Potential Field Guide for Humanoid Multicontacts
Acyclic Motion Planning
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Abstract—We present a motion planning algorithm that computes rough trajectories used by a contact-points planner as a guide to grow its search graph. We adapt collision-free motion planning algorithms to plan a path within the guide space, a submanifold of the configuration space included in the free space in which the configurations are subject to static stability constraint. We first discuss the definition of the guide space. Then we detail the different techniques and ideas involved: relevant C-space sampling for humanoid robot, task-driven projection process, static stability test based on polyhedral convex cones theory’s double description method. We finally present results from our implementation of the algorithm.

I. INTRODUCTION

Contact-points planning is a motion planning approach that aims at overcoming difficulties of cyclic gaited humanoid motion planning in unstructured and highly constrained environments. Examples of such planners are presented in [1] [2]. In [2] Best First Planning was adapted by growing the search tree in the space of sets of contacts. A key element of this contacts planner is the potential field that drives the search. It has to be carefully chosen as the planner may get trapped in contacts planner is the potential field that drives the search. It has to be carefully chosen as the planner may get trapped in

Algorithm 1 sampling-based collision-free motion planning.
1: initialize $\mathcal{G}(V \leftarrow \{q_I, q_G\}, E \leftarrow \emptyset)$
2: while no path found in $\mathcal{G}$ do
3: sample a random configuration $q_s$ in $C$
4: if $q_s \in C_{\text{free}}$ then
5: for all $q_V \in V \cap \text{NEIGHBOURHOOD}(q_s)$ do
6: if the direct path $\tau_d(q_s, q_V)$ lies in $C_{\text{free}}$ then
7: $V$.add($q_s$) and $E$.add($\tau_d(q_s, q_V)$)
8: end if
9: end for
10: end if
11: end while

Now we would like to adapt algorithm 1 in order to plan a
contact-points guide. The problem is that the path yielded by a contact-points planner lies on the boundary of \( C_{\text{obs}} \). Simply replacing \( C_{\text{free}} \) with \( C_{\text{obs}} \) in algorithm 1 would be a failing strategy as the measure of \( \partial C_{\text{obs}} \) is equal to zero. This means that the rejection rate at line 4 would be equal to 1. The second problem with this strategy concerns the linear direct paths in line 6, as \( \partial C_{\text{obs}} \) is generally a non-linear submanifold, a linear edge joining two of its elements will almost always be completely outside the submanifold.

Our solution is to consider a submanifold of \( C \) of non-zero measure, we label it \( C_{\text{guide}} \), that can be visually represented as a layer wrapping each connected component of \( \partial C_{\text{obs}} \). The idea, to some extent similar to [7], is to sample configurations “near” the obstacles; however, work in [7] focuses on 6D rigid robots, whereas our primary targets are polyarticulated humanoid robots. We will now detail our definition of \( C_{\text{guide}} \).

A contact situation between a body \( B_i \) of the robot and the obstacle region \( O \) is normally defined as

\[
\partial B_i \cap \partial O \neq \emptyset \quad \text{and} \quad \text{int}(B_i) \cap \text{int}(O) = \emptyset
\]

One way of adding a dimension, and thus creating a “volume”, to the submanifold \( C_{\text{guide}} \) could be to consider the body \( B_i \) as in contact with \( O \) if \( d(B_i, O) < \varepsilon_{\text{contact}} \), which is a positive fixed threshold. \( d \) denotes the Euclidian distance.

**Definition 1** (body-obstacle contact situation). A rigid body \( B \) is in contact with an obstacle region \( O \) if

\[
0 < d(B, O) < \varepsilon_{\text{contact}}
\]

In this situation, we denote by \( A_B \) and \( A_O \) respectively the closest points on the body and on the obstacle and by \( n = A_O A_B / \| A_O A_B \| \) the normal of the contact. The robot \( R \) is in contact in configuration \( q \in C_{\text{free}} \) if at least one of its bodies is in contact in configuration \( q \).

