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Haptic Guidance using Primitives for the Execution of Virtual Robotic Tasks

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Abstract

Haptic guidance is a powerful tool for people rehabilitation, for handcraft skills acquisition and all kind of enactive tasks. In this paper, different techniques to achieve reliable haptic feedback on the execution of virtual robotic tasks, based on the efficient combination of path planning methods and haptic guidance primitives, are presented.

The main contribution of this paper is a reliable system of force guidance based on haptic primitives. The whole proposal is constituted by: 1) a free collision path obtained using a deterministic sampling, hierarchical cell decomposition and harmonic functions 2) force feedback, achieved by means of elastic models, based on simple geometry elements, called haptic primitives, and 3) a virtual robotic task.

1 Introduction

This paper proposes three novel approaches for the teleoperation of virtual robotic tasks based on the combination of haptic guidance and path planning methods. In the proposed approaches, the force guidance is based on haptic primitives, which are elastic models over simple geometry elements. The path planner which supports the guidance, uses hierarchical cell decomposition, deterministic sampling and harmonic functions.

Path planning methods have been widely used on the autonomous execution of robotics tasks [1]. Haptic guidance is a powerful tool for people rehabilitation, sports training, handcraft skills acquiring and all kind of enactive tasks [2], such as drawing [3]. From the combination of the path planning methods and the haptic guidance based on primitives, a system able to guide the user to accomplish a robotic task, using on the fly calculated paths and a haptic device is presented.

To achieve haptic guidance, three main approaches have been studied: *1)* Haptic Guidance based on Probabilistic Roadmaps Methods, *2)* Haptic Guidance based on Attracting Balls and *3)* Haptic Guidance based on Local Channels and Local Paths.

The real potential of the proposed approach is to obtain a free collision path, to be followed using a haptic device, that is, integrating a path planner and haptic guidance. This approach has been explored, for example, with a potential field based path planner to guide the user in the manipulation of nano-particles in a simple virtual scene [4, 5].

Multimodal interfaces that include visual feedback, augmented reality aids and haptic feedback have been proposed to teleoperate using geometric constraints [6]. This approach uses a pre-defined path, nevertheless, a good improvement is to obtain the paths, which can be more complex, on the fly, as proposed in this paper.

The proposed methodology is able to construct the haptic guidance trajectories on the fly from a novel path planner, instead of using pre-defined or recorded trajectories as used in some other haptic guidance methods [7].

The Path Planner used in this work, to support the haptic guidance system is based on Harmonic Functions and Probabilistic Cell Decomposition whose output is a collision free channel of cells. The path planner was called the Kautham Planner and has been used to haptically guide a user on the execution of teleoperated assembly tasks, using a simple force-generation pattern based on balls [8].

In this paper, a punctual interaction paradigm is used to guide the user with a haptic device, that means that only force (but no torque) haptic feedback is used. Nevertheless, three-dimensional interaction may be used if the three-dimensional virtual object is transformed to a point (the haptic application point) and, by using temporal coherence, the $\mathcal{C}$-obsacles are constructed on the fly [9].

This paper is structured as follows: In section 2 the Haptic Primitives used for haptic guidance are introduced. In section 3, the haptic guidance based on Probabilistic Roadmap Methods is presented. In section 4 the approach of haptic guidance based on Attracting-Balls is detailed. In section 5, the approach to haptically guide the user using

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Local Channels and Local Paths is given. In section 6 some results and an application example is developed, finally in section 7, some conclusions are given.

2 Haptic Primitives

Haptic primitives are elastic models, based on simple geometry elements. To completely achieve haptic guidance, four haptic primitives were defined. In the following paragraphs, a detailed explanation on the implementation of each haptic primitive used in this work is given.

2.1 Directed-Force Haptic Primitive

It is a constant force on a given direction that is felt if the user configuration $\mathbf{q}_u$ is inside a specified region R, as defined in equation 1.

$$\mathbf{F}_d = \begin{cases} k_d \mathbf{u}_d & \text{if } \mathbf{q}_u \in R \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where:

- k_d is the constant magnitude of the force $\mathbf{F}_d$.
- $\mathbf{u}_d$ is the unit vector that gives the direction of the force.

2.2 Point-Attraction Haptic Primitive

Point-attraction haptic primitive is obtained from the $\mathbf{v}_t$ vector that goes from the current user configuration ($\mathbf{q}_u$) to the attracting point $\mathbf{p}$. Equation 2 shows the way the attraction force to the current point, i.e. the point haptic primitive, which is achieved using a spring-damper model.

$$\mathbf{F}_t = \begin{cases} 0 & \text{if } d_t > r_t \\ k_t \mathbf{v}_t & \text{if } d_t \leq r_t \end{cases} \tag{2}$$

where:

- k_t is the spring constant.
- $\mathbf{v}_t$ is the vector that goes from $\mathbf{q}_u$ to $\mathbf{p}$.
- d_t is the distance from $\mathbf{q}_u$ to $\mathbf{p}$, i.e. $d_t = \|\mathbf{v}_t\|$.
- r_t is the influence radius of the $\mathbf{F}_t$ force over the user. It is used to limit the region in which the force will be felt.

2.3 Segment-Attraction Haptic Primitive

Equation 3 describes the attraction force to the current line segment haptic primitive, which is achieved using a spring-damper model.

$$\mathbf{F}_f = \begin{cases} 0 & \text{if } d_f > r_f \\ k_f \mathbf{v}_f & \text{if } d_f \leq r_f \end{cases} \tag{3}$$

where:

- k_f is the spring constant.
- $\mathbf{v}_f$ is the vector that goes from $\mathbf{q}_u$ to its orthogonal projection onto the line segment.
- d_f is the distance from the point $\mathbf{q}_u$ to its orthogonal projection into the line segment, i.e. $d_f = \|\mathbf{v}_f\|$.
- r_f is the influence radius of the $\mathbf{F}_f$ force over the user. It is used to limit the region in which the force will be felt.

