Robust Path Planning in the Plane

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Abstract—This work presents an approach to plan motion strategies for robotics tasks constrained by uncertainty in position, orientation and control. Our approach operates in a \((x, y, \theta)\) configuration space and it combines two local functions: a contact-based attraction function and an exploration function. Compliant motions are used to reduce the position/orientation uncertainty. An explicit geometric model for the uncertainty is defined to evaluate the reachability of the obstacle surfaces when the robot translates in free space.

Index Terms—Fine motion planning, Uncertainty, Compliance.

I. INTRODUCTION

A nominal valid path for a robot task may not be executed correctly due to the discrepancies between the virtual exact world where the path is planned and the real world where the robot executes it. These discrepancies are called uncertainties. The purpose of this paper is to present a method to plan motion strategies for robotics tasks constrained by uncertainty in position, orientation and control. Our approach operates in a \((x, y, \theta)\) configuration space and it is based on the combination of two local functions: (1) a contact-based attraction function generates continuous motions to move the robot towards the next target configuration; and (2) an exploration function used to determine possible subgoals allowing to progress towards the ultimate goal when local minima are reached. The position uncertainty is reduced by planning compliant motions. The orientation uncertainty is reduced in contact by aligning a robot surface with an obstacle surface. The control uncertainty is explicitly considered by introducing a geometric model to evaluate the reachability of the obstacle surfaces when the robot translates in free space.

II. MOTION PLANNING UNDER UNCERTAINTY CONSTRAINTS

A. Problem Statement

We suppose a polygonal robot in an environment composed of polygonal obstacles. We assume \(C = \mathbb{R}^2 \times [0, 2\pi]\) as the configuration space. Our motion planning problem can be stated as: given an initial and a final configuration of the robot, \(q_0, q_f\) in the valid configuration space, find a valid path \(\pi\) under position, orientation and control uncertainties connecting \(q_0\) to \(q_f\). The reachability of a target configuration means that any path resulting from commanding a motion will actually attain this configuration given the position, orientation and control uncertainties. This criteria constrains the choice of possible configurations which can be included in \(\pi\).

B. Related Work

The uncertainty is present at all planning levels demanding different methods to cope with it. Refer to [5] for a review of the more relevant works about uncertainty in motion planning. Uncertainty in control has motivated the study of “compliant” and “guarded” motions in order to compensate the positioning errors ([13], [11], [14]). In the assembly planning domain, some techniques have been developed to construct complete fine motion strategies for assembly tasks. In most cases, there is not an explicit representation of the uncertainty. Instead, the degrees of freedom in contact situations are analysed in order to generate an assembly or disassembly plan ([8], [12], [4]).

A more general planning framework for the planning problem using an explicit model of uncertainty was introduced by [10], Applications of this approach are proposed in [3] and [9]. Another planning approach considering an explicit model of uncertainty is presented in [2].

We are interested in the local planning approaches because they can be applied in more complex robotics tasks. In particular, the potential field methods treat the robot as a point in configuration space under the influence of a magnetic field affecting its position [6]. Local methods are subject to fall in local minima. The Ariadne’s clew algorithm [1] allows breaking such blocked situations by exploring the surrounding space progressively trying to determine new subgoal configurations to continue the search of a path to the final configuration.

III. UNCERTAINTY

A. Uncertainty Models

The control error for a commanded velocity is modeled with the control uncertainty cone. This cone has its axis aligned with the commanded velocity and is opened by an angle \(2\eta < \pi\) depicting the maximum deviation error in control. The real velocity always falls inside this cone allowing to estimate the positioning error while the robot moves. The position uncertainty is modeled as a disk of radius \(\rho\) in the \(xy\) plane of the configuration space. The position uncertainty disk is centered at a nominal position \((x, y)\) and contains all possible real positions of the robot given its nominal one. The orientation uncertainty is modeled as an interval of length \(2\psi\) in the \(\theta\) axis. The orientation uncertainty interval is centered at a nominal value \(\theta\) and contains all possible real orientations of the robot given its nominal one. Combining these models, the position/orientation uncertainty of a nominal configuration \(q^* = (x^*, y^*, \theta^*)\) is represented as a cylinder of radius \(\rho\) and height \(2\psi\) centered at \(q^*\) and containing the real configuration \(q\) (figure 1). For a mobile robot, the size of the cylinder varies because the position/orientation errors accumulate while the robot navigates. This consideration is important and must be taken into account to produce robust paths for the robot (e.g. some situations when the robot must “jump” between the obstacles).

