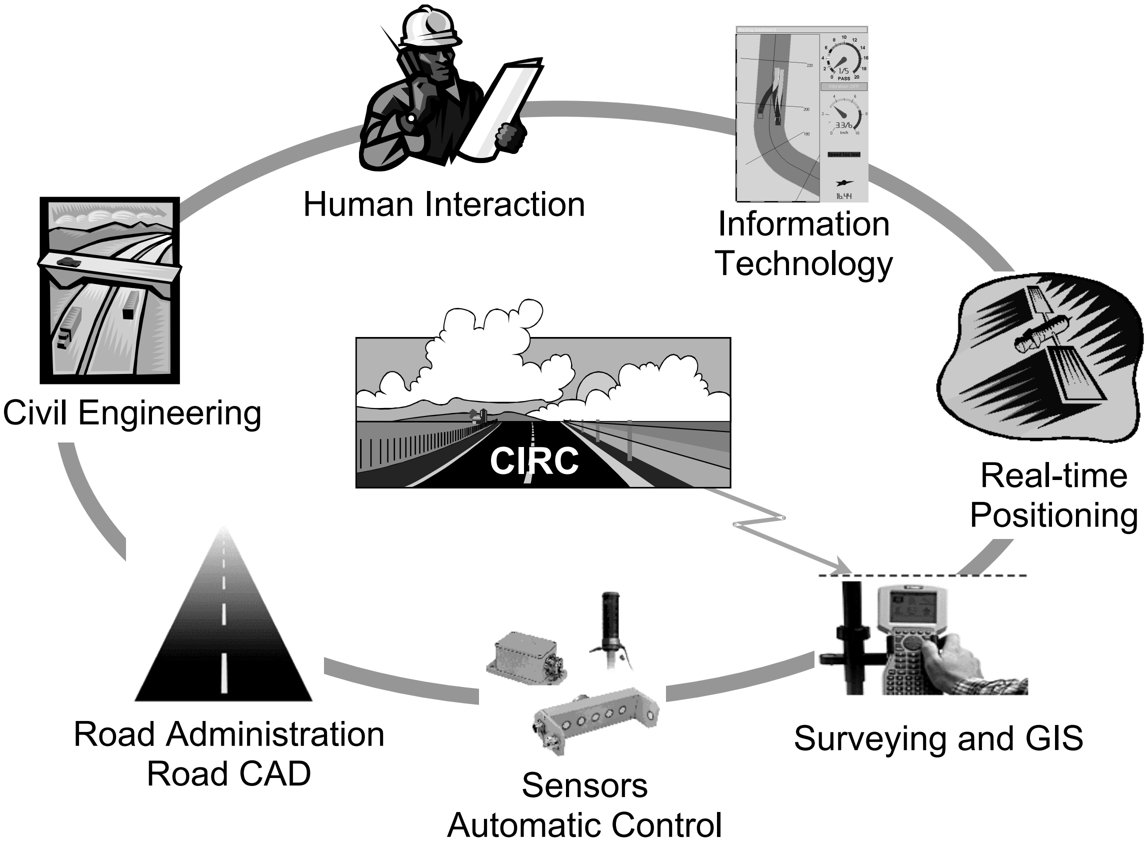

Fig. 2-1. Interdisciplinary nature of the Computer Integrated Road Construction.

As specialists from several fields need to co-operate efficiently, clear definition of interfaces, responsibilities and terminology is crucial. Also the MMI and psychological aspects proved to be very important for a successful CIRC implementation.

2.2.2. CIRC AS A SUBSET OF CIC

Several CIRC concepts can be derived from the more general concept of Computer Integrated Construction (CIC). It can be defined as the application of computer systems to integrate the management, planning, design, construction, and operation of constructed facilities. The concept of CIC is in turn derived from that of Computer

Integrated Manufacturing (CIM), which can be defined as an integrated information processing system for production planning and control [Sanvido, Medeiros 90]. Compared to other manufacturing industries we can mention these characteristic features of the construction industry, delaying the introduction of modern IT in the realisation of the construction projects [Willems 98]:

- one-of-a-kind character, large size and complexity of the construction product,
- low standardisation, low reuse of former designs, resulting in "starting from the scratch" approach,
- high level of competition, slim profit margins and tight legal regulations,
- reduced production times with high time pressure, leading to concurrent design and engineering,
- continuously changing co-operation alliances between involved organisations, complex sub-contracting structure,
- management traditionally based on improvisation skill rather than information management system,
- dependency on weather and soil conditions.

The application of CIC offers the following advantages [Willems 98]:

- better integration of activities, for example sub-contracting management,
- improved quality and quality control,
- higher use of standard elements, reuse of design,
- faster time-to-market, for example due to concurrent engineering, smoother transition between design and manufacturing,
- higher deployment of autonomous and automatic machines.

Research in the CIC field has shown that at the heart of any effective CIC system a three dimensional (3D) CAD model of a product is required [Teicholz, Fisher 94], [Reinschmidt et al. 91]. To integrate all parties involved in the project, a CIC system combines 3D CAD models with other project planning and management tools. In order to model the construction process, one needs to distinguish between the designed and actual product state. The project and eventually process information can be in most cases attributed to these geometrical models, offering a basis for intuitive visualisation. Visualisation is recognised as one of the most important tools for promoting interaction and collaboration between project team members.

Despite of this, the 3D CIC systems are not applied widely due to [Elzarka 01]:

- slim profit margins of the contractors, precluding spending on innovative systems,
- high degree of expertise required to operate such systems,
- lack of standards for information exchange,
- lack of construction-oriented software - focus on design,
- time-consuming nature of creating 3D models.

These shortcomings clearly apply also to the CIRC applications. However the specific nature of road construction makes it especially attractive for automation:

- mechanised tasks of repeatable, well-defined nature,
- specific geometry with a single dominant direction,
- simple, repeatable structure: layered, monolithic, with little assembly parts[6].

Except of the CIC paradigm, one can take the broader view on the existing applications of automation and computing in construction, which can be represented as poorly connected "islands" [Hannus Web]:

- Construction – Accounting and Data Management, Quantity Calculation, Production Planning and Automation.
- Engineering Design – CAD, Finite Element Analysis, Parametric design, Structural analysis.
- Architectural Design – 2D Draughting, 3D Visualisation.
- Product Modelling.
- Facility Management.

In this context CIRC can be seen as a connection between road CAD and Production Planning and Automation.

There are numerous efforts to define and standardise the data managed and exchanged between the mentioned "islands", for example:

- CAD standards, where DXF (Drawing eXchange Format) is an interesting example. It is a relatively simple and universal format, supported by most CAD software packages, used also in the road applications. As the abstraction level is low, project information has to be encoded, for example using colour or layer

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[6] For instance manholes, traffic signs or curbs.

information. The intervention of specialist is often required to verify and correct the received data.

- Product Modelling approaches: STEP [Schenck, Wilson 94], PDM/EDM: Product/Engineering Data Management, EDI: Electronic Data Interchange.
- IFC - Industry Foundation Classes, originated by IAI - International Alliance for Interoperability [iai Web] are data elements to describe building structure and associated processes. As of today the civil engineering domain and linear worksites are not covered.
- Internet-driven approaches, especially based on XML(eXtensible Markup Language) [aecXML Web] [bcXML Web] [ifcXML].

The mentioned approaches are necessarily abstract and comprehensive, possibly too complicated to be applied on-board. Several of them are actively driven industry initiatives, however until now there is no universal, dominant solution or standard. Road construction domain maintains its own set of standards, discussed in Sect. 3.6.

2.2.3. CIRC IN THE CONSTRUCTION PROCESS

CIRC can be applied in the road life cycle (Fig. 2-2.) at two phases: **construction** of the new road or **maintenance** of the existing road. Maintenance includes various measures to preserve and improve[7] the function of a pavement structure. Substantial part of the European motorways and trunk roads were built in the sixties and require increasingly intensive maintenance. Around *80..90%* of the road construction in Europe are nowadays maintenance tasks, making them an important case for CIRC. The distinction concerns mostly the initial state, size, budget and duration of the project, but not the technology, which is similar in both cases.

It is important to note that for each phase of the life cycle a suitable **information model** exists, IT- or paper-based: as-required, as-designed, as-planned, as-built, as-used, as-maintained, as-demolished etc. As of today these models are hardly interconnected, due to incompatibilities and distributed co-operation structure of the involved organisations.

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[7] Improvement measures are known as *rehabilitation.*

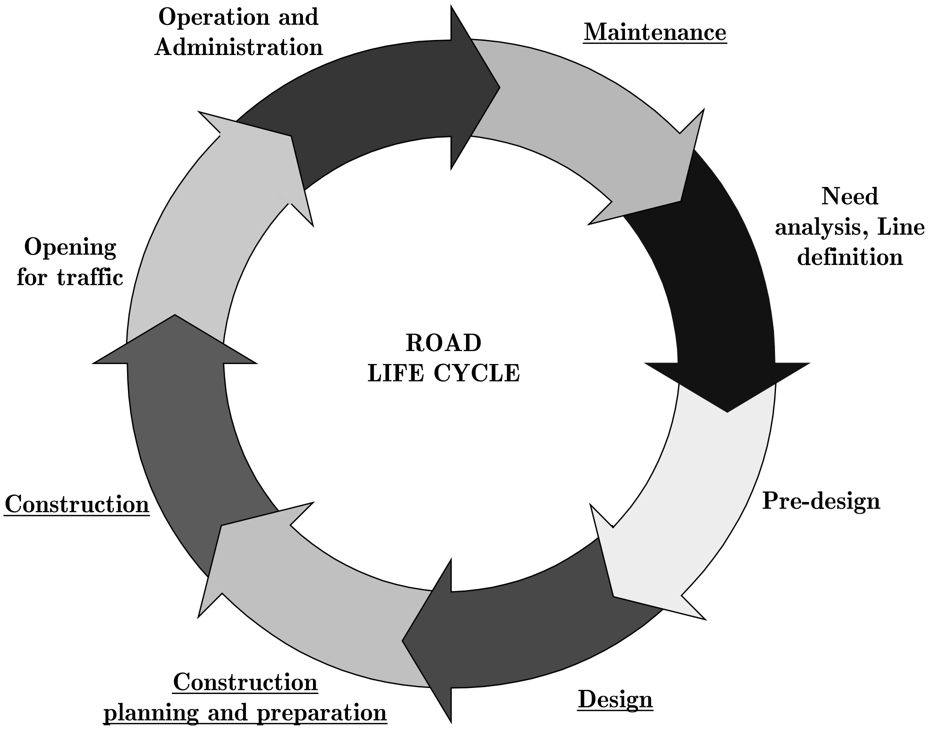

Fig. 2-2. Road life cycle.

The CIRC-relevant phases are underlined. A suitable information model exists in each phase: as-required, as-designed, as-planned, as-built, as-used, as-maintained, as-demolished etc. As of today these models are hardly interconnected.

The construction/maintenance involves the following operations:

- construction of bridges and tunnels (esp. new roads),
- earthmoving (esp. new roads):
  - cut and fill operations,
  - spreading of the aggregates,
  - levelling and compaction of the earthworks surface.
- milling and recycling (especially in maintenance phase),
- laying (building-in) of the pavement layers. Depending on their nature, this can involve:
  - asphalt laying and compacting of the flexible (asphalt) pavement, or
  - concrete laying (slip-form paving) of the concrete pavement.
- pavement compaction,
- placement of traffic signs, manholes etc.

The focus of this work is on the asphalt pavement operations: laying and compacting. However, the results can be directly applied to the concrete pavement operations, and with modifications to the earthmoving tasks.

The typical **layered structure** of the asphalt road is presented in Fig 2-3. [Circ]. It is relatively simple compared e.g. to the structure of the building. Moreover, as the pavement operations are normally performed layer by layer, the CIRC system needs to manage only one layer definition at a time.

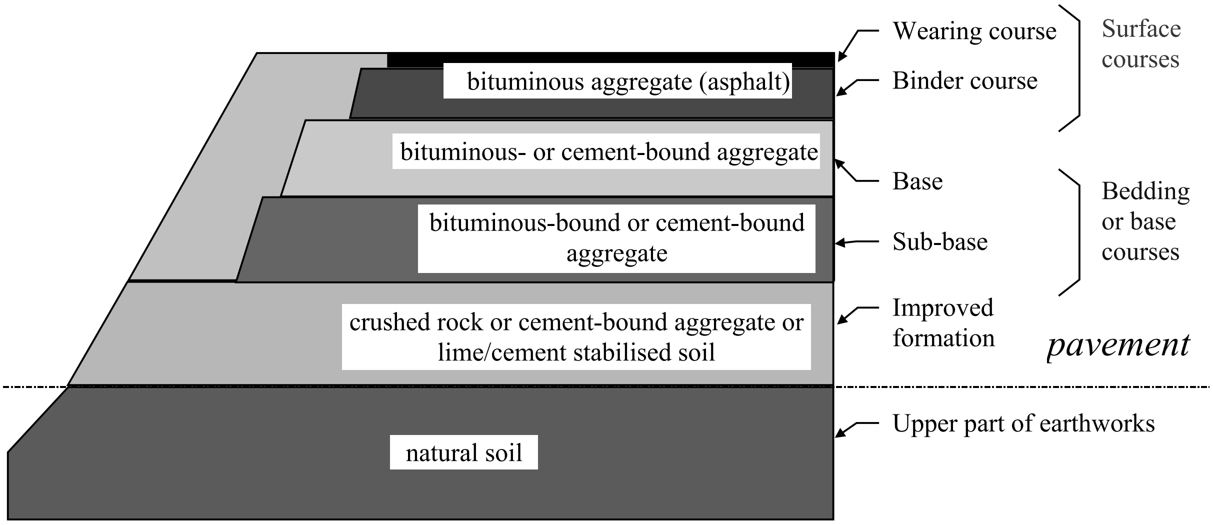

Fig. 2-3. Structure of a flexible pavement.

As the mentioned operations are performed by machines, well-defined and of repeatable nature, they are attractive for automation [Peyret 99]. In particular, most of the operations require tedious manual placement of the markers (lines, stakes, stringlines), in order to provide a reference for the machine operators. This operation is known as setting-out and can be replaced by CIRC ("virtual stringline").

Following Peyret's classification [Peyret 99], the involved machines can be grouped as follows:

a) profiling machines (eg. asphalt and concrete pavers, motor graders, milling machines),

b) surfacing machines (eg. compactors, bitumen spreaders, painters, heaters etc.) [8],

c) earthmoving and mining machines (eg. bulldozers, wheel loaders, excavators),

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[8] The mentioned processes are performed on the surface, but may affect the pavement in depth.

d) drilling machines (not discussed here).

The machines typically work in a team (e.g. rollers or bulldozers), therefore the **team functions** need to be addressed by the more advanced CIRC systems. On the asphalt worksite the profiling and surfacing machines work together, whereas in the case of the earthworks a co-operation between all three machine groups may be required. Combined with the variation of types and manufacturers, this situation can be described as a **heterogeneous worksite**.

The paver and a group of rollers can be treated as a closely working paving team. For example if the pre-compaction of the screed drops (e.g. due to the increase in speed or decrease of material core temperature [Monecke 99]), an additional roller effort may be used to obtain an equalised compaction effect [OSYRIS].

The surfacing machines operate in 2D environment, whereas profiling and earth moving machines require the third dimension. The classification as "2D" or "3D machines" is useful.

2.3. CIRC APPLICATIONS

In this section we will discuss the particular CIRC applications for different tasks and machine classes.

2.3.1. CIRC IN PROFILING: LEVELLING

Levelling (Ger. Nivellierung) is of central importance for profiling tasks. It is a task of controlling the elevation or thickness of material layer. This concerns both the control of the material placement (laying, spreading) and removal (grading, milling). Levelling of the asphalt layers cannot be corrected easily and must be performed within specified tolerances. The typical thickness values and corresponding tolerances for the road layers are shown in Fig. 2-4. [Circ].

Nowadays most profiling machines are equipped with 1D levelling controllers of the tool [Moba Web]. Two controllers have to be applied, as the tool, in the form of a screed, blade or milling drum (Sect. 2.6), has at least two degrees of freedom (DOFs). These DOFs are typically controlled by hydraulic actuators at the extremities of the tool. One can control the relative elevations (grades)[9] z or the cross slope of the tool

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[9] Thickness of the layer θ is just a special case of a relative elevation.

χ. A stringline, an existing layer, a road curb or laser plane can be applied as a vertical reference, sensed by mechanical, sonic or laser grade sensors. Additional DOFs may appear e.g. due to the break angle or extensions of the screed, but they are rarely controlled.

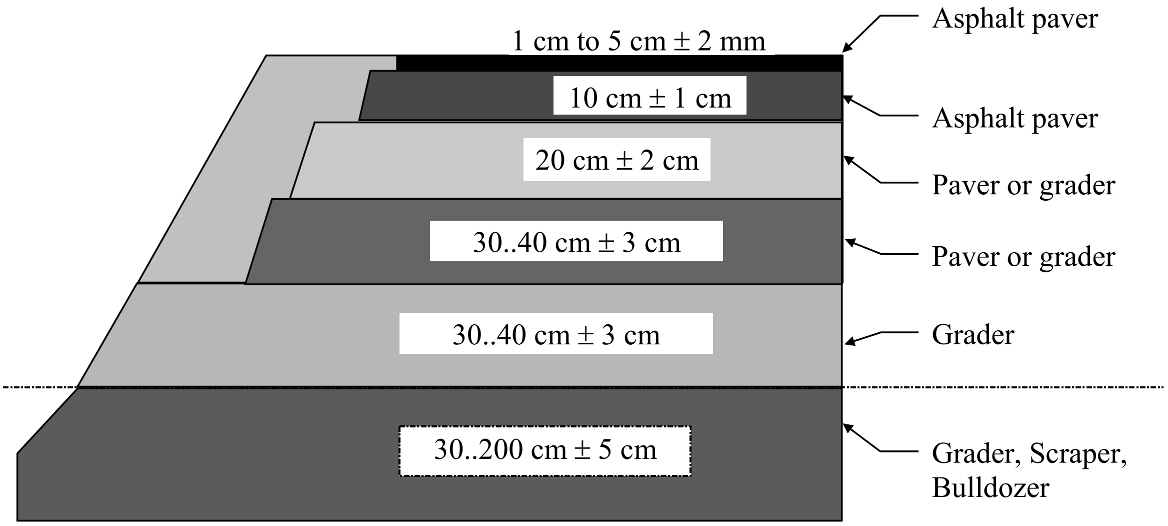

Fig. 2-4. Typical thickness, required accuracy and the machines applied to create the layers of the flexible pavement.

Separate controller is used for each DOF of the tool. The levelling error ε_z of the controller is calculated as:

$$\begin{aligned} z_{Des} &= const, \\ \varepsilon_z &= z_{Des} - z_{Pos}, \end{aligned} \tag{2.1}$$

where z is the controlled 1D grade, subscript $_{Pos}$ denotes actual position measured by the sensor and $_{Des}$ designed (set) position. The set position can be entered or modified manually. Based on the levelling error, the controller generates electric signals which command the hydraulic valves of the actuators, e.g. tow-point cylinders. Typically proportional control is used, i.e. the command signal proportional to the levelling error [Wagenbach 01]. Slope control can be formulated analogously.

As the **target/as-built comparison** takes place, a 1D levelling system can be considered as a simple realisation of a CIRC concept. However, the result of the comparison is not stored.

Predictive levelling can be realised if the deficiencies of the previous layer are known, taking into account the compaction ratio (Fig. 2-5. [Skibniewski et al. 01]). The corrected elevation or thickness of the new layer can be stored in the levelling system, for example as a function of distance:

$$z_{Des} = f\left(l_{Pos}\right). \tag{2.2}$$

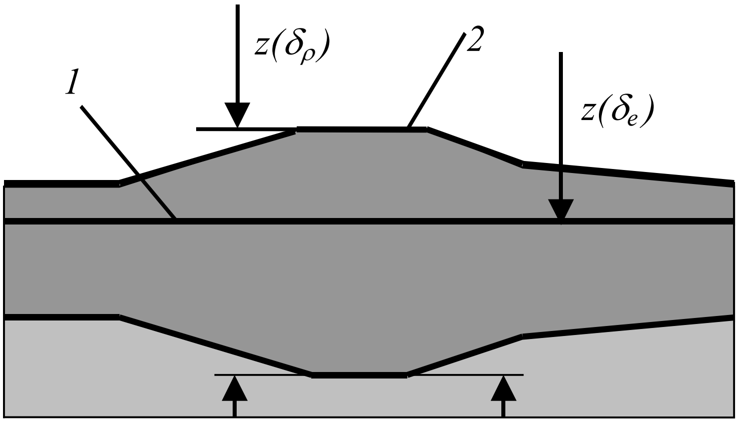

Fig. 2-5. Concept of predictive levelling to correct surface unevenness.
1 – after compaction, 2 – before compaction, z(δ_p) – grade at density δ_p, z(δ_e) – grade at density δ_e.

The 3D levelling application, also known as “virtual stringline”, is based on 3D positioning (typically from RTS) and a **Digital Terrain Model** (DTM, Ger. DGM - *digitales Gelände Model*). DTM is based on the design and describes the road as a height field over domain D:

$$z = f_{DTM}(x, y) \text{ for } (x, y) \in D. \tag{2.3}$$

One can derive the slopes by calculating the height field’s derivative in the desired direction. The application of the 3D levelling requires a sensor delivering the three-dimensional position estimation $\mathbf{p}_{Pos} = \left(x_{Pos} \quad y_{Pos} \quad z_{Pos}\right)$ in the same coordinate frame as DTM. The levelling error ε_Z can then be calculated as follows and input to the 1D levelling algorithm:

$$\begin{aligned} z_{Des} &= f_{DTM}\left(x_{Pos}, y_{Pos}\right), \\ \varepsilon_Z &= z_{Pos} - z_{Des}. \end{aligned} \tag{2.4}$$

The 3D sensor combined with the DTM becomes effectively a grade sensor. Typically a slope controller is used for another DOF.

Currently 3D levelling is applied in about 1% of the worksites [OSYRIS], mainly for new, big constructions (e.g. motorways, airfields). If the previous layer is correct, constant thickness is held manually or a fixed tool setting is used. For these reasons the 1D levelling or mixed 1D-3D applications remain very important and the scope of CIRC applications should not be limited to the 3D case.

For high slopes (e.g. railway construction) the levelling algorithm has to take into account that the tool's degree of freedom is in surface normal $\mathbf{n}$, not vertical direction. This requires a measurement of the unit normal $\mathbf{n}_{Pos}$ (for example with slope sensors) and projection of the measured position $\mathbf{p}_{Pos}$ on the DTM surface, which requires solving the following 3x1 non-linear equation for the levelling error in the normal direction ε_n.

$$\mathbf{p}_{Pos} + \varepsilon_n \mathbf{n}_{Pos} = \begin{bmatrix} x & y & f_{DTM}(x,y) \end{bmatrix}^T \tag{2.5}$$

Beside of the geometry, there are several factors influencing the levelling result, most importantly variation of machine speed and material properties, for example temperature and pre-compaction. Except of automatic control, presented algorithms can be used for validation of the correct geometry in subsequent layers, making the as-built survey obsolete.

2.3.2. CIRC IN SURFACING: ASPHALT COMPACTION

The focus of the compaction operation is to obtain uniform density, which is a crucial factor in ensuring satisfactory pavement performance. A *1%* decrease in the density is known to decrease the pavement lifetime by *10%*. At the same time the density is verified by laboratory tests for only about *one millionth* of the laid asphalt mass [OSYRIS]. As of today a strict adherence to the **compaction plan** (Fig. 2-6. [Hutschenreuther, Wörner 98]), repeated a fixed number of times, is the only means of achieving possibly uniform compaction over the paved area.

The lateral overlap, marked with the dashed lines, has to be kept constant. The lanes are to be changed over cold material, so as not to destroy the surface of the fresh material. The next repetition of the compaction plan is shifted due to the progressive movement of the paver. As the compaction process proceeds, the marks left by the compactor in the material are increasingly difficult to recognise. This makes it difficult to change the direction at the right places, avoiding longitudinal gaps. Additionally the segment length and compactor speed need to be co-ordinated continuously and adjusted accordingly to the speed of the paver and the road width, whereas the speed should be kept possibly constant.

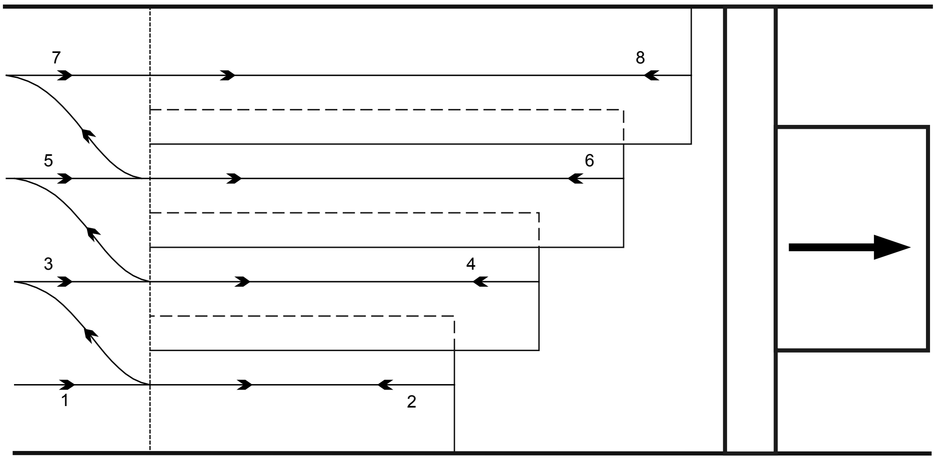

Fig. 2-6. Compaction plan for paving over the whole width.

Lateral overlap, marked with dashed lines, yields typically 10-15 cm.

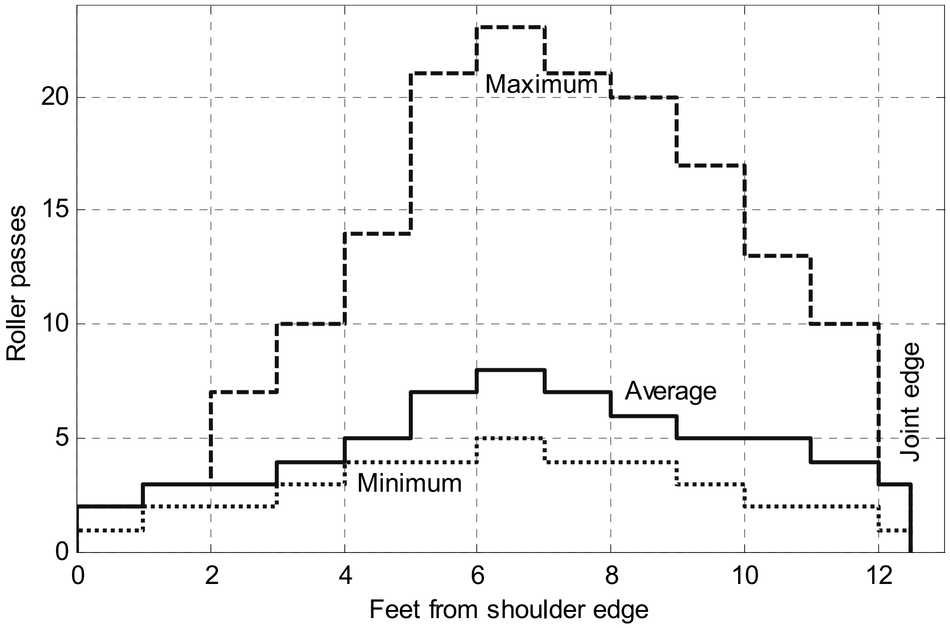

Fig. 2-7. Lateral variation of roller passes.

The observations were made at 23 locations in a 2-mile stretch of pavement, rolled with a 12-ton three-wheel roller.

Additionally the **temperature** of the layer is a crucial factor influencing the compaction process. Efficient compaction is possible only in a temperature window depending on the mix used, typically *100 .. 120-150°C.*

For these reasons it is very difficult to apply the compaction plan correctly. Already in the late sixties it became clear that the compaction plan is very difficult to keep in the practice (Fig. 2-7. [Kilpatrick, McQuate 67]). Clearly the two lateral extremities of a pavement, the joint and edge, tend to receive less compaction than the rest of the cross section. Moreover the section marked as "maximum" has been seriously over-compacted, as it received roughly 3 times more compaction energy compared to the average.

Also the more recent tests confirm, that the common result is over-compaction in the central area of the road and under-compaction close to the edges [Geodynamik Web]. As shown in Fig. 2-8. the maximum and minimum number of passes on a given lateral stripe can vary between *10* and *40*! It is clear, that the compaction pattern was not kept correctly.

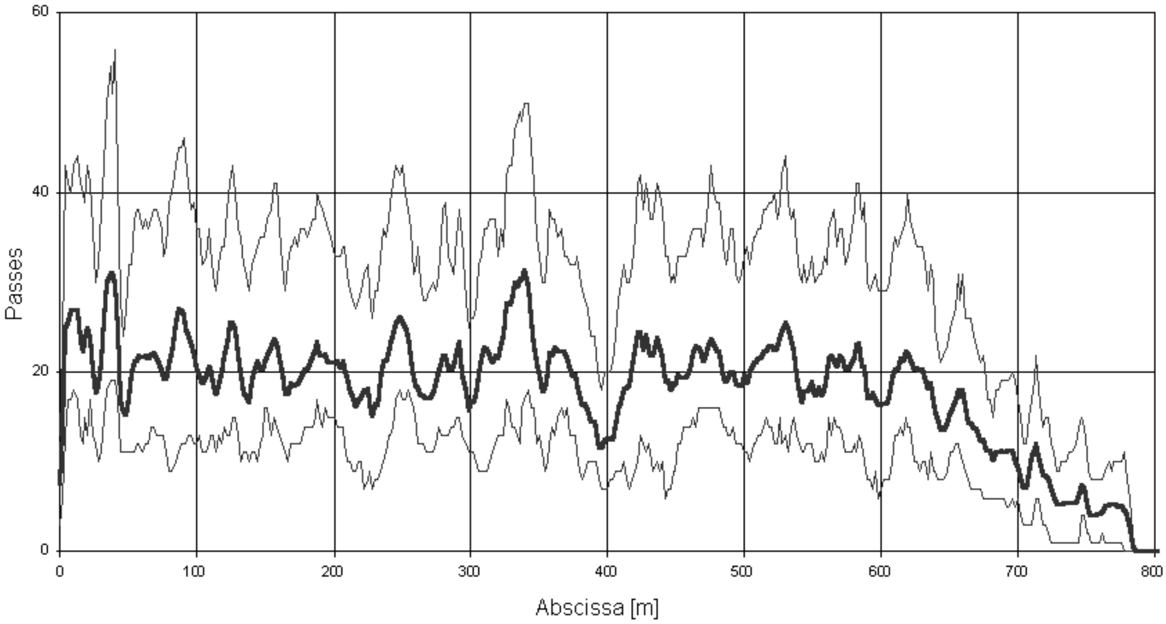

Fig. 2-8. Longitudinal variation of roller passes.

Minimum, mean and maximum number of drum passes in a cross section shown [Geodynamik Web].

Based on these findings, the principal problems in reaching the uniform compaction goal can be identified as:

- failing to keep the compaction pattern,
- temperature problems,
- problems with longitudinal junctions (changing direction too early or to late, moving junction),
- problems to keep the lateral overlap constant.

The compaction support system, for example based on GPS (Global Positioning System), can help the operator in dealing with these problems, by recording the performed passes and possibly monitoring the temperature [Circ] [Thurner 98]. Similar application for earth compaction is established as **dynamic compaction control** FDVK (Sect. 2.3.3). However, for asphalt compaction the following questions are still open and require further research:

- What is the compaction degree dispersion with the quality control methods in use today?
- What kind of improvement of pass count can be reached with GPS support system?
- What level of confidence can be reached on constant compaction degree given constant pass count?

The important progress has been made in the direction of an intelligent compactor, which can adapt vibration parameters to obtain optimal compaction results (e.g. Variomatic [Bomag Web]). However, despite of many efforts, as of today no practically usable methods for online measurement of pavement density or compaction ratio are known. There exist methods for the estimation of layer stiffness [Bomag Web] or fuzzy-like systems for compaction evaluation using a point system (ACD, Sect. 2.4.1.b). Also these systems require positioning and digital storage in order to produce useful results.

There are also ongoing attempts for a fully automated compacting systems [Krishnamurthy et al. 98] based on GPS, including the automatic trajectory planning. They are of special interest for autonomous landfill and waste management operations. The security requirements on the road worksite seem to be difficult to fulfil with such autonomous systems.

2.3.3. CIRC IN EARTHMOVING

The earthmoving is the most cost-intensive part of the most road construction projects and thus very interesting for CIRC applications, which include:

- Real time control of **mass transfer** for bulldozers or excavators, with the goal to optimise cut and fill opertions (e.g. CAES – Computer Aided Earthmoving System [Caterpillar Web]). To support the earthmoving process a 3D DTM is needed, based on points surveyed beforehand and updated in a real-time. The system is based on the similar principle like levelling, however the required accuracy is much lower. Traditionally triangulated data models have been used for this task [Oloufa 91]. The main task of the on-board system in this case is to monitor the volume transfer and visualise the discrepancies between the actual and the designed surface.

- **Dynamic compaction control** (Ger. FDVK - Flächendeckende dynamische Verdichtungskontrolle), is based on the real-time measurement of dynamic response of the support, which allows to estimate the degree of compaction [Geodynamik Web] [Kröber et al. 01] [Bomag Web]. Except of the compaction measurement, GPS based FDVK systems operate analogously to the asphalt compaction support systems described in the previous section.

The possibility to correct deficiencies at any time is the deciding difference compared to the pavement operations, which require costly removal of the faulty layer.

2.3.4. ECONOMICAL AND SOCIAL MOTIVATION

The application of CIRC concept can have important economical consequences, especially in B-O-T and B-O-O initiatives [CIRC], [OSYRIS], [OSYRIS RS]:

- Saving on the setting-out for the contractor. Setting-out of the wire and pegs for sub-base and base levelling may amount up to *10%* of the total project costs. It is expected that the application of CIRC can lower these costs below *5%*.
- Saving on the equipment use by avoiding excessive compactor passes (estimated to about *25%*).
- Digital quality assurance, saving on contractual penalties, limiting re-profiling/recycling of faulty layers.
- Improving the quality by equalising the compaction ratio and improving the evenness.
- Optimising the use of equipment and logistics of the material flow.
- Gaining of the knowledge base, allowing to find the reasons for road failures (e.g. material, compaction, temperature problems).
- Material saving through the optimisation of the layer thickness, which nowadays is often oversized. This saving may amount to 5% of material volume.

Moreover, the application of CIRC can bring these advantages in the social and environmental dimension [CIRC], [OSYRIS]:

- Improved safeguarding of the workers (reduced number of manual checks required around the running machines).
- Optimisation of periods and quality of the maintenance works.

- Valorisation of the road works, traditionally considered as dirty, dangerous and low-tech, including education and training opportunities.
- Environmental aspects: enhancing recycling potential by keeping record of the used material, lowering the resource consumption.

2.4. STATE OF THE ART OF CIRC APPLICATIONS

The short overview presented in this section describes the key features of a few selected CIRC systems, focusing on the their geometric modelling capabilities. The goal is to capture the similarities and typical functional patterns, rather than to present an exhaustive catalogue or market survey. In most cases little is known about internal workings of the commercial systems. For this reason much attention is paid to the research systems, most importantly to the results of CIRC and OSYRIS projects.

