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Motion Planning for Manipulators with Many Degrees of Freedom – The BB-Method

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Preface

The topic of this book – automatic path and trajectory planning – is an important area of robotics. In this decade robotics – similar to some other areas of computer science – was shaped by striving for systems with more intelligence, more autonomy, and more freedom of choice. The conception of such inherently complex systems posed new challenges: in research as well as in the reorientation process of the often traditionally shaped application domains.

In industrial manufacturing these efforts were strengthened and supported by the target of an integrated computer support comprising all steps from design to product. Due to these efforts more and more products and their manufacturing production lines are completely modelled with CAD-tools.

Due to this, product properties cannot be determined only when a prototype is available, but already during the development process by using computer simulation. Examples from the car manufacture are driving characteristics, crashtests, design of manufacturing cells or digital mock-up. This extensive use of computers leads to cost reduction and shorter development cycles.

Within the industrial area we thus find robots, which operate in a well-known – because described by CAD-models – real or simulated environment. In the real environment up to today the robots usually still move only on predefined paths. Unexpected errors cause a halt in the production. In the future autonomy will be used to handle unexpected error situations. Among other tools path planning is mandatory for this. In the simulated environment, for example during the design of the manufacturing cells or within mock-up simulation, suitable collision-free paths have yet to be found. Here computer-aided path planning, for example with the algorithms developed by Mr. Baginski, is important.

Computer-aided path planning is helpful or even indispensable in many other application domains. In order to show the diversity of the domains, the following scenarios are mentioned:

- A multilegged and highly articulated robot executes inspection work in a sewer system (a partially well-known environment).
- A service robot in a hospital delivers meals. It knows the static objects and recognizes moving objects by sensors, e.g. a camera. The robot must find its way to the target and then move his arms to place the meal correctly.
- Virtual humans or other objects with joints, move in a virtual environment to a goal position to grasp an object. The movement of the human altogether and the movement of the individual parts of the body have to be calculated with the constraint "the movement must look natural".

In many scenarios pertinent to industrial manufacturing, paths for robots with six or more joints can now be calculated within a short time by the BB-algorithm presented in this book.

Nevertheless there are still many other path planning problems without satisfying algorithms to solve them. An example is path planning in very tight and complex obstacle spaces, which are typical for digital mock-up simulation. Another example is path planning for hyperredundant robots under many, also nongeometrical boundary conditions. In the last section of this book Mr. Baginski shortly points to some unsolved problems and his ideas for extending the BB-method to their solution.

I would be happy to see a rapid transfer of Mr. Baginski's algorithms for path planning into the industry and hope that many new impulses for research in path planning are triggered by this book.

Munich, October 26, 1998 — Hans-Jürgen Siegert

Abstract

A new approach for manipulator motion planning - the BB-method - is introduced. A collision-free path is found by incrementally modifiying an initial, usually colliding, path. The method described alters the robot's motion in its physical workspace, utilizing *virtual* rating functions that are based on *reducing* and *expanding* the robot's geometry model. The BB-method is able to plan motions for redundant and hyperredundant manipulators. With this, it stands in contrast to most other motion planning methods usually developed in an abstract configuration space. Due to their complexity, they are not applicable to real robot tasks.

The experimental experiences with the BB-method prove the main thesis of this work: an efficient and effective motion planning scheme can be build upon careful examination and utilization of the *spatial properties* of the motion of a robot manipulator. The algorithmic complexity of collision free path planning is only linear in the number of degrees of freedom, and the effective computational effort is not necessarily increased for an increased number of joints. The BB-method is local and heuristic, therefore it is an incomplete motion planning algorithm. Within this work, all major properties of the BB-method are characterized and analysed in detail.

This work is a basis for further explorations of the various properties, possibilities, extensions and further developements of the BB-method. But nonetheless, efforts were taken to identify all necessary requirements of a motion planning system and to introduce the pradigm of *virtual geometry modification* in a way all aspects can be handled. The existing prototype implementation allows real-time planning (up to a few seconds) of motions for typical six degree of freedom industrial manipulators in practical cases, as well as fast planning for multiple kinematic devices with several tens of joints. The planning allows the assertion of safety distances to handle control and modelling uncertainties, and a local length reduction of the path, yielding motions that require less time and less energy if they are executed in reality.

Kurzfassung

Das BB-Verfahren, ein neuartiges Verfahren zur Bewegungsplanung für Manipulatoren, wird vorgestellt. Eine kollisionsfreie Bahn wird gefunden, indem eine initiale, üblicherweise kollisionsbehaftete Bahn schrittweise verändert wird. Das dargestellte Verfahren modifiziert die Roboterbewegung im Arbeitsraum, unter Ausnutzung *virtueller* Bewertungsfunktionen, die durch *Verkleinerung* und *Vergrößerung* des Geometriemodells des Roboters bestimmt werden. Das BB-Verfahren ist auch für redundante und hyperredundante Manipulatoren anwendbar. Es unterscheidet sich damit ganz wesentlich von den meisten anderen aus der Literatur bekannten Ansätzen. Diese basieren überwiegend auf der Planung in einem abstrakten Konfigurationsraum und sind aufgrund ihrer Komplexität nicht für realistische Anwendungen geeignet.

