

UNIVERSITAT POLITÈCNICA DE CATALUNYA

Programa de Doctorat:

AUTOMATITZACIÓ AVANÇADA I ROBÒTICA

Tesi Doctoral

**FINE-MOTION PLANNING FOR ROBOTIC
ASSEMBLY UNDER MODELLING AND
SENSING UNCERTAINTIES**

Jan Rosell Gratacòs

Director: Prof. Luis Basañez Villaluenga

Institut d'Organització i Control de Sistemes Industrials

Juny de 1998

A la Mireia

Acknowledgements

Aquesta tesi és el resultat del meu treball de recerca relitzat a l'Institut de Cibernètica (actualment Institut d'Organització i Control de Sistemes Industrials), primer com a becari predoctoral finançat pel Comissionat per a Universitats i Recerca de la Generalitat de Catalunya, i posteriorment com a professor associat del Departament d'Enginyeria de Sistemes, Automàtica i Informàtica Industrial. Aquest treball, però, no hagués estat possible sense l'ajut tècnic i el suport moral de moltes persones.

En especial voldria donar el meu agraïment:

Al professor Luis Basañez que m'ha brindat la possibilitat de treballar en el camp de la robòtica, guiant-me en la recerca amb rigor científic.

Al tots els companys de l'Institut i en particular a Raúl Suárez, a qui he seguit els passos de prop i amb qui he pogut comptar sempre per discutir temes tècnics o simplement per parlar, a Miguel A. García amb qui he compartit moltes hores al laboratori de robòtica i de qui he après força coses, i a Susana Velazquez per la seva amistat al llarg d'aquest camí que hem recorregut conjuntament des que vam entrar a l'Institut.

Finalment i de manera molt especial, a la Mireia, amb qui he compartit tantes coses i amb qui espero fer un llarg camí, i al meu fill Pol, que m'ha esperonat per poder arribar a la meta: *“Pare, quan acabaràs el llibre?”*

Contents

1	Introduction	1
1.1	Framework	1
1.2	Objectives	3
1.3	Related work	4
1.3.1	Compliance	4
1.3.2	Fine-motion planning	5
1.3.3	Reactive Control	9
1.3.4	Contact identification	11
1.4	Overview	12
2	Basic Motion Planning	15
2.1	Preliminaries	15
2.2	One basic contact situations	16
2.2.1	Representation in configuration space	16
2.2.2	Set of contact orientations	21
2.3	Two basic contacts situations	21
2.3.1	Representation in configuration space	21
2.3.2	Set of contact orientations	23
2.4	Three and more basic contacts situations	29
2.4.1	Representation in configuration space	29

2.4.2	Set of contact orientations	29
2.5	Considering all the geometric constraints	31
2.5.1	Configuration space construction algorithm	32
2.5.2	An example	36
2.6	Partition of the configuration space	36
2.6.1	Partition of the free-space	39
2.6.2	Partition of the contact-space	43
2.7	Motion planning algorithm	47
2.7.1	Search policies	47
2.7.2	Performance	48
2.8	Analysis of reaction forces	48
2.8.1	Force decomposition	48
2.8.2	Force decomposition in the dual plane	52
2.8.3	Partition of the dual plane	55
3	Contact Uncertainty Analysis	59
3.1	Sources of uncertainty	59
3.1.1	Modelling uncertainty	60
3.1.2	Sensing uncertainty	61
3.2	Analysis in physical space	63
3.2.1	Modelling uncertainty on the contact edge	64
3.2.2	Modelling uncertainty on the contact vertex	67
3.2.3	Sensing uncertainty	68
3.3	One basic contact situations	69
3.3.1	Nominal contact condition	69
3.3.2	Contact condition in the presence of uncertainty	70
3.3.3	The orientation ϕ_o^i	74

3.3.4	Construction of the Contact Position Region	77
3.3.5	Construction of the Contact Position Domain	84
3.3.6	Contact identification	88
3.4	More than one basic contact situations	92
3.4.1	Contact uncertainty dependence	95
3.4.2	Independent sources of uncertainty	100
3.4.3	Dependent sources of uncertainty	102
3.4.4	Dependent and independent sources of uncertainty	102
3.4.5	Contact identification	110
3.5	Uncertainty reduction	111
3.5.1	Estimation of the orientation of the contact edge	111
3.5.2	Estimation of the position of the contact vertex	112
3.5.3	Estimation of the position of the contact edge	116
3.5.4	Modification of the \mathcal{C} -arcs	116
3.6	Force analysis	117
3.6.1	One basic contact situations	117
3.6.2	More than one basic contact situations	124
3.6.3	Contact identification from force information	128
4	Motion Synthesis	133
4.1	Path synthesis overview	133
4.2	Compliant motion	134
4.3	Path synthesis	134
4.3.1	Path evaluation	135
4.3.2	Path synthesis algorithm	142
4.4	Motion commands	146
4.4.1	Component to follow a \mathcal{C} -arc	147