We can now define \( C_{\text{guide}} \) as

\[
C_{\text{guide}} = \{ q \in C_{\text{free}} \mid R \text{ is in contact in configuration } q \}
\]

and then plan a collision-free path in \( C_{\text{guide}} \) using algorithm 1 and replacing in it all the occurrences of \( C_{\text{free}} \) by \( C_{\text{guide}} \). This would produce a path that could be tricky to follow by the contact-points planner [3] as the latter will have to compute statically stable configurations along this path, and may need to stray significantly from the given path to find these stable configurations. So we have to refine the definition of \( C_{\text{guide}} \) to take static stability into account.

Considering the laws of rigid body dynamics applied to \( R \) and assuming that there are no limits to the torques we can apply to the robot joints (which is only an approximation), the static stability condition is simply written

\[
\begin{align*}
\sum_{f \in \mathcal{F}} f + mg &= 0 \\
\sum_{f \in \mathcal{F}} \mathcal{M}_O(f) + \mathcal{M}_O(mg) &= 0
\end{align*}
\]

where \( \mathcal{F} \) is the set of all contact forces applied to the robot, and \( \mathcal{M}_O \) is the moment of a force in a point \( O \in \mathbb{R}^3 \). \( m \) is the mass of the robot and \( g \) the gravity vector. For simplicity we have modeled any surface contact as a discrete set of punctual contacts applied at chosen points distributed over the contact surface (we intentionally do not make it explicit in our formulas for readability’s sake). Each contact force \( f \in \mathcal{F} \) applied on the robot at a point \( A \in \partial R \) with a normal \( n \) lies in a friction cone \( \mathcal{C}_{A,n,\theta} \), \( \theta \) being the angle of the cone that depends on the friction coefficient between the body and the obstacle, \( A \) is the apex of the cone, and \( n \) defines the revolution axis of the cone.

**Definition 2** (static stability situation). The robot \( R \) placed in a configuration \( q \in C_{\text{free}} \) is statically stable if

\[
\forall i \in I(q), \quad \exists f_i \in \mathcal{C}_{A_{B_i},n_i,\theta_i}, \quad \text{s.t.} \quad \begin{cases}
\sum_{i \in I(q)} f_i + mg = 0 \\
\sum_{i \in I(q)} \mathcal{M}_O(f_i) + \mathcal{M}_O(mg) = 0
\end{cases}
\]

where

\[
I(q) = \{ i \in \{1, \ldots, m\} \mid 0 < d(B_i(q), O) < \varepsilon_{\text{contact}} \}
\]

We can now introduce our new definition of \( C_{\text{guide}} \) as

\[
C_{\text{guide}} = \{ q \in C_{\text{free}} \mid R \text{ is statically stable in configuration } q \}
\]

and once again try to adapt algorithm 1. This is still not enough, as the rejection rate of our sampling would still be very high. This is the reason why we have decided to split the sampling procedure into two distinct phases: the sampling of a more or less uniform random configuration \( q_s \) in \( C \), followed...
by a projection process of \( q_0 \) to try to make it fit inside \( C_{\text{guide}} \). This projection process is for now only applied on the sampled configurations, and on some discretization points along the linear direct path. There is no guaranty, however, that the whole continuous direct path is inside \( C_{\text{guide}} \).

Finally, we get algorithm 2, which is the adaptation of algorithm 1 taking into account the previously discussed points. \( p : C_{\text{free}} \rightarrow C_{\text{guide}} \) denotes the projection function.

### Algorithm 2 contact-points guide planning

1. initialize \( G(V \leftarrow \{q_I, q_G\}, E \leftarrow \emptyset) \)
2. while no path found in \( G \) do
3. sample a random configuration \( q_\text{free} \) in \( C \)
4. if \( q_\text{free} \in C_{\text{free}} \) then
5. apply projection \( q_\text{project} = p(q_\text{free}) \in C_{\text{guide}} \)
6. for all \( q_V \in V \cap \text{NEIGHBOORD}(q_\text{project}) \) do
7. if \( (v \text{ a discretization of of} \) \( \tau_d(q_\text{project}, q_V) \) lies in \( C_{\text{guide}} \) then
8. \( V.\text{add}(q_\text{project}) \) and \( E.\text{add}((\tau_d(q_\text{project}, q_V)) \)
9. end if
10. end for
11. end if
12. end while

We will now get into the detail of the different steps of execution of algorithm 2, especially the lines 3 and 5.