The presentation of standalone rolling (eg. Bomag Variocontrol [Bomag Web]), 1D levelling (eg. Mobamatic [Moba Web]) and some more complex systems (e.g. GeoROG, CAES [Cat Web]) is omitted, as it can be found elsewhere (also [Frank 98] [Hoffmann 01]).

2.4.1. COMPACTOR SYSTEMS

2.4.1.a. Pass counting – CIRCOM

Fig. 2-9. presents the data flow principle of the CIRCOM system in the multi-compactor (MultiCIRCOM) configuration [Circ]. The positioning sub-system (PSS) elaborates a precise position of the compactor using Kalman filtering of measurements from the GPS receiver and additional inertial sensors. Thanks to the additional sensors the limited operation under GPS shadow is possible. The position and the speed are transmitted to the board sub-system (BSS). The BSS displays the actual position on the coloured map showing the **pass map**[10], assisting the operator in obtaining the correct number of passes. Vector description in Cartesian coordinate system (ribbons, Sect. 4.4) is used to store the movement of the machine. The pass maps are exchanged with the other machines in the fleet in order to compute distributed pass maps (see Sect. 4.5.1).

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[10] Or pass count map.

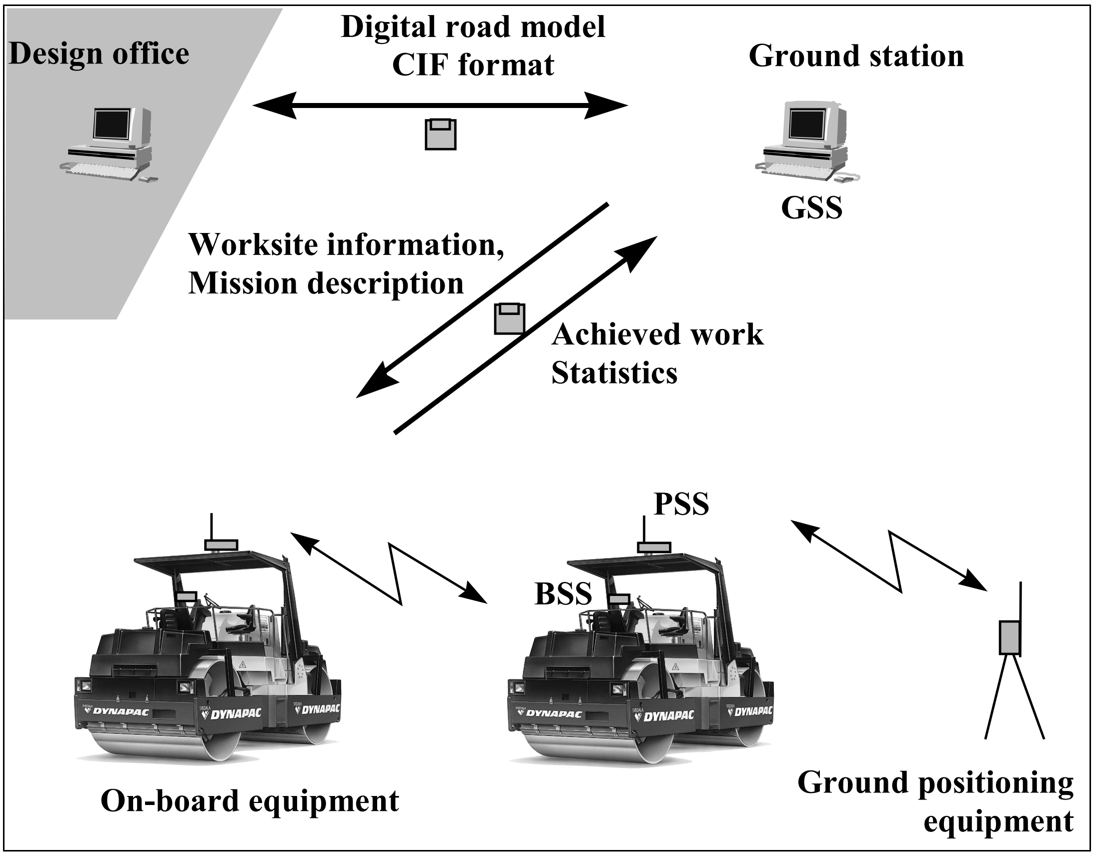

Fig. 2-9. CIRCOM data flow principle.

GSS – Ground Subsystem, CIF – CIRC Interchange Format, PSS – Positioning Subsystem, BSS – On-Board Subsystem

The BSS exchanges the target and as-built state with the ground sub-system (GSS). As it was not possible to adopt any of the existing road design formats, a portable CIF (CIRC Interchange Format) has been designed for the transfer of the worksite description. Similar formats have been defined for mission, achieved work and statistics.

2.4.1.b. Geodynamik ACD System

In the Asphalt Compaction Documentation (ACD) system [Thurner 98] [Geodynamik Web] the GPS measurement of the machine positions are stored in a curvilinear raster. The road axis necessary for the raster definition is not transferred from the design, but measured on the paver, allowing for autonomous operation. The raster size is configurable, with the typical size of 2 x 0.2 m.

The compaction history is documented by:

- the time, mix temperature and layer thickness when the mix is leaving the paver,

- a series of events in the form of individual drum passes. The time, asphalt surface temperature and roll speed of each drum pass are recorded.

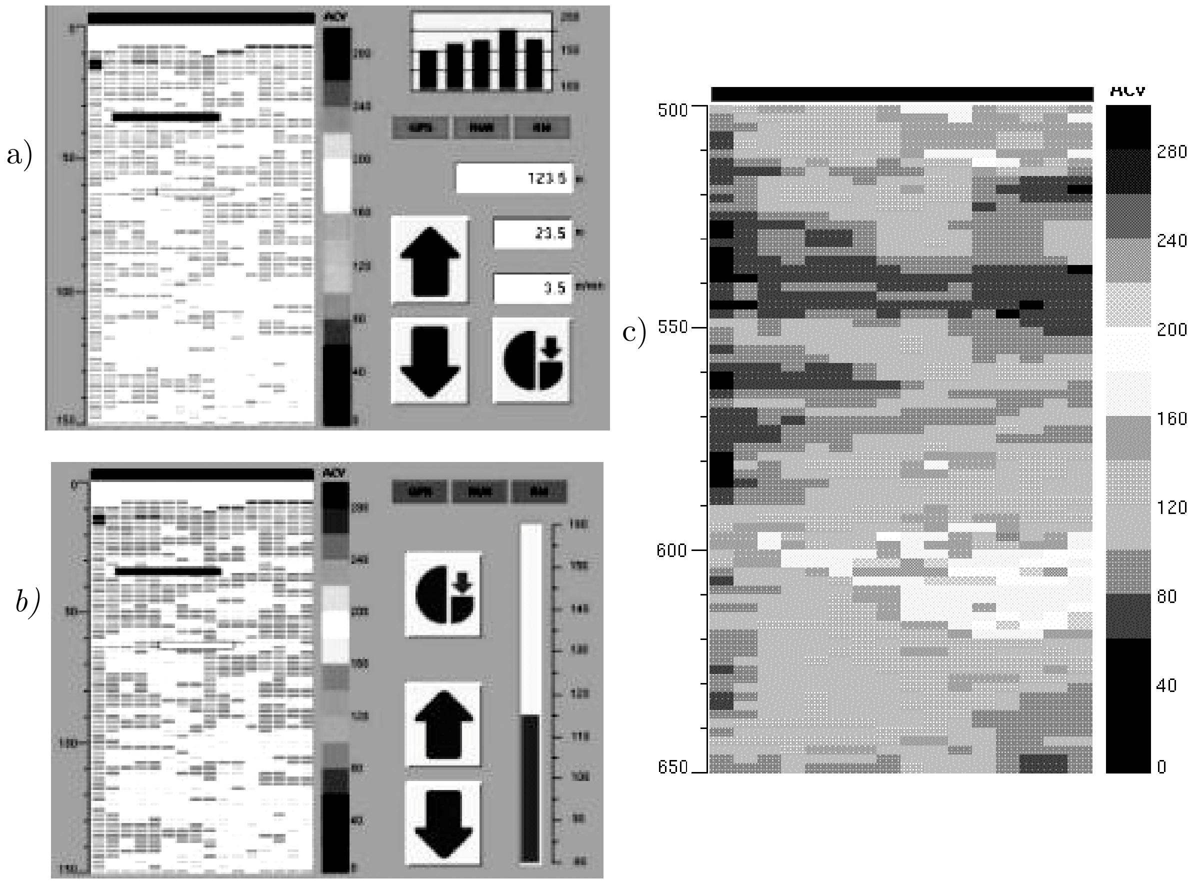

Fig. 2-10. Compaction raster in the ACD system.

a) the paver system b) the roller system c) documentation [Geodynamik Web].

Each separate drum pass is evaluated in terms of the incremental effective compaction it produces. The cumulative result is expressed in points called ACV (Asphalt Compaction Value) and presented on a map (Fig. 2-10.).

The magnitude of the compaction increment is calculated in a fuzzy-like manner from known or measured parameters: [Geodynamik Web]

- accumulated compaction result prior to the current event, calculated as a sum of the pre-compaction and the incremental compaction results from all previous drum passes,
- the hot-mix temperature at the current drum pass,
- the properties of the hot-mix (compactability, thickness),
- drum data (line load, radius, static, vibratory, oscillatory),
- the rolling speed of the drum at the passage,

- the time after paving.

The rules of the point system are not publicly known and need to be adapted by the contractor depending on the machine type and material used. The correlation between ACV value and compaction ratio needs yet to be proven statistically.

2.4.2. 3D LEVELLING SYSTEMS

3D levelling systems can be applied to several profiling and earthmoving machines (Sect. 2.2.3). The core function is the automatic grading without manual setting-out. Robotic Total Station is used to track a prism mounted on the tool. The algorithms described in Sect. 2.3.1 are applied to control tool's elevation and/or attitude. As examples of 3D levelling systems we can mention:

- Moba-Leica system [Moba Web] is based on the Leica RTS [Baum et al. 98] and spaghetti-type DTM (Sect. 4.3.2), input in the form of D45 data format (Sect. 3.6). The CAD project is maintained in the onboard computer. Two-axial slope sensor on the prism's mast, connected stiffly to the tool is applied to measure the attitude of the tool and calculate the elevations of the control points. Two 1D controllers are command the actuators. This system has been successfully used on pavers, graders and milling machines.
- Topcon 3DMS system [Topcon Web]. Characteristic to this system is the placement of processing outside of the machine. The DTM is managed outside of the machine on a laptop connected to a RTS. The control deviations are sent to the machine using unique optical communication technology based on the tracking beam.
- CIRPAV system is based on the similar architecture to CIRCOM (Fig. 2-11.). Several components are reused, most importantly the ground station. Also the same worksite description format is utilised, but two systems are not inter-operating in real time. The position information of the screed is provided by the PSS, which is based on LaserGuide positioning technology [Gorham 94] [Bouvet et al. 00] in the prototype. Thanks to the modular architecture another positioning solution (e.g. RTS) can be also applied. There are two different kinds of outputs: the digital output for the control of the screed, and the graphical display of levelling map. Compared to the other levelling systems, the major difference is the ability to store and analyse the process results.

- GeoROG system [Hoffmann 01], based on the road design software package, supporting a wide range of GPS and RTS positioning sensors.

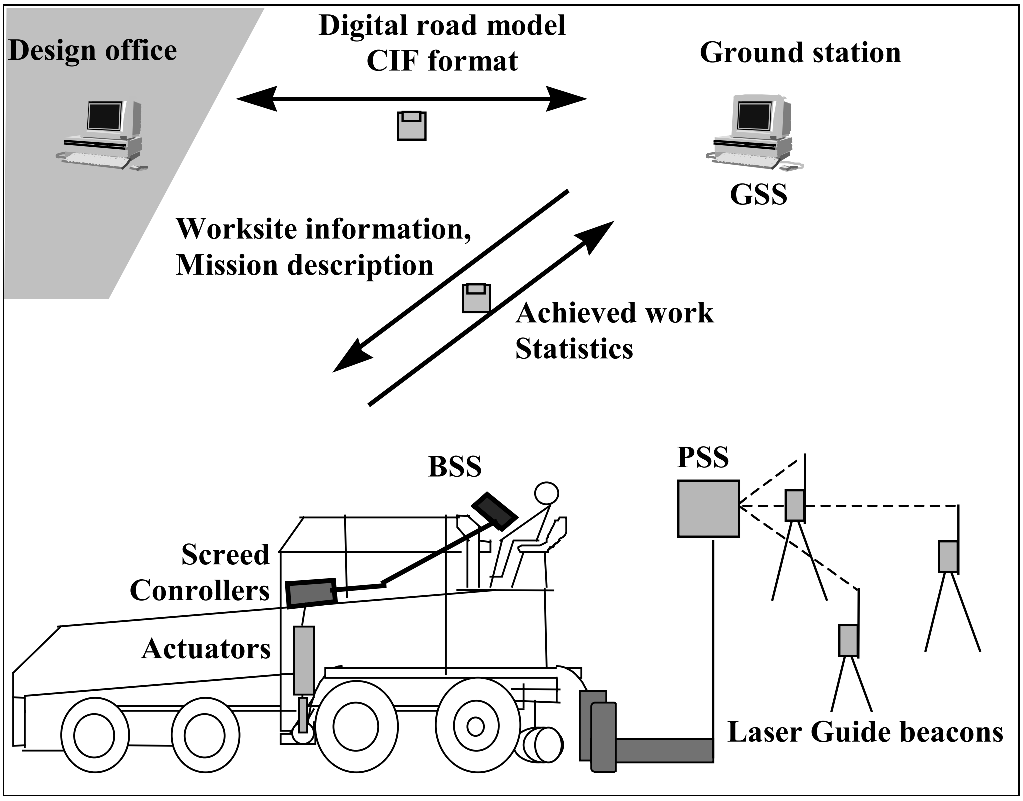

Fig. 2-11. CIRPAV system structure.

CIF – CIRC Interchange Format, PSS – Positioning Subsystem, GSS – Ground Subsystem, BSS – On-Board Subsystem.

2.4.3. ROAD WORKSITE SUPPORT SYSTEMS

Several more comprehensive systems address the **worksite functions** (e.g. OSYRIS, CAES [Caterpillar Web] or Construction Equipment Support Information System CESIS, Fig. 2-12. [OSYRIS]). Their common properties are:

- modular structure (e.g. support for multiple positioning devices),
- wireless communication for team functions,
- sharing of the infrastructure (e.g. reference GPS station, wireless repeaters).

OSYRIS is discussed below as an especially interesting example of a site support system.

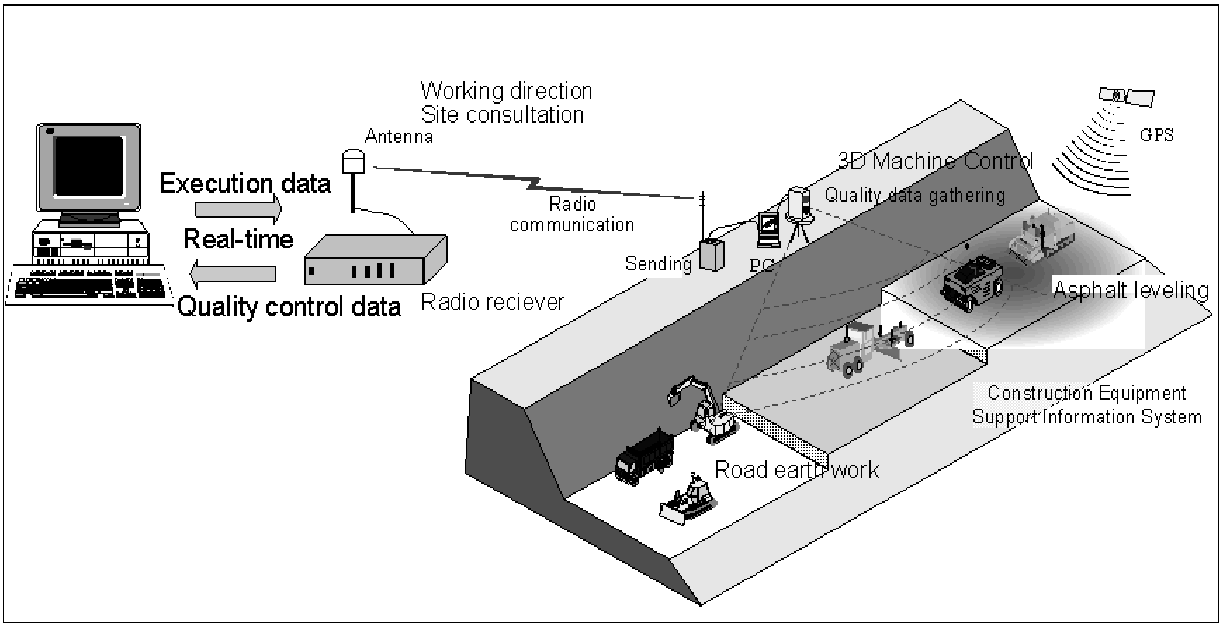

Fig. 2-12. The CESIS concept.

2.4.3.a. OSYRIS system

OSYRIS system (Open System for Road Information Support) is a based on a general **component framework**. Currently existing components are specialised towards an asphalt pavement site. Scalability and modularity of the system offers an opportunity to select only necessary components and configure the system as small or as large as required.

The components are assigned to the three hierarchy levels: **office**, **on-board computer** and **measurement and control system** (Fig. 2-13. [Ligier et al. 01]). The information exchange standards at each level of system hierarchy are specified:

- **On-board communication** is based on CANopen (CAN – Controller Area Network) standard. This layer realises communication between the various sensors and actuators present on the machine and the on-board computer. Using an abstraction of a data dictionary, it forms a substrate for advanced machine operation. For example it is possible to automatically detect connected sensors or move the on-board computer to a differently equipped machine.
- **On-board computer communication** is based on Microsoft COM (Component Object Model) and OPC (OLE for Process Control). This layer implements the communication between the components of the on-board software and wireless communication between the on-board computers on different machines. It enables

easy access to the construction process information, flexible configuration and offers a possibility to extend the functionality of the on-board software.

- ❖ **Mobile Services** are wireless site networking services based on TCP/IP. They allow for on-line communication between the machines, and between the machine and Product Model, so as to exchange relevant process information.
- ❖ **On-board – Office communication** cover design, mission and as-built information and are based on XML (eXtensible Markup Language). The OSYRIS XML format allows to describe the designed and as-built road in vector and raster way, including the various process parameters.
- ❖ **Office Product Model** is a central storage of object-oriented information about the road under construction together with appropriate access methods.

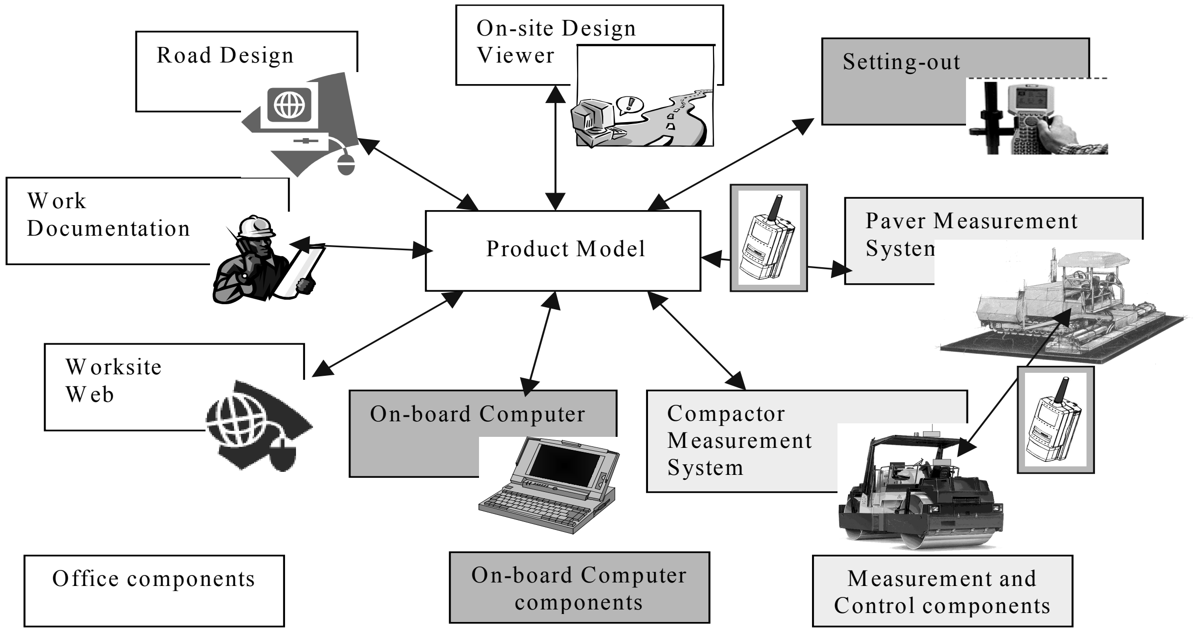

Fig. 2-13. Structure and the components of the OSYRIS system.

The OSYRIS specifications enable high level of modularity and manufacturer-independent co-operation between the components of the worksite support system. Advanced functionality like automatic configuration, cooling model or co-operation between pavers and rollers can be implemented on top of these flexible interfaces [Jurasz et al. 02].

2.4.4. SUMMARY

The geometric modelling properties of the existing CIRC systems are summarised in the following table (Fig. 2-14.).

System	Positioning	Design input	Data model	Parameters	Team functions
Compactor systems					
CIRCOM	GPS+inertial	CIF	Vector/Ribbons	Vibration	Distributed pass map
ACD	GPS	None - sampling at the paver	Curvilinear raster	Surface temperature	Distributed pass/temperature map.
Levelling systems					
1D	1D	Manual/reference	None	(no storage)	None
Moba+Leica	RTS	D45	Vector/Spaghetti	(no storage)	None
CIRPAV	Laser Guide	CIF	Vector/Ribbons	Elevation, Slopes, Time	None
Site support systems					
CAES	GPS	DXF, ASCII	Triangular	Elevation, Slopes	Distributed cut/fill map
Osyris	Modular, incl. GPS, RTS, 1D	CIF,XML,DXF	Vector/Ribbons	Several, freely configurable	Distributed pass/temperature map

Fig. 2-14. Comparison of the geometric modelling capabilities of CIRC systems

2.5. FUNCTIONAL ANALYSIS OF A GENERIC CIRC SYSTEM

2.5.1. INTRODUCTION

In this chapter the **functional analysis** of the generic CIRC system is conducted, in order to establish more formally the definitions of the system components and understanding of the information flow. The analysis is based on the published functional structure of the CIRC and OSYRIS systems, but attempts to encompass to the extent possible the other systems presented and classified in the previous chapter, as well as the ISO TC127 standardisation initiative presented in the next section.

2.5.2. ISO TC127 STANDARDISATION INITIATIVE

A functional analysis based on the CIRC, OSYRIS and Topcon systems has been performed in the framework of ISO TC127 WG2, [Peyret, Miyatake 01], [Peyret 02]. The result was a logical model of a Site Information System (SIS, Fig. 2-15.), allowing to identify the data flows to be standardised.

In order to study the geometric modelling aspects we need to pursue this analysis further in order to study also the non-standardised data flows (marked as white arrows), but we can base our analysis and terminology on this result.

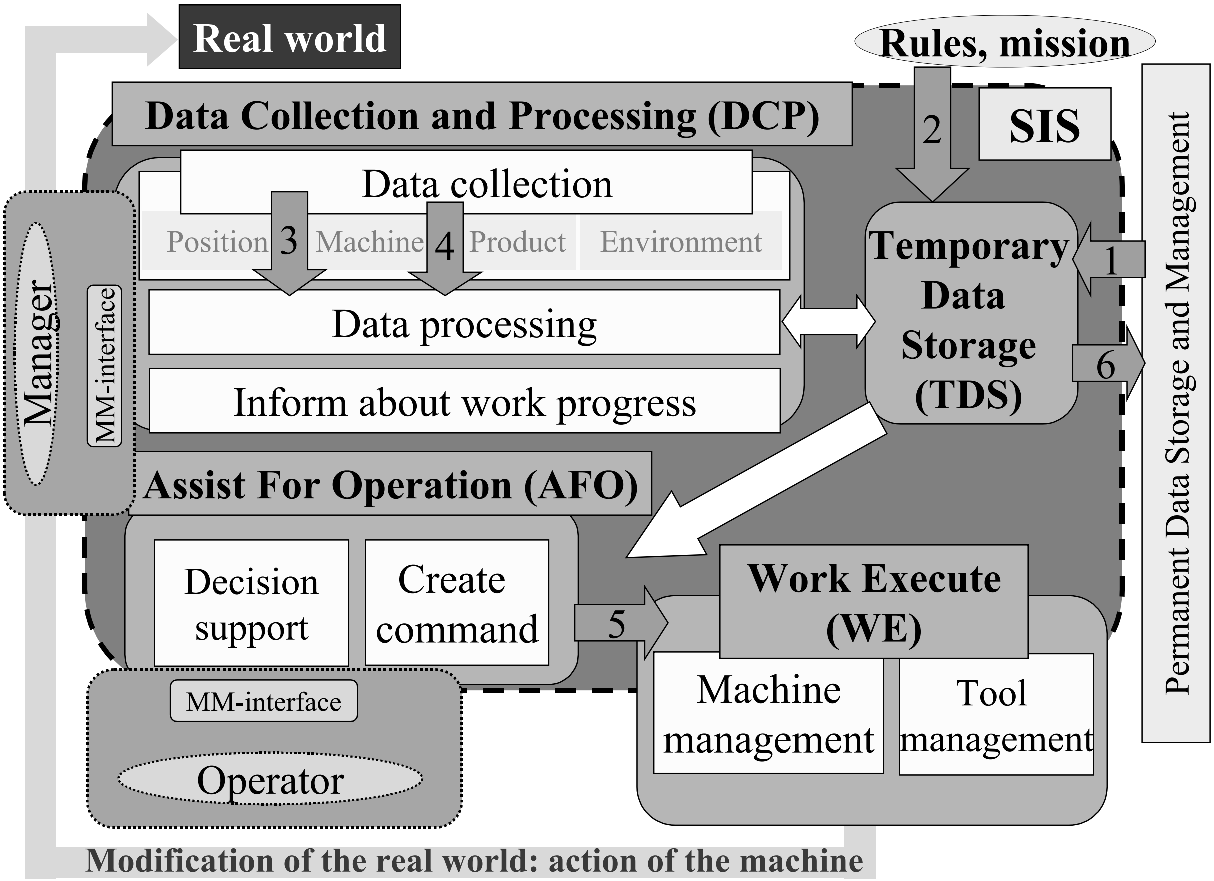

Fig. 2-15. The basic logical model of the Site Information System (SIS)

The data flows to be standardised marked as grey arrows: 1- Design data, 2 - Mission data, 3 - Real-time Position and speed data, 4 - Real-time machine sensors (and achieved surface) data, 5 - Real-time deviations for machine controls, 6 - As-built and work documentation data. White arrows – non-standardised data flows. [Peyret 02]

2.5.3. FUNCTIONAL ANALYSIS RESULTS

CIRC is an IT system managing the information about the road construction process. The construction process can be considered as a state transformation from an initial state into the as-built state, possibly close to the target state. The main functions of the CIRC system are to **capture the current as-built state** of the road and to **compare it with the target state**.

The information about target state will be most often defined as a part of a contract, normally in the form of the road design ("what") and additional contract conditions ("how"). The digital input to the CIRC system may in such circumstances come directly from the road design system, using as of today one of many existing formats [Okstra Web], [DV Merkblatt]. The additional contract conditions may to different extent describe the "how": the required methodology and the execution details [ZTV Asphalt].

In the case of functional contracts, the target state will be primarily defined in terms of the road functionality, e.g. limits on rutting (Ger. Spurrillen), and the methodology will be left for the contractor to define.

In the case of a small maintenance contract, the target state may be inaccurate and not available in a digital form. In this case there is a need to extend the target description within the CIRC system, for example using a on-site design tool.

The comparison between the target and as-built state can be performed on-line and used to **guide** the working personnel or to **control** machines. It may also be performed a posteriori and utilised as a **quality report**, for example included in a road database. The as-built information may also be used by contractor as a part of his knowledge base in order to optimise the process and work organisation. This will often be the case for functional or Build-Own-Operate (B-O-O) type of contracts.

We will now analyse the generic CIRC system using a methodology of hierarchical functional decomposition, leaned on the Structured Analysis and Design Technique (SADT) [Ross 95]. The basic context diagram of CIRC system can be drawn as in the Fig. 2-16. below. From the point of view of the information flow the CIRC system (in the complex version) wraps the road construction process.

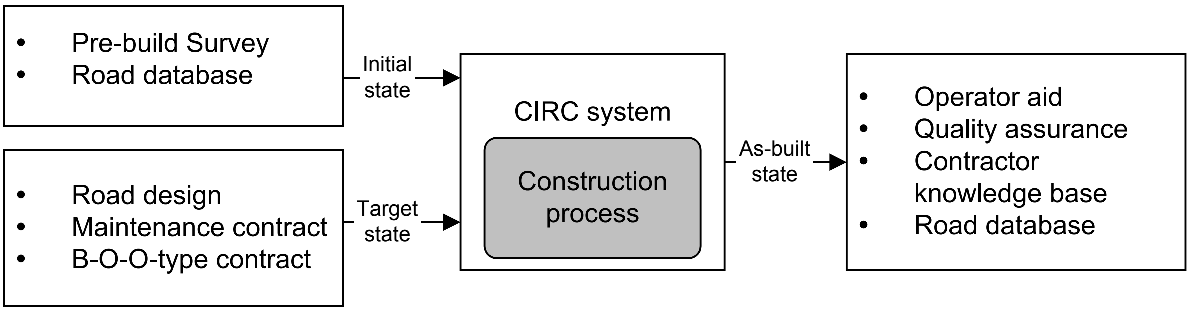

Fig. 2-16. Basic CIRC context diagram.

In a real-world system the inputs and outputs of a CIRC system may be minimal or missing. For example, in the case of a simple 1D levelling system, the target description is implicit (in form of a reference) and there is no initial or as-built output. Such a basic system is effectively becoming a part of the machine and should conceptually be placed within he construction process boundary. However, it still performs the capture and comparison functions, and can be considered as a CIRC system in the sense defined above.

Until now, the following functions of the CIRC system have been identified:

- to import, and possibly capture or extend the target state,
- to capture and store the information about the road construction process (as-built information),
- to compare the design with the execution record,
- to guide the machines and operators, and
- to provide digital quality report to the site managers and road owner.

Even at this very general level some problems inherent to CIRC paradigm are visible:

- input and output data formats are not standardised,
- target state may be missing, incomplete or requires improvement in order to be used in a CIRC type of system,
- target state may to different extent include execution details,
- the data flow is not stable and may vary widely between different projects, organisations and countries, and
- ownership of the data has to be clarified, possibly in the contract.

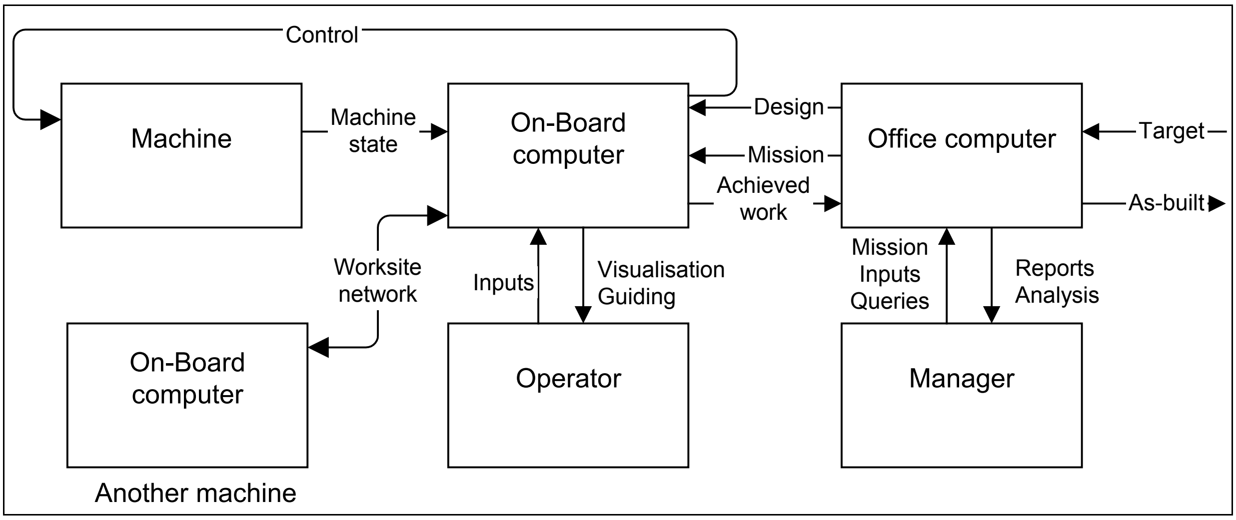

Fig. 2-17. Functional decomposition of a CIRC system.

A first level of functional decomposition of a CIRC system is presented in Fig. 2-17. The target state has been subdivided into target state of the road (called the **design**) and the target state of the machines (called **mission**). It corresponds to the "what" and "how" discussed above. The as-built information is formed from the achieved work description and manual inputs.

Further decomposition of the on-board computer system is shown in Fig. 2-18. below. Machine state has been further divided into position, tool geometry and process data.

With a more elaborate position estimation (e.g. data fusion with Kalman filtering) it is necessary to distinguish between position measurements and estimated position.

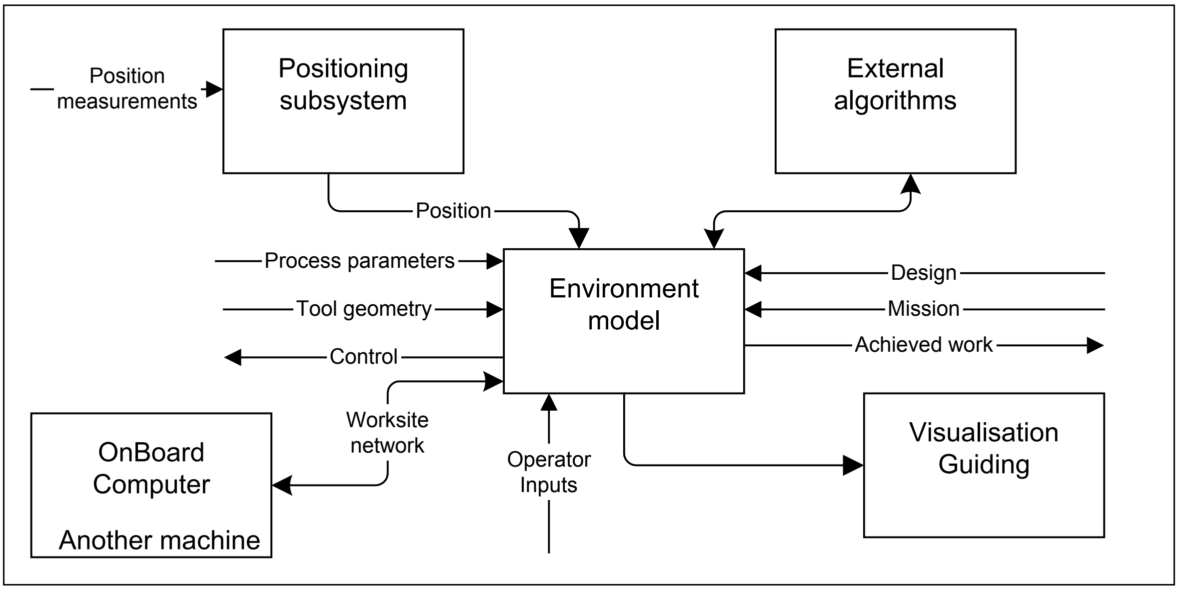

Fig. 2-18. Functional decomposition of an on-board computer system.