B. Determining the “Visibility” of a C-Obstacle

Let \(q_{min}\) be the contact configuration resulting from a local minimum situation (e.g. \(q_{min}\) in figure 2). The set of unconstrained translating directions which may unblock the robot can be calculated using the surfaces of the C-obstacle(s) containing \(q_{min}\). These directions can be determined using a simple geometric construction referred as the translational freedom cone ([8]). The visible space

![Fig. 1. The position/orientation uncertainty cylinder related to a configuration in free space (a). The projection of the uncertainty cylinder for a configuration in contact space (b).](image-url)
for $q_{\min}$ corresponds to all configurations inside of this cone, and its *visible contact space*, $C_{VCS}(q_{\min})$, corresponds to all contact configurations within the visible space as shown in figure 2. These configurations can be grouped into the visible surfaces and visible edges of the $C$-obstacles. It is important to notice that the translational freedom cone contains a set of motion directions which can be followed to break the contact with a simple translation motion of the robot. No considerations are taken to determine obstructions with other obstacles for longer motions (i.e. clear linear paths between $q_{\min}$ and the visible surfaces and visible edges may not exist). Analogously, the *adjacent contact space*, $C_{ACS}(q_{\min})$, is defined as the union of the boundaries of the $C$-obstacles containing the configuration (figure 2).

![Fig. 2. The visible contact space and the adjacent contact space related to the local minimum configuration $q_{\min}$.](image)

A strategy to push the robot away from a local minimum configuration is to move it to another configuration within the adjacent or visible contact spaces. A subgoal in the adjacent contact space can be reached using compliant motions by following the contour of the obstacle(s). Unfortunately, reaching a subgoal in the visible contact space is more complicated given the position and control uncertainties associated to a free space motion necessary to jump to another obstacle. The reachable area of the visible surfaces depends on the control error associated with the velocities (motion directions) which are necessary to attain them and the distance from the departing configuration $q_{\min}$.

**C. Determining the “Reachability” of a Visible Surface**

Once the visible contact space is determined, the *reachability* of the visible surfaces is calculated in terms of uncertainty in position and control. A geometric construction referred as the forward projection is used to determine the reachable area of a visible surface and the set of velocities which can be commanded to achieve it according to the uncertainty constraints (figure 3).

Since the position uncertainty in configuration space is represented as a disk of radius $\rho$ (this radius is constant for a manipulator arm, for a mobile robot its length is a function of the traversed distance), every visible surface must be reduced by $\rho$ on its borders to constrain the areas of undesired contacts (i.e. vertex-vertex contacts). The reduced surfaces whose “length” is less than or equal to the diameter of the uncertainty disk are discarded because robust motions to reach them may not be feasible. Next, for each non-discarded surface, two lines departing from the borders of the reduced surface and tangent to the uncertainty disk associated to $q_{\min}$ are projected until they intersect. The resulting cone explicitly represents the positioning errors that can be associated with the set of translation velocities (motions directions) between $q_{\min}$ and the visible surface.

Using a very precise control mechanism, selecting any velocity from the cone guarantees reaching the surface. Unfortunately, a commanded velocity has an associated control error represented by the control uncertainty cone (see section III-A). Therefore, the potential velocities must be validated according to the control errors. This is done by narrowing each side of the cone of velocities with the maximal deviation control error $\eta$ (parameter defining the control uncertainty cone). The resulting interior cone contains the set of “safe” velocities which can be commanded to reach the reduced visible surface considering the position and control uncertainties. The angle of the interior cone depends on the distance and the size of the surface that must be reached. Sometimes, this angle equals zero meaning that the surface cannot be robustly reached.

The final step on the construction of the forward projection for translation is to project the cone of safe translating velocities from $q_{\min}$ to the surface obtaining the “reachable area of contact”. Consequently, any velocity selected from the set of safe velocities, starting from the nominal configuration $q_{\min}$ will end up on this area. It is important to remark that the forward projection does not guarantee a clear path to the visible surface. Some obstacles may constrain the motion causing a deflection in the path, and even its full obstruction (local minima).

In order to estimate the effects of the position and orientation uncertainties while executing a combined translation/rotation motion aimed at reaching a visible surface, it is necessary to construct a continuous forward projection for the uncertainty cylinder of the target configuration (figure 4). In practice, such constructions are complex. Instead, an approximation can be useful. The orientation uncertainty interval related to the target contact orientation is determined according to the angle difference with the actual orientation. Next, planar forward projections in the $xy$ plane are constructed to the lowest, highest and the target orientation values for the interval. The resulting projection segments are joined and an approximation of the continuous forward projection is obtained.

**IV. THE PLANNING APPROACH**

The planning approach proposed in this work combines two local functions (as proposed in the Ariadne’s clew algorithm [1]):

- A *search function*. Its purpose is to locally generate compliant and free space motions (combining translations and rotations) in order to move the robot towards selected target configurations (which are selected according to the uncertainty constraints). This function has been implemented using a contact-based attraction function.