### B. Sampling random configurations

In this section we detail line 3 of algorithm 2.

Our humanoid robot \( R \) is represented as a kinematic tree of \( m \) joints \( J_1, \ldots, J_m \). The root joint \( J_1 \) is a six-dimensional free flyer that evolves in the C-space \( \mathbb{R}^3 \times SO(3) \), or, if the translations are bounded, \( [x_{\text{min}}, x_{\text{max}}] \times [y_{\text{min}}, y_{\text{max}}] \times [z_{\text{min}}, z_{\text{max}}] \times SO(3) \). The remaining joints are revolute joints yielding the C-space \( \prod_{i=2}^{m} [\theta_{i,\text{min}}, \theta_{i,\text{max}}] \). The total C-space is consequently

\[
C = \mathbb{R}^3 \times SO(3) \times \prod_{i=2}^{m} [\theta_{i,\text{min}}, \theta_{i,\text{max}}]
\]

that we can write in a more expressive way as

\[
C = C_{\text{position}} \times C_{\text{orientation}} \times C_{\text{posture}}
\]

A random C-space variable \( Q \) is as such a vector of three independent random C-space variables \( Q = (Q_{\text{position}}, Q_{\text{orientation}}, Q_{\text{posture}}) \).

1) Position sampling: \( Q_{\text{position}} \) can be either a uniform random variable if the workspace \( W \) is bounded or a spatial Gaussian random variable otherwise.

2) Orientation sampling: For the orientation we would like to bias the sampling in order to favor some interesting orientations for a humanoid robot, such as the standing-up orientation for a walk, the laying-down orientation for a crawl, or a slightly front-leaned orientation for a climb. \( SO(3) \) being homeomorphic to the unit quaternian sphere \( S^3 \), we need a random variable that looks like a Gaussian distribution on the sphere \( S^3 \) around one of its points \( q_0 \) that would represent one of the orientations above. The Von Mises-Fisher distribution [8] achieves this very purpose. Given a mean unit vector \( q_0 \) and a concentration parameter \( \kappa \in \mathbb{R}^+ \), the probability density function of the Von Mises-Fisher distribution on the sphere \( \mathbb{S}^{p-1} \subset \mathbb{R}^p \) is

\[
f_{q_0, \kappa}(q) = C_p(\kappa) \exp(\kappa q_0^{T} q)
\]

\( C_p(\kappa) \) is a normalization constant

\[
C_p(\kappa) = \frac{\kappa^p/2-1}{(2\pi)^{p/2}I_{p/2-1}(\kappa)}
\]

where \( I_v \) denotes the modified Bessel function of the first kind and order \( v \). The parameter \( \kappa \) controls the concentration of the distribution around \( q_0 \). The bigger \( \kappa \) the more concentrated the distribution. \( \kappa = 0 \) yields a uniform distribution over the sphere. An algorithm for simulating a Von Mises-Fisher random variable is given in [9].

3) Posture sampling: Now we want to sample the posture space \( C_{\text{posture}} = \prod_{i=2}^{m} [\theta_{i,\text{min}}, \theta_{i,\text{max}}] \). We could immediately choose for \( Q_{\text{posture}} \) a uniform random variable. However, this would produce postures that once again are not interesting enough for a humanoid robot, especially when the dimension \( m - 1 \) of this manifold is relatively high (\( m - 1 = 30 \) in our humanoid platform). To solve this problem we choose to reduce the dimensionality of \( C_{\text{posture}} \) by sampling in the affine space generated by the standing-up posture \( q_{\text{key}_0} \) and a certain number of key postures \( q_{\text{key}_1}, \ldots, q_{\text{key}_n} \). These latter postures should be relevant for a humanoid robot and could represent for example the sitting-down posture, the four-legged posture, etc. To remain within the joints limits, we consider the bounded space

\[
C_{\text{posture}} = \left\{ q_{\text{key}_0} + \sum_{i=1}^{n} \lambda_i (q_{\text{key}_i} - q_{\text{key}_0}) \mid (\lambda_i)_i \in (\mathbb{B}_k^n)^+ \right\}
\]

where \( (\mathbb{B}_k^n)^+ \) is the positive quadrant of the unit ball of dimension \( n \) for the \( k \)-norm \( \| \cdot \|_k \)

\[
(\mathbb{B}_k^n)^+ = \left\{ (\lambda_i)_i \in [0,1]^n \mid \sum_{i=1}^{n} \lambda_i \leq 1 \right\}
\]

that we sample uniformly.