The introduced entities are gathered in the following glossary:

Road owner is a party commissioning the construction act in form of a contract and managing the road after it has been built. Supervisor may act on behalf of the road owner, controlling the conduction of the works. Road owner may manage the information about owned roads in a form of a road database.

Contractor is a party conducting the construction process. In the case of B-O-O or B-O-T contract, the contractor may also act as, or on behalf of the road owner.

Contract is a legal arrangement between the road owner and the contractor concerning the road construction process. It may contain requirements concerning functionality of the product, construction methodology or quality assurance.

As-built state is a combination of the achieved work and other information gathered in the construction process, traditionally managed in the paper form (e.g. laboratory results). It is the final result from the CIRC system for the next phase of the road lifecycle.

Initial state may include survey information, information about existing road subject to a maintenance procedure etc.

Target state consists of the **design** ("what") and **mission** description ("how").

Design is a description of a target road, most importantly its geometry, in a suitable digital form. The source of the design is normally the design office using a CAD system. The simplest CIRC systems (e.g. 1D levelling systems) do not require the design explicitly. The part of design transferred to the on-board computer should normally be limited to the relevant scope (for example only limited area or selected layer). It may happen that the design is missing, incompatible, inaccurate or outdated. In this case manual intervention may be required on site. To avoid the dependency on the design and problems with its digital transfer, some systems attempt to capture the shape of the road online, for example when laying.

Mission is a description of the task to be performed by a given machine. It can be as simple as operating area indication or as complicated as a step by step operating plan. Missions can be expressed geometrically as trajectories (curves or polylines) or areas with associated target parameters. The missions may be shared by multiple machines or specified individually. In a minimal version of an implicit or tacit mission no record of mission exists.

Achieved work description is a record of work execution. The most important part is the achieved geometry, for example surface laid by the paver or a pass map of the roller. Additionally the process data may be attributed to the achieved geometry. Achieved work may also include **Events** relevant to the conduction of the mission, They can be used to describe the state of the machine (e.g. machine working normally, transferred, idle), indicate abnormal situations (e.g. GPS shadow), etc.

Manager can represent a contractor (site manager) or the road owner (resident engineer). He/she manages the fleet of the machines, prepares the missions, provides manual input (e.g. laboratory test results, annotations) and verifies the results.

Operator's function is to steer the machine according to the target state. He/she may manually input the information which is not automatically measured by the system. Under some conditions the operator may also enter or adapt the mission, or even manages the mission himself (tacit mission).

On-board computer is a processing unit managing the as-built information gathered on the machine and possibly controlling it. System exist (e.g. Topcon, Sect. 2.4.2) where the processing unit is placed off-machine, however the term “on-board computer” is adopted as the managed information concerns strictly one machine. It may also be a simpler processing unit (e.g. micro-controller). It must allow real-time operation. Centralised or distributed architectures are possible, in the second case the on-board computer may be implemented in the form of the networked structure. As of today, the on-board computer is in the most cases an add-on system to the machine control system.

Position measurement is an output of the positioning sensor, e.g. GPS receiver, robotic total station or sonic distance sensor. The positioning sensor is normally not a part of the machine.

Position is the position and attitude of the machine tool. It can be also thought of as a most important part of the process data, since without recording position no documentation functions can be performed.

Tool geometry describes the shape of the machine tool (e.g. drum, screed or blade) relative to the measured position. It may be fixed or variable (e.g. extendable screed). It is a part of **Machine description**.

Process parameters contain the information about the current process state as measured on the machine or entered manually by the operator. It can include parameters of the machine and its tool, temperature of the material, thickness of the layer etc.

Machine state consists of position, tool geometry and the process parameters at the given time instant. It may be stored explicitly in the on-board database (environment model) and used to derive the achieved work or discarded, so that the achieved work information is not stored.

Environment model (**on-board database**) is the main storage for the geometry-based information processed by the on-board computer. It contains the target and actual road state, that is design, mission and achieved work, for the time of work execution. Its content may be reduced to contain only design, or only some target parameters. The storage can be performed in the cumulative way (for example by counting the compactor passes for given grid cell) or by storing the complete history of the process, represented by the present and past machine states.

Machine description contains the basic properties of the machine: type, identification, geometry of the machine and the tool. Most of these properties are static, except possibly for the **Tool geometry**. For the multi-machine systems a description is needed for each machine forming a **Fleet description**. Typically the machine and fleet description belong to the **Mission**.

Visualisation involves a MMI (typically in the graphical form) allowing the operator to investigate the current state of process and the machine. Common form of visualisation are maps of the process parameters (for example a compactor pass map, a levelling or temperature map) and different types of gauges.

Control of the machine is an optional function of a CIRC system, which can be performed directly (using actuators) or indirectly (by **Visualisation** and **Guiding** to the operator). Comparison between the target and as-built state is necessary for Control function.

Worksite network can be optionally applied to exchange the process information, which is relevant to more than one machine (for example the passes of compactors working together in a team). In most cases real-time wireless technology can be used. The worksite network may also be utilised as a medium of information exchange between the on-board and office computers, however as of today the range is often not sufficient. In the minimum version, the function of the worksite network may be performed in the form of offline information exchange using removable mass memory media.

External algorithms may extend the functionality of the on-board computer. Especially promising is the application of smart sensors, i.e. post-processing algorithms using the information gathered by the CIRC system to derive valuable information. Examples include:

- Cooling model smart sensor, which estimates the mean core temperature of the layer and time left for compaction during the process, based on the laying temperature, time passed and external conditions [Jurasz et al. 02],
- Compaction expert systems Dynapac CompBase and PaveComp, which advise on the screed and compaction parameters to be applied (number of passes, vibration frequency and amplitude etc,) in given conditions [Dynapac Web],
- Pre-compaction smart sensor for a paver, which estimates the pre-compaction level reached under the screed from the laying parameters [Monecke et al. 97, 98, 99].

2.6. PROCESS AND TOOL MODELLING

In order to model the **road product**, one needs to represent its geometry, structure and construction processes [Willems 98]. We will start from the fundamental issues of tool and process modelling, delaying the geometry modelling aspects to the next Chapter. The layered road structure is relatively simple compared to other construction domains (Sect. 2.2.3).

The tool model, its position and the associated process parameters are the basic elements of the process model. These issues require the definition of coordinate systems and their transformations.

2.6.1. TOOL GEOMETRY

Mechanically, the machines applied in road construction are composed of several stiff bodies. Of the greatest interest for CIRC is the **tool**, the part performing the actual work in physical contact with the material, for example:

- paver screed (Ger. Fertigerbohle),
- grader blade (Ger. Schar),
- compactor drum (Ger. Walzenbandage, Walze),
- bulldozer shovel (Ger. Planierraupenschild),
- milling drum of the milling machine (Ger. Fräswalze).

It follows that the tool geometry can be described by a **piecewise-linear structure**, defined in the local coordinate frame of the machine (Sect. 2.6.3.b). Additional degrees of freedom (e.g. varying screed width or brake angle) need to be taken into account by measurement or manual input.

The complexity of tool geometry may vary depending on the required accuracy (Fig. 2-19.). For example *50%* of the required memory and CPU time can be saved by modelling the performance of two compactor drums with a single virtual drum attached to the mass centre (1D compactor model). Inaccuracies arise due to the boundary effects when changing the driving direction. Areas treated with only one drum are ignored and the pass map can be simplified to the driver's benefit. Still, due to the overlapping, the half-passed areas will be uniformly compacted, if the next pass meets the former correctly one on the compaction map.

The piecewise linear structure describing the tool can be stored as a list of points with topological information in the local coordinate system of the machine (Sect. 2.6.3.b), related to the measured position. Additionally the machine geometry may be stored in the same form to obtain a schematic visualisation of the machine.

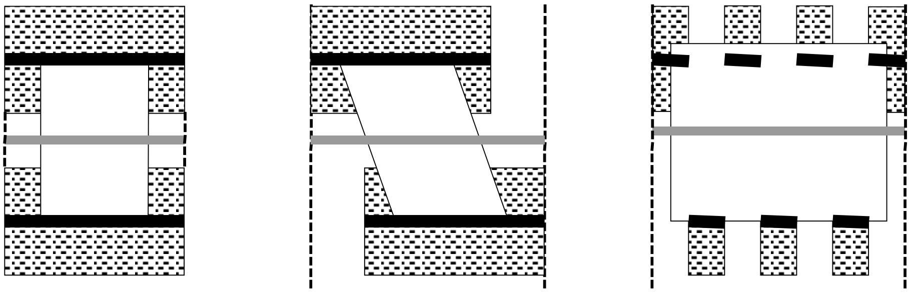

Fig. 2-19. Tool geometries of different rollers approximated by piecewise-linear structures.

The complexity and accuracy of the tool geometry may vary according to the need (thick black lines - higher accuracy, thick grey lines – simplified models).

2.6.2. TOOL POSITION

The **position** is a **state vector** describing the coordinates of a well defined point on the tool. In the 2D and 3D cases also the angular position, or *attitude* is required. In the 3D case sometimes the term “6D position” is used to describe the Cartesian position combined with the attitude.

For 2D machines the position definition consists of:

- coordinates on the plane (x, y), or curvilinear coordinates (u,w),
- heading (also known as yaw or azimuth) φ,
- speed v (signed or unsigned). In the second case the direction is additionally needed for machines working in both directions.

For 3D machines the following are additionally needed:

- elevation z,
- roll (lateral slope, also known as cross slope or cross fall) χ,
- pitch (longitudinal slope) λ.

The slopes (pitch and roll) are small and often expressed as angle tangent value in percent. In the 1D case the position is reduced to the relative elevation z, thickness θ, or distance l. Additionally slopes or speed may be known.

The **positioning subsystem** can only provide estimations of the state vector at the discrete time moments. The quality of the estimation is sometimes available in form of standard deviation estimation or dilution of precision. The **positioning frequency** is typically constant, and must be chosen accordingly, in order to capture the movements of the tool due to steering, tool control, and acceleration/decceleration. This requirement may also be specified in the frequency domain, using a Nyquist frequency criterion. Similarly to positioning frequency, the **latency** is important for real time applications [Bouvet, Garcia 00].

2.6.3. COORDINATE SYSTEMS

The choice of the **coordinate system** applied in road construction depends strongly on the national or local practice. Several kinds of coordinate systems may be concurrently used on the road construction site:

- Cartesian (geodetic or geographic) systems (Sect. 2.6.3.a),
- Geocentric systems, most importantly WGS-84 (World Geodetic System 1984) used by GPS,
- Curvilinear system, defined along the road axis (Sect. 3.4.4),
- Local coordinate systems of the machines, for specifying tool and machine geometry (Sect. 2.6.3.b).

The road is normally designed in a Cartesian coordinate system. Most naturally the CIRC system should apply the same coordinate system as the one used for the road design, called **worksite coordinate system**. It is not practical to employ the geocentric coordinates directly. There exist CIRC systems (e.g. ACD, Sect. 2.4.1.b) working primarily in curvilinear coordinates (“stationing”). Curvilinear organisation may also be utilised in the road database, although newer road databases are based on geodetic systems.

Also a CIRC system may work primarily in only one Cartesian or curvilinear system, managing the other types of coordinates only on the input (e.g. GPS) or output (e.g. displaying current curvilinear position). The Cartesian definition of an axis is required for transformation between Cartesian and curvilinear system (Sect. 3.4.4).

2.6.3.a. Worksite coordinate system

The worksite coordinate system may be a national geodetic system or a local coordinate system defined specifically for a given project. National geodetic systems are based on division of the country area in grid cells, zones or meridian stripes and chosen datum.[11] Many systems can be in concurrent use in one country. Some common European systems are listed exemplary below [Voser Web]:

- Gauss-Krüger system in Germany, based on Rauenberg (Potsdam) datum with Bessel ellipsoid,
- Lambert system in France,
- RT-90 system in Sweden,
- National Grid Coordinate System kkj (Fin. Kartastokoordinaattijärjestelmä) in Finland,
- ETRS (European Terrestrial Reference System) [Willis 96], [Voser 98].

Most of the national systems, except of the French Lambert system, are of **left-handed orientation**. The universal CIRC system should be transparent with respect to the orientation of the coordinate system. To avoid confusion it is recommended to define the external interfaces in terms of Northings and Eastings[12], rather than values labelled with “X” and “Y”.

The left-handed coordinate system is very confusing for non-surveyors, as many well-known results of analytic geometry and trigonometry have to be converted. It is even more difficult to make internal processing (e.g. visualisation) configurable with respect to the coordinate system orientation. Therefore it is justified and necessary to consistently apply one system orientation internally and convert the orientation of incoming and outcoming data upon need. In this spirit, a traditional right handed coordinate system is used for further analysis, so that the classical results of mathematics can be applied directly.

The **coordinate transformations** between different datums can only be approximated using statistical methods based on a number of identical points, for which the coordinates are known in both frames. The parameters of 3 parameter transformations (datum shifts) or 7 parameter (Helmert) transformations are known for many national systems [Voser Web] [EPSG Web]. However, the accuracy of such

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[11] Datum is a set of parameters describing placement, scale and orientation of a coordinate system relative to another coordinate system.

[12] Or in the case of Gauss-Krüger, Hochwert and Rechtswert.

transformation is typically around few meters, making them unsuitable for CIRC applications[13]. The length unit (in Europe typically 1m) has to be known and kept constant for calculation of the derived quantities, e.g. speed. Regional transformations with dm accuracy can be used for surfacing applications. Millimetre accuracy transformation for levelling purposes are also known [Yanalak, Baykal 01]. However, at such high level of accuracy the Earth itself cannot be considered a rigid body anymore, due to long-term tectonic or local geophysical deformations [Willis 96]. Therefore, especially for bigger worksites an own local coordinate system may be defined, together with the appropriate transformations.

The coordinate transformations can be implemented within the **positioning sensor** (e.g GPS receiver), but often little is known about the accuracy of the applied algorithms. Therefore a CIRC system should perform the datum transformations using the well-defined formulae [EPSG Web], allowing for easy configuration of the parameters. Efforts for automatic reference system management, which could be readily applied in CIRC applications are underway [Voser 98].

2.6.3.b. Machine coordinate system

For the definition of machine-relative geometry it is convenient to introduce a local machine coordinate system X'Y'Z' (Fig. 2-20.). In adopted convention the vehicle follows the X' axis.

For the right-handed coordinate system the positive yaw is measured to the left, positive pitch is downwards and a positive roll is to the right. For the left-handed system the positive yaw is to the right, pitch is as above downwards, positive roll to the left. Conversion to the system of another orientation involves swapping of X and Y values and inverting the signs of heading and roll.

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[13] For example a 7 parameter WGS-84 – Gauss-Krüger transformation for Germany yields in Baden-Württemberg 95 cm (60 cm RMS) error. Similar transformation for Baden-Württemberg only yields 12 cm (10 cm RMS) error [Labonde Web].

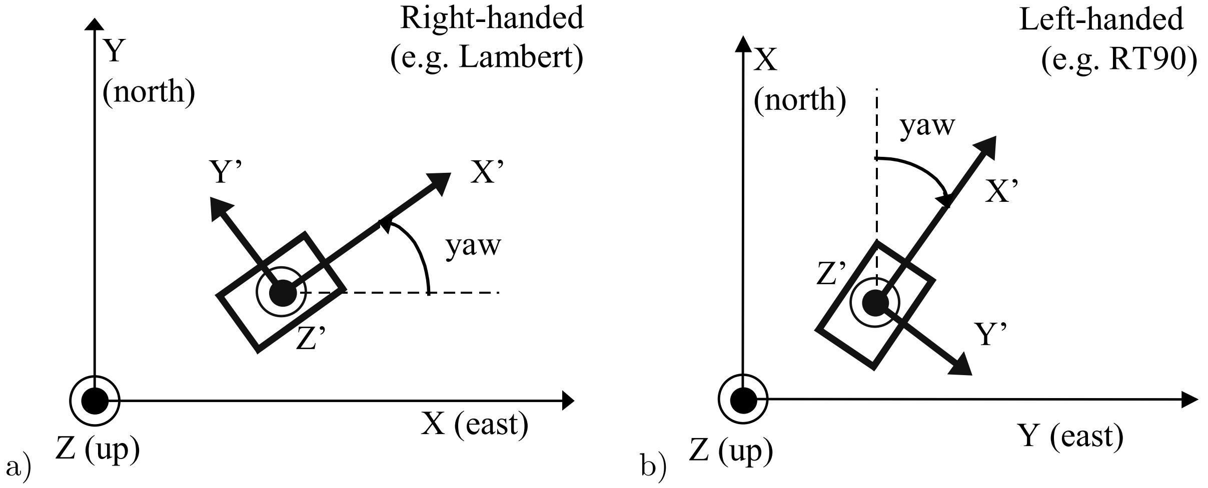

*Fig. 2-20. Worksite (*XYZ*) and machine (*X'Y'Z'*) coordinate systems: a) left- b) right-handed.*

2.6.3.c. Transformation between machine and worksite coordinates

The transformation between machine and worksite coordinate system consists of translation by machine position and heading, pitch and roll rotations. It is convenient to describe the single rotations using the following matrices:

Heading rotation around Z axis:

$$\mathbf{R}_H = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.6}$$

Pitch rotation around Y axis:

$$\mathbf{R}_P = \begin{bmatrix} \cos\lambda & 0 & \sin\lambda \\ 0 & 1 & 0 \\ -\sin\lambda & 0 & \cos\lambda \end{bmatrix} \tag{2.7}$$

Roll rotation around the X axis:

$$\mathbf{R}_R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\chi & -\sin\chi \\ 0 & \sin\chi & \cos\chi \end{bmatrix} \tag{2.8}$$

According to Euler's rotation theorem, any rotation may be described using three angles. The application of 3 rotation angles to describe the attitude is known as Euler Angle Representation [Weisstein Web]. The order of applying the rotations is significant, and there are several conventions in use.

The **tool attitude** is typically measured by slope sensors relatively to the gravity vector. Errors will arise if the measured slope angles are used as rotation angles, as the second rotation will modify the slope resulting from the first rotation. In order to remedy this effect we now derive a rotation matrix describing concurrent, rather than sequential slope and pitch rotations. The columns of the rotation matrix are the images $\mathbf{e}_x', \mathbf{e}_y', \mathbf{e}_z'$ of the unit vectors $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$. From the definition of slope angles we obtain $\mathbf{e}_x' = \mathbf{R}_P\mathbf{e}_x$ and $\mathbf{e}_y' = \mathbf{R}_R\mathbf{e}_y$, which corresponds to the first column of $\mathbf{R}_\mathrm{P}$ and the second column of $\mathbf{R}_\mathrm{R}$ respectively. The third column can be obtained by vector multiplication $\mathbf{e}_z' = \mathbf{e}_x' \times \mathbf{e}_y'$, guarantying the orthonormality of the resulting slope rotation matrix:

$$\mathbf{R}_{PR} = \begin{bmatrix} e_x' & e_y' & e_z' \end{bmatrix} = \begin{bmatrix} \cos\lambda & 0 & \sin\lambda\cos\chi \\ 0 & \cos\chi & -\cos\lambda\sin\chi \\ -\sin\lambda & \sin\chi & \cos\lambda\cos\chi \end{bmatrix}. \tag{2.9}$$

Finally the combination of rotations and translation can be applied to map the tool description points from the local coordinate frame of the machine $\mathbf{p}'_\mathrm{Tool}$ to the coordinate frame of the worksite $\mathbf{p}_\mathrm{Tool}$:

$$\mathbf{p}_{Tool} = \mathbf{R}_H\mathbf{R}_{PR}\left(\mathbf{p}'_{Tool} - \mathbf{p}'_{Pos}\right) + \mathbf{p}_{Pos}, \tag{2.10}$$

where primes denote local machine coordinates, $\mathbf{p}'_\mathrm{Pos}$ is the placement of the positioning sensor, $\mathbf{p}_\mathrm{Pos}$ is the measured position and $\mathbf{p}_\mathrm{Tool}$ is a tool position in worksite coordinates.

2.6.4. PROCESS PARAMETERS AS TOOL POSITION ATTRIBUTES

Tool position is only a part of the **process state**. To obtain a useful picture of the process, a number of additional parameters has to be considered. This concerns not only an as-built state, but also the target state, containing the definitions of the desired parameter values.

In both cases the attributes need to be spatially referenced. The as-built process parameters can be considered as attributes of machine positions. For the target state a superset of position (for example mission area) has to be considered.

The process parameters may include:

- state of the machine, e.g. working, stopped, anomaly,
- material properties, e.g. temperature, used aggregates, bitumen contents,
- tool parameters, e.g. vibration and tampering amplitude, frequency,
- geometrical measurements, e.g. thickness, evenness,
- machine parameters, e.g. hydraulic oil pressure,
- environmental conditions: e.g. air temperature, wind speed.

One can consider interpolating or extrapolating strategy for interpreting the process parameters between the sampling points. Extrapolation principle offers less accuracy, but allows to save considerable amount of memory by storing only changed attributes.

2.7. CONCLUSIONS

CIRC can be considered a **specialisation of CIC** concept, particularly promising due to the high mechanisation and repetitive, well defined nature of the road tasks. Specific geometry and structure of the road are the enabling factors.

There exist **economical** and **functional motivation** for the application of CIRC systems. The analysis of the existing systems allows to define common functions and information content. The fundamental function of a CIRC system is the **capture of the as-built state** and **comparison** with the **target state** of the road. This requires **position estimation**, as it is not useful to consider the process information without a placement. **Digital environment model** is required to manage the target road state, consisting of the **design** and **mission** definition, and the current **as-built state**, which can be derived from present and past **machine states**.

In order to model the **road product**, one needs to represent its **geometry**, **structure** and construction **processes**. The process can be modelled using the piecewise linear **tool model** with associated **process parameters**. The **layered road structure** is relatively simple to represent, as only one layer needs to be managed at a time. It remains to handle the geometrical modelling aspects.

The **maintenance** aspect of CIRC application is very important, but has been largely neglected until recently. Although the primary scope of CIRC is the road construction site, this methodology can be applied for other linear civil engineering projects, e.g. railway or canals.

3. Interaction between road CAD and CIRC

3.1. OVERVIEW

Modelling of the **road geometry** is crucial to any CIRC application. The **road design** influences the functioning of CIRC systems directly (with transferred design description) and indirectly (through road's geometrical nature). Important analogies can be drawn, as both processes are IT-based and need to model the same object. **Continuous road model**, also known as dynamic cross section is required for the precise definition of the road geometry.

The road curves and surfaces resulting from current road design methodology are described using terms of Computer Aided Geometrical Design and Differential Geometry as **clothoid splines** and **clothoid ruled surfaces**. As they are not directly suitable for CIRC implementation, practical design approximation methods have to be sought. As of today, the simple methods based on **sampling and polyline interpolation**, analogous to setting-out procedure, are used with no guarantees on approximation accuracy. To fill this gap, several methods of estimating elevation, curvilinear coordinates and slopes are studied. The estimates on approximation accuracy and sampling methods with guaranteed worst-case accuracy are given. New methods based on **lincubic tensor product surfaces** prove particularly advantageous, allowing for correct interpolation between **static cross sections** and major reduction of sampling point set. Further on several **digital design exchange standards** are surveyed.

3.2. INTRODUCTION

Traditionally the role of the CAD system ends with printouts for the construction team and coordinate lists for surveyors performing the setting-out tasks. As of today many CIRC systems import the design as **coordinate lists** (Sect. 2.4.2). Even if the design is not directly available to the CIRC system (as for 1D levelling systems) the shape of the road has clearly great influence on the functioning of the CIRC system.

The application of CIRC puts new requirements on the road CAD systems. It is clear that both IT systems need to co-operate to obtain the best possible result. Especially in the context of the maintenance works this co-operation has to be very cost-effective.

3.3. DESIGN PROCESS

The way from the concept of the road to the road design which is ready to be realised is performed in the following steps [Rebolj 99] [Dunker, Gleue 75] [Pietzsch 89]:

- **Pre-design.** After the traffic analysis, the conceptual sketch of the new road is prepared. This involves choice of the network nodes to be connected and the determination of the possible corridors between them, based on the available geographical information. The corridor represents the design boundaries and takes into account negative (zones to be avoided, e.g. inhabited or protected areas) and positive (obligatory areas, e. g. network nodes, possible placement of bridges and tunnels) design constraints. It may include also constraints in the elevation.
- **Design of the road geometry.** Nowadays the road design is virtually always performed with help from a specialised CAD system. Normally, the design of the road is prepared long before the construction starts by specialist team, very often this work is outsourced by the road owner. Their work is concentrated on the geometry. Two distinct methodologies are established: traditional projected design and modern 3D design based on continuos model of the road. They are described in greater detail further on.
- **Presentation and evaluation.** Possibly several variants of corridors and designs may be prepared and evaluated. This may involve economic and environmental analyses (e.g. noise, pollution) and photo-realistic 3D visualisations. Corrections or optimisations of the design may be required after this step.
- **Transfer to the contractor.** In this step the import into the CIRC system will be performed.

3.3.1. PROJECTED DESIGN

In some countries the road design must be performed in **3 planar projections**. In Germany this procedure is known as "3-Tafel-Projektion" [RAS-L 95] and is based on the following three projections of the road:

- Horizontal projection (Ger. Lageplan),

- Vertical projection (Ger. Höhenplan),
- Cross section (Ger. Querschnitt).

Normally the projected design refers to the **road axis** [Pietzsch 89]. However, in some cases also the edge could be chosen as a reference. For two-carriageway roads separate designs may be made for each carriageway. This concerns especially the vertical design in difficult terrain. For this reason, it is justified to speak **of road alignments** as the crucial part of the design.

3.3.1.a. Horizontal design

The **ground plan** of the road is a combination of the three basic elements: line segments, circle arcs and clothoids [Pietzsch 89].

As a **line segment** is the shortest connection between two points, straight roads were preferred since the Roman times. Driving along the straight line was believed to be the easiest for the driver. Nowadays the application of long line segment in road design is depreciated, as they are boring for the driver and difficult to visually integrate in the road environment. Instead clothoid sections or low curvature are recommended [Pietzsch 89].

The **circle arc** has also been used in the road construction since the very beginning, whenever a change of direction was necessary, or due to 3 non-collinear constraints.

The **clothoid**, also known as an Euler curve, a spiral of Cornu or even a road builder's curve (Ger. Straßenbauerkurve) plays a special role in road and railroad construction. It is a planar curve, which curvature grows proportionally to its arc length. Its Cartesian coordinates can be expressed as [Schnädelbach 83]

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = A \begin{bmatrix} \int_0^t \cos\frac{\tau^2}{2} d\tau \\ \int_0^t \sin\frac{\tau^2}{2} d\tau \end{bmatrix} = A\sqrt{\pi} \begin{bmatrix} C\left(t/\sqrt{\pi} \right) \\ S\left(t/\sqrt{\pi} \right) \end{bmatrix}, \tag{3.1}$$

where A – clothoid parameter (scale factor), *C(x)*, *S(x)* - Fresnel sine and cosine integrals:

$$\begin{aligned} C(x) &= \int_0^x \cos\frac{\pi}{2} u^2 du, \\ S(x) &= \int_0^x \sin\frac{\pi}{2} u^2 du. \end{aligned} \tag{3.2}$$

A vehicle driving at a constant speed along the clothoid will undergo linearly changing centrifugal acceleration. Smooth curves can be nicely integrated within the road environment and are good for keeping driver's attention.

An example of a horizontal alignment design is shown in Fig. 3-1. [Weiß 01].

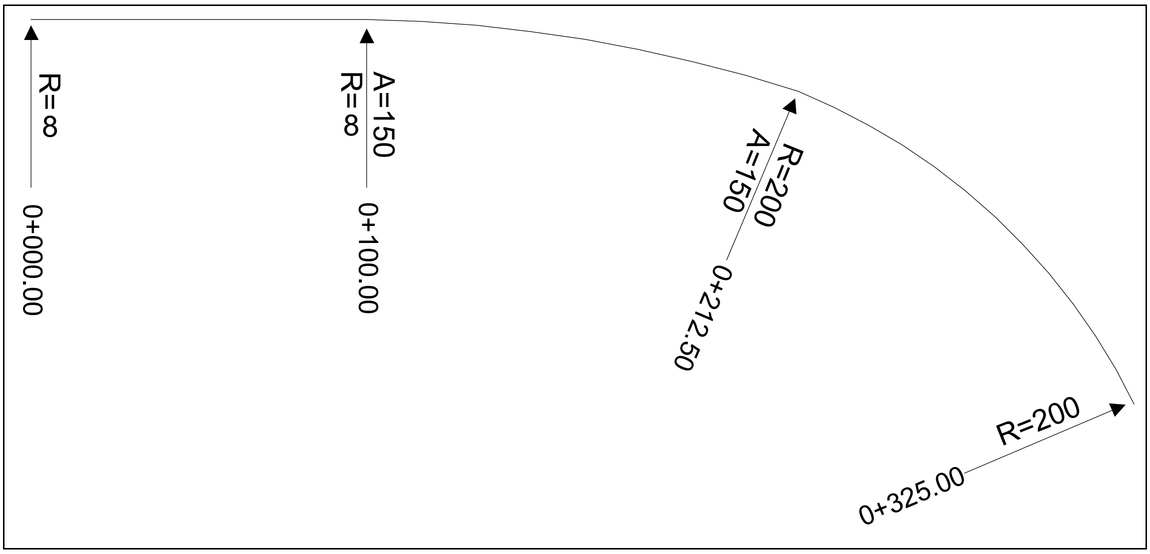

Fig. 3-1. An example of a horizontal design.

3.3.1.b. Vertical design

The **vertical design** of the road describes the change of elevation in function of the alignment length $z = f(l)$. The basic design property of the vertical design is the longitudinal slope (**long slope**), expressed in percent. It should not exceed maximum allowed values, related to the design speed.

The design process is based on height information taken from the maps or digital terrain model, presented as comparison between existing and designed longitudinal cross section. To improve the readability, the vertical scale is normally magnified (e.g. *10 x*) for presentation. The goal is to obtain possibly harmonised shape of the road, reducing at the same time the required mass transfer and avoiding excessive slopes. Clearly any change in the alignment's horizontal design requires the vertical design to be reiterated.

Two types of elements can be applied in vertical design:

- **Straight lines** are the prevailing elements of constant slope.
- **Circle arcs** are used to round the connections between line elements.

The arcs are normally approximated by parabolas[14]. Using a quadratic parabola, the height at a given point of the design can be calculated as [Dunker, Gleue 75]

$$z(l) = z(0) + s_{L0} l \pm \frac{l^2}{2H}, \tag{3.3}$$

where s_{L0} – initial slope, H - vertical radius of curvature (Ger. Halbmesser)[15].

The change of the length (stationing) due to imposed height is normally ignored. An example of a vertical alignment design is shown in Fig. 3-2. [Weiß 01].

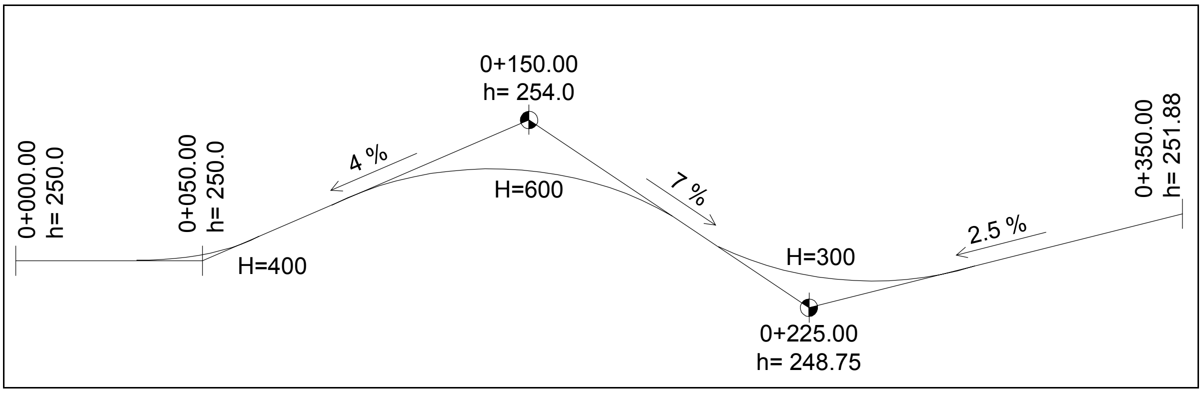

Fig. 3-2. An example of a vertical design.

3.3.1.c. Cross section

The **cross section** is used to define the road surface along the 3D alignment resulting from horizontal and vertical design. Lateral slope (**cross slope**) is its most important property. The cross section consists only of linear elements, but it varies along the road. This happens mostly due to the superelevation (Ger. Verwindung), which partially compensates the centrifugal acceleration. Cross section is typically applied in the vertical plane, not normally to the alignment, which may have consequences for the steep roads.

The cross section may be static or dynamic [Kornbichler 99]:

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[14] [RAS-L 95] allows only quadratic and cubic parabolas. The differences between parabolas and circle arc are neglectable in this case.

[15] In Germany symbol H is used to avoid confusion with the horizontal curvature radius R. This convention is also adopted here.

- A **static cross section** is defined at the fixed intervals (stations) only, based on typical templates (Ger. Regelquerschnitt) [RAS-Q 96], which are adjusted to match local conditions. The intermediate geometry is not explicitly defined, but can be estimated by interpolation.
- A **dynamic cross section** is the automation of the template. It is a rule-based model, describing the location of derived points as offsets from the main alignment, where the offsets are functions of governing variables (design speed, curvature, long slope etc). An example cross section shown in Fig. 3-3. produces a 3D road model shown in Fig. 3-4. [OSYRIS].

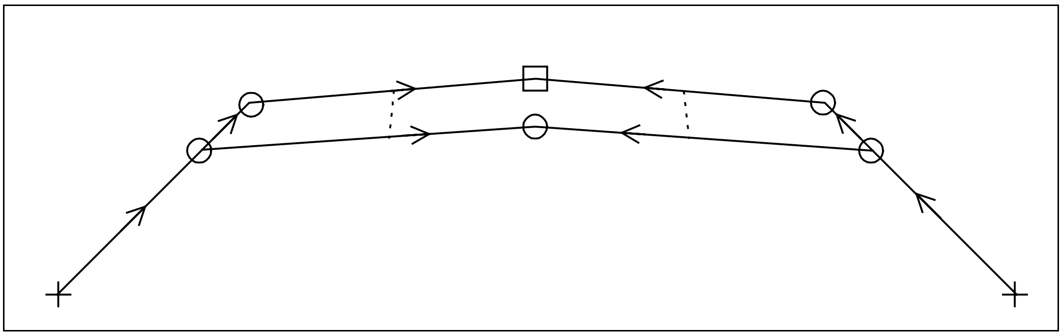

Fig. 3-3. An example of a rule-based cross section design

The arrows represent rules, pointing from the derived to the primary points. The symbols represent points generating road curves, square is the connection point to the main alignment.