4.4.2	Accommodation components	148
4.5	Task execution	150
4.5.1	Task execution procedure	150
4.5.2	A case study	151
5	Conclusions	159
5.1	Contributions	159
5.2	Future work	161
5.2.1	Improvements	161
5.2.2	Extension to 6 d.o.f.	162
5.2.3	Application to mobile robots	162
A	The Dijkstra Algorithm	163
B	The Dual Representation of Forces	165

List of Symbols

\mathcal{C} -space	Configuration space
\mathcal{C}' -space	Parametrized translational configuration space
\mathcal{C}_{free}	Subset of the \mathcal{C} -space corresponding to non-contact configurations that satisfy all the geometric constraints of the task
$\mathcal{C}_{contact}$	Subset of the \mathcal{C} -space corresponding to the contact configurations
$\{W\}$	Reference frame attached to the workspace
$\{T\}$	Reference frame attached the manipulated object
ϕ	Orientation of $\{T\}$ with respect to $\{W\}$
ψ_T	Orientation with respect to $\{T\}$ of the normal to the contact edge
ψ_W	Orientation with respect to $\{W\}$ of the normal to the contact edge
R_ϕ^S	Set of contact orientations of a contact situation involving a set S of basic contacts
\mathcal{F}_i	\mathcal{C} -face
$f'_i(\phi_o)$	\mathcal{C}' -segment
\mathcal{F}'_i	\mathcal{C}' -face
\mathcal{E}_{ij}	\mathcal{C} -edge
\mathcal{E}'_{ij}	\mathcal{C}' -edge
$\mathcal{L}'_{ij}(\phi)$	Supporting curve of \mathcal{E}'_{ij}
\mathcal{V}_{ijk}	\mathcal{C} -vertex
\mathcal{V}'_{ijk}	\mathcal{C}' -vertex
\mathbf{F}_i	Subset of \mathcal{F}_i that satisfies all the constraints
\mathbf{E}_{ij}	Subset of \mathcal{E}_{ij} that satisfies all the constraints
\mathbf{V}_{ijk}	\mathcal{C} -vertex that satisfies all the constraints
\vec{n}	Direction normal to \mathcal{F}_i at the contact configuration
\vec{t}_r	Direction of pure rotation about the contact point
\vec{t}_p	Direction perpendicular to \vec{t}_r and \vec{n}
\vec{t}_s	Direction of pure sliding
\vec{t}_q	Direction perpendicular to \vec{t}_s and \vec{n}
Π_t	Tangent plane
Π_f	Friction plane
Π_r	Rotation plane
\vec{e}^-, \vec{e}^+	Edges of the generalized friction cone
μ	Coefficient of friction
π'_t	Line composed of the dual points of the forces that belong to Π_t
π'_f	Line composed of the dual points of the forces that belong to Π_f
π'_r	Line composed of the dual points of the forces that belong to Π_r
T'_p	Dual representation of the direction \vec{t}_p
N'	Dual representation of the direction \vec{n}
T'_r	Dual representation of the direction \vec{t}_r
(x_o, y_o, ϕ_o)	Observed configuration of the robot
ϵ_t	Manufacturing tolerances
ϵ_s	Imprecision in the positioning of the static objects
ϵ_m	Imprecision in the positioning of the object in the robot gripper
ϵ_{ϕ_r}	Imprecision in the orientation of the robot
ϵ_{p_r}	Imprecision in the position of the robot