- An *explore function*. Its purpose is to generate appropriate subgoals in contact space trying to guide the robot towards the
coping with this problem, the radius $\rho$ of the position uncertainty disk is augmented on each iteration according to the control error $\eta$. A simple vicinity collision test between the disk and the neighbor C-obstacles is performed on each iteration to determine possible eventual collisions due to control errors (figure 5b).

When a “safe” collision occurs, the position uncertainty disk becomes a segment over the contacting surface. When the robot moves along the surface, this segment continues to grow because its exact position is unknown. The position uncertainty is completely eliminated when the robot detects a vertex (because its position is accurately known).

The orientation uncertainty $\psi$ increases while the robot rotates in free space. This uncertainty can only be reduced when the robot is in contact with an obstacle. In this case, the robot tries to align one of its contact surfaces with the obstacle contact surface. After that, in order to maintain a low level of orientation uncertainty, the attraction function tries to keep a surface-surface contact while the robot slides along the obstacles (even if a change of obstacle surface is necessary).

Remark: In order to evaluate the position/orientation uncertainties in the attraction function, the parameter $UC = (\rho, \psi, \eta)$ containing the uncertainty constraints must be added to the equation 1.

B. Exploring the Contact Space

1) Exploring the Adjacent Contact Space: The purpose of exploring the adjacent contact space is to apply compliant motions to follow the boundary of the obstacle(s) trying to push the robot away from the local minima while keeping a low position uncertainty. If $q$ is a local minimum configuration, a finite number of adjacent subgoals, $AS_q \subset C_{contact}$, is randomly placed in its associated adjacent space, $C_{adjCS}(q)$. Then, the best adjacent subgoal $\beta_i$, for each adjacent C-obstacle $CB_i$, is determined according to an adjacent exploration function, $ADJ_{EXPLORE}$. This function selects the subgoal which maximizes the geodesic distance $^2$ to the landmarks in $CB_i$. $\beta_i$ is used as a subgoal for the attraction function. The contact configuration resulting from searching $\beta_i$ defines a new landmark on the C-obstacle(s) in contact with the robot.

Selecting the Adjacent Subgoal: Let $L_i = \{q_{i,1}, \ldots, q_{i,n}\}$ be the set of known landmark configurations defined on the C-obstacle $CB_i$. For each $q_{i,k} \in L_i$ there is an associated set of subgoals $AS_{q_{i,k}}$ placed in $C_{adjCS}(q_{i,k})$. A subgoal in the set $AS_{q_{i,k}}$ is denoted as $\alpha_{i,k}$. Let $AS_i = \{AS_{q_{i,k}} \mid q_{i,k} \in L_i\}$ be the set of adjacent subgoals placed on the boundary of $CB_i$. The $ADJ_{EXPLORE}$ function selects the adjacent subgoal in $AS_i$ evaluating the largest geodesic distance from $L_i$, i.e.: 

$$ADJ_{EXPLORE}(L_i, AS_i) = \max_{\alpha_{i,k} \in AS_i} F_{adj}(L_i, \alpha_{i,k})$$

$^2$: The geodesic distance is defined as the shortest distance between two points in the boundary of an object following its contour.
where \( F_{adj}(L_i, a_{i,k}) \) is defined as the shortest geodesic distance between its arguments, i.e.:

\[
F_{adj}(L_i, a_{i,k}) = \min_{a_{i,j} \in L_i} \| q_{i,j} - a_{i,k} \|_{\text{geodesic}}
\]  
(4)

Once \( \beta_i \) is determined, the attraction function is started trying to reach it by sliding along the C-obstacle surfaces.

Sometimes, the adjacent exploration might not be enough to solve a local minimum situation. For this reason, the visible contact space must be explored simultaneously trying to find new contact configurations which might break them.

2) **Exploring the Visible Contact Space:** The purpose of exploring the visible contact space is to place subgoals in the reachable visible surfaces of the non-visited C-obstacles. To reach these subgoals, free space motions (jumps) are necessary to move the robot between the C-obstacles. When a local minimum is detected, its corresponding contact configuration defines a new landmark, \( q \). A finite number of \( \nu \) visible subgoals, \( V_{S_{vis}} \subset C_{\text{contact}} \), is randomly distributed within the reachable visible contact space \( C_{visCS}(q) \). The best visible subgoal is then selected according to the explore evaluation function \( \text{VIS EXPLORE} \). This function uses the Euclidean distance to evaluate the subgoals. Intuitively, \( \nu \) is the potential reachable configuration having the longest Euclidean distance to the set of landmarks over the C-obstacles. Once the subgoal \( \nu \) is determined, the attraction function is reactivated forcing the robot to jump through free space executing a straight line motion between \( q \) and \( \nu \). The motion is terminated when the subgoal is reached or when a local minimum situation is detected defining a new landmark.