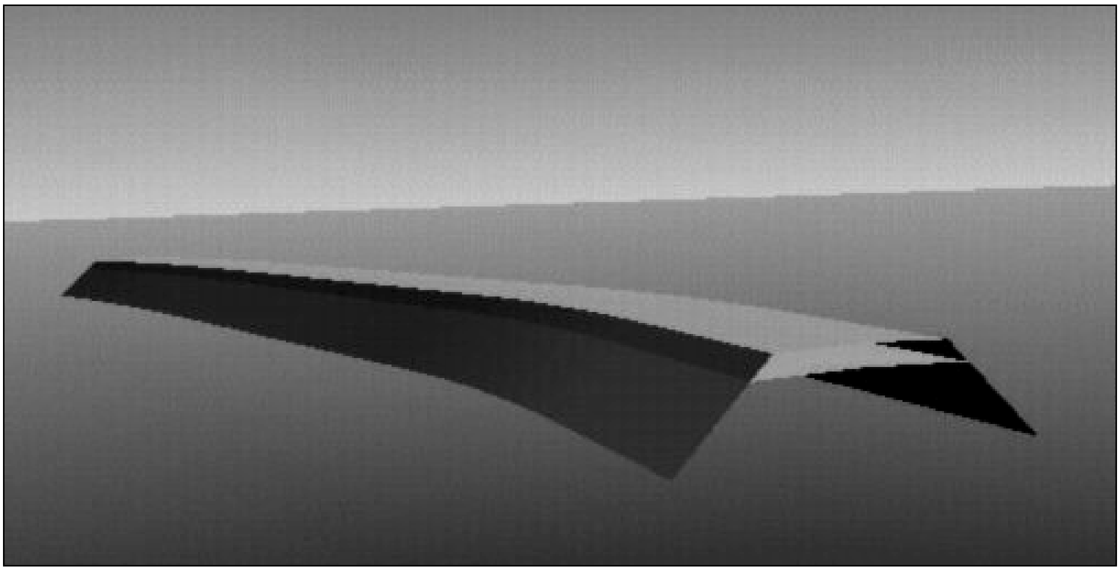

Fig. 3-4. Application of a rule-based cross section

3.3.1.d. Synthesis

The three dimensional shape of the road is synthesised as shown in the Fig. 3-5. [Rebolj 99]. The change of curvature and length due to superimposing of the third dimension are ignored. Other disadvantages are due to the sequential nature of the design process. A change in the in the earlier phase requires reiteration of the consecutive phases.

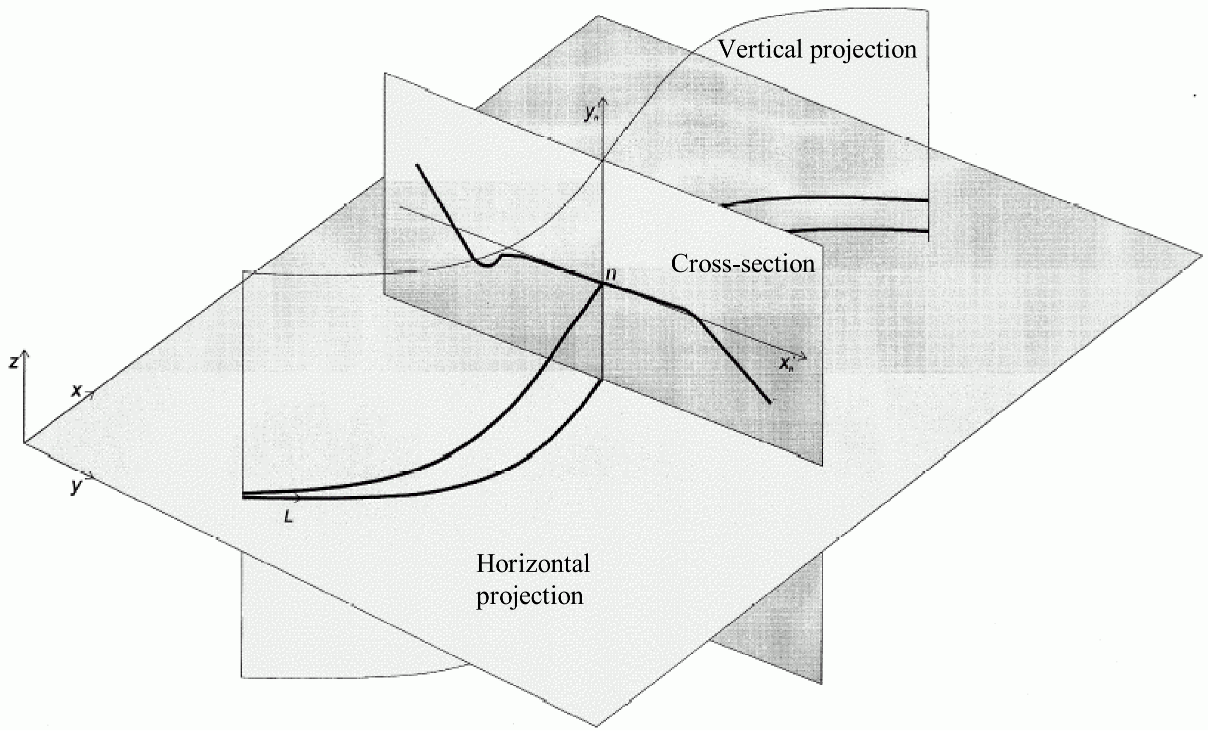

Fig. 3-5. Synthesis of the road design from axes projections and the cross section.

3.3.2. 3D ROAD DESIGN

The road design procedure in three separated projections has to be compared with the direct 3D modelling techniques, widely used in modern engineering (automobile industry, shipbuilding, some fields of architectural design etc.). Despite of attempts since 1942 to establish a **3D design methodology** [Kühn 02], and shortcomings concerning spatial curvature and torsion [Psarianos 82], the classical design procedure is not likely to be replaced.

The road designer needs to exert control over two key points of the design: curvature and mass transfer. Polynomial and rational splines[16], basic tools of Computer Aided Geometrical Design (CAGD) [Farin 89], have been recently applied to road alignments [Kühn 02]. However, designed to produce visually pleasing results, the mentioned

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[16] A spline is a piecewise function, which may have a simple local representation, but satisfies some global conditions, for example continuity and smoothness [Weisstein Web].

splines do not allow the direct control of the curvature. For this reason the 2D clothoid splines applied in road design have been introduced to other fields of CAGD [Walton, Meek 90]. Due to their non-linearity and numerical complexity, so far they didn't find a wide use outside of road and railway domain. The generalisation to spatial clothoid splines with controlled and continuous curvature and torsion is not trivial [Li et al 01].

For the above reasons it seems unlikely that the widely accepted projected design should soon become obsolete. Moreover the resulting road alignments should be of similar nature (low, continuous curvature), independent of the design procedure. If the 3D alignments are defined explicitly, design sampling and approximation for CIRC purposes should become easier than in the projected case.

3.3.3. CONCLUSIONS

The CIRC applications are influenced by the road design practice, which as of today is based on projections. **Main alignment** (axis, centreline) is the most important part of the design, defined in separate horizontal and vertical design steps. The horizontal design is governed by curvature. The mass transfer issues play the deciding role in the vertical design. The key point for CIRC case is a sufficiently exact definition of the crucial elements: alignments and edges. It is guaranteed when **the continuous model of the road**, derived from the axis and dynamic cross section, has been applied.

3.4. ROAD CURVES AND SURFACES

In this section we will introduce a description of the design geometry in terms of **Differential Geometry and Computer Aided Geometric Design**, in order to discuss the properties and possible approximations of curves and surfaces of the design and road curvilinear coordinates.

3.4.1. BASIC TERMINOLOGY

In the road synthesis process, as the cross section definition is applied along the main alignment, the traces of the cross section vertices form space curves, describing the secondary alignments: edges and axes of the road layers. Such curves, mostly parallel to the main alignment will be called **road curves**, and the surfaces spanned between will be called **road surfaces**.

We will consider plane (2D) curves $\mathbf{C}_2$ and space (3D) curves $\mathbf{C}_3$, expressed parametrically over an interval *(a,b)* as [Gray 98]:

$$\begin{aligned}&\mathbf{C}_2 : (a,b) \to \mathbb{R}^2, \mathbf{C}_2(t) = \begin{bmatrix} x(t) & y(t) \end{bmatrix}^T,\\ &\mathbf{C}_3 : (a,b) \to \mathbb{R}^3, \mathbf{C}_3(t) = \begin{bmatrix} x(t) & y(t) & z(t) \end{bmatrix}^T.\end{aligned} \tag{3.4}$$

As $\mathbf{C}_3$ curves are more general, in the following we use $\mathbf{C}$ to mean $\mathbf{C}_3$ wherever possible. The road curves are at least $\mathbf{C}^1$ continuous, with continuous curvature also $\mathbf{C}^2$ continuous.

The arc length of the curve over an interval *(a,b)* is defined as

$$l(a,b) = \int_a^b \left\| \dot{\mathbf{C}}(t) \right\| dt = \int_a^b \sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}\, dt\,. \tag{3.5}$$

Using t as analogue to time we define **curve's speed** as

$$v(t) = \frac{dl}{dt} = \left\| \dot{\mathbf{C}}(t) \right\| = \sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}\,. \tag{3.6}$$

In the design process the **2D simplification** is typically applied, that is the third dimension's contribution to length and speed is ignored:

$$\begin{aligned}&v_2(t) = \sqrt{\dot{x}^2 + \dot{y}^2},\\ &l_2(a,b) = \int_a^b \sqrt{\dot{x}^2 + \dot{y}^2} dt.\end{aligned} \tag{3.7}$$

Road curves belong to the curves whose speed is everywhere defined and non-zero, which are called **regular**. It is important not to confuse *t* and speed with the parameters of vehicles driving on the road. We can however freely re-parameterise the curve by setting *t = f(t')* where *f'(t) > 0.* Then using

$$\dot{\mathbf{C}}'(t') = \dot{f}(t') \cdot \dot{\mathbf{C}}(f(t')) \tag{3.8}$$

it is possible to find the representation corresponding to any given speed/time model. Differential geometry offers important results for the class of the **unit-speed curves** (*v*(*t*) *= 1*), that is curves parameterised by their length. For road curves it is practical to use **constant-speed parameterisations** (*v*(*t*) *= A > 0* for some *t* range). However, any monotonic curve (sgn(*v*) = *const*) can be re-parameterised to unit-speed using (3.8). This corresponds to using **curvilinear abscissa** as curve parameter (Sect. 3.4.4).

For convenience we will use both constant speed parameterisation $\mathbf{C}(l)$ and unit speed parameterisation $\mathbf{C}(t)$.

The **curvature** of a $\mathbb{R}^n$ curve can be defined as an unsigned rate of change of tangent direction, or a failure of a curve to be a straight line [Gray 98]

$$\kappa(t) = \frac{d\varphi}{dl} = \frac{\left\|\dot{\mathbf{C}} \times \ddot{\mathbf{C}}\right\|}{\left\|\dot{\mathbf{C}}\right\|^3}. \tag{3.9}$$

It follows that for constant speed curves curvature is equal to $\frac{1}{v}\left\|\ddot{\mathbf{C}}\right\|$. In the planar case (3.9) can be rewritten using a determinant

$$\kappa_2(t) = \frac{d\varphi}{dl} = \frac{\left|\dot{\mathbf{C}}\ddot{\mathbf{C}}\right|}{\left\|\dot{\mathbf{C}}\right\|^3} = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\left(\dot{x}^2 + \dot{y}^2\right)^{\frac{3}{2}}}. \tag{3.10}$$

The curvature $\kappa_2(t)$ of a planar curve is a signed value; if for some t range the sign of the curvature is constant, the following can be said, when moving in a direction of increasing arc length:

- $\kappa(t) > 0$ – curve is turning left,
- $\kappa(t) = 0$ – curve is a part of a straight line,
- $\kappa(t) < 0$ – curve is turning right.

Accordingly a **radius of curvature** obtained as $R(t) = 1/\kappa(t)$ can be treated as a signed value for plane curves. As discussed in the previous section, the curvature is the primary design information. The curvature of the road curves is by their nature relatively low. For example for 6 m wide roadway with the design speed $V_{85} = 90$ *km/h* the absolute curvature should not exceed $3°/100$ *m* [Pietzsch 89].

The *Fundamental Theorem of Plane Curves* [Gray 98] states that the plane unit-speed curve can be determined up to Euclidean motion[17] from its curvature. It follows that all 2D constant-speed curves can be defined by initial point **P**, tangential angle function $\varphi(t)$ and a speed constant v. The Cartesian representation of the curve can be found from the following Fresnel integral

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[17] Any combination of translations, rotations and reflections.

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = v \begin{bmatrix} \int_0^t \cos\varphi(\tau)\,d\tau \\ \int_0^t \sin\varphi(\tau)\,d\tau \end{bmatrix} + \mathbf{P}\,, \tag{3.11}$$

where **P** – curve's starting point, and the length and curvature are given by

$$\begin{aligned} l(t) &= v \cdot t, \\ \kappa(t) &= \frac{1}{v}\dot{\varphi}(t). \end{aligned} \tag{3.12}$$

Additionally **torsion** is required to describe fully a space curve. It can be defined as a failure of the curve to lie in the plane [Gray 98], or as a turning rate of the local plane of curvature, called osculating plane [Farin 89]

$$\tau(t) = -\frac{d\beta}{dl} = \frac{\left|\dot{\mathbf{C}} \;\; \ddot{\mathbf{C}} \;\; \dddot{\mathbf{C}}\right|}{\left\|\dot{\mathbf{C}} \times \ddot{\mathbf{C}}\right\|^2}, \tag{3.13}$$

where β – orientation of the osculating plane. The *Fundamental Theorem of Space Curves* [Gray 98] states that the space unit-speed curve of non-zero curvature can be determined up to Euclidean motion from its curvature and torsion. It is not directly useful for the road curves, due to the prevailing linear segments of zero curvature, but can be applied once the road surface is defined. However, due to the separate vertical design, torsion is not a primary design information and is not continuous for road curves [Psarianos 82].

3.4.2. MAIN ALIGNMENT AS A CLOTHOID SPLINE

The road main alignment is piecewise, structure of elements $\mathbf{E}_i$: line segments, circle arcs and clothoids. It can be expressed as a unit or constant speed **piecewise parametric spline** with the non-decreasing knot sequence t_i:

$$\begin{aligned} \mathbf{C} &= \bigcup_i \mathbf{E}_i, \\ \mathbf{C}(t) &= \mathbf{E}_i(t) \text{ for } t_{i-1} < t \le t_i. \end{aligned} \tag{3.14}$$

It is important to note that in the projected design process two independent splines are specified in horizontal and vertical plane, including the separate knot sequences. For this reason one needs to consider two separate, partial curvatures: horizontal and vertical. For modern roads the partial curvature (in horizontal or vertical plane) of the main alignment is a continuous, piecewise linear function of arc length: $\kappa(l) = 0$ for lines, $\kappa(l) = const$ for arcs and $\kappa(l) = al+\kappa_o$ for clothoid segments. Minor discontinuities are possible due to rounding of element parameters. It follows that the axis tangential angle

$$\varphi(l) = \int_0^l \kappa(\lambda)\,d\lambda + \varphi_0 \tag{3.15}$$

is a $\mathbf{C}^2$ spline consisting of linear and 2nd order parabolic segments. Similarly the long slope is piecewise linear.

The main alignment is at least twice continuously differentiable ($\mathbf{C}^2$) in unit- or constant-speed parameterisation, but not in all possible parameterisations. To take this into account a concept of **geometric continuity $\mathbf{G}^n$** can be introduced [Farin 89]. Main alignment and other road curves are $\mathbf{G}^2$, that is curvature and tangent direction, which are parameterisation-independent, are continuous. The tangent magnitude is parameterisation-dependent and not necessarily continuous.

3.4.3. ROAD CURVES AS OFFSETS OF CLOTHOID SPLINE

Offset curves arise whenever a curve needs to be shifted equidistantly in the given direction and appear very often in the context of geometric modelling. Examples include generation of tool paths, offsets due to the material thickness and definition of the tolerance zones. Clearly, the road curves are offsets curves of the main alignment. Offset curve $\mathbf{C}'(t)$ to the given curve $\mathbf{C}(t)$ can be expressed as

$$\mathbf{C}'(t) = \mathbf{C}(t) + w\,\mathbf{n}(t)\,, \tag{3.16}$$

where w is the offset distance and $\mathbf{n}(t)$ is the unit normal vector pointing in the desired direction. For the road curves the offset distance is measured parallel to the road surface and the following normal should be applied[18]:

$$\mathbf{n} = \begin{bmatrix}-\sin\varphi\cos\chi & \cos\varphi\cos\chi & \sin\chi\end{bmatrix}^T = \mathrm{unit}\begin{bmatrix}-\sin\varphi & \cos\varphi & \sin\chi\end{bmatrix}^T, \tag{3.17}$$

where $\mathrm{unit}(\mathbf{x}) = \mathbf{x}/\|\mathbf{x}\|$ and $\chi = \arctan s_C$ is the cross slope angle. For small cross slopes the following (approximately unit) normal can be used:

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[18] Parameter t omitted for brevity.

$$\mathbf{n}_h = \begin{bmatrix} -\sin\varphi & \cos\varphi & s_C \end{bmatrix}^T \approx \mathbf{n}. \tag{3.18}$$

This corresponds to measuring the offset distance horizontally.

The basic properties of the offset curve in the planar case are as follows:

$$\begin{aligned} \kappa' &= \frac{\kappa}{o}, \\ dl' &= o \cdot dl, \\ \varphi' &= \varphi, \\ \mathbf{t}' &= o \cdot \mathbf{t}, \end{aligned} \tag{3.19}$$

where primed values describe the offset curve and $o = 1 + w\kappa$ is an **offset coefficient**, with the same sign convention for w as for curvature. Typically offsets are much smaller than curvature radii and $|o-1| \ll 1$, $o_{-w} \approx 1/o_w$.

It is important to note that the offset curve has the same parameterisation as the original curve, which allows for **synchronous sampling**, that is each sampling point on the offset curve is offset to the corresponding sampling point on the original curve, so that both points have the same curvilinear abscissa (Sect 3.4.4).

Despite the simple nature of (3.16), for many curve families the offset operation is not trivial. Most notably, offset curves of clothoids are no longer clothoids: let κ be a non zero linear function of l. Then

$$\kappa' = \frac{\kappa}{1 + w\kappa} \approx \kappa - w\kappa^2 \tag{3.20}$$

is no longer linear in l, but can be approximated using a 2nd order clothoid.

From (3.19) it follows that the offset curve is constant-speed only if the curvature is constant. Additionally, the long slope of the offset curve is influenced by the rate of change of the cross slope:

$$s_L' = s_L + w\frac{ds_C}{dl}. \tag{3.21}$$

3.4.4. CURVILINEAR COORDINATE FRAME

The cross section is expressed in the **curvilinear coordinate frame**, where the main alignment serves as the principal axis. The coordinates are **curvilinear abscissa** (distance along the axis) and **ordinate** (distance from the axis). Such coordinate frame can also be easily applied in the field using relative measurements and has a long tradition in road construction. Moreover the curvilinear presentation is especially compact and meaningful.

Also in the CIRC context the low cost, simple relative measurements (e.g. with odometer, laser or sonic distance meter) are favoured compared to expensive Cartesian positioning devices (e.g. GPS or RTS). The curvilinear reference frame can be applied in a CIRC system for the following tasks:

- displaying current position in curvilinear coordinates,
- transformation of positioning measurements between curvilinear and Cartesian reference frame,
- rudimentary design.

The curvilinear coordinates (Ger. krummlinige Koordinaten) are defined formally in the field of vector analysis [Bourke, Kendall 77]. They are mainly used to simplify integrals and differential equations using symmetry or dominant direction. Let's consider a transformation from general curvilinear coordinates $(u,w) \epsilon\, \mathbb{R}^2$ to Cartesian coordinates $(x,y)\ \epsilon\, \mathbb{R}^2$:

$$x = x(u,w), \quad y = y(u,w)\,. \tag{3.22}$$

In the 3D case we can introduce z and h as the third dimensions and adopt the following notation:

$$x = x(u,w,h), \quad y = y(u,w,h) \quad z = z(u,w,h)\,. \tag{3.23}$$

Further on the 2D form is used for brevity. Of practical value are the systems where the functions x,y are at least $\mathbf{C}^1$ and allow one-to-one correspondence between the pairs (x,y) and (u,w). This requires that the Jacobian of transformation does not vanish:

$$|\mathbf{J}| = \begin{vmatrix} \dfrac{\partial x}{\partial u} & \dfrac{\partial y}{\partial u} \\ \dfrac{\partial x}{\partial w} & \dfrac{\partial y}{\partial w} \end{vmatrix} \neq 0\,. \tag{3.24}$$

The values of Jacobi matrix and Jacobian for given point $\mathbf{P}=(u,w)$ can be interpreted geometrically as linearisation parameters of transformation around $\mathbf{P}$. The rows of $\mathbf{J}$

are the transformed coordinate axes in P's neighbourhood. The value of Jacobian is a surface change factor in the transformation, it vanishes whenever one of the vectors vanishes or they become parallel[19]. This corresponds to some surface being irreversibly compressed to line or point by the transformation. This will happen for example at the local centre of curvature. It follows that the domain of the curvilinear transformation is limited by the local circle of curvature.

Due to the piecewise nature of the main alignment, the curvilinear coordinates are defined **locally** around each element of the alignment. The alignment normals can be used to partition the plane and to define consistent curvilinear transformation.

If the tangents to coordinate lines at any given point are perpendicular, such coordinate system is called **orthogonal**. In particular, the orthogonality is important to simplify the measurements in the field.

In the 3D case the orthogonality is an ambiguous requirement, as there are indefinitely many normals to the abscissa. For a curve with non-zero curvature a local orthogonal reference frame called the **Frenet frame** can be defined [Gray 89] [Farin 89]. In addition to the unit tangent vector, the principal normal vector laying in the osculating plane and the binormal vector (normal to both tangent and principal normal) can be chosen as the base of the Frenet frame. The space curve can be expressed in the Frenet frame with curvature and torsion using Frenet-Serret formulas [Gray 89].

Two practically important possibilities for 3D curvilinear coordinate frame are:

- **Horizontal coordinates.** W axis is horizontal, H axis vertical, $z = h + const.$ Such coordinates are especially easy to apply using gravity vector.
- **Binormal coordinates.** W axis is parallel, H axis normal to the road surface. This choice corresponds to the Frenet frame, with principal normal defined also for zero-curvature segments.

Both definitions correspond to different ways of specifying the cross section.

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[19] Or, in 3 or more dimensions, linearly dependent.

3.4.5. ROAD TOPOLOGY

Until now a CIRC application for a **simple road** has been discussed, that is a layered structure (Sect. 2.2.3), consisting of one carriageway without crossings, entries or exits. More complex road structures with multiple carriageways and connecting elements like crossings or roundabouts require additional insight.

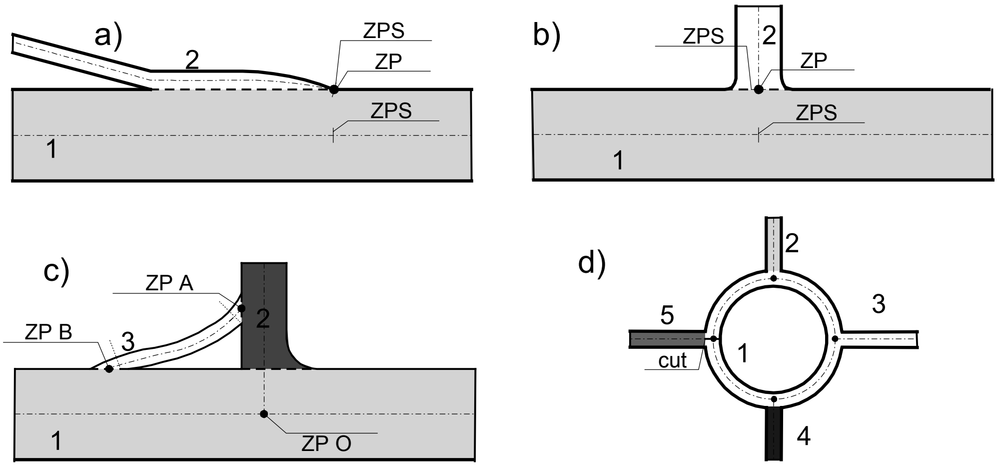

Fig. 3-6. Partitioning of complex road network topologies into simple roads.

The different colours and numbers represent the simple roads. ZP (zero points) are the origins of the local curvilinear systems as stored in the road database. ZP S mark topological connections between the local curvilinear systems.

From the topological point of view simple roads are elements of the road network, which can be represented as a **directed graph**. It follows that any road structure can be represented as concatenation of simple roads (Fig. 3-6.) This result may derived from the road network description, perhaps with manual intervention. A disjoint structure like two-carriageway roads can be handled without such difficulty. Similar partitioning may be necessary to describe a multilevel crossing or serpentines as a height field (Sect. 2.3.1).

3.4.6. ROAD SURFACES

The offset operation determines also the **road surface**, which is spanned between two road curves in a way defined by the offset vectors. Due to the piecewise-linear nature of the cross section, road surface is a **ruled surface**[20] [Farin 89], that is every isoparametric line in lateral direction is a straight line. We can classify road surfaces,

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[20] Also known as swept surface [Willems 98].

spanned in a linear manner between clothoid spline offsets, as clothoid spline ruled surfaces or **linclothoid spline surfaces**.

3.4.7. CONCLUSIONS

Road curves can be defined as a special class of (planar or space) parametric curves with the following properties:

- Offset clothoid spline nature,
- Low, continuous curvature and low torsion,
- Constant or nearly constant speed,
- Independent definition in horizontal plane and vertical direction. In particular the spline nodes and curvatures are independent in both directions.

The offset operation determines other road curves and road surfaces based on the main alignment. **Road surfaces** are ruled surfaces spanned between road curves.

As only partial 2D curvatures are considered in the projected design, the consideration of space road curves has limited use in this case, but should be interesting in the 3D design context. It is interesting to study the 3D curvature and torsion of the space road curves and surfaces describing today's roads.

The differential geometry offers alternative possibilities road curve description, for example one can fully describe a unit-speed 2D curve by initial point and tangential angle function.

3.5. DESIGN APPROXIMATION

As discussed in the Chapter 2, a CIRC system needs to perform **efficiently**, among other tasks, visualisation, geometric searching and, in 3D application, vertical interpolation of the design. These would be difficult to accomplish using clothoid splines and associated ruled surfaces of the road design. It is more practical to **approximate the design** using primitives which can be handled more efficiently. The design approximation induces errors of different nature in the on-board tasks mentioned above.

In this section we discuss the requirements, analyse the possible approaches and discuss the errors caused by design approximation, searching **for economical representations** in terms of memory and CPU time. We will start with the road curve approximation and afterwards generalise our approach towards the road surfaces.

3.5.1. ROAD CURVE APPROXIMATION

3.5.1.a. Introduction

The goal of the approximation of a parametric road curve $\boldsymbol{C}(t)$ is to find the approximating curve $\hat{\mathbf{C}}(t)$, such that the error is minimal. Different norms for the error can be adopted, but most often one is interested in giving a **worst-case** guarantee and limiting a maximal error

$$\left\|\mathbf{C}(t)-\hat{\mathbf{C}}(t)\right\| \leq \varepsilon\,, \qquad (3.25)$$

rather than posing a guarantee for the root mean squared error or standard deviation.

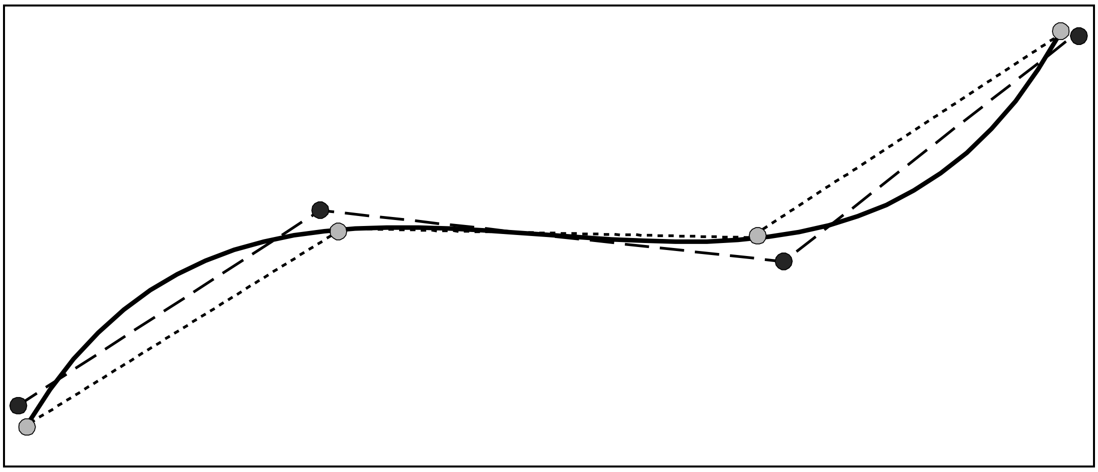

Fig. 3-7. Polyline approximation of a curve by sampling and interpolation (dotted line) or least-squares approximation (dashed line).

Polylines are used especially often in the design approximation context [Circ], due to their simplicity. They are exact for zero curvature elements. The **polyline interpolation** is analogous to the traditional setting-out procedure. The wire for levelling support (staking out, or "wire and pegs") corresponds directly to the interpolating polyline. **Triangular Irregular Networks** (TINs) can be obtained easily by adding diagonals[21] between the polylines. They are the favourite representations for the DTMs [Oloufa 91].

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[21] A diagonal of a planar polygon is a line segment connecting its vertices laying completely inside the polygon, not intersecting any edges [O'Rourke 93].

In addition to the requirement for the approximation error also the number of nodes (points) should be kept small. Two strategies are possible for choosing the nodes (Fig. 3-7.): **least squares approximation** (minimising mean squared error) **or sampling and interpolation**. Traditionally the uniform sampling approach with the *5* or *10 m* sampling interval has been used for setting-out. The uniform sampling is straightforward to apply for the surveyor, especially when using clothoid tables with the fixed grid [Osterloh 91]. In the case of a CIRC system it is no longer a requirement, however it is often adopted for simplicity.

Least squares approximation could offer smaller errors provided that a "good" sequence of nodes can be found. However, except of the simplicity, sampling has further advantages. Selecting the sampling nodes for the main alignment and using synchronous sampling corresponds to selecting cross sections, which will be maintained in the sampled design.

3.5.1.b. Accuracy requirements

As discussed in Sect. 2.2.3, the required accuracy of the approximation depends on the application (in general higher for levelling than for surfacing) and the phase of the works (the closer to the final surface the higher). In the 3D case a separate requirement for a vertical error will be posed, typically much more stringent than in the plane. Currently there exist no specifications for such accuracy. However, similar specifications exist for the setting-out and supervision, for example the current German standard [RAS-Verm 02] defines the following requirements (in terms of standard deviation):

- for geodetic points of construction structures (Ger. Bauwerkspunkte): less than *1 cm* in XY plane, $<$ *2 mm* in Z direction,
- project geometry (alignments, axes etc.): $<$ *3 cm* in XY, $<$ *1 cm* in Z,
- alignments (Ger. Leitlinien):
  - earthworks: $<$ *4 cm* in XY, $<$ *1.2 cm* in Z,
  - base course: $<$ *3 cm* in XY, $<$ *8 mm* in Z,
  - wearing course: $<$ *3 cm* in XY, $<$ *4 mm* in Z.

These requirements are posed on the selected points of the design, not globally, however we can use them as a reference for specifying the following requirements on the design approximation:

- **Planar curve approximation:** is placement relative to the alignments maintained? This is important for visualisation and steering, and a prerequisite for correct vertical approximation, therefore discussed first. Typical value: *5..30 cm*.
- **Surface approximation:** accuracy of the DTM is very important for the determination of the levelling error. This depends strongly on the type of the used approximation, discussed in Sect. 3.5.3. Typical value: *1..5 mm*.
- **Curvilinear coordinates:** are the distances along and across the road maintained? This issue is related to approximation accuracy concerning direction and curvature. Typical value: *5..30 cm*.

Additional requirements for sought approximation may be posed, especially if the primary design information (curvatures, angles, abscissas) is sampled as well. For example, as **uniform sampling** has been traditionally applied for setting-out, the user may wish to see the stationing at constant intervals. Thus some approximation nodes may be predetermined. On the other hand, one is free to choose the approximation nodes only if the continuous model of the road is used.

Constrains may also be posed for the **evenness** of the approximation. It is not possible to preserve smoothness of the design, in terms of the continuous derivatives, with the piecewise linear model. Rapid changes of designed slope may negatively influence the levelling algorithm.

For the typical task of finding design elevation at measured point (Sect. 2.3.1) horizontal and vertical errors are connected by the road slope. For example in the case of *4 %* slope (max. longitudinal slope for A-class roads with design speed of *120km/h* according to [RAS-Q 96]) already *5 cm* deviation in horizontal plane corresponds to *2 mm* error in elevation.

3.5.1.c. Polyline approximation of a circle arc

The part of a circle arc of a length Δl can be approximated by a chord of length Δl_c (Fig. 3-8.). Two kinds of approximation errors can be defined.

Orthogonal error[22] is a maximum distance between the arc and the chord. It can be approximated using second order Taylor expansion, provided that the arc angle is

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[22] Also known as *flatness*, but this term could cause confusion in the 3D case.

sufficiently small, which will be the case for correct sampling:

$$\varepsilon_{orth} = R\left(1-\cos\frac{\alpha}{2}\right) \approx \frac{1}{8}R\alpha^2 = \frac{1}{8}\Delta l^2\kappa\,. \tag{3.26}$$

Analogously, **length error** is the difference between the arc length and chord length and can be approximated using third order Taylor expansion. In both cases the approximation overestimates the error:

$$\varepsilon_{len} = \Delta l - \Delta l_c = \Delta l - 2R\sin\frac{\alpha}{2} \approx \frac{1}{48}R\alpha^3 = \frac{1}{48}\Delta l^3\kappa^2\,. \tag{3.27}$$

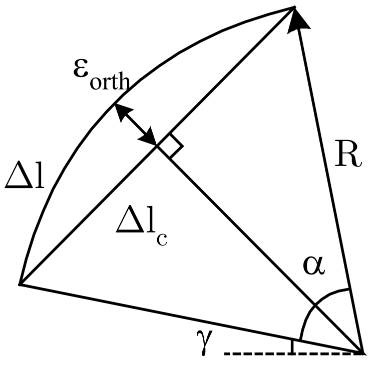

Fig. 3-8. Circle arc approximated by a chord.

The following can be said about polyline approximation errors for the offset curves (Sect. 3.4.3):

$$\begin{aligned} \varepsilon_{orth}' &= o\cdot\varepsilon_{orth}, \\ \varepsilon_{len}' &= o\cdot\varepsilon_{len}. \end{aligned} \tag{3.28}$$

The orthogonal error grows faster with curvature and segment length, it is also more critical. Given acceptable error, the **correct sampling length** can be therefore defined using Eq. (3.26):

$$\Delta l = 2R\arccos\left(1-\frac{\varepsilon_{orth}}{R}\right) \approx \sqrt{8\varepsilon_{orth}R}. \tag{3.29}$$

This simple result, presented graphically in Fig. 3-9., can be applied not only in the plane, but also independently in the vertical direction, bearing quite serious consequences. For typical sampling sequences (*Δl = 5* or *10 m*) the vertical error is surprisingly high for the vertical arcs, for example respectively *1 cm* and *4 cm* for an arc with vertical radius $H = 300\ m$. Uniform sampling with $2\ m$ interval would be very expensive for few *km* long design. The above result applies of course also to the classic wire and pegs solution, although the inertial behaviour of the machine in the subsequent passes certainly smoothens the resulting surface. However, in the CIRC application one would prefer more exact description of the surface, also for subsequent levelling control discussed in Sect. 2.3.1.