### C. Projection process

We detail now line 5 of algorithm 2. What we mean by projection here is an operation that tries to bring a given configuration sample in \( C_{\text{free}} \) inside \( C_{\text{guide}} \). The idea of projection was introduced in [10] and further investigated in [11]. The process we choose is to use a stack of tasks solver based on generalized inverse kinematics called hppGik and presented in [12]. A task is a function \( f : C \rightarrow \mathbb{R} \) that we would like to bring to zero, i.e, to solve \( f(q) = 0 \), \( q \in C \). Suppose we have sampled a random configuration \( q_\text{free} \). From this configuration we want to compute a statically stable configuration, thus we have to create contacts with the neighboring obstacles, given that the more contacts we create the more stable the configuration.
is likely to be. On the other hand, the more contacts we create the more we deform the original posture and reduce the mobility for the next posture, this is why we should create the “minimum” number of contacts to ensure the stability. To create a contact between a body $B$ and the obstacle region $O$ we need to bring it to a distance closer than $\varepsilon_{\text{contact}}$. Let us define the goal point $A_{\text{goal}}$ as the point translated from $A_O$ by a $\varepsilon_{\text{contact}}/2$ distance following $n$, and the goal plan $P_{\text{goal}}$ as the plan normal to $n$ in $A_{\text{goal}}$. The task that we want to formalise is “bring the point $A_B$ in the plan $P_{\text{goal}}$”, i.e. bring to 0 the corresponding task function

$$f(q) = (A_{\text{goal}} - A_B(q)) \cdot n$$

where $(\cdot, \cdot)$ denotes the Euclidean scalar product. To solve the task $f(q) = 0$ we implement the Newton’s method for finding zeros of a function (the same idea is suggested [1]). To do so we linearize $f$ around a start configuration $q_0$ as

$$f(q) \approx f(q_0) + \frac{\partial f}{\partial q}(q_0).dq$$

where $dq = q - q_0$ and then we solve the linear system

$$f(q_0) + \frac{\partial f}{\partial q}(q_0).dq = 0$$

using generalized inverse kinematics to compute the pseudo-inverse of $J(q_0) = \frac{\partial f}{\partial q}(q_0)$ that we denote $J(q_0)^\dagger$. The solution $q_1$ of the system is thus given by

$$q_1 = q_0 - J(q_0)^\dagger f(q_0)$$

The Newton’s method consists in iterating again starting now from $q_1$, meaning that we construct a sequence $(q_n)_{n \in \mathbb{N}}$ recursively as

$$q_{n+1} = q_n - J(q_n)^\dagger f(q_n)$$

that supposedly converges to the solution. However, in our task of bringing the body close to the obstacle, we do not really need to converge to the exact solution, but rather to converge towards a static stability situation, even though this latter is far from the exact solution. This is why we have chosen the Newton’s method, as we can stop its execution after each single iteration to test the static stability of the intermediate solutions, and can reach the static stability after few iterations. Now we would like to bring not only one body $B$ close to the obstacle region $O$, but the maximum number of bodies $B_1, \ldots, B_m$ to $O$, this means that we need to solve the system of equations:

$$\bigcap_{i=1}^m f_i(q) = 0$$

or the linearized version

$$\bigcap_{i=1}^m f_i(q_0) + \frac{\partial f_i}{\partial q}(q_0) dq = 0$$

The stack of tasks solver hppGik [12] allows us to solve such a system with priorities, meaning that it solves the first equation, then it tries to solve the second equation at best while remaining in the solution space of the first equation, and so on. The priority we choose is the distance to obstacle, as we try to bring closer with the highest priority the closest body to the obstacles. Let $i_1, \ldots, i_m \in \{1, \ldots, m\}$ be the indexes of the bodies sorted in increasing order of distance to $O$, i.e.

$$d(B_{i_1}, O) \leq d(B_{i_2}, O) \leq \ldots \leq d(B_{i_m}, O)$$

The hppGik solver solves, in the order of priority, the following stack of tasks:

$$\bigcap_{j=1}^m t_j : f_{i_j}(q_0) + \frac{\partial f_{i_j}}{\partial q}(q_0) dq = 0$$

where $t_j$ is the task of priority $j$.