**Selecting the Visible Subgoal:** Let \( L = \bigcup_{CB_{i} \in C} L_i \) be the set of known landmarks defined on the C-obstacles. For each \( q_{i,k} \in L \) there is an associated set of subgoals \( V_{S_{vis}} \) placed in \( C_{visCS}(q_{i,k}) \). A subgoal in the set \( V_{S_{vis}} \) is denoted by \( v_{i,k} \). Let \( S = \{ V_{S_{vis}} | q_{i,k} \in L \} \) be the set of visible subgoal placed on the boundaries of the C-obstacle(s). The \( \text{VIS EXPLORE} \) function selects the visible subgoal in \( S \) evaluating the largest Euclidean distance from \( L \), i.e.:

\[
\text{VIS EXPLORE}(L, V_{S}) = \max_{v_{i,k} \in \mathcal{S}} F_{vis}(L, v_{i,k})
\]  
(5)

where \( F_{vis}(L, v_{i,k}) \) is defined as the shortest Euclidean distance between its arguments, i.e.:

\[
F_{vis}(L, v_{i,k}) = \min_{q_{i,j} \in L} \| q_{i,j} - v_{i,k} \|
\]  
(6)

Once \( \nu \) is determined, the attraction function is started trying to reach it using the uncertainty models described in section III-A.

### D. Examples

We present two examples to illustrate how the algorithm extracts a robust solution for the same motion task under different values for the uncertainty parameters.

An important aspect to remark in the next figures is the evaluation of the uncertainty. On one hand, the position uncertainty disk increases in free space. It becomes a segment when a “safe” contact is reached (however to illustrate it, we must use a disk). The position uncertainty segment increases while the robot slides along a surface. This segment becomes a point when a change of obstacle surface is detected. On the other hand, the orientation uncertainty is reduced in contact space by aligning a robot surface and an obstacle surface. It is applied if the robot reaches a “safe” contact after moving in free space or if the robot detects a change of obstacle surface while sliding.

For the first example, the radius of the position uncertainty disk at \( q_0 \) is set to \( \rho_0 = 3.0 \), and the angle of the control uncertainty cone to \( \eta = 4.0 \) degrees. The orientation uncertainty at \( q_0 \) is set to \( \psi_0 = 0.0 \). Initially, the attraction function guides the robot to a local minimum configuration \( q' \) between the C-obstacles \( CB_3 \) and \( CB_4 \) (figure 6). The adjacent exploration function places an adjacent subgoal \( \beta_3 \) around the boundary of \( CB_4 \). Next, the attraction function reaches it from \( q' \) leaving a clear path to the final configuration (figure 7).

The second example shows a robust path for the same motion task but with an increased control uncertainty cone, \( \eta = 8.0 \) degrees.
for the robot. It generates compliant motions in contact space to reduce the position/orientation uncertainty of the robot, and robust free space motions when jumps through free space are necessary; and (2) an exploration function which generates subgoals within the contact space allowing to progress towards the ultimate goal when local minima are found. This function applies two different exploration procedures to evaluate random subgoals in two regions referred as the adjacent and the visible contact spaces.

The contact-based planning strategy presented here produces valid paths not considered by traditional collision-free motion planning strategies which only select those motions which avoid contacts with the obstacles. The main advantage of producing motions in contact is that the position/orientation uncertainty of the robot can be reduced resulting in more robust actions. The uncertainty in control for a commanded velocity is explicitly considered using a geometric model referred as the forward projection. This construction allows to estimate the “reachability” of the goal regions when jumps through free-space are necessary. This strategy can be applied to plan the motions of a mobile robot or a robot arm manipulating polygonal objects in the plane.

Future work will consider the introduction of kinematics constraints which limit the motion of the robot. Experiments with a holonomic mobile robot will be developed.

V. Conclusions and Future Work

This paper presented a local approach to plan uncertainty constrained motions of a polygonal robot in an environment composed of polygonal obstacles using the configuration space \((x, y, \theta)\). The approach is based in a progressive exploration of the contact space. Two local functions are combined in a planning algorithm: (1) a contact-based attraction function which generates differential motions

![Fig. 6. First local minimum configuration \(q'\) between \(CB_3\) and \(CB_4\).](image)

![Fig. 7. The final path generated by the motion planning algorithm.](image)

![Fig. 8. An alternative path for the same motion task using larger uncertainty values (\(\eta = 8.0\) degrees).](image)

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