Either we need to **adapt the sampling** to curvature using (3.29), or more **flexible approximation primitives** than a chord are needed.

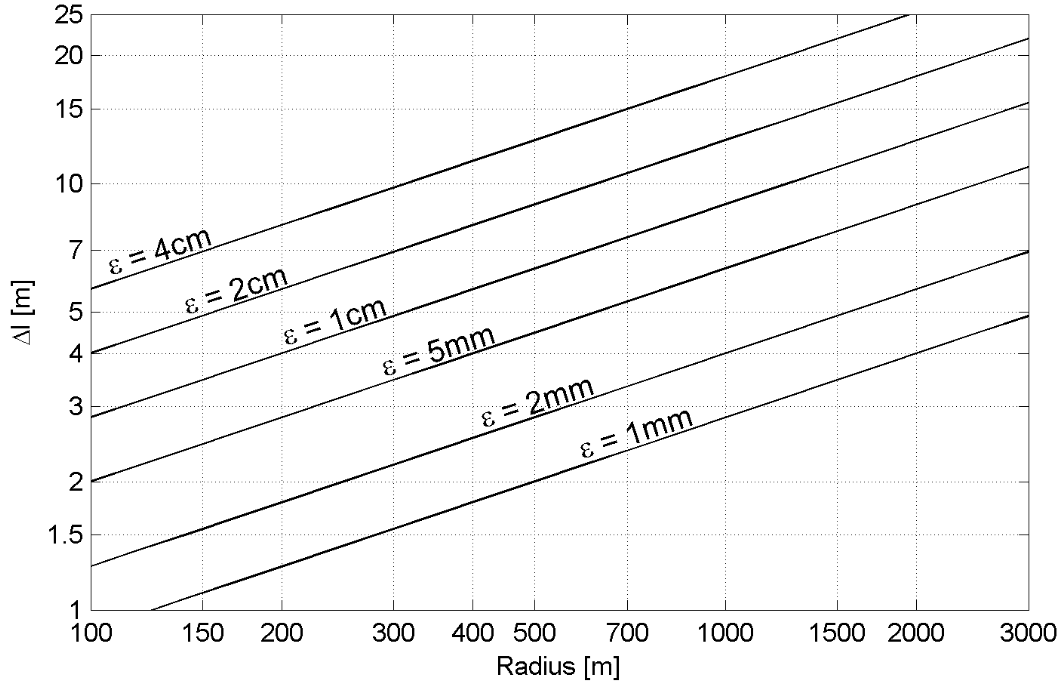

Fig. 3-9. Maximum sampling interval depending on curvature radius and required accuracy.

3.5.1.d. Polyline approximation of a clothoid

Using a local approximation with an arc, the result (3.29) can be also used for clothoid, due to the fact that its curvature changes monotonously. If a uniform sampling is desired, applying a maximum curvature would guarantee fulfilling the error requirement. However, as the error is proportional to the curvature, the sampling would be too tight outside of the area of highest curvature.

In order to optimise the sampling by equalising the error we can also apply (3.29) sequentially, in the direction of decreasing curvature. In this way we can find the next sampling point $l_{n+1} = l_n + \Delta l$ given the previous sampling point l_n. We need to sample curves of increasing curvature backwards. This simple **sequential adaptation rule** can be adopted for any curve with monotonous curvature, in particular for clothoid offsets.

Trying to optimise the sampling even further by applying a linear model of curvature

$$\begin{aligned} &\kappa(l+\Delta l) = \kappa(l) + \alpha \Delta l, \\ &\alpha = \pm \frac{1}{2A^2}, \end{aligned} \tag{3.30}$$

and taking the arithmetic mean for the midpoint we arrive at the following cubic equation for optimal adaptive sampling:

$$\Delta l^2 \left(\kappa\left(l\right) + \alpha \Delta l\right) = 8\,\varepsilon_{orth}. \tag{3.31}$$

In the practice it can be solved in 2-4 *Newton-Raphson* iterations using the previous solution as an initial point.

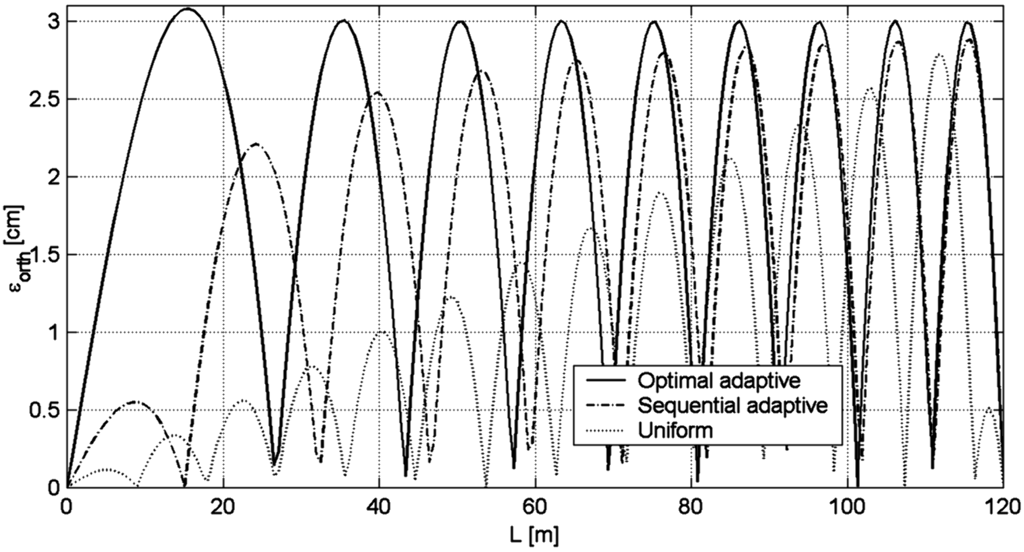

Fig. 3-10. Error of clothoid sampling.

L=120 m, A = 200, K=3 km^{-1}, required accuracy 3 cm.

Solid line – optimal sampling (11 points), dash-dotted line – approximated adaptive sampling (11 points), dotted line – uniform sampling (15 points).

The results can be verified in the numerical simulation (Fig. 3-10.). **Adaptive sampling** take bigger steps when the curvature is low, decreasing the step length appropriately with the growing curvature. ***25-30%*** **less points** are required to obtain *3 cm* accuracy when adaptive sampling is used. Optimal and sequential adaptation are nearly equivalent, therefore simper **sequential adaptation** can be recommended.

We conclude that adaptive sampling may bring serious savings in terms of memory and CPU consumption. This is especially important for modern roads, when long clothoid segments of low curvature are used. The method of sampling in **non-increasing curvature** direction can be generalised to all road curves.

3.5.1.e. Cubic spline approximation of a road curve

After surveying the possibilities of adopting the step size, interpolants more flexible than a straight line can be applied. One of the basic tools of CAGD which can be applied here is a **Hermite cubic interpolation** [Farin 89] [de Boor 01]. Such interpolant can be expressed in terms of the endpoints and tangents at the endpoints as

$$\mathbf{p}(u) = \begin{bmatrix} H_0^3(u) & H_1^3(u) & H_2^3(u) & H_3^3(u) \end{bmatrix} \begin{bmatrix} \mathbf{p}_0 & \mathbf{p}_1 & \dot{\mathbf{p}}_0 & \dot{\mathbf{p}}_1 \end{bmatrix}^T, \tag{3.32}$$

where $H_i^3(u)$ for $i = 0, 1, 2, 3$ and $0 \leqslant u \leqslant 1$ are cubic Hermite polynomials:

$$\begin{aligned} H_0^3(u) &= 2u^3 - 3u^2 + 1, & H_1^3(u) &= -2u^3 + 3u^2, \\ H_2^3(u) &= u^3 - 2u^2 + u, & H_3^3(u) &= u^3 - u^2. \end{aligned} \tag{3.33}$$

The spline of Hermite interpolants can be spread between the sampling points to obtain a $\mathbf{G}^2$ approximation of a road curve. However, generally it no longer constant speed.

This interpolation scheme is **practical**, as it is fairly **simple and local**, that is it relies only on the information from the interpolated interval. However, it requires the information about the design tangents

$$\dot{\mathbf{p}} = k\,\mathrm{unit}\begin{bmatrix} \cos\varphi & \sin\varphi & s_L \end{bmatrix}^T, \tag{3.34}$$

where factor $k \approx \Delta l$ is due to reparameterisation (3.8). The offset tangents can be derived from the main alignment tangents using (3.19). In the absence of the tangent information one can attempt to estimate them numerically, or solve to make the tangents continuous across the nodes, leading to well-known **cubic spline interpolation** [de Boor 01].

The **orthogonal error** reaches the maximum in the middle of the arc, and shows quartic dependency on the sampling interval:

$$\varepsilon_{orthCub} = R\left(1 - \cos\frac{\alpha}{2} - \frac{\alpha}{4}\sin\frac{\alpha}{2}\right) \approx \frac{1}{384} R\alpha^4 = \frac{1}{384}\Delta l^4 \kappa^3 . \tag{3.35}$$

Attempts to improve the approximation further by varying the parameterisation constant proved effective only for large angles. The result shown in Fig. 3-11. shows big improvement over linear interpolation, especially with **low-quality sampling**. In particular, the design can be recovered with millimetre accuracy if low-quality *25 m* sampling has been applied (e.g. due to the static cross sections used in the design process). M**emory conservation** by factor ***10..30*** is possible.

Further improvements may involve:

- evaluation of numerical tangent strategies (e.g. Bessel, Catmull-Rom tangents [Farin 89]),
- application of more complex curves (e.g. quintic Hermite interpolation, rational splines).

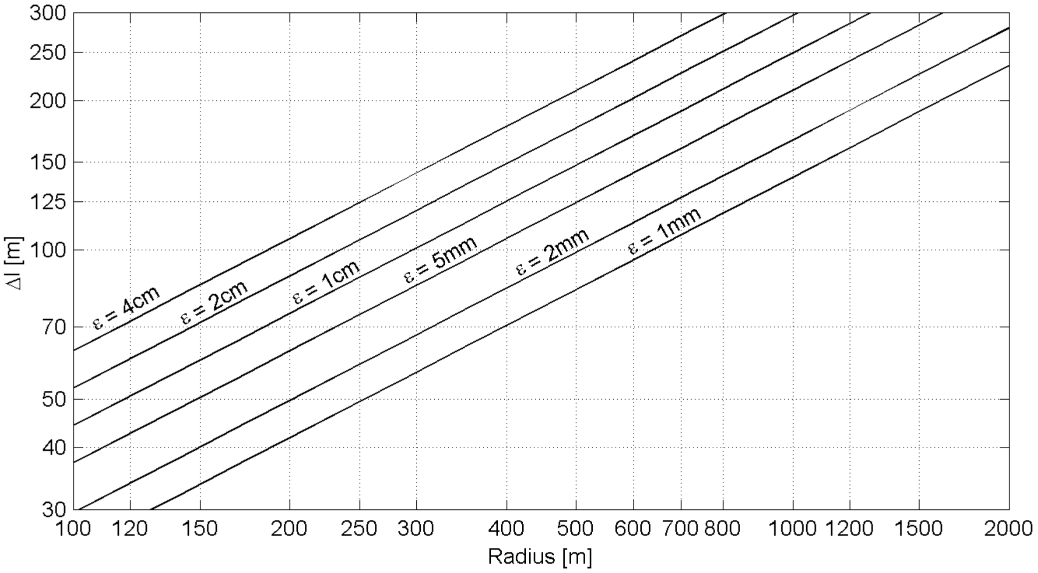

Fig. 3-11. Maximum sampling interval for cubic approximation.

3.5.1.f. Conclusions

Interpolation with linear and cubic elements is practical in CIRC context. Simple, traditionally applied **linear interpolants** behave poorly with **vertical curvature**. The **cubic curves** promise much higher accuracy at the cost of specifying the tangent direction. The **error estimates** can be used independently in the plane and vertical direction. The sampling rate can be adopted to allowable error with simple rules based on curvature.

3.5.2. LINEARISATION OF CURVILINEAR COORDINATES

As shown in the Fig. 3-12., it is simple to extend the concept of the polyline approximation and **locally linearise** the curvilinear coordinate system with a Cartesian system UW oriented along the line segment $\overline{ab}$. The domain of the local system is limited by the normals (shown as dashed lines) in order to eliminate ambiguities. Global abscissa value at *a* or *b* is required to calculate the approximated global curvilinear coordinates. Linear interpolation can be applied for improved accuracy if both values are available.

The approximate local curvilinear coordinates *(u,w)* for any given point *(x,y)* within the domain of UW can be found by solving the equation

$$\begin{bmatrix} x - a_x \\ y - a_y \end{bmatrix} = \begin{bmatrix} \mathbf{t} & \mathbf{n} \end{bmatrix} \begin{bmatrix} u \\ w \end{bmatrix}, \tag{3.36}$$

where **t**, **n** are unit tangent and normal respectively. The solution is

$$\begin{bmatrix} u \\ w \end{bmatrix} = \begin{bmatrix} t_x & t_y \\ t_y & -t_x \end{bmatrix} \begin{bmatrix} x - a_x \\ y - a_y \end{bmatrix}. \tag{3.37}$$

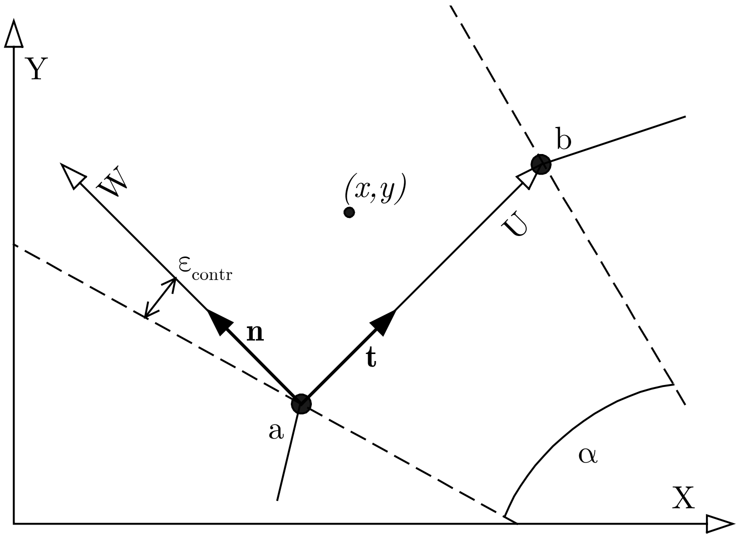

Fig. 3-12. Linearised curvilinear coordinates.

The local system UW based on a line segment $\overline{ab}$ results from an **isometric transformation** of the original system XY (translation and rotation). The above equations correspond to the rotation components of the direct and inverse transformations respectively. Thus the Jacobians of both transformations are equal to 1 and do not vanish.

For non-zero curvature errors are introduced. The dominant part of the **longitudinal error** Δu is due to the fact that the W axis is not parallel to the normals and the contraction of the surface between them is not taken into account. Component due to the **length error** (3.27) is much smaller. Eq. (3.27) can be used to estimate the **lateral error** Δw:

$$\begin{aligned} \Delta u &= \varepsilon_{len} + \varepsilon_{contr} \approx \varepsilon_{contr}, \\ \Delta w &= \varepsilon_{orth} \approx \frac{1}{8} \Delta l^2 \kappa, \end{aligned} \tag{3.38}$$

where the error due to the contraction is

$$\varepsilon_{contr} = w \sin \frac{\alpha}{2} \approx \frac{1}{2} w \Delta l \kappa. \tag{3.39}$$

The longitudinal error will grow quickly with the distance from the alignment and dominate the total error. This effect cannot be equalised by adaptive sampling. For moderate curvatures the error will reach **dm level** at the road edge, even with **tight sampling**.

We conclude that the linearisation (3.36), although straightforward and fast, is **inherently imprecise**. Application of more flexible cubic or bilinear interpolation is closely related to the issue of the road surface approximation, which is handled in the next section together with the numerical experiments on the linearisation.

3.5.3. ROAD SURFACE APPROXIMATION

As of today, after the reference points have been set out, the surface between them is created as a combination of linear interpolation (wire and pegs) and behaviour of the team and machines in subsequent passes. In other words, the final road surface is created in the process of **"natural interpolation"**. As discussed in Sect. 3.3.1.c, the CAD system using static cross section may not define the road surface at all, relying on the natural interpolation between the set-out points. In this case we can hardly discuss the errors of surface approximation.

In the 3D CIRC system the road surface must be unambiguously defined as a DTM height field, which attempts to approximate the original design (Sect. 2.3.1). This may happen in a Cartesian

$$z = \hat{z}(x,y) \approx z(x,y) \quad \text{for} \quad (x,y) \in D\,, \tag{3.40}$$

or a curvilinear domain

$$z = \hat{z}(u,w) \approx z(u,w) \quad \text{for} \quad (u,w) \in U \times W\,. \tag{3.41}$$

In this section we will study different **sampling strategies and interpolation techniques** with respect to the fidelity of the DTM. We will use the curvilinear representation for the convenience of presentation and notation.

One often has to **extrapolate** the approximation (3.41) beyond the original design, especially sideways. This may happen due to inexact steering and positioning errors when the levelling algorithm (Sect. 2.3.1) is applied on the edge of the layer. This is a major difference compared to the typical DTM interpolation scenario.

The maximum and RMS (root mean square) values of the following errors, arising from the approximation, will be used as figures of merit:

- height error: $\Delta z = z(u,w) - \hat{z}(u,w)$,
- slope errors: $\Delta s_L = \dot{z}_u - \dot{\hat{z}}_u, \quad \Delta s_C = \dot{z}_v - \dot{\hat{z}}_v$,
- errors of the curvilinear transformation: $\Delta u = u - \hat{u}(x,y), \Delta w = w - \hat{w}(x,y)$.

We suppose the approximation to work well for straight lines and flat surfaces, and expect the errors to increase with increasing curvature and slopes. In order to study this effect a **synthetic road** has been defined (Fig. 3-13.) which becomes increasingly curvy and warped:

- In the plane it is interesting to evaluate the influence of the increasing curvature, hence we choose a clothoid as a horizontal design. The parameters are $A = 200\ m$, length $L = 400\ m$ and final radius of curvature $R = 100\ m$.
- In the vertical direction it is interesting to have a non-zero curvature. An arc with a vertical radius $H = 2000\ m$ has been chosen, so that the long slope varies between -10 and $10\ \%$.

- To obtain a realistic cross section, the cross slope is linearly dependent on the curvature. Final cross slope is *12%*, width *W = 20 m*. To simplify the analysis the roof shape wasn't used.
- The sampling should be synchronous and uniform due to the constant vertical curvature. A moderate sampling interval of *20 m* has been chosen. As a reference, a linear interpolation would result in a vertical error of *2.5 cm*.

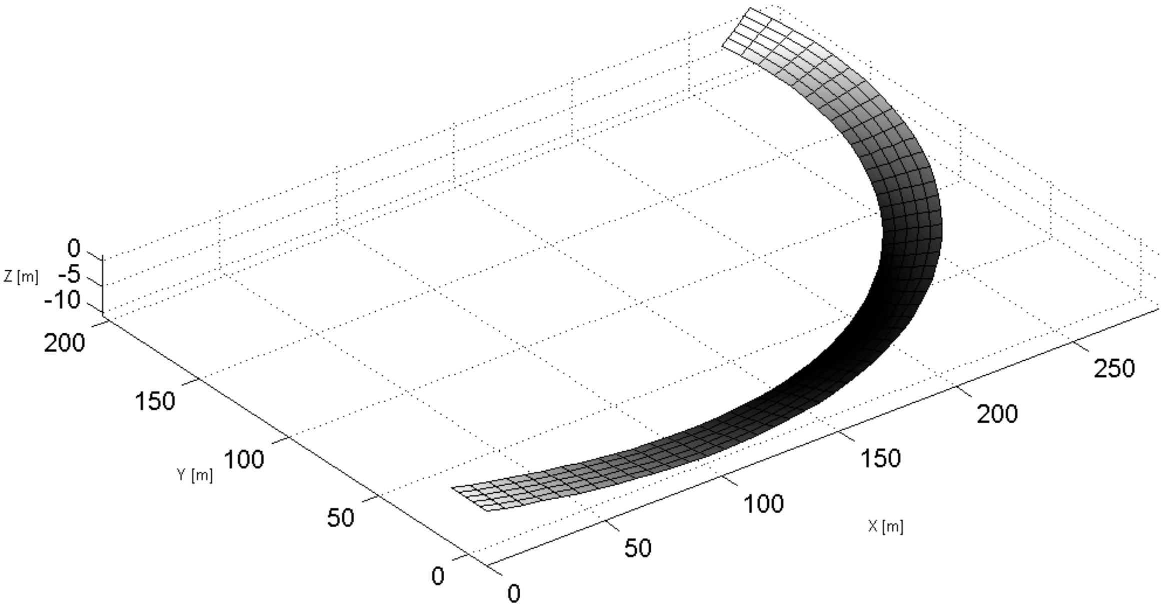

Fig. 3-13. Synthetic road for numerical tests.

3.5.3.a. Triangular and bitriangular interpolation

Spatial interpolation with TINs is a basic method of defining DTMs, and has also been successfully practised in CIRC applications [Circ] [Frank 98]. However, because of the ordering imposed by the road and the advantages of the synchronous sampling, the basic interpolation unit is a **quadrilateral**, not a triangle. One can partition the quadrilateral using the shorter diagonal, obtaining globally (with a proper sampling) a restricted Delaunay triangulation (Sect. 4.4.2.a, Fig. 3-14.). The resulting surface can be improved by partitioning by both diagonals (which will typically be of similar length) and taking the average This approach is called **bitriangular interpolation** and tries to avoid sharp edges.

The triangular interpolation can be conveniently expressed using **barycentric coordinates** [Bartelme 95] [Weisstein Web]. Given three non-collinear points A,B,C, the barycentric coordinates of a point **P** with respect to **A**,**B**,**C** are *a,b,c*, such that:

$$\begin{aligned}\mathbf{P} &= a\cdot\mathbf{A}+b\cdot\mathbf{B}+c\cdot\mathbf{C},\\ 1 &= a+b+c.\end{aligned}\tag{3.42}$$

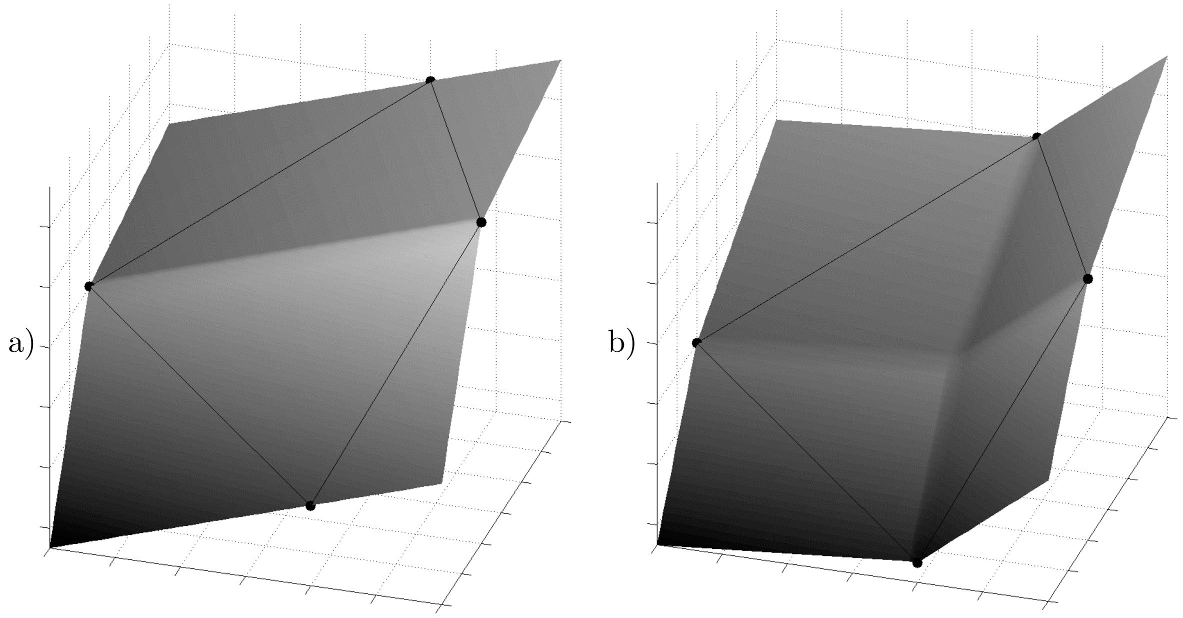

Fig. 3-14. a) Triangular and b) bitriangular interpolation.

The barycentric coordinates of **P** can be expressed as

$$a=\frac{|BCP|}{|ABC|},\quad b=\frac{|CAP|}{|ABC|},\quad c=\frac{|ABP|}{|ABC|}=1-a-b\,,\tag{3.43}$$

where $|ABC|$ is a signed area of the triangle ABC

$$|ABC|=\frac{1}{2}\left|\overrightarrow{AB}\times\overrightarrow{AC}\right|.\tag{3.44}$$

As the barycentric coordinates are invariant under affine transformations, and triangles parallel to the Z axis can be removed, the area quotients can be efficiently calculated in the projection on the XY plane using 2D vector products [O'Rourke 93].

The barycentric coordinates are useful for containment tests (a point lies in the triangle if and only if $0\leqslant a,b,c\leqslant 1$). This can be used to introduce the interpolation grid, but is not useful when extrapolation has to be applied. Instead a two-phase test is necessary, first for the containment between normals and then for the side of a diagonal.

The barycentric coordinates can be used for interpolation of any numerical properties of A, B and C, including elevation. If the slopes at A, B and C are known, they can also be interpolated using (3.42), but the result would not fit the interpolating plane. Instead, the slope in the direction represented by a unit vector **d** can be calculated using a scalar product with a unit normal to the triangle surface

$$s_d = \arcsin\left(\mathbf{d} \cdot \mathrm{unit}\left(\overrightarrow{AB} \times \overrightarrow{AC}\right)\right). \tag{3.45}$$

The above equation can be used for slopes $-\pi/2 .. \pi/2$.

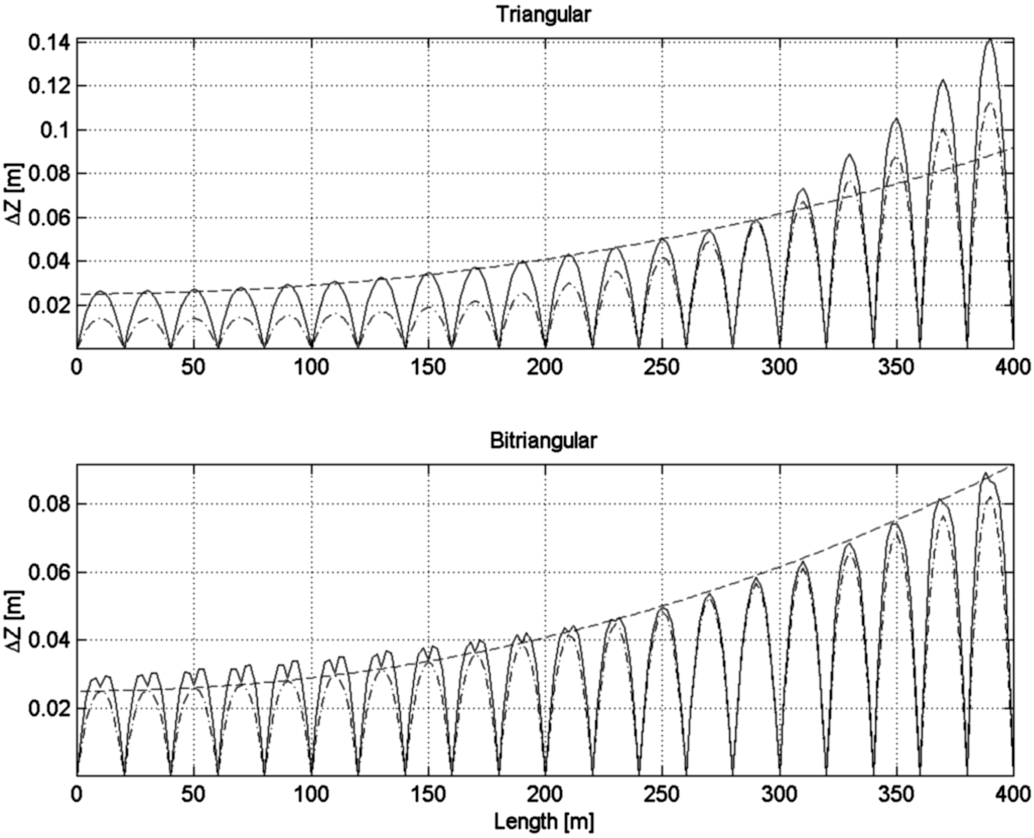

Fig. 3-15. Elevation error of triangular and bitriangular interpolation

Solid lines – maximum, dash-dot – RMS, dashed – estimated error ε_{tri}.

The **elevation error** of triangular interpolation, shown in Fig. 3-15. can be estimated by a superposition of the orthogonal errors in horizontal and vertical directions

$$\varepsilon_{tri} = \varepsilon_{orthZ} + s_C \varepsilon_{orthXY}, \tag{3.46}$$

The impact of the orthogonal error in the plane grows quickly. Further experiments show that even for a flat axis ($s_L = 0$), the warping of the surface due to the variable cross slope causes an additional vertical error ε_{warp}, which can be estimated as a vertical distance between the diagonals

$$\varepsilon_{warp} \approx \frac{1}{2}\frac{ds_C}{dl}\Delta l \frac{W}{2}. \tag{3.47}$$

As discussed in Sect. 3.5.2, the longitudinal error dominates the total error of the linearised curvilinear transformation (Fig. 3-16.). Lateral error is well estimated by ε_{orth}, longitudinal error is bound between ε_{len} and ε_{contr}. The last value can be also used as an estimate of the total error.

We conclude that the **improvement** due to the bitriangular interpolation is **not significant**, except of a warping error, which is reduced four times.

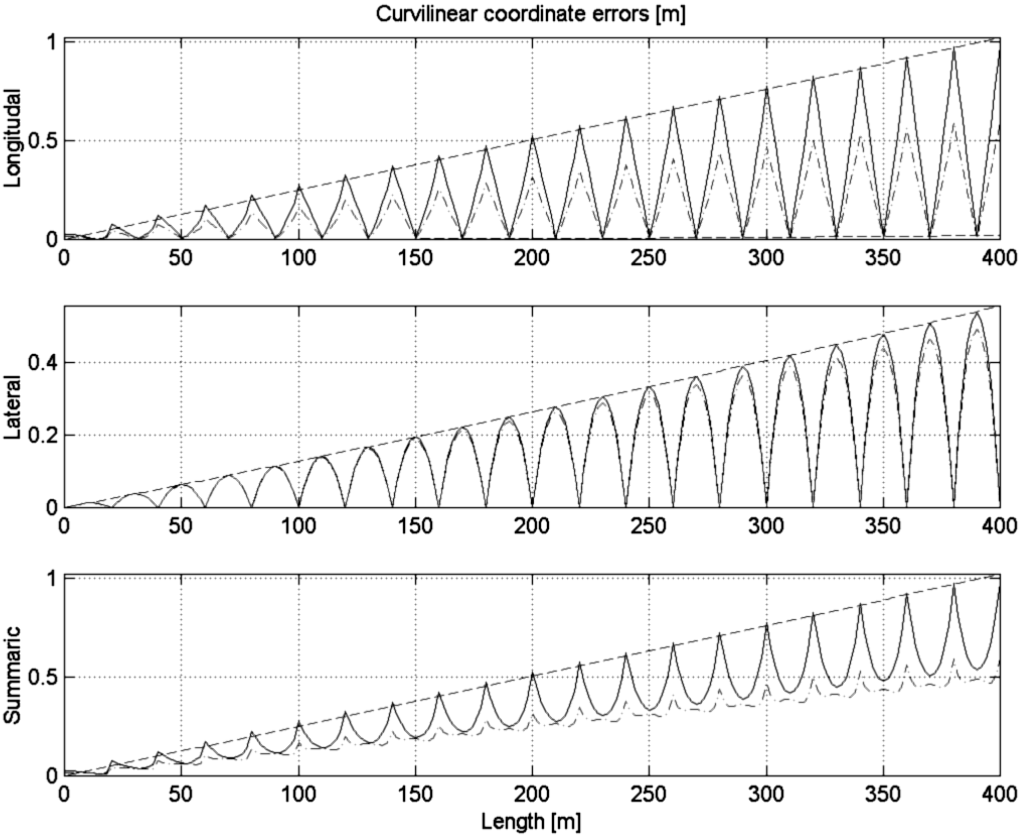

Fig. 3-16. Curvilinear coordinate errors with linearisation

Solid lines – maximum, dash-dot lines – RMS error, dashed lines – error estimations.

3.5.3.b. Bilinear interpolation

Bilinear surface is the simplest example of a **tensor product**[23] **surface**, a concept widely applied in CAGD to derive a surface from a definition of *2* curves [Farin 89] [Mortenson 85]. Given two sets of base functions $F_i(u)$ and $G_j(w)$, $i = 1..k$, $j = 1..l$, $0 \leqslant$

---

[23] Tensor product of functions $f(x)$, $g(y)$ can be defined as $h(x,y) = f(x) \cdot g(y)$.

$u,w \leqslant 1$, such as for the purpose of parametric curve definition (e.g. Hermite polynomials of Sect. 3.5.1.e), one can define a tensor product surface as

$$\mathbf{p}(u,w) = \sum_{i=1}^{k}\sum_{j=1}^{l} \mathbf{b}_{ij} F_i(u) G_j(w)\,, \tag{3.48}$$

or more conveniently in the matrix form

$$\mathbf{p}(u,w) = \mathbf{FBG}^T, \text{ where } \mathbf{F} = \begin{bmatrix} F_1(u) & \dots & F_k(u) \end{bmatrix}, \ \mathbf{G} = \begin{bmatrix} G_1(w) & \dots & G_l(w) \end{bmatrix} \tag{3.49}$$

and $\mathbf{B}$ is a three dimensional interpolation tensor, chosen so that $\mathbf{p}$ fits existing points, curves or surfaces. The depth of $\mathbf{B}$ corresponds to the dimension of $\mathbf{p}$, which can be arbitrary, so that the tensor product equation (3.48) can be applied to interpolate several variables (e.g. elevation, temperature etc.) concurrently.

Eq. (3.48) can be understood as a mapping between a unit square in $\mathbb{R}^2$ and a surface in $\mathbb{R}^n$. This mapping introduces dimensionless, local curvilinear coordinates, justifying the reuse of the symbols u and w. With proper scaling and offset, it can be readily applied to estimate the global curvilinear coordinates.

Bilinear interpolation is a 2D generalisation of linear interpolation, in matrix form

$$\mathbf{p}(u,w) = \begin{bmatrix} 1-u & u \end{bmatrix} \begin{bmatrix} \mathbf{p}_{00} & \mathbf{p}_{01} \\ \mathbf{p}_{10} & \mathbf{p}_{11} \end{bmatrix} \begin{bmatrix} 1-w \\ w \end{bmatrix}. \tag{3.50}$$

As shown in Fig. 3-17., the resulting surface ("hyperbolic paraboloid") is ruled in both directions. As the linclothoid surface is ruled only in the lateral direction, the isoparametric lines are matched quite exactly in lateral direction, but the longitudinal arcs cannot be matched. We conclude that the results of Sect. 3.5.1.c can be applied to study the accuracy of a bilinear interpolation.