Die Ergebnisse der Versuche mit dem BB-Verfahren belegen die Kernthese dieser Arbeit: ein leistungsfähiges und praktisch anwendbares Bewegungsplanungssystem kann durch geeignete Auswertung und Nutzbarmachung der *räumlichen Eigenschaften* der Bewegungen eines Manipulators entwickelt werden. Die algorithmische Komplexität der Planung kollisionsfreier Bahnen ist nur linear in der Anzahl der Freiheitsgrade, und der effektive Planungsaufwand wird durch Hinzufügung zusätzlicher Gelenke nicht notwendigerweise vergrößert. Das BB-Verfahren ist ein lokales und heuristisches Planungsverfahren, es ist daher unvollständig. In dieser Arbeit werden alle wesentlichen Eigenschaften des Verfahrens beschrieben und detailliert analysiert.

Diese Arbeit versteht sich als Basis für die weitere Untersuchung der Eigenschaften, Möglichkeiten, Erweiterungen und Ergänzungen des BB-Verfahrens. Nichtsdestotrotz wurde versucht, alle notwendigen Teilaspekte eines Bewegungsplanungssystems zu identifizieren und das Paradigma der *virtuellen Geometrieverformung* in einer Weise einzuführen, daß alle relevanten Aspekte berücksichtigt werden können. Die vorliegende prototypische Implementierung ermöglicht die Planung von Bewegungen für typische sechsgelenkige Industrieroboter in praktischen Anwendungsbeispielen in Echtzeit (maximal wenige Sekunden), und ebenso sehr schnelle Planung für komplexe (auch gegabelten) kinematische Strukturen mit beliebig vielen Freiheitsgraden. Dabei können Sicherheitsabstände eingehalten werden, die Modellierungs- und Steuerungsunsicherheiten berücksichtigen, und die Bahnen können lokal verkürzt werden, was in der Praxis zu verringerten Verfahrzeiten und verringertem Energieaufwand führt.

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List of Symbols

Formula Symbols

The following convention is used: vectors and sets of vectors are written in a lower case bold typeface ($\mathbf{v}$), matrices and vector-valued maps are written in an upper case bold typeface ($\mathbf{M}$), and scalar values are written in italics (d).

$\mathbf{u}$, $\mathbf{v}$, $\mathbf{w}$	Cartesian points
G_i	Geometry model of link i
G^{+d}	Model isotropically expanded by d
$\mathbf{R}$	Rotation matrix
$\mathbf{t}$	Translation vector
${}_i\mathbf{T}_j$	Homogeneous transform
${}_i\mathbf{T}_j(\mathbf{q})$	Configuration-dependent transform
${}_i^s\mathbf{T}_j$	Scaling transform, scaling factor s
n	Number of joints / links
n_i	Number of joints preceeding link i
v_i	Joint preceeding joint i / link preceeding link i
I_i	List of joints preceeding link i
W	Workspace
W_{free}	Free workspace
q_i	Joint value of joint i
$\mathbf{q}$	n-dimensional configuration
$\mathbf{q}_{start}$, $\mathbf{q}_{goal}$	Start/goal configurations
C	Configuration space
C_{free}	Free configuration space
C_{coll}	Colliding configuration space
$\mathbf{P}$	Path
$\bar{\mathbf{P}}$	Linear path segment
$\hat{\mathbf{P}}$	Polygonal path
$\delta_{\min}$	Smallest displacement for path planning
$\delta_{\max}$	Largest displacement for path planning
$\Delta_i(\mathbf{q}_a, \mathbf{q}_b)$	Estimated cartesian motion for link i
$\mathbf{c}^a$	Replacement candidate set for configuration $\mathbf{q}_a$

f_{step}	Relative displacement step size
f_{divide}	Path segment subdivision factor
z_{random}	Maximum number of random subgoals
$d_{\max_i}$	Desired safety distance for link i
$\mathbf{d}_{\max}$	n-dimensional vector of desired safety distances
$\mathbf{d}_{\bar{\mathbf{p}}}$	Safety distances of a path segment
ρ	Threshold ratio for path shortening
λ	Segment length threshold for path shortening
τ	Tolerance for collision detection
γ_{scale}	Approximation precision for scaling based rating
γ_{dist}	Approximation precision for expansion based rating
t_{scale}	Planning time for collision-free path
t_{dist}	Planning time for safety distances
t_{short}	Planning time for path length reduction
m_{dist}	Approximate quality of safety distances
m_{short}	Length ratio achieved by length reduction

Algorithms

To clarify the presentation, prototype algorithms are used throughout this work. A PASCAL-style notation is used for the control structures.

Q_{scale}	Scaling based path rating (p. 51)
ModifySegmentScale	Scaling based path modification (p. 61)
DivideSegmentScale	Path segment subdivision (p. 62)
PlanScale	Collision free path planning (p. 63)
PlanGlobal	Random global planning (p. 74)
Q_{dist}	Expansion based path rating (p. 79)
ModifySegmentDist	Expansion based path modification (p. 83)
DivideSegmentDist	Path segment subdivision (p. 85)
PlanDist	Planning safety distances (p. 87)
CutTriangle	Local path length reduction (p. 99)
PlanShort	Length reduction planning (p. 100)
SegmentColl	Collision test for a path segment (p. 109)
SweptObjColl	Collision test for a moving object (p. 114 and 118)
SweptStepColl	Collision test for an intermediate segment (p. 117)
ObjColl	Collision test for two objects (p. 118)
BisectScale	Approximation of scaling (p. 120)
SweptObjGetScale	Scaling of a moving object (p. 121)

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