Finally we give algorithm 3 of the projection process, in which we introduce one new task per iteration in order to deform as little as possible the posture. We also stop the process after a maximum number of iterations, after which we discard the current configuration and we start again the process with a new $q_0$ according to algorithm 2.

### Algorithm 3 projection process

1. sample a random configuration $q_0$
2. set $q_0 \leftarrow q_0$
3. COUNTER $\leftarrow 1$
4. while $q_0$ is not statically stable and COUNTER $< \text{MAX\_ITERATIONS}$ do
5. sort the bodies $d(B_{i_1}, O) \leq \ldots \leq d(B_{i_m}, O)$
6. $q_0 \leftarrow$ solution of the stack of tasks $(t_1, \ldots, t_{\text{COUNTER}})$
7. COUNTER $\leftarrow$ COUNTER $+ 1$
8. end while
9. return $q_0$
We will now get into the detail of line 4 of algorithm 3, in which we have to test the static stability of a configuration.

D. Testing the static stability

Suppose we have the robot \( R \) in configuration \( q \) and we want to check whether or not it is statically stable in this configuration, according to definition 2. In order to get a linear system, we need to consider the modeling of each friction cone \( C_{A_i, n_i, \theta_i} \), as discrete polyhedral cone with a finite number of generators \( u_{i,1}, \ldots, u_{i,n_i} \).

\[
C_{A_i, n_i, \theta_i} = C(u_{i,1}, \ldots, u_{i,n_i}) = \{ \sum_{j=1}^{n_i} \lambda_j u_{i,j} / \lambda_1, \ldots, \lambda_{n_i} \in \mathbb{R}^+ \}
\]

which is the set of all non negative linear combinations of the generators. With this modeling, we have

\[
f_i \in C_{A_i, n_i, \theta_i} \iff \exists (\lambda_{i,j})_{j=1..n_i} \in (\mathbb{R}^+)^{n_i}, f_i = \sum_{j=1}^{n_i} \lambda_{i,j} u_{i,j}
\]

allowing us to rewrite the static stability condition as a linear problem

\[
\exists (\lambda_{i,j})_{i \in I(q)} \in \prod_{j=1..n_i} (\mathbb{R}^+)^{n_i}, \quad \lambda_{i,j} u_{i,j} \in (\mathbb{R}^+)^n
\]

s.t.

\[
\begin{align*}
\sum_{i \in I(q)} & \lambda_{i,j} u_{i,j} + m g = 0 \\
\sum_{j=1..n_i} & \lambda_{i,j} u_{i,j} + \mathcal{M}_O(\lambda_{i,j} u_{i,j}) = \mathcal{M}_O(m g) = 0
\end{align*}
\]

The system of two 3-dimensional equations can be written as a single 6-dimensional equation, putting

\[
a_{i,j} = \begin{pmatrix} u_{i,j} \\ \mathcal{M}_O(u_{i,j}) \end{pmatrix} \quad \text{and} \quad v = -\begin{pmatrix} m g \\ \mathcal{M}_O(m g) \end{pmatrix}
\]

the static stability condition then becomes

\[
\exists (\lambda_{i,j})_{i \in I(q)} \in \prod_{i \in I(q)} (\mathbb{R}^+)^{n_i}, \quad \sum_{j=1..n_i} \lambda_{i,j} a_{i,j} = v
\]

which can be read as the membership of \( v \) in the cone generated by the \( a_{i,j} \) vectors

\[
v \in C(a_{i,j})_{i,j}
\]

To solve this system, we used some results that come from the polyhedral convex cone theory that we detail hereafter.