In order to apply (3.50) as DTM equation we need to find a reverse mapping $(x,y) : \mathbf{p}_{xy}(u,w) = \begin{bmatrix} x & y \end{bmatrix}^T$, that is to find a point (u,w) which gets mapped to a given point (x,y). This can be done in few *Newton-Raphson* iterations, especially if a good starting point is obtained by linearisation of the quadrilateral. Than the elevation (and possibly other properties) can be interpolated by direct mapping $z = \mathbf{p}_z(u,w)$. Result: the elevation error (Fig. 3-18.) does not vary in the lateral direction, but otherwise the improvement against the triangular case is not significant.

Concerning the curvilinear coordinates (Fig. 3-19.), the longitudinal error of bilinear transformation is very small and can be approximated by ε_{len}. The lateral error is the same as in the linearised case. The total error can be estimated by ε_{orth}.

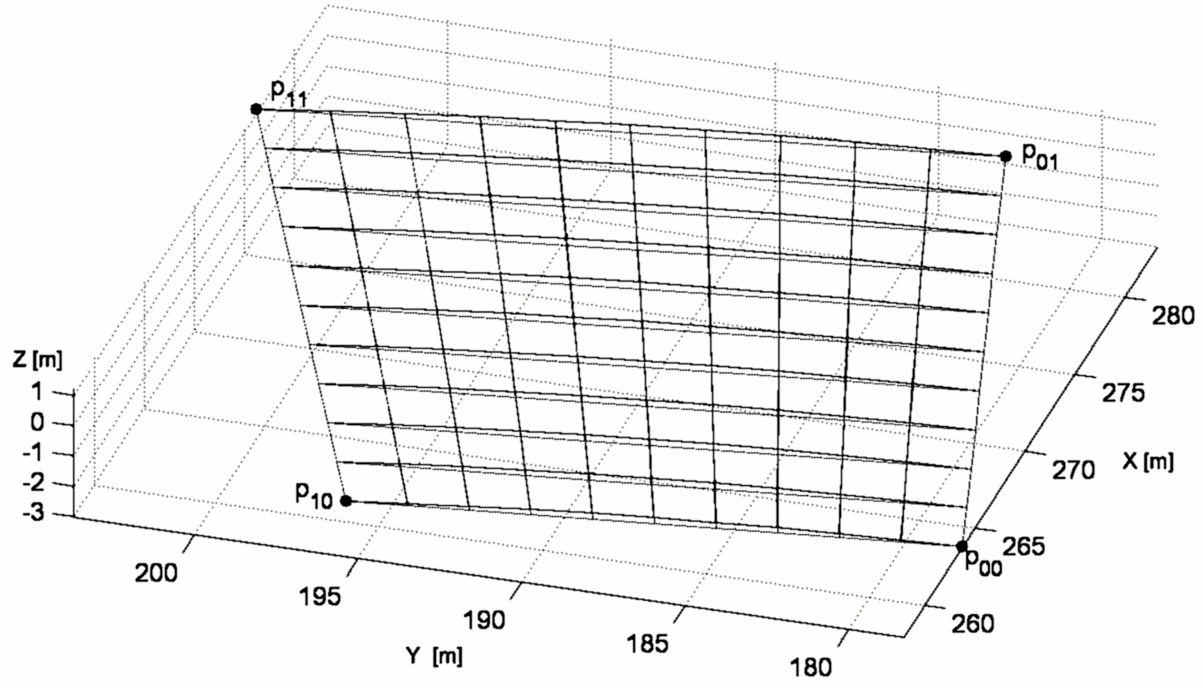

Fig. 3-17. Bilinear interpolation of a linclothoid surface.

The final 20 m segment of the test road. Isoparametric lines are matched in the lateral, but not in the longitudinal direction.

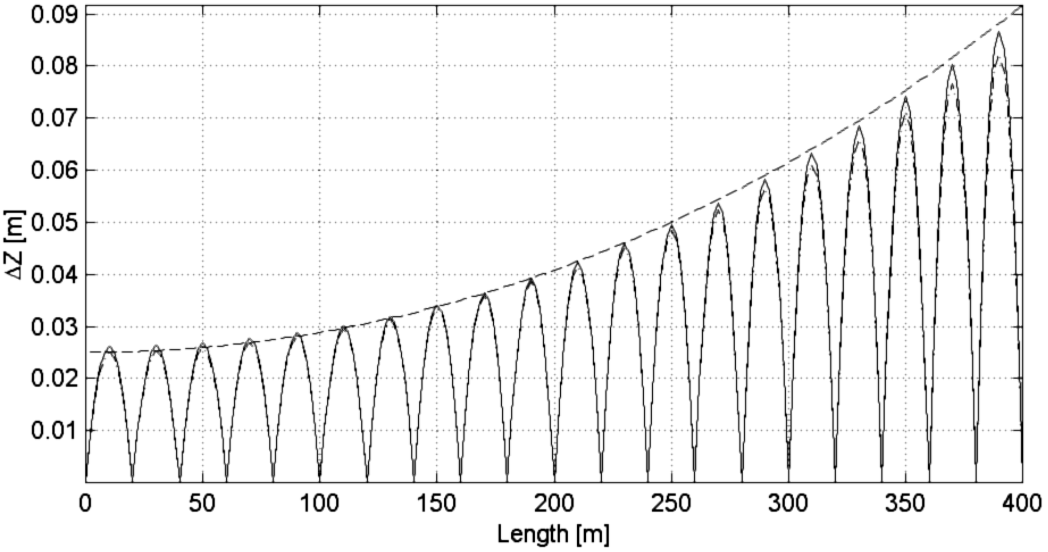

Fig. 3-18. Elevation error of the bilinear interpolation

Solid lines – maximum, dash-dot – RMS, dashed - estimated error ε_{tri}. Maximum and RMS errors are very close – error does not significantly vary laterally.

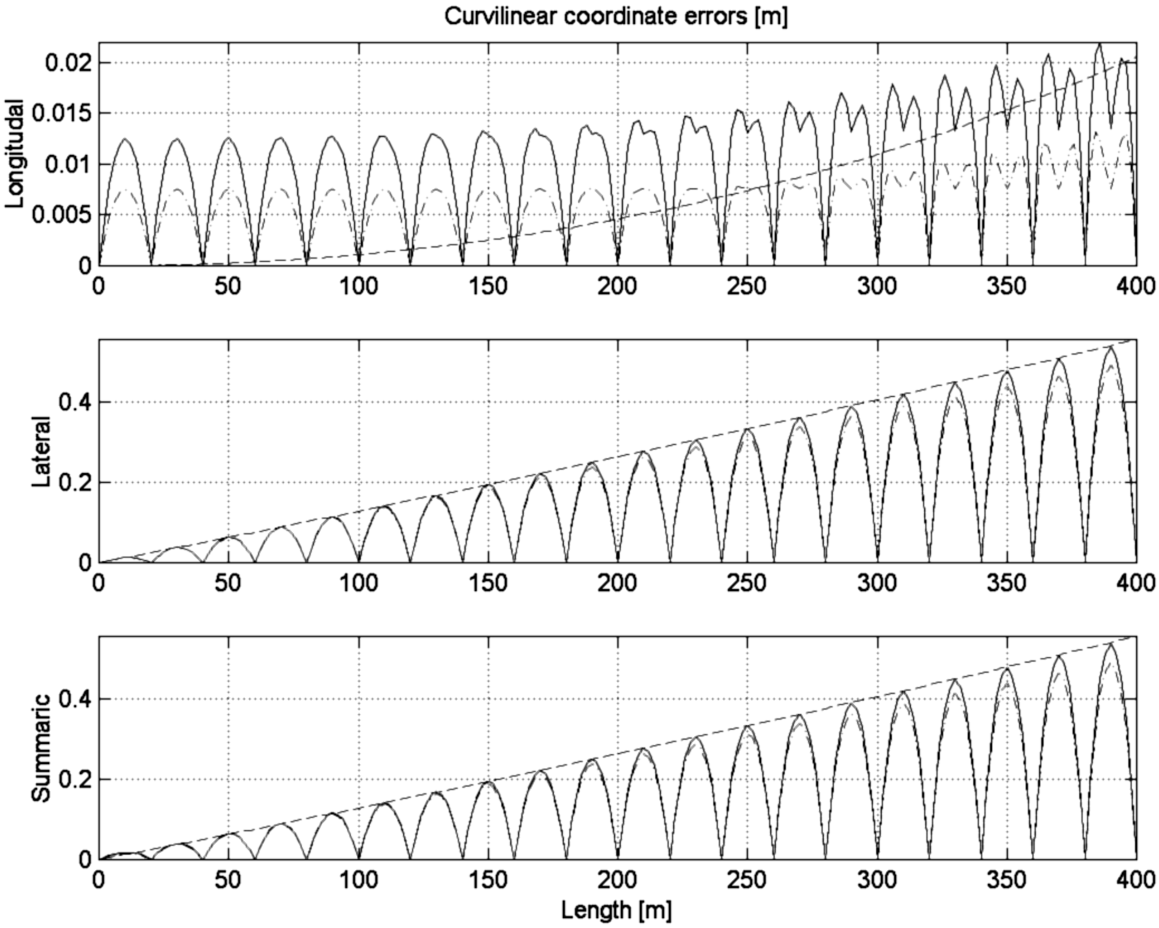

Fig. 3-19. Curvilinear coordinate errors with bilinear transformation

Solid lines – maximum, dash-dot lines – RMS error, dashed lines – error estimations.

3.5.3.c. Lincubic interpolation

We can now apply the concept of the tensor product surface to combine a **longitudinal cubic interpolant** of Chapter 3.5.1.e with a **linear lateral interpolant**:

$$\mathbf{p}(u,w)=\mathbf{FBG}^T\,, \tag{3.51}$$

where **B** is an interpolation tensor, **F** and **G** cubic and linear base functions sets:

$$\mathbf{F}=\begin{bmatrix}H_0^3(u) & H_1^3(u) & H_2^3(u) & H_3^3(u)\end{bmatrix}, \tag{3.52}$$

$$\mathbf{B}=\begin{bmatrix}\mathbf{p}_{00} & \mathbf{p}_{10}\\ \mathbf{p}_{10} & \mathbf{p}_{11}\\ \dot{\mathbf{p}}_{u00} & \dot{\mathbf{p}}_{u10}\\ \dot{\mathbf{p}}_{u10} & \dot{\mathbf{p}}_{u11}\end{bmatrix}, \tag{3.53}$$

$$\mathbf{G}=\begin{bmatrix}1-w & w\end{bmatrix}. \tag{3.54}$$

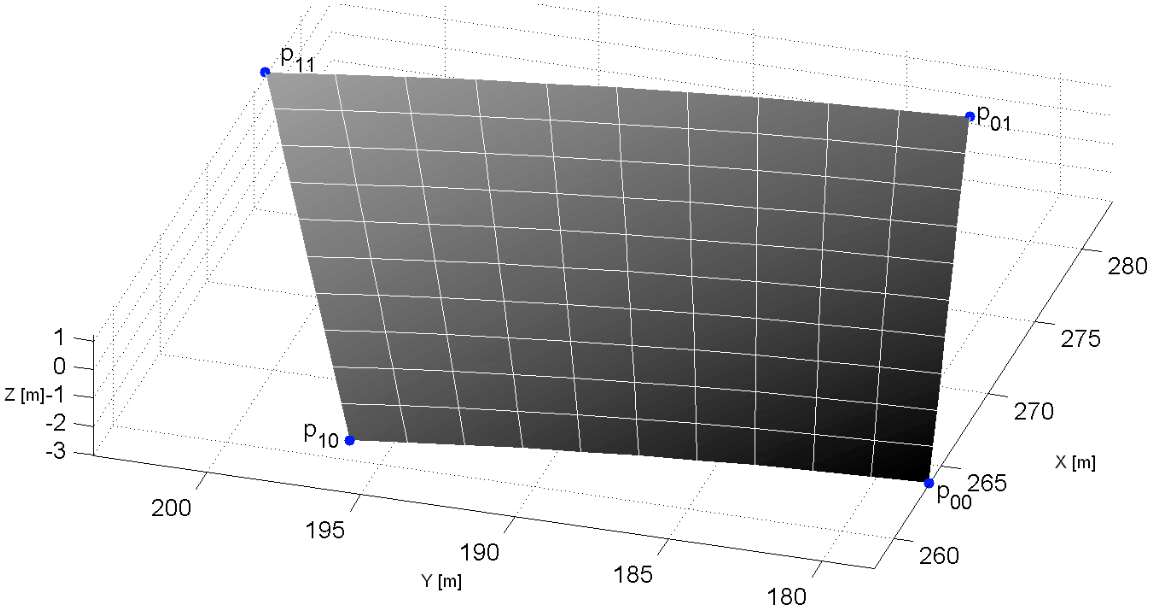

Fig. 3-20. Lincubic interpolation of a linclothoid surface.

The final 20 m segment of the test synthetic road. The isoparametric lines are matched so well, that no errors are visible in presented scale.

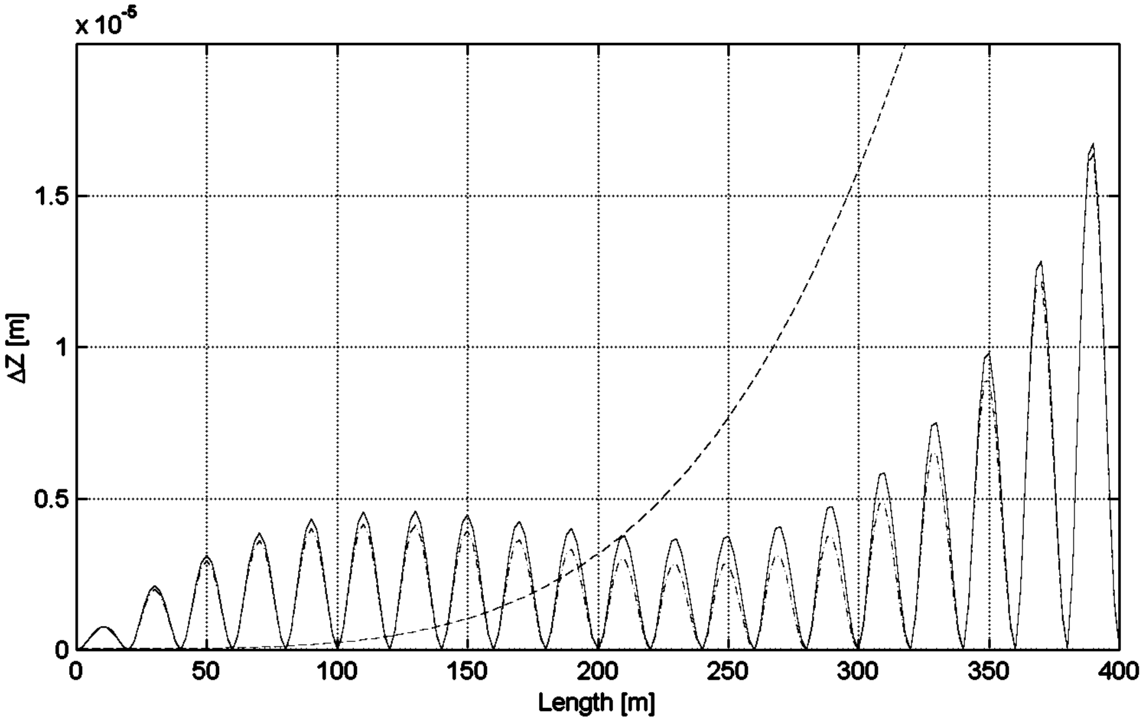

Fig. 3-21. Elevation error of lincubic interpolation.

Solid lines – maximum, dash-dot – RMS, dashed - estimated error ε_{tri}.

The errors of the resulting surface, shown in Fig. 3-20., are not visible compared to Fig. 3-17. The elevation error (Fig. 3-21.) has been **dramatically improved** compared to the bilinear case; the error is below *20 μm*! The simple error estimation

$\varepsilon_{Cub} = \varepsilon_{orthCubZ} + s_C \varepsilon_{orthCubXY}$ due to (3.46) and (3.35) is only partially effective.

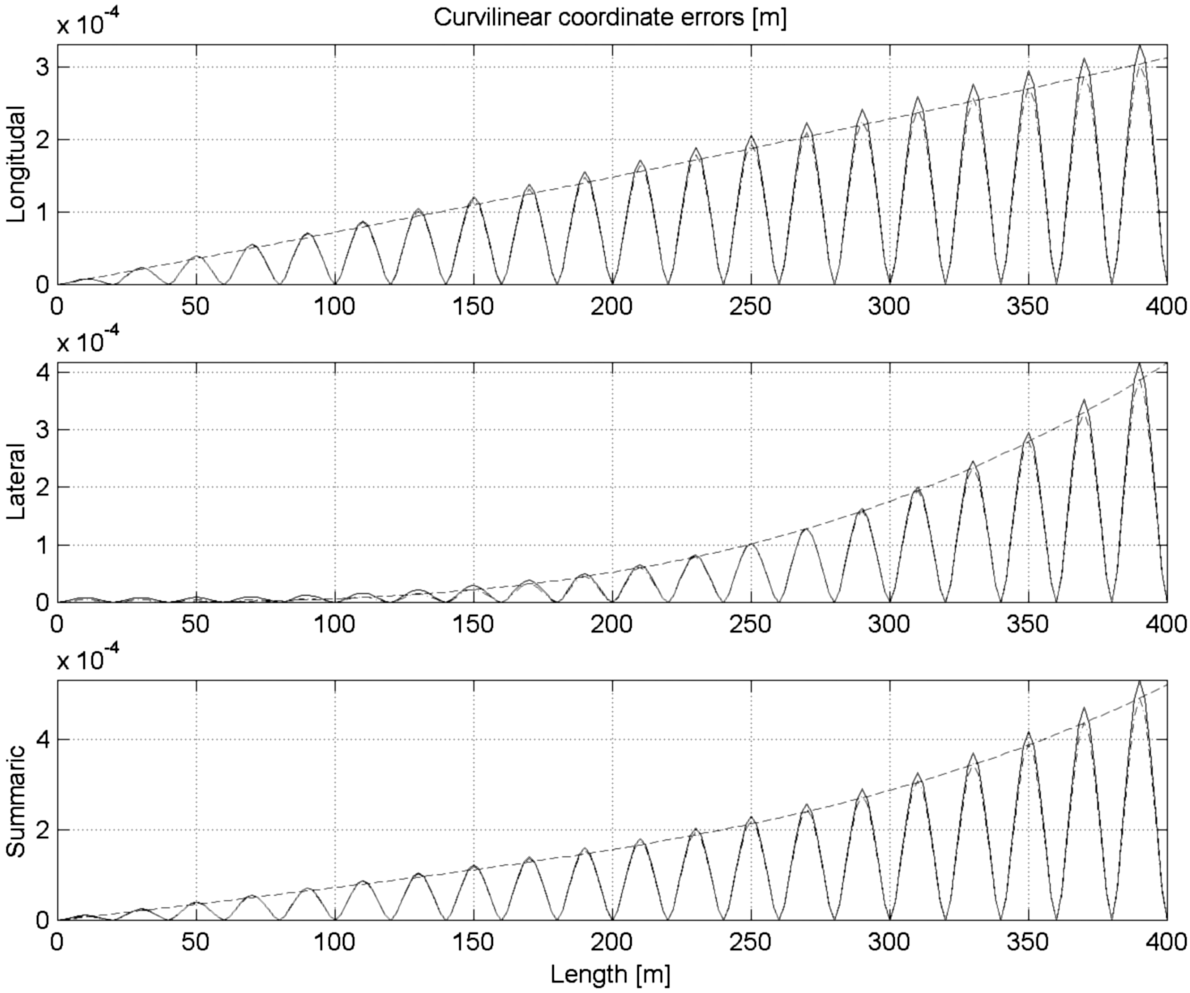

Fig. 3-22. Curvilinear coordinate errors with lincubic transformation.

Solid lines – maximum, dash-dot lines – RMS error, dashed lines – error estimations.

The Jacobi matrix

$$\mathbf{J} = \begin{bmatrix} \dfrac{\partial p_x}{\partial u} & \dfrac{\partial p_y}{\partial u} \\ \dfrac{\partial p_x}{\partial v} & \dfrac{\partial p_y}{\partial v} \end{bmatrix} = \begin{bmatrix} \dot{\mathbf{F}}_u \mathbf{B}_x \mathbf{G}^T & \dot{\mathbf{F}}_u \mathbf{B}_y \mathbf{G}^T \\ \mathbf{F}\mathbf{B}_x \dot{\mathbf{G}}_v{}^T & \mathbf{F}\mathbf{B}_y \dot{\mathbf{G}}_v{}^T \end{bmatrix} \tag{3.55}$$

can be used to find **reverse mapping** by *Newton-Raphson* iterations. The slopes can be calculated as

$$\begin{aligned} s_L &= \frac{1}{\Delta l} \dot{\mathbf{F}}_u \mathbf{B}_z \mathbf{G}^T, \\ s_C &= \frac{1}{W} \mathbf{F}\mathbf{B}_z \dot{\mathbf{G}}_v{}^T, \end{aligned} \tag{3.56}$$

where W - road width.

Also the curvilinear errors (Fig. 3-22.) have been greatly improved and lie in the sub-millimetre range. The longitudinal error has been verified experimentally to grow proportionally to $\Delta l \, \kappa$. The estimate (3.35) for lateral error holds.

3.5.3.d. Conclusions

The accuracy and resulting size of the design approximation vary strongly depending on used method. The simplest approximation methods based on **linear interpolants** (triangular, linearised curvilinear transformation etc.) offer rather **poor performance**, which requires tight sampling for curvy and warped roads. With requirement for high accuracy, tight manual setting-out becomes tedious and expensive. A **3D levelling scenario** should be preferred.

Qualitatively all interpolation methods based on linear interpolants are similar, and little improvement can be reached by applying more complex interpolation schemes. The new interpolation methods based on **cubic splines** offer major improvements concerning precision and memory consumption, at the cost of specifying additional tangent information in the design exchange. The application of methods for numerical tangent estimation remains to be studied.

Design approximation methods based on **tensor product surfaces** can be applied to solve both levelling and curvilinear transformation problems concurrently. The required iteration can be efficiently implemented. The derived and heuristic error estimates have been confirmed by the experiments and can serve as a basis for an adaptive sampling strategy. The new precise curvilinear transformation can be used to implement CIRC systems working primarily in the curvilinear coordinates, where the road geometry can be expressed most naturally.

The interpolation methods described here can also be adopted to create continuous road surface based on discrete position measurements, for example as a rudimentary design for a maintenance project.

3.6. DIGITAL DESIGN TRANSFER

3.6.1. INTRODUCTION AND REQUIREMENTS

The road design needs to be **transferred** with **minimal losses** between the involved parties, primarily road owner, designer and surveyors. Traditionally the construction team has been excluded from this digital data flow, using only paper version of the design. With the introduction of CIRC, this situation is about to change.

From the point of view of a CIRC system the following requirements are posed towards the design exchange format:

- flexible structure and adequate contents (e.g. possibility to specify heading, abscissa, curvature etc. in addition to the coordinates),
- simplicity, resulting in the ease of implementation and robustness,
- sufficient accuracy,
- small size of the resulting files.

From the results of the previous section it follows that the choice of the **design approximation** method has a deciding influence on the transfer format. Depending on the applied method and required accuracy an adaptive sampling procedure can be implemented in the non-increasing curvature direction (Sect. 3.5.1.d) using the given error estimates.

3.6.2. CASE STUDY DARNIEULLES

As mentioned before, the design is often not available digitally for the small and maintenance worksites. This was the case for the full scale CIRCOM tests, performed on a *2 km* long site – bypass of Darnieulles (Le Vosges, France) in October 1999 [Peyret 00b]. The design has been performed by an independent company about two years prior to the start of the construction. The design was available in the following forms:

- as a low-quality copy of the paper design drawing,
- in the form of the coordinate list for the axis, including the 3D coordinates and curvilinear abscissa, sampled at *50 m* intervals.

At the construction time, the design firm has moved and the design in the CAD format could not be found. As the applied road CAD software was not available, this form was anyhow not useful.

As the design accuracy is not critical for the compactor system (required $accuracy < 1m$), and only a 2D design was required, it has been decided to redesign the axis based on the coordinate list. In this way the match in the geographical coordinates was guaranteed. A 3D road design system was used for this purpose.

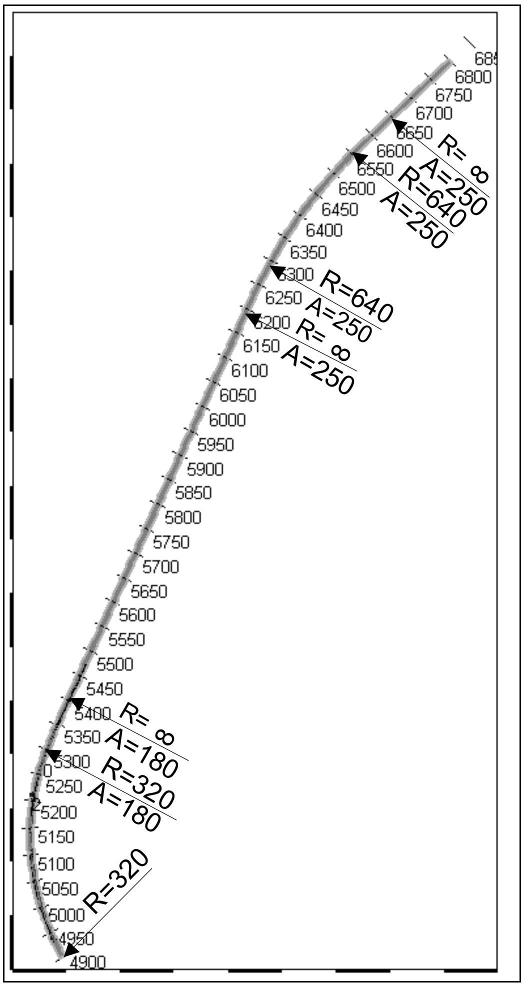

Fig. 3-23. The worksite of Darnieulles and the reconstructed horizontal design.

Scale unit 100 m.

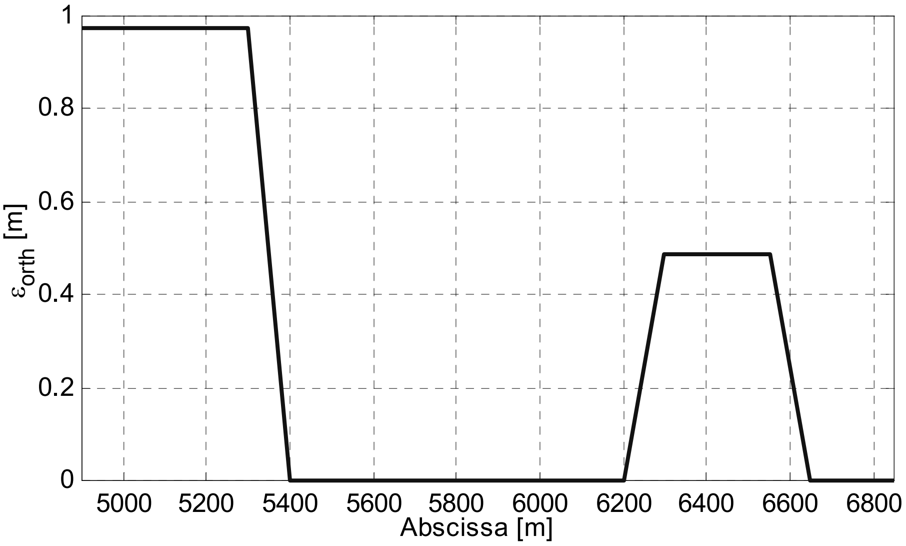

Fig. 3-24. Orthogonal error along the abscissa.

In the redesign process, the tangential and normal angles of the axis and the road edges were recreated. All the lines were sampled at *50 m* intervals, which seems rather loose, but allowed to limit the number of transferred points and improved the performance of the CIRCOM system.

The stations were labelled additionally with the abscissa value and the normal angles (Fig. 3-23.). Unfortunately, the paper copy of the design drawings has been lost and the axis design (elements and their parameters) is not available today for further analyses. However, as the exact abscissa values and longitudinal error is known, it is possible to reconstruct the curvature profile and horizontal axis design from the available data using (3.27):

$$\kappa = \sqrt{\frac{48\,\varepsilon_{len}}{l^3}}\,. \tag{3.57}$$

Using the reconstructed curvature profile and Eq. (3.26) it is now possible to calculate the orthogonal error as shown in the Fig. 3-24. The error introduced by the design approximation is surprisingly big compared to the positioning precision (*<30 cm*) of the compactor system. On the other hand, the previous passes, not the design present the primary reference for the driver.

We can conclude that in addition to portable design exchange formats, also methods for **quick capturing of the worksite geometry** are necessary, such as OSYRIS Setting-Out tool [OSYRIS], especially for small worksites. For surfacing tasks one can drop the design transfer, which results in less intuitive presentation, but reduces the required effort.

3.6.3. STATE OF THE ART

The design can be transferred either in the **original form**, as ordered lists of elements in horizontal and vertical projection (Sect. 3.3.1), or as a **design approximation** (Sect. 3.5). In the projected case the portable definition of a dynamic cross section poses a problem.

Examples of existing formats include:

- D45 format belongs to the family of very basic formats introduced in the 60's at IBM in Stuttgart [Günther 01] [DVMerkblatt 97]. This simple format is just a list of numbered 3D points and can be adopted for polyline approximated design. However, the topological information (e.g. ordering of points along alignments) and primary design information (e.g. curvatures, heading, abscissa values) is missing. The level of abstraction is low, but it is easy to implement this format in the CIRC system (Sect. 2.4.2).

- DXF (Sect. 2.2.2) offers generic geometric objects (e.g. polylines and arc), which can be used for design approximation. Low level of abstraction forces to drop to attributes or encode them as colours.
- CIF (CIRC Interchange Format) is a generic format defined in CIRC project (Sect. 2.4.1.a) for a portable definition of the projected design with a static cross section. Corresponding formats have been designed for design approximation (WSI – worksite information), achieved work (ACW, with a fixed set of process parameters) and statistics (STS). Polyline approximation of design is performed at the office computer, according to required accuracy.
- OSYRIS XML (Sect. 2.4.3.a) extends the CIF family of formats. Thanks to XML substrate, much higher level of flexibility (for example freely definable process parameters) is possible. Among other parameters it is possible to specify the primary design attributes, preserving them.
- OKSTRA (Objektkatalog für das Straßen- und Verkehrswesen) [Okstra Web] [Weiß 01] is a new German standard for the exchange of the road information. It includes separate projected geometry model for new roads and 3D model for existing roads. The projected geometry model is based on a list of elements (axis parts) involving their properties: type, beginning station, length, heading and clothoid parameter (Fig. 3-25., [Weiß 01]). Only static cross sections are implemented at the moment. A rule based implementation is in preparation [Kornbichler 99]. The cross sections elements may have optional string properties defining their semantics, for example “level of wearing course”. The 3D geometry model is based on point, line (including arcs and splines), surface and volume objects. Both projected and 3D models could be used as CIRC input. Moreover a compliant method for expressing CIRC achieved work has been proposed [Weiß 01]. However, OKSTRA format is too complicated and verbose for an on-board computer to apply it directly. An intermediate conversion is required.
- LandXML [LandXml Web] is an industry initiative to establish XML data standard format for civil engineering and survey data used in the land development and transportation industries. It is possible to specify the alignments, and 3D road surface data. The scope of the initiative includes “Post-design”, including

construction and maintenance, but at the moment the approach seems very design-centric.

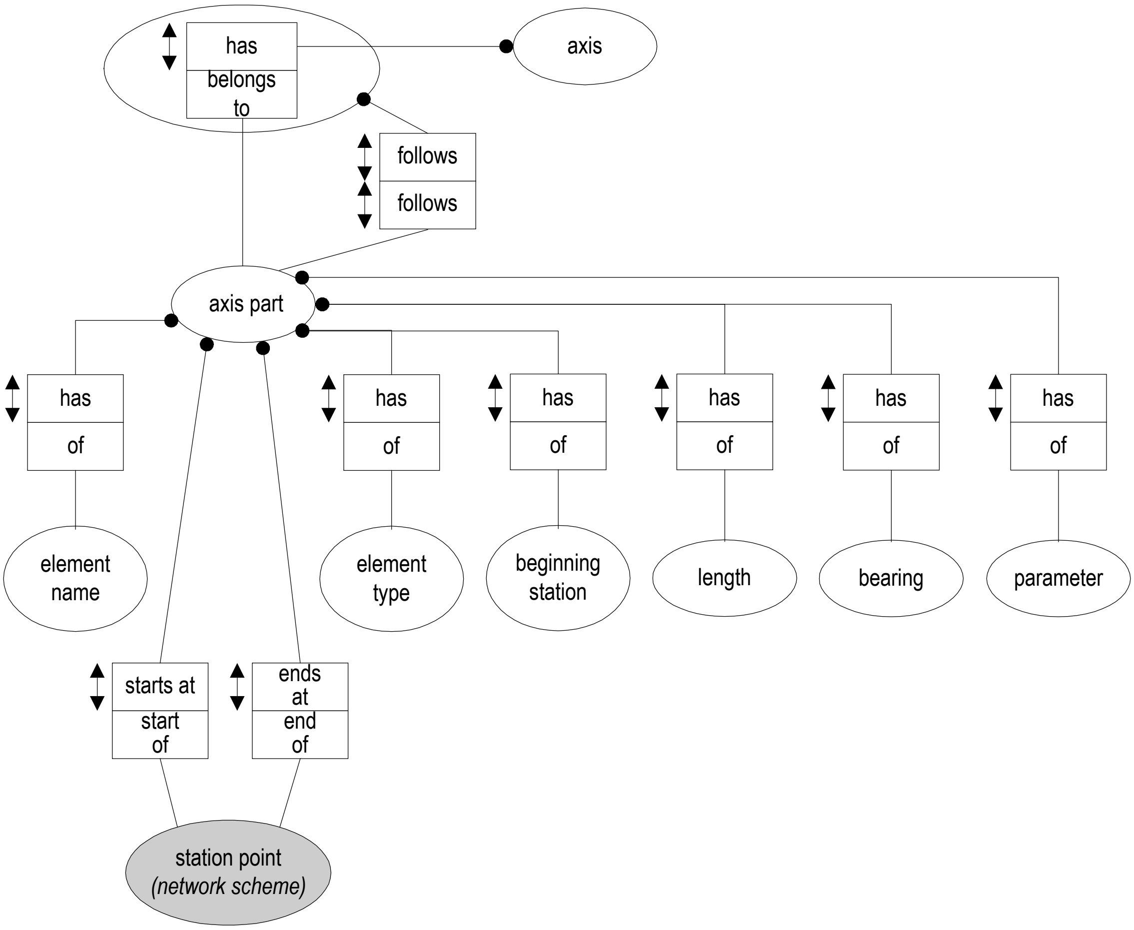

Fig. 3-25. NIAM road axis data scheme in OKSTRA.

We conclude that the "simple" formats for approximated design (D45, WSI) can be readily applied in CIRC application, but are limited in terms of flexibility and abstraction level. As another extremity the "complex" formats (OKSTRA, LandXML) support both original and approximated design and provide enough input information, but cannot be used directly by an on-board computer. An optimal scenario involves the conversion between "complex" and "simple" format at the office computer level (Sect. 2.5.2), including the design approximation. The CIRC on-board computer needs an efficient, specialised design exchange format, for example OSYRIS XML. The same applies to the achieved work format, which is not yet covered by the existing and emerging standards.