$[\phi_{o_m}, \phi_{o_M}]$	Range of possible actual orientations of the manipulated object due to ϵ_{ϕ_r}
ϵ_v	Uncertainty in the position of the the contact vertex due to the imprecision in the positioning of the objects
ϵ_{t_v}	Uncertainty in the position of the the contact vertex due to the manufacturing tolerances
ϵ_e	Uncertainty in the position of the vertices of the contact edge due to the imprecision in the positioning of the objects
ϵ_{t_e}	Uncertainty in the position of the vertices of the contact edge due to the manufacturing tolerances
e	Contact edge
V	Contact vertex
β	Deviation in the orientation of e
$\mathbf{C}(x, y, r)$	Circle of radius r centered on (x, y)
$\mathbf{R}(e, V_a, \beta)$	Region where the vertex V_a of e lies for a given deviation β
$\mathbf{E}(\beta)$	Region that contain all the possible realizations of e
$\mathbf{L}_r(\beta), \quad \mathbf{L}_{V_a}(\beta)$ and $\mathbf{L}_{V_b}(\beta)$	Partition of $\mathbf{E}(\beta)$
$\mathbf{L}(\beta)$	Geometric figure obtained from $\mathbf{L}_{V_a}(\beta)$ and $\mathbf{L}_{V_b}(\beta)$
α_m and α_M	Deviations in the orientations of the adjacent edges to the contact vertex
$\mathbf{V}(\alpha_m, \alpha_M)$	Region where the contact vertex lies
ϕ_o^i	Orientation that satisfies that the basic contact i takes place iff it can take place at ϕ_o^i
Δ_ϕ^i	Orientation gap between ϕ_o^i and the nominal contact orientations of contact i
$\mathbf{U}^i(\alpha, \beta)$	Contact Position Region for contact i and deviations α and β
ϕ_t^i	Orientation used to test the contact condition; $\phi_t^i = \phi_o^i + \Delta_\phi^i$
P_o	Center of $\mathbf{U}^i(\alpha, \beta)$
$\text{Box}(\mathbf{U}^i(\alpha, \beta))$	Bounding box of $\mathbf{U}^i(\alpha, \beta)$
r and d	Sides of $\text{Box}(\mathbf{U}^i(\alpha, \beta))$
D_{rm}, D_{rM}, D_{dm}	Distances from the origin of $\{W\}$ to the sides of $\text{Box}(\mathbf{U}^i(\alpha, \beta))$
D_{dM}	
$\mathbf{U}^i(\Delta_\phi^i)$	Contact Position Domain
$\text{Box}(\mathbf{U}^i(\Delta_\phi^i))$	Bounding box of $\mathbf{U}^i(\Delta_\phi^i)$
β_m, β_M	Minimum and maximum possible values of β for a given Δ_ϕ^i
S	Set of basic contacts
C_S	Nominal contact situation involving the basic contacts of S
ϕ_o^S	Orientation that satisfies that C_S takes place iff it can take place at ϕ_o^S
D	Set of dependent sources of uncertainty affecting the basic contacts of S
I	Set of independent sources of uncertainty affecting the basic contacts of S
ϵ_D	Sum of the maximum deviations in the contact position due to D
ϵ_I	Sum of the maximum deviations in the contact position due to I
$\Delta_\phi^{S_i}$	Orientation gap between ϕ_o^S and the nominal contact orientations of contact $i \in S$
$\Delta_{\phi_I}^{S_i}$	Deviation in orientation due to the independent sources of uncertainty that affect contact i
$\Delta_{\phi_D}^S$	Deviation in orientation due to the dependent sources of uncertainty that affect all the contacts of S

$ \Delta_{\phi_D}^{S_i} _{max}$	Maximum absolute value of the deviation in orientation of contact $i \in S$ due to the dependent sources of uncertainty
$ \Delta_{\phi_I}^{S_i} _{max}$	Maximum absolute value of the deviation in orientation of contact $i \in S$ due to the independent sources of uncertainty
$\mathbf{U}_I^{S_i}(x, y, \Delta_{\phi_I}^{S_i})$	Contact Position Domain built considering $D = \emptyset$ and $I \neq \emptyset$, and located with respect to (x, y)
$\phi_t^{S_i}$	Orientation used to test the contact condition; $\phi_t^{S_i} = \phi_o^S + \Delta_{\phi}^{S_i}$
$P_S(\phi)$	Nominal contact position of C_S for an orientation ϕ
$\mathbf{U}_D^{S_i}(\Delta_{\phi_D}^S)$	Contact Position Domain built considering $D \neq \emptyset$ and $I = \emptyset$
ϕ_t^S	Orientation used to test the contact condition; $\phi_t^S = \phi_o^S + \Delta_{\phi_D}^S$
$\mathbf{U}_D^S(\Delta_{\phi_D}^S)$	Intersection of the Contact Position Domains $\mathbf{U}_D^{S_i}(\Delta_{\phi_D}^S)$ for all the contacts of S .
(x_t, y_t)	Point of $\mathbf{U}_D^S(\Delta_{\phi_D}^S)$
\mathbf{G}_S	Generalized Force Domain
\mathbf{G}'_S	Dual representation of \mathbf{G}_S
l_v	Segment that approximates \mathbf{G}_i
\mathbf{W}	Region where the lines of forces of \mathbf{G}_i lie
\mathbf{W}_0	Region \mathbf{W} computed when $\mu = 0$
$\mathcal{H}(P_1, \dots, P_n)$	Convex hull defined by the points P_1, \dots, P_n
s	Sub-set of S with $\inf(n - 1, 3)$ basic contacts
\vec{g}_o	Measured generalized reaction force
\mathbf{H}'_S	Dual region associated to the basic contacts of S
$N(c)$	Number of all the possible contact situations of the assembly task
$C(c)$	Set of contact situations that a given configuration c is compatible with
$F_{\mathcal{A}}$	Finite set of configurations of a \mathcal{C} -arc
n_i and n_g	Initial and goal nodes of a path in a graph.