**Polyhedral convex cone theory:** Let \( C(a_1, \ldots, a_m) \) be the cone generated by \( a_1, \ldots, a_m \) in \( \mathbb{R}^n \)

\[
C(a_1, \ldots, a_m) = \left\{ \sum_{j=1}^{m} \lambda_j a_j \mid \lambda_1, \ldots, \lambda_m \in \mathbb{R}^+ \right\}
\]

the dual cone (also called the polar cone) \( C^p \) is defined as

\[
C^p(a_1, \ldots, a_m) = \left\{ x \in \mathbb{R}^n \mid \forall i \in \{1, \ldots, m\} \ x^T a_i \leq 0 \right\}
\]

Minkowski [13] demonstrated that the polar cone is a cone too, i.e. \( \exists b_1, \ldots, b_k \in \mathbb{R}^n \) such that

\[
C^p(a_1, \ldots, a_m) = C(b_1, \ldots, b_k)
\]

The Farkas lemma [14] states that \( (C^p)^p = C \) i.e.

\[
C(a_1, \ldots, a_m) = C^p(b_1, \ldots, b_k)
\]

this result allows us to test the membership of a vector \( x \in \mathbb{R}^n \) in the dual of the cone instead of the cone itself

\[
x \in C(a_1, \ldots, a_m) \iff x \in C^p(b_1, \ldots, b_k)
\]

or

\[
\exists (\lambda_j)_{j} \in (\mathbb{R}^+)^m \ x = \sum_{j=1}^{m} \lambda_j a_j \iff \forall i \in \{1, \ldots, k\} \ x^T b_i \leq 0
\]

The second member of this latter equivalence is much easier to check than the first one, if we could compute the vectors \( b_1, \ldots, b_k \). The Motzkin’s double description algorithm [15] achieves this. We implemented a variation of the original algorithm, proposed by Padberg [16], that allows us to compute a minimal set of generators for the dual cone.

III. RESULTS

We implemented the ideas presented in the previous section within the HPP framework using KineoCAM’s software KineoPath Planner and KineoWorks as a core collision-free motion planning and collision detection module. The model we used for the humanoid robot is HRP-2 [17] which has 36 degrees of freedom (including the free-flyer). The collision-free path planning algorithms we choose are either basic PRM [5] or bidirectional RRT [6].

The main scenario we considered is the highly constrained one demonstrated in [3] which consists in standing up from a chair and going away from a table. The robot is sitting on the chair in initial configuration and is standing by the table at final configuration. The guide obtained is shown in figure 3 while the contacts points plan is illustrated in figure 4. Using the distance to goal as a potential function the robot ends up climbing the table and the contacts planning stops after having consumed all the memory resource of the computer. With the provided guide the contacts planner finds the solution in approximately 3h30min on a standard Pentium IV system, after approximately 10min of computation for the guide.

![Fig. 3. Guide planning for the out-of-table-and-chair scenario.](image)

We also tested the guide planner on other scenarios on which we have not yet tested the contacts planner, simply to demonstrate the ability of the guide planner of going through different situations (Figs. 5a and 5b).
we plan to investigate in future work.

in order to make it fit inside

would be to apply a projection to the whole linear direct path

test line 7 with higher probability; however, a better solut ion

dimension and thus “volume” to

is for now a linear direct path linking method. We added a

path between two guide space’s configurations, and which

need to work on the linking method that computes the direct

remains an unanswered question in our work. We also still

two configurations in guide space lies in the guide space

algorithm 2. Ensuring that the continuous direct path linki ng

The time is consumed both on distance computation and stack

computing time at the contacts-guide planner’s level remai ns

at the contact-points planner’s level is theoretically infi nite,

Although the gain in computing time that we achieve

at the contact-points planner’s level is theoretically infinite,

computing time at the contacts-guide planner’s level remains relatively high for scenarios such as 5a and 5b (a few hours).

The time is consumed both on distance computation and stack of tasks solving which are solicited at each iteration of the algorithm.

IV. Conclusion

Improvements of our contacts guide planner are still possible and need to be considered, especially regarding line 7 of algorithm 2. Ensuring that the continuous direct path linking two configurations in guide space lies in the guide space remains an unanswered question in our work. We also still need to work on the linking method that computes the direct path between two guide space’s configurations, and which is for now a linear direct path linking method. We added a dimension and thus “volume” to \( C_{\text{guide}} \) in order to pass the test line 7 with higher probability; however, a better solution would be to apply a projection to the whole linear direct path in order to make it fit inside \( C_{\text{guide}} \). These are all questions we plan to investigate in future work.

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