3.7. CONCLUSIONS

The road design process determines the geometry for CIRC application, strongly influencing its operation. Independent of the applied projected or direct 3D methodology, **design approximation** methods with guaranteed accuracy can be derived if the continuous model of the road is available. New road modelling methods based on **cubic Hermite splines** and **lincubic tensor product surfaces** can be used to implement very accurate algorithms for modelling of 3D road surfaces and curvilinear coordinates.

The presented insight in the modelling methods for the designed geometry gives the mathematical foundation for modelling of the machine environment presented in the next Chapter.

4. CIRC Digital Environment Model

4.1. OVERVIEW

In Chapter 2. the **target** and **as-built road** were identified to be the main elements of the CIRC digital environment model. Its computer implementation is discussed now. The problem statement is followed by the state of the art presentation. Existing data models show considerable drawbacks, especially for the **heterogeneous worksite**. To circumvent this situation a novel **ribbon data model** is introduced. It provides a universal structure to store efficiently all geometrical and process information on a road construction machine, yet is compatible with all data models in current use. The ribbon data model offers the flexibility and the performance required for the universal on-board representation of the environment in road construction. It can be applied for **all three required machine groups**, and as of today it has been successfully verified for two of them in several full-scale tests. As opposed to the other data models in use, the ribbon model can accommodate complex geometry and comprehensive physical process attributes, offers machine independence and enables inter-machine co-operation.

4.2. PROBLEM STATEMENT

The IT system for road machine support has to deal with several kinds of objects, for example lines and surfaces describing designed road, curvilinear reference frame, and additional objects like surveyor monuments, bridges or orientation signs. Beside these geometrical entities equipped with physical attributes, non-geometrical entities like machine fleet or work team need to be modelled.

Traditionally, the term *Digital Terrain Model* (DTM) of GIS origin [Floriani et al. 98] has been applied to describe the required modelling as a whole, but it is considered too limited taken into account the diversity of required entities. Therefore we adopt here the term **Digital Environment Model** (DEM), coming from the context of robotics.

Many of the entities mentioned above originate from the process of the road design. As discussed in Chapter 3., they are usually modelled as concatenation of line segments, clothoids and arcs. In simplified form the design entities can be also given as discrete 2- or 3D polylines. Some designed process attributes, like a material type or an optimal temperature range are often not provided digitally.

In the course of the project execution the designed description is augmented by the **trajectory of machine tool**, as defined by the positioning and the tool geometry. The process parameters, e.g. the material temperature or the current vibration amplitude can be attached to each position, thus forming the description of the actual road surface, but also of the processes which created it.

The mentioned geometrical objects lie mostly along the site axis and can be conveniently represented in the curvilinear coordinate system. It is **anisotropic** in the sense that characteristic scales in a curvilinear coordinate system differ widely. For example the typical grid size could be *2 m* in longitudinal, *0.5 m* in lateral and *1 cm* in the vertical direction. That is why specialised ways of representing the road objects are needed, as compared to methods applied in all-purpose CAD and CAM systems.

The universal DEM should support surfacing, profiling and earth moving machines (Sect. 2.2.3). On an asphalt pavement worksite, data exchange is required between **surfacing and profiling** machines (paver and rollers), whereas in the case of earthwork site the co-operation between the **earth moving and profiling** machines (bulldozers, wheel loaders, graders, pavers etc.), possibly also surfacing machines (rollers) is necessary. For the efficient data exchange the same or compatible data models should be used on all involved machines.

Two operation modes are possible: **online** exchange through the wireless site network or **offline** data gathering using mass memory medium. In any case, the DEM should allow for efficient combining and exchanging of data between different machine groups.

4.3. ROAD DATA MODELS - STATE OF THE ART

The road data models in current use follow one of the two dual paradigms: **raster** or **vector** description. Vector description is an **entity based paradigm**, where objects fill up the space, and raster description is a **space oriented paradigm**, where each point in space has some properties. Neither approach appears to be superior in all tasks.

Taking into account the application area, the models in use can be further classified into the following groups (Fig. 4-1.):

a) **Raster descriptions**,

b) Multiple polyline (**multi-polyline**) representations, also known as *spaghetti models*,

c) **Digital Terrain Models**, typically TIN based,

d) **Road network databases**.

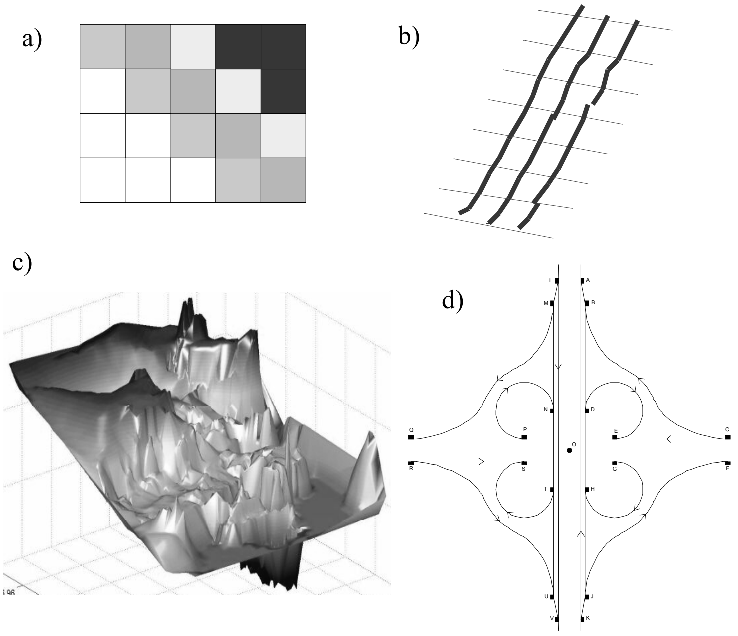

Fig. 4-1. Road DEMs a) Raster b) Multi-Polyline c) DTM d) Road network.

Except of the application-specific road network databases, the other data models in use are based on the generic modelling methods applied in GIS domain. It can be easily seen that **conversion** of information between these descriptions can be a cumbersome task, and **information loss** is inevitable. Clearly, the conversion between representations mentioned above is difficult and without loss of information can only be done upward the list. In particular, a raster compaction map cannot be directly incorporated in the road network database based on cartographic representation. An external reference, for example to a file, is the only way to organise such information.

4.3.1. Raster description

Raster descriptions are simple and effective. They are is commonly used for compaction documentation [Thurner 01] [Bomag Web]. The raster mapping between a point *(x,y)* and a raster cell *(i,j)* can be expressed as

$$\begin{aligned} i &= \left\lfloor \frac{x - x_o}{D_x} \right\rfloor \text{ for } x_o \leq x < x_o + n_x D_x, \\ j &= \left\lfloor \frac{y - y_o}{D_y} \right\rfloor \text{ for } y_o \leq y < y_o + n_y D_y, \end{aligned} \tag{4.1}$$

where $0 \leqslant i < n_x$, $0 \leqslant j < n_y$, D_x and D_y are raster grid sizes, x_o, y_o is a raster centre and n_x, n_y are raster extents in x and y directions respectively. The brackets represent floor rounding, which is responsible for the information loss.

It is important to note that the raster grid can be defined in the Cartesian or curvilinear coordinate system (Sect. 3.4.4). The Cartesian raster is ineffective for road applications due to the linear geometry of the road. Only a fraction of cells is really used. Rectangular grid must be applied in order to avoid the dependency of grid precision on the machine heading.

With a **curvilinear grid** one can achieve serious efficiency improvement thanks to the optimisation of the cell size. Different longitudinal and lateral resolutions can be specified. However, as pointed out in Sect. 3.5.2, it is not trivial to define the curvilinear transformation and a precise definition of the alignment is required.

In the simple form of a **cumulative raster** only the last known values of the attributes are stored in each grid cell. This form is especially simple to implement in form of a 2D array of structures. However, valuable information gets lost in the cumulative raster. For example at the end of the day there is no way to tell which compactor performed well, and which produced pass omissions.

In order to alleviate this problem a **raster with history** can be applied. In this scheme the process parameters are be appended to the history list each time the cell is entered by the machine. Additional memory is consumed for this purpose. However, in the case of the Cartesian grid, the overhead incurred by unused cells is reduced. The machine paths can be approximately extracted from the raster with history. **Quadtree structures** of cells [Samet 90], as applied in landfill applications [Kunighalli et al. 95] can be considered a further refinement of this technique, allowing to ignore the unused areas ("virtual cells"). The raster with history allows to approximately recover the machine paths and, for very small grid sizes, converges with the vector description.

The major disadvantage of the raster description is the irreversible loss of the placement information. Thus the raster definition must be decided a priori. Conversion between different rasters is lossy and the produced image of the achieved work is not intuitive, especially with curvilinear raster.

With the precise curvilinear transformation introduced in Sect. 3.5.3 it seems possible to implement **levelling systems based on curvilinear raster**, as it corresponds directly to the uniform sampling. However, no such systems are currently known. Raster application in earthmoving systems seems to be difficult. For these reasons the raster description should not be adopted as a universal DEM basis.

4.3.2. MULTI-POLYLINE MODELS

Multi-polyline representations, also known as *spaghetti models* [Floriani et al. 98], are simplified DTMs as used by many levelling systems (Sect. 2.4.2). The polylines represent longitudinal or cross profiles. Existing implementations often pose limitations, for example the points have to be implicitly paired. They allow exact tool control, but are often limited to the design description only.

The GIS term “spaghetti model” is adopted to express the model’s limitation to represent the topological dependencies [Bartelme 95]. Indeed, instead of modelling an entity “road”, only the edges are modelled. The interpolation of the road surface between the edges is not specified.

A D45 data format widely used in Germany is a typical example of a muli-polyline model (Sect. 3.6.2).

4.3.3. DIGITAL TERRAIN MODELS (DTM)

Digital Terrain Models (DTM) are normally based on **Triangulated Irregular Networks** (TINs). They originate from surveying and GIS applications and are focused at representing a static, complex 3D geometry [Floriani et al. 98].

In CIRC context they are applied for earthwork applications, for bulldozers, graders and excavators. Initially the height map of the terrain is surveyed. Then the height points are grouped in triples using the well known triangulation algorithms [Held 01]. The **Delaunay triangulations** (dual to the Voronoi diagram) are preferred in many applications, as they are known to maximise the minimal angle, minimise the maximum circumcircle and minimise the maximum containing circle [Floriani et al. 98]. The Delaunay triangulation covers entire convex hull and manually placed **breaklines** are necessary to restrict some connections. In particular the curvature radii of the inner road alignment can be used to limit the triangulation to the inside of the road.

During the work the DTM must be updated in real time. However, the tool trajectory is not readily described by triangles. Moreover, in this geometry-centric paradigm the process parameters are difficult to place. They should be attributed to triangle edges, which are normally not stored as entities.

4.3.4. ROAD NETWORK DATABASES

The road network databases are nowadays complex systems organised around road network topology. They may adopt curvilinear or geographical description and cover different application areas (e.g. safety and pollution analysis, maintenance management etc.), depending on national practice. The road network databases are important for CIRC import (design transfer, Sect. 3.6) and export. Compatibility has to be ensured, most importantly in terms of the reference frame. External references have to be applied if the compatibility is not assured.

One example of a modern road network model is implemented in German OKSTRA (Objektkatalog für Straßen- und Verkehrwesen) [Okstra Web]. An extension of Okstra for CIRC achieved work data has been proposed (Fig. 4-2., [Weiß 01]). It includes the following objects:

- parameter list – points with connected named process parameters,
- raster diagram – describing compaction, temperature maps etc.,
- material recipe.

4.3.5. CONCLUSIONS

None of the surveyed data models can be readily applied as an universal DEM for CIRC. Raster models are not verified in the levelling context. Existing vector models are of limited use as the achieved work storage. A new data model needs to be developed.

Of the two basic choices, the **vector** type of description seems more promising. Levelling applications are possible. The vector model requires more processing and puts more stringent requirements on computing resources, but maintains full description of the work achieved by the machine and its evolution in time, allowing for example to replay the recorded mission or to guide another machine along the path of the former. Realistic, intuitive images of the worksite can be produced.

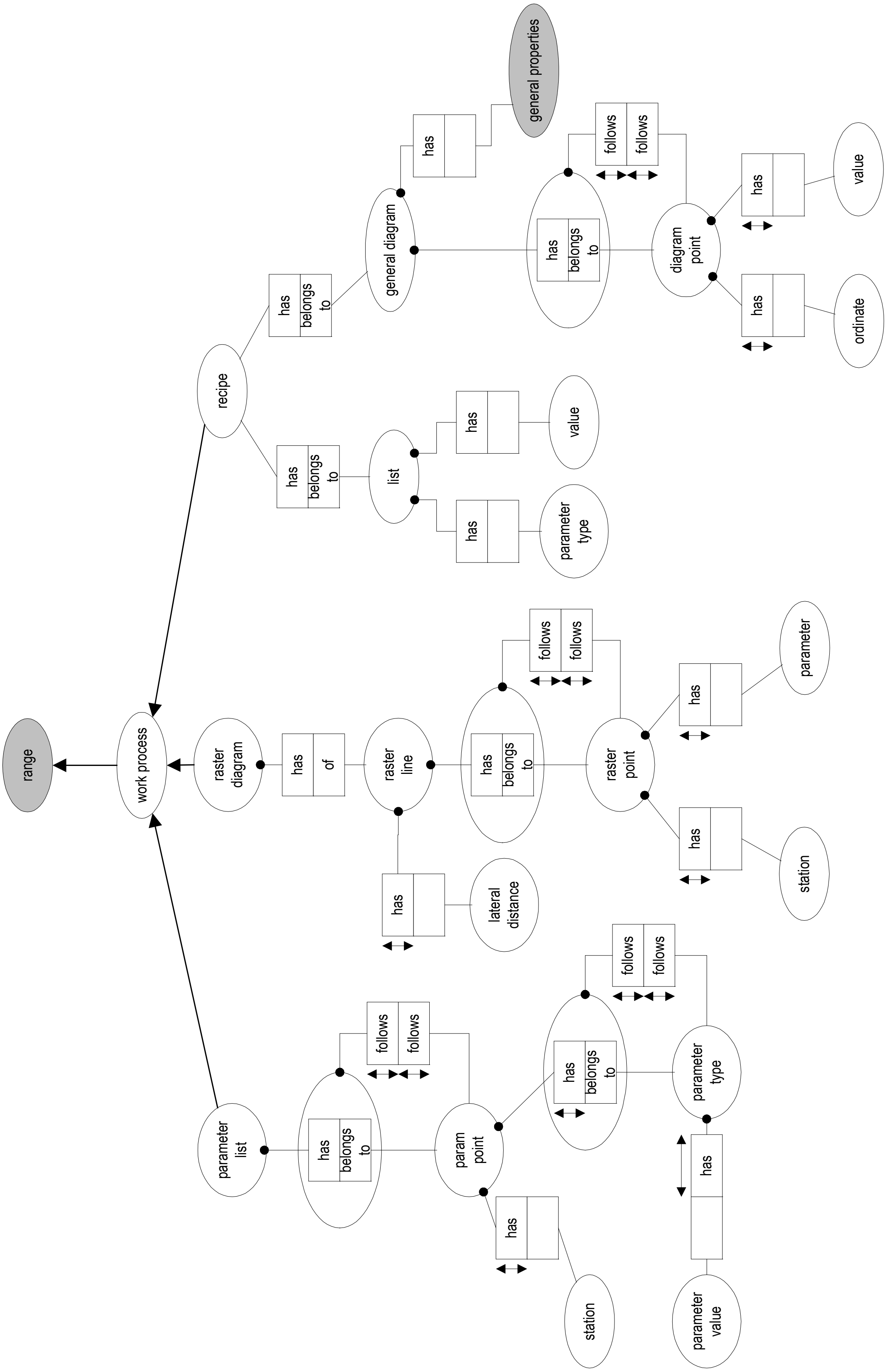

Fig. 4-2. Proposition of OKSTRA extension to include CIRC achieved data (NIAM).

4.4. RIBBON DATA MODEL

In order to fill the mentioned gap, a novel **ribbon data model** has been developed as an universal DEM for profiling and surfacing application. It combines the most important advantages of the presented data models, supporting **the inter-machine data exchange** and ensuring the **export and import** capabilities to and from other data models in current use.

The ribbon data model has been developed in the frame of the CIRC project (Sect. 2.4.1.a and 2.4.2). After further extension it formed an on-board part of OSYRIS Road Product Model (Sect. 2.4.3.a).

4.4.1. RIBBONS

4.4.1.a. Definition

Ribbon is a figure created by moving a planar figure called **generator** along a curve called **axis** or **spine** [Rosenfeld 86]. The resulting ribbon is planar only in the special case when the spine is a plane curve and generator is a 1D structure defined in the curve's plane. Otherwise one obtains a 3D ribbon. The **ordering** of spatial information based on the orientation of the spine is a very useful property of a ribbon model.

English term "paved ribbon" is often adopted to describe road [Pushkarev 63] and analogously the ribbon concept can be readily applied to the road geometry. The **clothoid spline** forming the main alignment is a natural choice for a spine. The generator is a piecewise-linear structure describing the cross section of the road, applied orthogonally (horizontally or binormally, Sect. 3.4.4) to the spine and possibly varying in function of the axis length. It follows that a road can be described as a **clothoid ribbon**.

In addition to **continuous ribbons** defined above, one can also introduce **discrete ribbons**, when the generator's intermediate positions are defined only at finite number of points. Such ribbons can readily implemented using computers.

Some classes of ribbons and their basic properties are discussed in a survey by Rosenfeld [Rosenfeld 86]. Of special interest in our case are **Brook's ribbons** [Brooks 81], where the generator is a straight-line segment of varying length, connected normally to the axis at its midpoint. Other classes of ribbon-like structures are disk-based

Blum ribbons [Blum 73] and Brady ribbons with “local symmetry” [Brady, Asada 84]. Bhattacharya and Rosenfeld [Bhattacharya, Rosenfeld 95] have studied geometric and topological properties of discrete ribbons, concentrating on triangular and rectangular ones. It has been shown that **quadrangular data models** may have advantages over triangles in the domains of scattered data analysis and elasticity analysis based on finite element methods [Ramaswami et al. 98]. Continuous ribbons are also successfully applied in modelling of DNA structures [Bhattacharya, Rosenfeld 95].

The ribbon description of the road is based on the observation, that the smooth road curves and surfaces can be well approximated by multiple piecewise-linear structures, like polylines and sets of polygons, justified by the results of the previous Chapter. The discrete ribbons are concatenations of quadrilaterals. However, to model triangles and polylines it is necessary to allow the **degenerated** (double) **vertices**. The ribbon may have at most *2* degenerate vertices, thus the quadrilaterals may be reduced to triangles or line segments. The points can be modelled by the vertices alone.

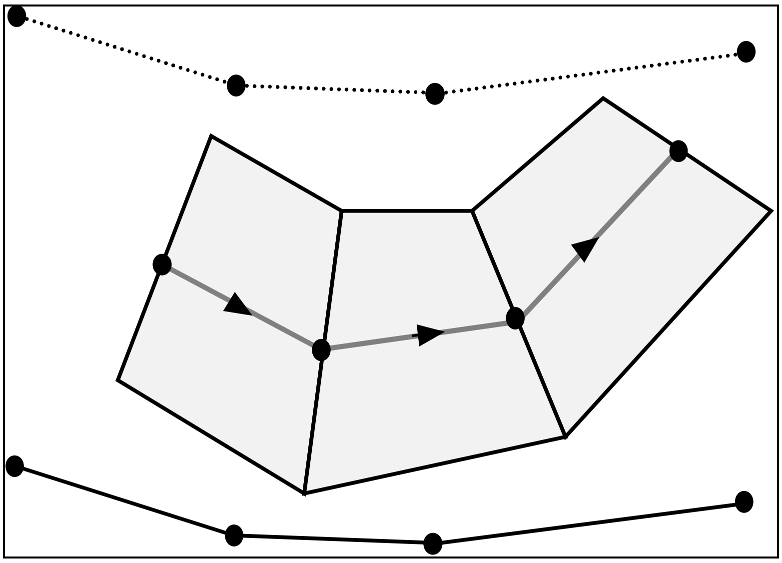

Fig. 4-3. Polyline ribbons: pointset, polyline, polyquad.

Our ribbon can be viewed as a **generalisation of a polyline**; it is a polyline with width, which is oriented in 2D or 3D space. We will call it **polyline ribbon** (Fig. 4-3.). For simplicity we will restrict ourselves to the symmetric ribbons. The polyline ribbon can be classified as a discrete, generalised case of a Brook’s ribbon.

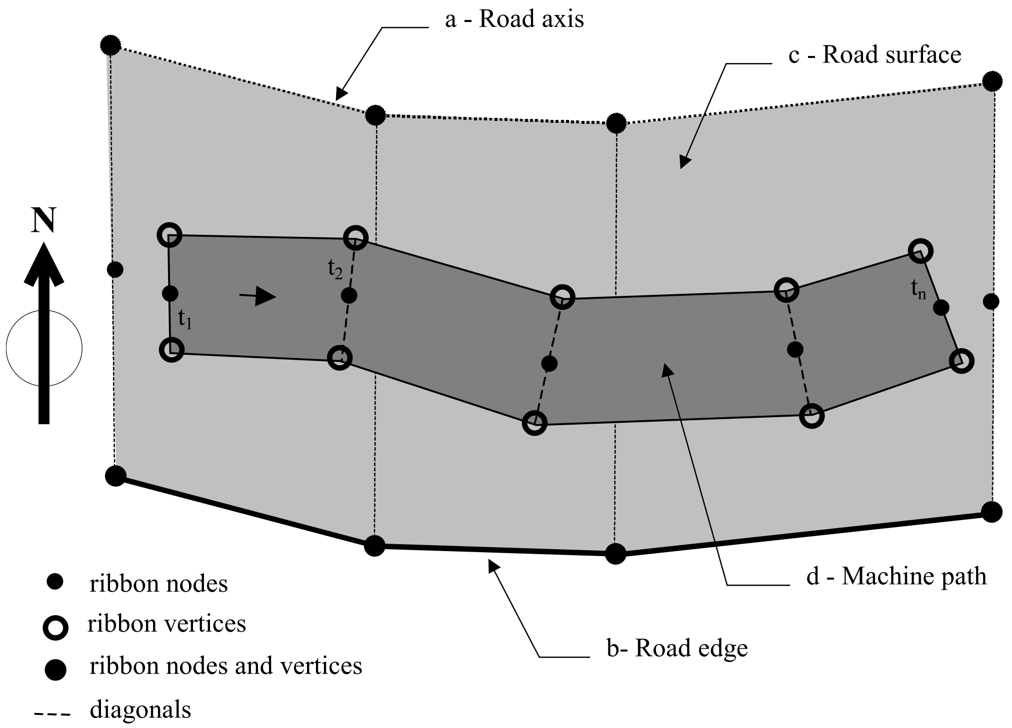

Fig. 4-4. Sample 2D ribbons in worksite coordinates.

a - road axis, b – road edge, c – road surface, d - machine path.

We will now introduce the terminology for further discussion (Fig. 4-4.). The length of the generator is called **ribbon width**. The **ribbon axis** is itself a ribbon of the width zero. The width is non-negative and may vary along the ribbon. For example, the width is a non-zero constant for ribbon describing the surface treated by the machine, variable for road surface ribbon and zero for polyline and point ribbons. The vertices of the ribbon axis are called **ribbon nodes**. The coordinates and the width are the obligatory node parameters. It is optional for the node to have various **attributes**, for example time or speed. One often needs to distinguish between the edges of ribbon quadrilaterals (called **ribbon quads**). Let's consider a **non-self intersecting** (NSI, [Bhattacharya, Rosenfeld 95]) ribbon, like the one describing the surface treated by a working paver. The positions of the machine are the intermediate positions of the ribbon generator. They are called **ribbon diagonals**. The diagonals are well defined by position and orientation at the nodes, which has to be considered as primary information. The **side edges** of the ribbon are connecting the diagonals in an attempt to interpolate between the known positions of the machine, and have to be considered as secondary information. Same applies to the **axis segments**, which connect the ribbon nodes.

4.4.1.b. Worksite modelling with ribbons

Work performed by a construction machine, with the positions of the tool sampled regularly in time, can be readily described by one or more discrete ribbons. Fig. 4-5. shows sample ribbons visualised in a compactor system MMI.

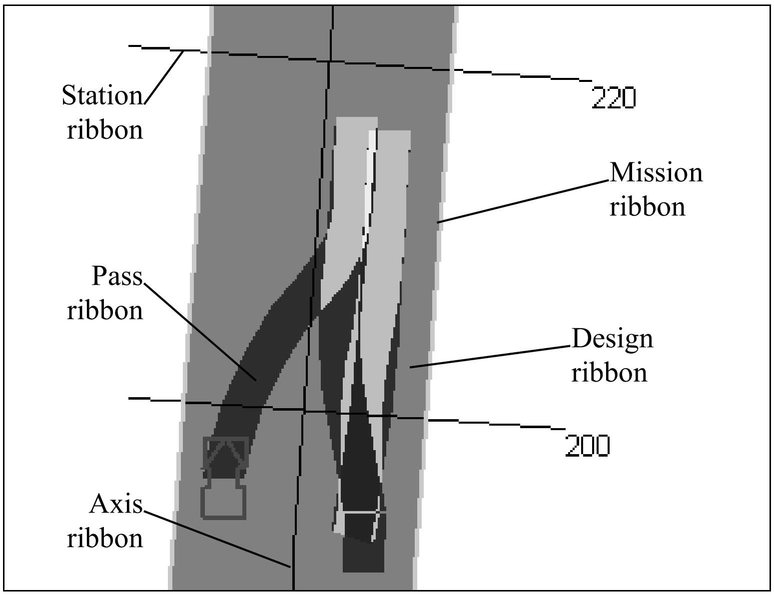

Fig. 4-5. Ribbons visualised in compactor system MMI.

The simplified tool model is used for the compactor.

The number of ribbons required is equal to the number of edges of the piecewise-linear tool representation (Sect. 2.6.1). The introduced ribbons can be readily applied with simple linear, symmetric tool geometry. For more complicated tool geometry one can consider non-symmetric ribbons, for example to model the varying extents of the screed, or more general class of ribbons with a piecewise linear generator. However, both classes of ribbons are more difficult to implement, and can be conveniently and economically represented as concatenation of polyline ribbons.

Also the main alignment, whole design and mission can be stored as ribbons. Polyline ribbons suffice for design approximated with polylines. Original design and approximations other than polyline one require the possibility to specify cubics, arcs or clothoid segments as side edges and axis segments. Different approximations can be applied concurrently for different purposes, for example a simplified polyline approximation for visualisation, and lincubic approximation for levelling tasks.

The process attributes may be associated with the nodes (e.g. time, speed, temperature) or with the segments (e.g. machine in a valid working state or not).

The latest implementation of ribbons allows for freely definable attributes, identified by name and unique code, which can optionally be associated with left, middle or right point of the diagonal [OSYRIS]. Interpolation or extrapolation principle is applied to bind these attributes to the segments (Sect. 2.6.4 and 4.4.1.d).

In computer's memory a ribbon is conveniently represented as a list or vector of nodes. A node can have a "break" attribute, allowing to represent non-continuous structures in one ribbon. Thanks to the ability to represent discontinuous structures, the ribbons can be applied to model more complex topologies, for example crossings or roundabouts (Sect. 3.4.5). A continuous group of ribbon quads is called a **ribbon section**. A single ribbon section can be applied to model a **simple road** in the 2D case. In 3D case two sections need to be concatenated laterally in order to model a roof-shaped road, and additional ribbons may be required for emergency lanes.

Adding a break requires an additional starting node in a next section. Ribbon and section lengths can be defined as

$$\begin{aligned} RibLen &= \sum_{Sections} nodes = \sum_{Sections} SectLen + \sum_{Sections} breaks \\ SectLen &= \sum_{Section} segments. \end{aligned} \tag{4.2}$$

For optimal **memory and time efficiency** the number of nodes and breaks should be minimal. The continuity of the ribbon corresponds to the continuity of the road objects, usually placed along the dominant curvilinear axis. As long as the ribbon remains continuous, only one node with attributes has to be stored for each new ribbon segment [Bhattacharya, Rosenfeld 95]. Also in the visualisation pipeline only one node (two 3D points) has to be processed for each segment, as the other one can be reused from the previous iteration.

Compared with triangles, the quadrangles as basic building blocks of the model are not guaranteed to be **convex and flat**. These two important issues have to be accounted for in a ribbon based CIRC system and are discussed in the two following sections.

4.4.1.c. Ribbon deficiencies

The ribbon quad may become **concave** if the diagonals or side edges intersect (see Fig. 4-6.). Both deficiencies are typically positioning errors and are not specific to the ribbon representation. They concern especially the **machine ribbon**, which is constructed in real time. For other ribbons the convex property can be ensured in the offline **ribbonisation algorithm** (Sect. 4.4.2). Concave quads pose several problems. Visualisation of a generic, possibly concave quad is computationally more expensive. The rapidly changing levelling error may destabilise the automatic control algorithm. Moreover, the processed area is not accounted for correctly. For these reasons the concave quads have to be avoided.

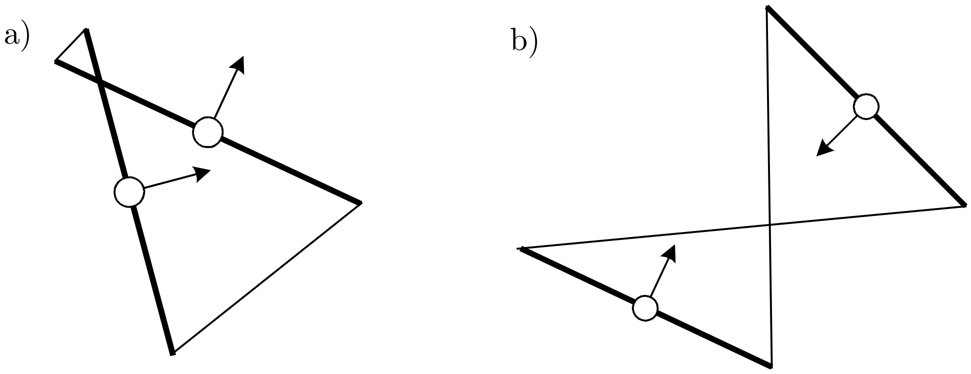

Fig. 4-6. Concave ribbon segment a) intersecting diagonals b) intersecting side edges (heading slip).

The **intersecting diagonal** case may arise if the estimated angular velocity of the machine is high compared to the linear velocity, or more precisely when

$$\frac{1}{2}\omega w > v\,, \tag{4.3}$$

where w – ribbon (tool) width, ω – angular, v – linear velocity. This is possible for machines equipped with caterpillar. For the other types of drives it means that the machine has slipped laterally, which is not likely under normal working conditions and suggests error of position estimation. This deficiency may be efficiently corrected by skipping the offending positions until a position resulting in a correct, convex quad has been received.

The other kind of concave deficiency results from an instantaneous change of heading by $\pm\pi$, which justifies the name: **heading slip**. It results from the ambiguity between the speed sign and heading, which is not resolved correctly by the positioning algorithm. It can be explicitly prohibited for machines with one working direction (e.g. paver). Otherwise the manual correction of the driving direction seems to be the only plausible solution to this problem.

Both types of concave deficiencies may naturally also result from serious **undersampling** of the machine positions, for example due to temporary malfunction of positioning algorithm, such as a GPS shadow. A realistic example of a deficient compactor ribbon captured using a low-cost, low-precision GPS receiver with about *80 cm* RMS accuracy is shown in the Fig. 4-7.

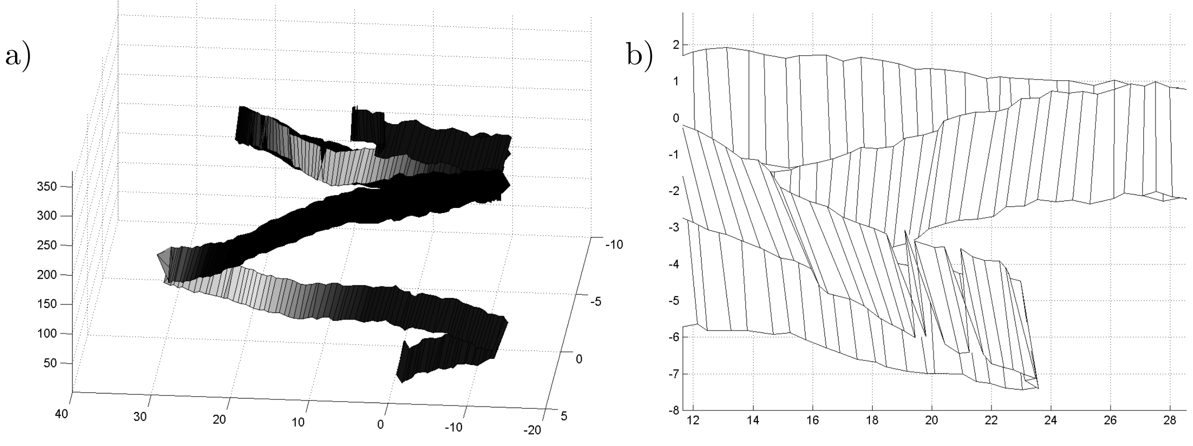

Fig. 4-7. Ribbon deficiencies.

a) bad quality self-intersecting compactor ribbon (X, Y in meters, time shown in seconds on Z axis)

b) skewed and concave quads in a magnified view.

The positioning noise is visible as a jagged ribbon edge. The heading estimate given by the GPS receiver is typically derived from the difference vector between subsequent measurements and is thus rather noisy, especially when the speed is low. This effect is well visible when the direction changes, even though the angle slips have been removed manually. Moreover the ribbon quads are skewed due to a low frequency drift in the heading estimation. It results in the underestimation of the treated surface by the factor

$$\frac{\hat{S}}{S} = 1 - \frac{1}{N}\sum_{i=1}^{N}\left|\cos\Delta\varphi_i\right|, \tag{4.4}$$

where $\hat{S}$ - estimated treated surface, S – true treated surface, $\Delta\varphi_i$ –heading error, N – ribbon length.

The above example suggests the necessity of including additional heading estimates in the positioning estimation. The **pipe filter** (Sect. 4.4.2.a) has also proved efficient in handling input data with poor heading quality.

4.4.1.d. Elevation and attribute interpolation

In the 3D case the principle of the ribbon representation doesn't guarantee that the quadrilaterals will be **planar**. This reflects the non-planar nature of the road surface and has to be opposed to the planar triangular representation. Several simple and efficient definitions of the interpolating surface over the quad can be adopted, most notably the interpolation strategies discussed in Sect. 3.5.3.

The interpolation concerns not only the elevation, but also other ribbon attributes. For most attributes linear interpolation along the ribbon axis or curvilinear axis is often sufficient. Stepwise extrapolation may also be applied to efficiently reduce the memory consumption. 3D interpolation is required only for parameters varying in both longitudinal and lateral direction, such as elevation, thickness or temperature.

The following interpolation strategies can be applied to calculate intermediate values of elevation and other ribbon attributes:

- **1D polynomial interpolation**, most importantly 0th (extrapolation) or 1st degree (linear interpolation) along the ribbon axis or curvilinear axis,
- **triangular** or **bitriangular interpolation**,
- **bilinear interpolation**,
- **lincubic interpolation**.

The ability of quads to model the smooth 3D surfaces is their important advantage compared to the triangular model. The discrete, but smoothly interpolated ribbon is certainly a better approximation of the road surface than the triangulated surface created on the same nodes. The bilinearly interpolated ribbon is still non-smooth at the diagonals. Lincubic and higher order tensor product surfaces can be applied to obtain a geometrically smooth surface (ribbon spline) up to the arbitrary chosen derivative. In this case the side edges are no longer straight, requiring more complicated visualisation. For this reason **hybrid interpolation strategies** can be considered, e.g. linear interpolation for projected visualisation and precise lincubic interpolation for the levelling purposes.

4.4.2. RIBBON ALGORITHMS

In this chapter the most important ribbon algorithms are discussed. In particular the **conversion methods** to and from other data models mentioned in Sect. 4.3 are presented.

4.4.2.a. Position input and filtering

The incoming positions and process attributes can be readily stored in ribbons forming the achieved work description. The memory requirements can be minimised without loss of information by exploiting the smoothness of the road geometry. For instance, nearly co-linear points can be ignored without major information loss (see Fig. 4-8.), if the attribute values remain constant. This procedure is called a **pipe filter**. The savings of *60-90%* have been obtained in experiments for typical machine movements with the pipe diameter of similar order as the positioning accuracy.

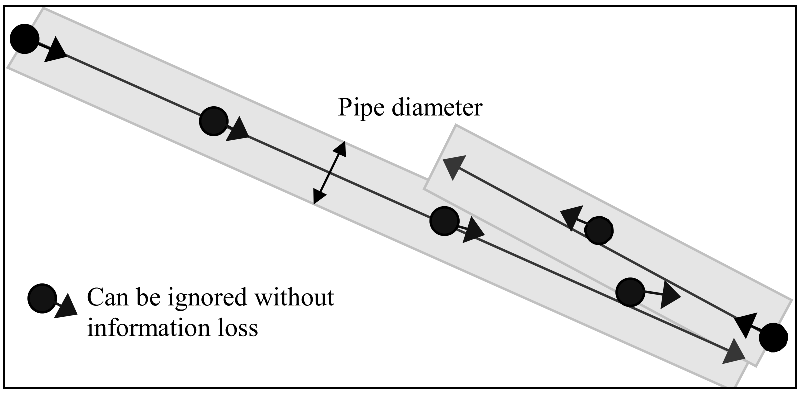

Fig. 4-8. Pipe filter applied to compactor positions

4.4.2.b. Ribbonisation of flat polygons

The incoming design and mission descriptions are converted into ribbons in the process called **ribbonisation**. Points and polylines can be readily inserted into ribbons, while pipe filter can be applied to drop redundant points. Thus, conversion from raster and line representations to the ribbons is straightforward. However, incoming polygons and tessellated surfaces have to be **quadrangulated** prior to inserting into the ribbons.

Ribbonisation of the design geometry is commonly performed only once per session and therefore not time-critical. However, its quality has great impact on the memory requirements and the time complexity of the further processing, in particular on the

visualisation process. As mentioned in the Sect. 3.5, it is recommended to adopt synchronised sampling, so that selected design cross sections are maintained.

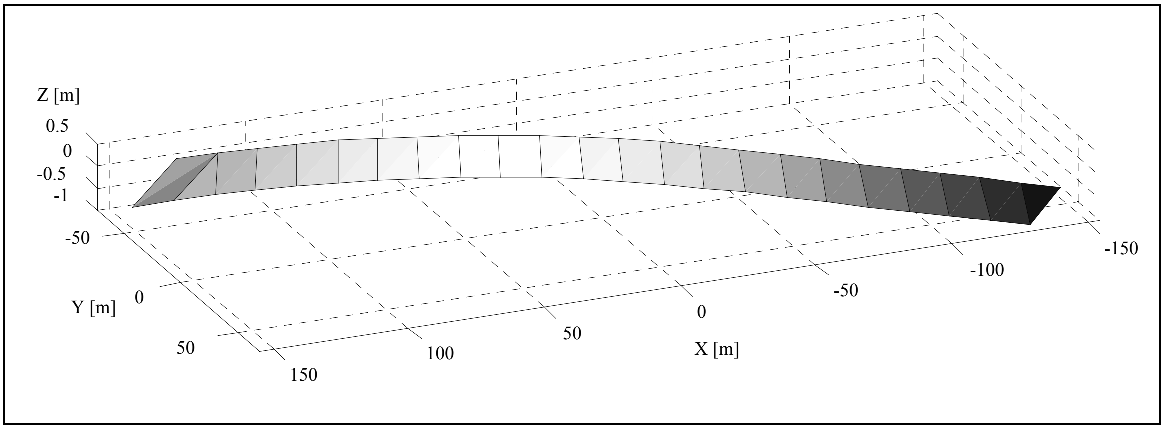

Fig. 4-9. Delaunay ribbonisation of a multi-polyline road design.

Multi-polyline models, as well as "narrow" polygons, can be effectively converted into ribbons in linear time by *Delaunay ribbonisation*[24] (Fig. 4-9.). This algorithm starts at the polygon ear[25] and proceeds incrementally along the curvilinear axis, choosing the shortest of three possible diagonals. Triangles can be inserted to improve the representation. In this way the skewed geometries and ordering problems can be easily dealt with.

4.4.2.c. Ribbonisation of triangulated surfaces

The more complex problem of a **TIN surface ribbonisation** is specific to the earthmoving application (Sect. 2.3.3) and concerns the initial state, typically surveyed manually.

As a triangle is a ribbon of length *1* (with two overlapping vertices), any triangulated surface with *N* triangles is a concatenation of *N* ribbons. However, with two nodes per triangle face, this "naive" representation is **not optimal** and costs four times more with respect to memory and time compared to the connected ribbon of length *N*.

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[24] It can be shown that the resulting tessellation can be directly derived from a restricted Delaunay triangulation.

[25] Polygon ear is a vertex, such that the connection of neighbouring vertices is a diagonal. Each polygon has at least 2 ears [O'Rourke 93].

Let's consider a **dual graph of triangulation**, that is the graph of connections between triangles via common edges. The "naive" representation can be improved by joining the adjacent triangles along the paths in the graph. Moreover, joining of triangles into quadrilaterals may further decrease the number of required nodes. This is possible whenever the entry and exit edges of the quadrilateral are not adjacent ("**opposite doors**"). Compared to the design sampling problem, we do not have to maintain the diagonals, only the vertices, which correspond to elevation measurement points.

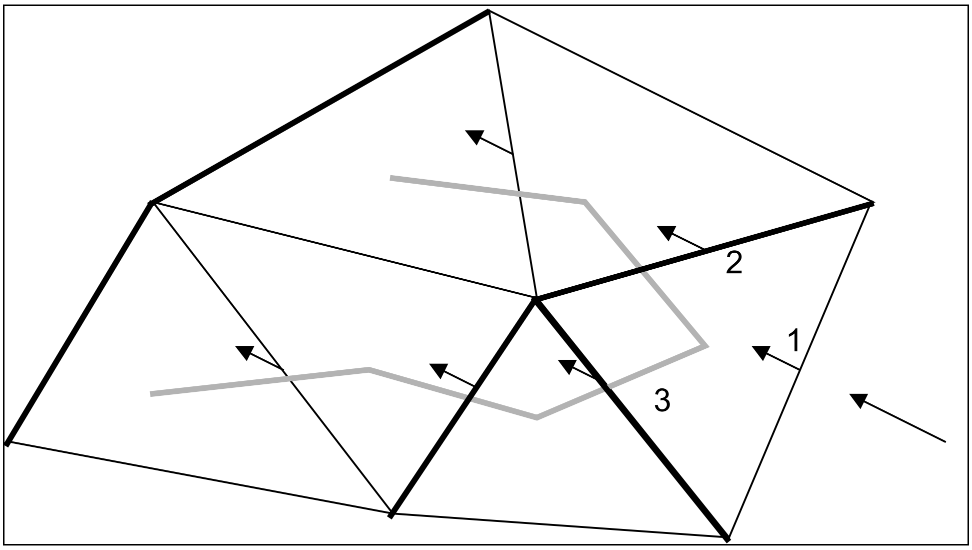

Fig. 4-10. Dual triangulation graph walking algorithm.

The walking sequence is determined by a chosen direction and edge ordering. The triangles can be entered only in the chosen direction (marked as small arrows) and exited according to the edge order. The tree of the graph is marked as thick grey line. The ribbon diagonals marked as thick black lines.

The closely related problem of finding **optimal triangle strips** for fast visualisation of triangulated surfaces has been widely studied by the computational geometry community. The optimal solution requires visiting all triangles along the **Hamiltionian path**[26]. The problem of finding it is related to the travelling salesperson problem, and thus **NP-hard** [Arkin 94] [Evans et al. 96a]. The additional condition posed by "opposite doors" rule requires the triangulation to be **sequential**, that is the turns in the path need to alternate left-right. The sequential, Hamiltionian triangulation

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[26] Hamiltonian cycle/path in undirected graph is a simple cycle/path connecting all vertices. Such a graph is called hamiltonian [Cormen et al. 90].

can be applied to derive the optimal ribbonisation, reducing the number of required nodes, memory and processing time by the factor of four.

However, solving the TIN ribbonisation problem optimally is not practical. The **regular** and **almost-regular** grids are often adopted. Typically the grid will be related to the direction of the main alignment. In these cases the TIN ribbonisation is particularly easy. In general case various **heuristics** for generating good triangle strips have been proposed by [Evans et al. 96b], [Speckmann, Snoeyink 01], [Xiang et al. 99] and others. The **graph walking** method by [Speckmann, Snoeyink 01] is especially suitable for the CIRC application thanks to its simplicity and the utilisation of the dominant road direction (Fig. 4-10.). It served as a basis for other linear time heuristic methods, for example Fast Triangle Strip Generator FTSG [Xiang et al. 99]. We applied a FTSG method to a sample DTM. The achieved **sub-optimal reduction** amounts to ***2.7*** (Fig. 4-11.).

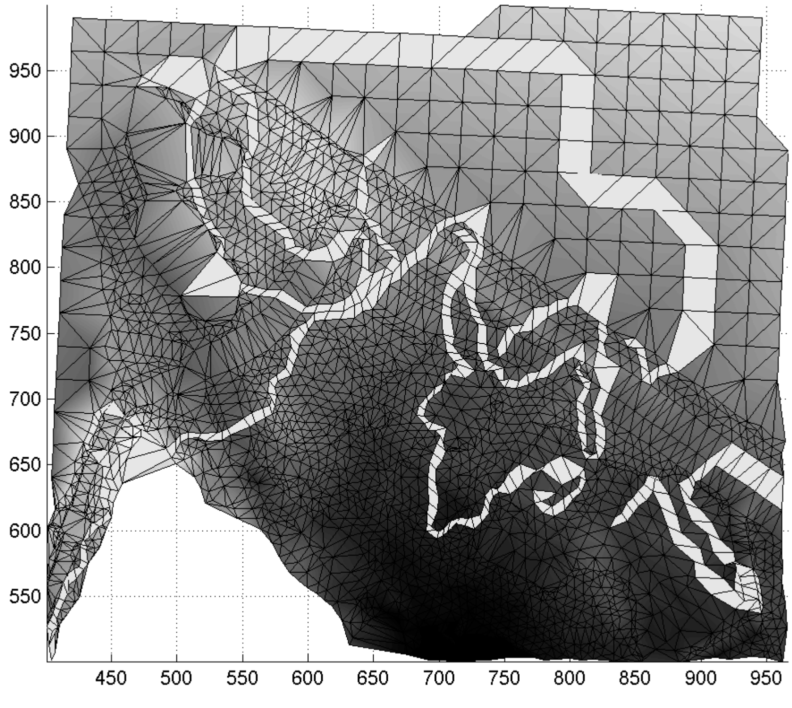

Fig. 4-11. 5 longest ribbons (50..100 nodes each) in the TIN DTM.

The DTM contained 5k triangles and 381 ribbons The overall number of nodes was reduced from 10k to 4k using a fast heuristic described in [Xiang et al. 99].

We can conclude that ribbon description can be considered a generalised triangulation. Known algorithms can be applied to obtain nearly-optimal ribbonisations.

4.4.2.d. Visualisation

In visualisation process the ribbon is a converted to a raster representation (**bitmap**). Two kinds of graphical outputs are common: **parameter map** (including elevation) and **pass map** (examples are given in Sect. 4.5).

The visualisation pipeline consists of:

- **geometric searching**, to find the relevant nodes (e.g. currently visible),
- **coordinate mapping** (projection) from the worksite to the raster reference frame,
- **rasterisation** of the geometrical primitives (quads, triangles or polynomial patches).

Similar algorithm can be applied to **export** the contents of the ribbon database in raster file form. Thanks to the vector processing, smooth scrolling, rotation and zooming are possible. The time complexity is basically linear, but **geometric hashing** (e.g. gridding or quadtree techniques [Samet 90]) can be adopted to reduce the number of displayed ribbon nodes depending on the actually viewed region of the worksite. In this way real-time visualisation can be achieved with moderate hardware requirements.

4.4.2.e. Curvilinear transformation

The **curvilinear coordinates** (Sect. 3.4.4) are often required to export the work description in format suitable for road network database. Moreover the ribbons can be expressed in both Cartesian and curvilinear coordinate systems.

If the curvilinear reference frame is expressed in the Cartesian coordinate system and it has been ribbonised, it is possible to efficiently **convert** between the curvilinear and Cartesian coordinate spaces using methods described in Sect. 3.5.3. In this way the curvilinear measurements such as travelled or vertical distance can be converted into Cartesian worksite reference system.

In an incremental case, as for the moving machine, the conversion between both reference frames can be done in a constant time. It is also possible to maintain the whole DEM contents in both reference frames, obtaining two **alternative presentations** (Fig. 4-12.), available at any time.

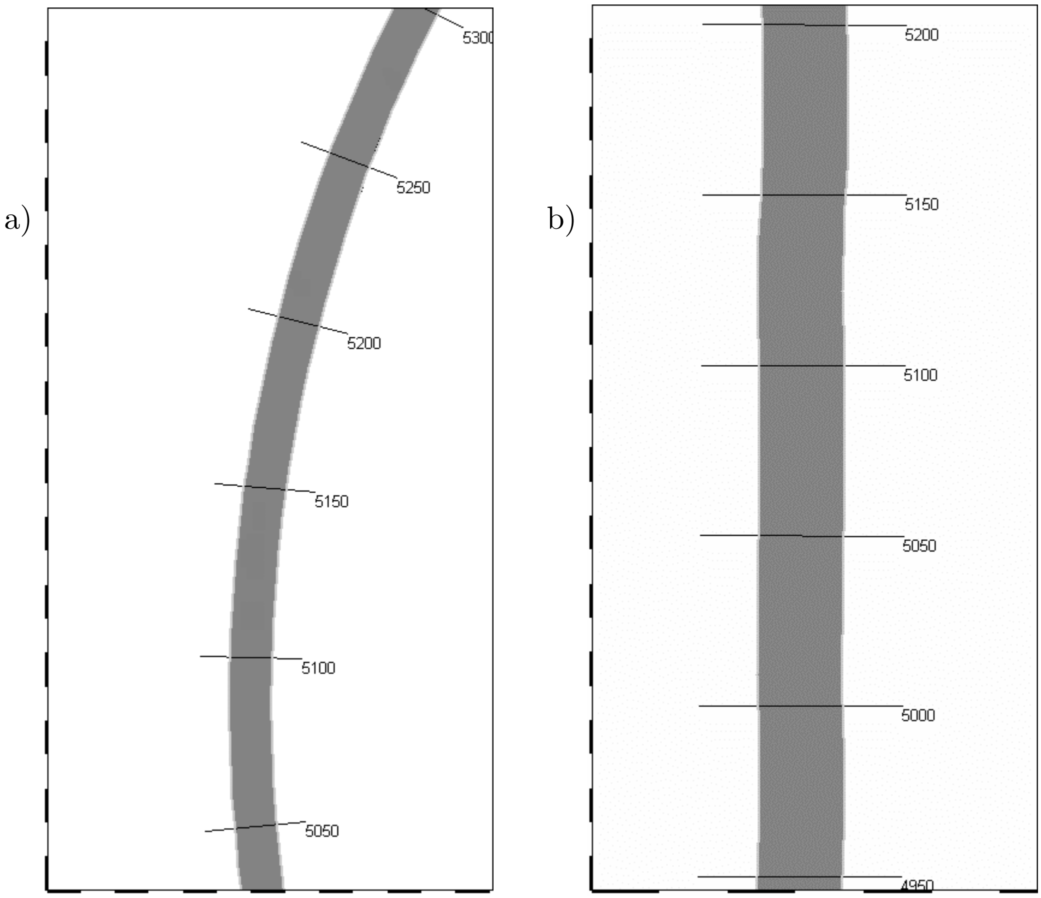

Fig. 4-12. Straightening the ribbons with linear approximation.

a) Cartesian view, b) curvilinear view. Scale unit = 10m. The artefacts are due to the low precision of the linearised transformation (Sect. 3.5.2) and the low sampling quality (Sect. 3.6.2).

4.4.2.f. Site networking

The **wireless data exchange** protocols are required to enable the team functionality, for example a **distributed pass map** or a **temperature map** describing asphalt cooling. In the multi-machine environment the ribbon node is a **natural quantum** for the data exchange algorithm. Information management is greatly simplified by ordering imposed by the ribbon representation. Moreover, thanks to the uniform environment modelling method, it is possible to **interconnect** profiling and surfacing machines in the process information exchange. Thus the information gathered during the laying process can be applied to optimise the compaction process.

The **multicast** [Tanenbaum 96] is the natural operating mode of the site network, utilising the broadcast nature of the radio medium. In this mode most of the nodes are transmitted only once. Only if the receivers recognise missing nodes the retransmission is requested, resulting in a **reliable multicast**. Care must be taken to avoid excessive retransmission requests, resulting in **message implosion** (Fig. 4-13.). The author developed an efficient worksite networking scheme based on the specialised reliable multicast architecture and the standard datagram protocol of TCP/IP [Tanenbaum 96]. It is presented in greater depth in [Peyret et al. 00a].

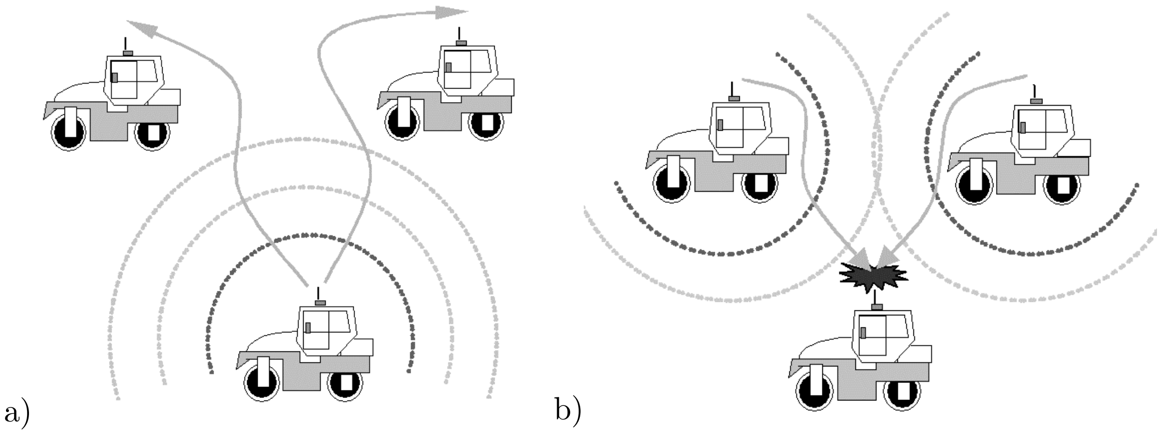

Fig. 4-13. a) Multicast principle, b) Collision due to message implosion.

The machines working in an asphalt team stay within few hundred meters from the paver, which moves slowly (few m/min) along the worksite, which can be of several km in length. Suitable wireless LAN technology allows for wireless transmission over the distances of *0.3..1.5 km*, which is normally sufficient, as the information about distant machines is less relevant and thanks to the **soft relaying** property of the multicast communication scheme [Peyret et al. 00a]. The communication distance can be extended with repeater devices or directional antennas. Due to the moving nature of the worksite it is often not practical to establish a complete coverage.

Compared to the other construction areas, the personnel and equipment in road construction team vary only incidentally, for example due to the machine breakdown. As the teams are not created ad hoc, the identities of involved machines can be described in advance in a form of the **fleet description** (Sect. 2.5.3). However, the machines may leave the worksite temporarily, for example to fetch water or fuel. This results in a **varying topology** of the site network. Scenarios need to be considered for a machine entering the worksite, to guarantee quick availability of the current as-built status. Otherwise the reliable multicast principle guarantees that the missing information will be gradually exchanged.

One can consider a **client-server** structure with a central node, for example on the paver. However, due to varying topology it is advantageous to store the complete set of worksite data (designed state and current state) in each of the **machines (peer-to-peer** structure), rather than to implement a client-server scenario. The described site network is a distributed system with a large degree of redundancy, resulting in improved robustness.

4.4.3. Conclusions

The **ribbon model** is a **universal** and **efficient** means for maintaining the environment model. It can accept all known road data models as an input. Only the conversion of the TIN DTM is not straightforward, but several algorithms which can be readily applied are known. As all the vertices are preserved, the raster, multi-polyline and triangulated models can be created from the ribbon data model easily and without loss of precision. It is well suited for **site networking**, enabling important distributed applications.

For these reasons the ribbon data model is currently discussed by ISO TC-127 standardisation committee as a possible part of future standard for data controlled earth–moving operation (Sect. 2.5.2) [Peyret 02].

4.5. APPLICATION RESULTS

Fig. 4-14. The compactor used for the CIRCOM and MultiCIRCOM full-scale trials.

Fig. 4-15. The ribbon-based MMI during compacting operation.

The ribbon data model has been validated in several full-scale tests:

- During one compactor CIRCOM tests on A84 close to Villedieu-Les-Poeles, France in Summer 1998 (Figs. 4-14. and 4-15.) the basic ribbon algorithms have been validated in the worksite conditions. The ribbon database proved to be able to process the design, store the data for the whole working day and display it precisely in real time.

- During the paver CIRPAV tests in Nantes, France in Winter 1999/2000 the 3D modelling capabilities required for levelling functionality were successfully tested on a test track.
- In the course of the paver OSYRIS tests in Elz, Germany in Autumn 2001 the free attribute storage capability and extended 3D modelling capabilities were proven on a test track.
- During the OSYRIS tests with a paver and two compactors on E22 close to Oskarshamn in southern Sweden in Autumn 2003 the co-operation between the profiling and the surfacing machines was verified in the worksite conditions (Fig. 4-16.).

Fig. 4-16. Fleet of a paver and two rollers equipped with ribbon-based systems during OSYRIS worksite tests.

The GPS and laser plane positioning equipment is mounted on masts. The static roller is equipped with a low-cost positioning solution using two code-differential DGPS receivers and additional sensors.

The **insightful graphical presentation** is the most important aspect of the described CIRC implementations based on ribbons. The operators can see the results of their own and team work immediately. The dominant axis has influence on the MMI design, favouring the page-oriented map presentation.

As all the movements of the machines are stored in ribbons, it is possible to export and analyse extensively the work progress and process information. Alternatively, it is possible to export the parameter map in raster form.

The ribbon description is permanent; it can be quickly stored in mass memory before the system is switched off and loaded upon start. The contents of DEM is stored repeatedly. In the case of the system failure, the last saved state can be restored.

In the next sections we will discuss the particular aspects of the geometric modelling for the defined classes of machines.

4.5.1. SURFACING SUPPORT: COMPACTOR

The **pass map** is of particular interest for the operator in the surfacing case. It helps to obtain the uniform process result, in particular improved compaction. An example as implemented in CIRCOM system is shown in Fig. 4-17.

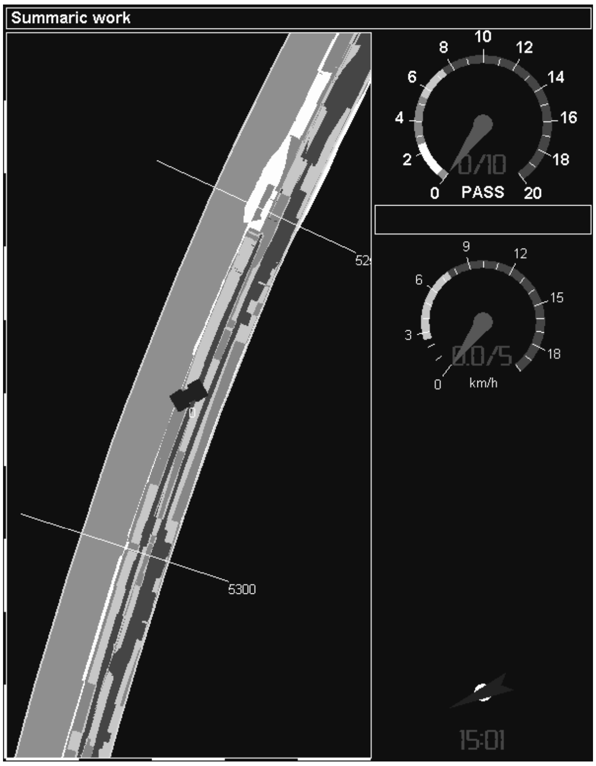

Fig. 4-17. Ribbons in surfacing application – CIRCOM MMI.

A pass map and gauges for critical process parameters: number of passes and speed form the core of the MMI. Each colour represents different number of passes. Additionally the error and informative messages can be shown.

The pass map is based on the compactor trajectory, described by a **self-intersecting ribbon**. It is discontinuous due to work breaks, missing positioning data etc. It can be seen that the polygon clipping technique as proposed in [Li et al. 96] would lead to creation of prohibitively many polygons and is not practical.

The pass map is calculated efficiently, allowing for a real-time visual feedback. The screen update rate can be as high as *5 Hz*. For the sake of universality, the 3D approach is applied uniformly, also for apparently 2D compactor systems. The cost of storing the additional coordinate is compensated by uniform handling.

4.5.2. PROFILING SUPPORT: PAVER

The main task of the on-board system on the profiling machine is the **levelling algorithm**, most importantly the calculation of the designed elevation, given the current position. The MMI (as implemented in CIRPAV system) consists of an **overview map**, a **cross section view** and a **trajectory view** (Fig. 4-18.). Additional parameters are displayed by the more comprehensive OSYRIS system (Fig. 4-19.).

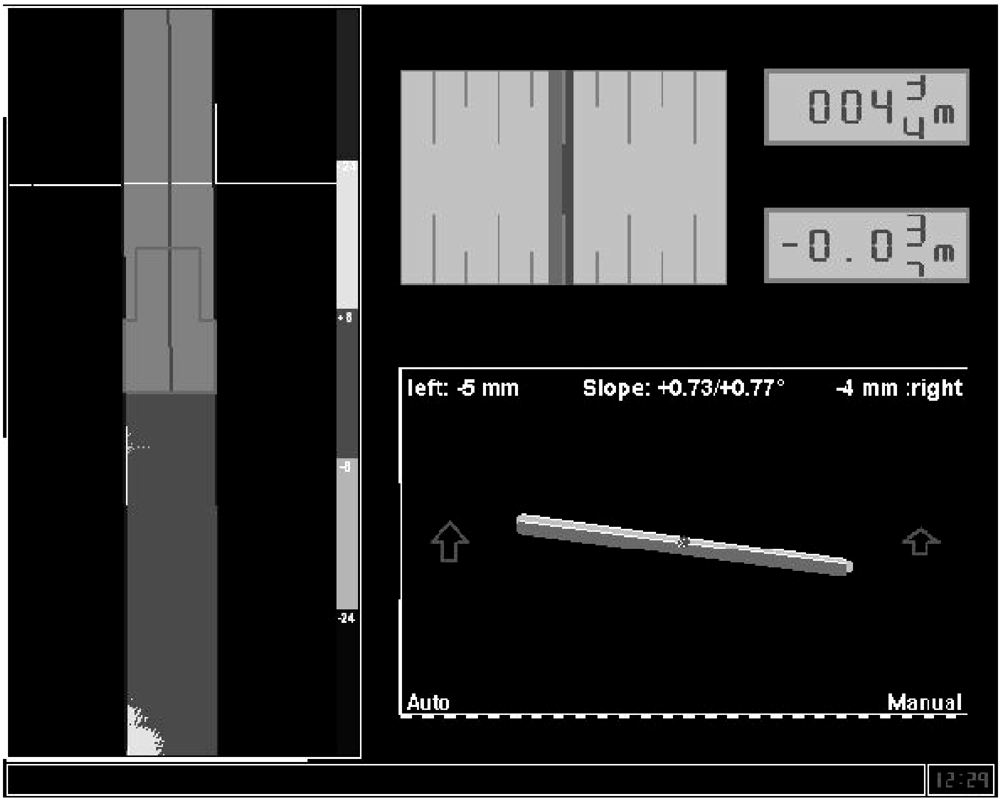

Fig. 4-18. Ribbons in profiling application – CIRPAV MMI.

A pass map, cross section view and trajectory view are essential parts of the MMI.

To assure robust interpolation in the 3D levelling application it is important to guarantee the non-self intersection (NSI) of the generated ribbons, so as to obtain the height field description. While any interpolation method described in Sect. 3.5.3 can be chosen, bitriangular interpolation was applied as an optimisation of TIN. Even if only 1D levelling is used, the ribbon-based profiling system can still be very useful, storing and displaying the maps of the thickness or elevation and other process parameters, for example temperatures. Such system can also be easily adapted for the grader or milling machine.

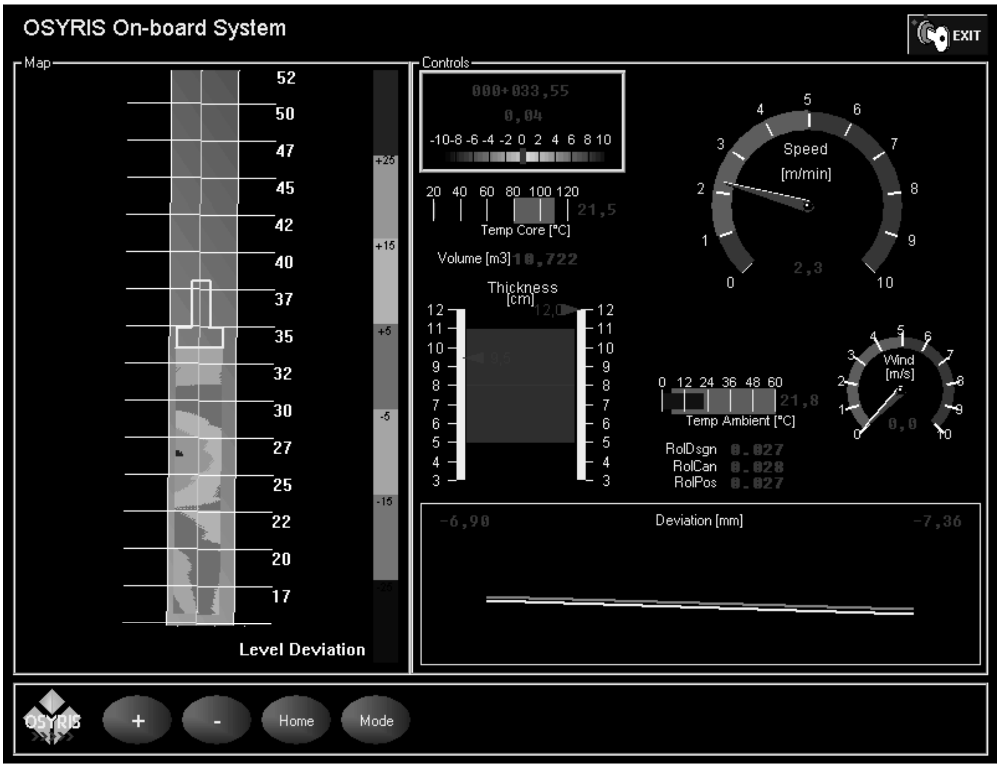

Fig. 4-19. Ribbons in profiling application – OSYRIS Paver MMI.

Important process parameters can be shown to the operator on the pass map or visual gauges.

4.5.3. EARTHMOVING SUPPORT

As of today, the ribbons have not been applied for earthmoving support, even when it is possible to describe the TIN-based DTM using ribbons (Sect. 4.4.2.c). After a good ribbonisation of an initial state has been found, it needs to be effectively updated in the real time, as the work proceeds. Further research is needed to verify if it is better to repeatedly modify the existing ribbons so as to ensure the NSI property (similar to a profiling system), or to collect all machine paths and create the terrain map cumulatively (as in the case of a surfacing system).

4.6. CONCLUSIONS

Existing data models show **considerable drawbacks**, especially for **the heterogeneous worksite**. Several of those drawbacks can be avoided with the novel ribbon data model, sporting the following features:

- **Universality**: all the relevant objects on the work site are represented in uniform and coherent way. The possibility of efficient conversion to and from other representations in current use is assured.
- **Object paradigm**: the physical attributes are compactly stored in the database together with the geometrical objects they apply to.
- Support for the online (**site network**) and offline **data exchange**.
- Exact and fast **3D modelling and visualisation**, using the primitives discussed in Chapter 3.
- **Safe permanence**: the database is robust and remains safe in the case of power or system failure.

The ribbon data model offers the **flexibility** and the **performance** required for the universal on-board representation of the environment in road construction. It can be applied for all three required machine groups, and as of today it has been successfully verified for two of them in full-scale tests. As opposed to the other data models in use, the ribbon model can accommodate both **complex geometry** and numerous physical **process attributes** and offers **machine independence**. It is well suited for site networking, enabling machine co-operation and important **distributed applications**. For these reasons it has been proposed as a part of future international standard for data controlled earth–moving operation.

Ribbon approach can also be applied to other linear civil engineering structures, like railways, canals or tunnels.

5. Closing Conclusions and Outlook

Comparing the vehicle and the road as the two key components of the road transport system, it is clear that the car manufacturing process has been subject to unparalleled progress in terms of production automation, quality control and refinement of the manufacturing methods. Similar progress, with comparable benefits, is yet to be expected for the road construction industry. Implementation of the CIRC concept is a step in this direction.

The universal and efficient geometrical modelling methods developed in the course of presented work are an important prerequisite for a successful CIRC implementation. Hopefully they will become part of future international standards. However, many other conditions must be met, for example improved cost-benefit ratio and attractive, robust functionality. Further research and implementation work is necessary to meet these goals.

The forthcoming work can build on the presented concepts. In particular, further dissertations resulting from the major work performed in CIRC domain at the TMB are planned:

- New cost-efficient, robust positioning methods based on low-cost GPS can be analysed using ribbons.
- Asphalt temperature estimation extends the functionality and brings added value to the CIRC system. The simulations are based on the ribbon data model.
- Advanced levelling algorithms can be formulated and analysed. In particular it seems interesting to study the levelling behaviour in the presence of the approximation errors discussed in Sect. 3.5.
- Worksite optimisation is possible based on the working patterns, which can be identified in the conducted tests, stored in the ribbon form.

It remains also to analyse the impact of the CIRC systems application on the road construction quality. In particular a statistical study of the new compaction control methods is essential for further work (Sect. 2.3.2). Moreover the human interaction aspects influence greatly the results and are well worth further research.

With the growing economical motivation, the CIRC systems will certainly evolve further. Especially the site networking and team functionality will be of growing importance with the wider introduction of the wireless technology to the road worksites. If the requirements concerning robustness, flexibility and ease of operation are fulfilled, the support systems should also receive growing acceptance. Hopefully they will help to build excellent, durable roads in a quality-conscious way.

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