2.4 Attracting-Ball Haptic Primitive

The attracting-ball primitive for two concentric balls: the exterior one B_e with radius r_e and the interior one B_i with radius r_i, and it is defined as:

$$F_b = \begin{cases} 0 & \text{if } \|\mathbf{v}_b\| < r_i \\ k_b \frac{\mathbf{v}_b}{\|\mathbf{v}_b\|} & \text{if } r_i \leq \|\mathbf{v}_b\| < r_e \\ \left[k_b + k_o(\|\mathbf{v}_b\| - r_i)\right] \frac{\mathbf{v}_b}{\|\mathbf{v}_b\|} & \text{otherwise} \end{cases} \tag{4}$$

where:

- k_b is the constant magnitude of the force.
- $\mathbf{v}_b$ is the vector that goes from the user current configuration $\mathbf{q}_u$ to the center of the primitive.
- k_o is the constant of the proportional force outside of the ball B_e.
- r_i is the radius of the ball B_i
- r_e is the radius of the ball B_e

Figure 1 depicts the Attracting-Ball haptic primitive.

3 Haptic Guidance based on Probabilistic Roadmaps Methods

It is a haptic guidance that uses the solution path τ to constrain the user. The path is composed by line segments that connect the initial configuration q_{ini} with the final configuration q_{end}. The haptic guidance can be done generating

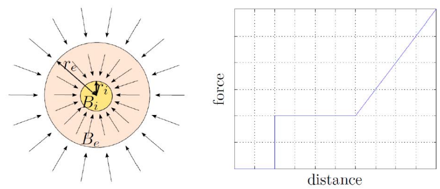


Figure 1: Attracting-Ball Haptic Primitive

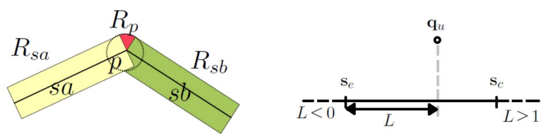


Figure 2: PRM based Path Guidance

a proportional force from the current user configuration $\mathbf{q}_u$ to the current line segment.

Each line segment s has an attraction region R_s, which is the region in which the normalized length L, of the vector from the initial point of the line segment to the user position, over the vector from the initial point to the final point of the line segment, satisfies: $0 \leq L \leq 1$. Furthermore, each point-attraction primitive ($\mathbf{p}$) has an attraction region R_p which is defined below.

In order to give force continuity, two adjacent attracting-segments primitives (sa and sb), and a point-attracting primitive ($\mathbf{p}$), are used (see Fig. 2).

Therefore, the segment-attraction primitive of the segment sa is used while the user is inside the attracting region R_{sa}, i.e. the segment region R_{sa} is the region that satisfies the following condition:

$$\mathbf{q}_u \in R_{sa} \text{ if } 0 \leq L_{sa} \leq 1 \tag{5}$$

The segment-attraction primitive of the segment sb is used while the user is inside the attracting region R_{sb}, but not inside the region R_{sa}, i.e. the segment region R_{sb} is the region that satisfies the following condition:

$$\mathbf{q}_u \in R_{sb} \text{ if } 0 \leq L_{sb} \leq 1 \text{ and } L_{sa} > 1 \tag{6}$$

Finally, the user is attracted to the point p, if he/she is inside a region R_p defined as:

$$\mathbf{q}_u \in R_p \text{ if } L_{sb} < 0 \text{ and } L_{sa} > 1 \tag{7}$$

i.e. region R_p is the region in which the user is not inside R_{sa} neither inside R_{sb} (see the red region in Fig. 2).

Equation 8, which is a combination of equations (1), (2) and (3) is used to generate the necessary forces to accomplish Haptic Guidance based on Probabilistic Roadmaps Methods (see Fig. 3).

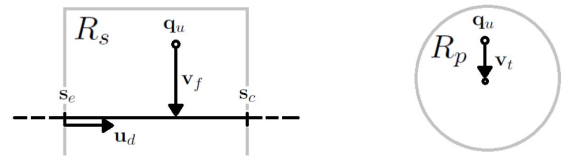


Figure 3: PRM based Path Guidance force components

$$\mathbf{F}_{prm} = \begin{cases} k_f\mathbf{v}_f + k_d\mathbf{u}_d & \text{if } \mathbf{q}_u \in R_s \\ k_t\mathbf{v}_t & \text{if } \mathbf{q}_u \in R_p \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where:

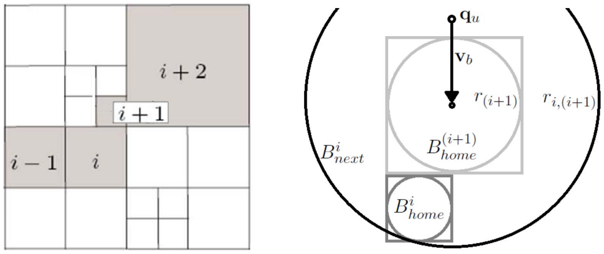
- $\mathbf{F}_{prm}$ is the rendered force for PRM based haptic guidance.
- k_d, k_t and k_f are constants.
- $\mathbf{u}_d$ is the unit vector that gives direction to the directed-force primitive. This vector points from the start point to the final point of the segment s.
- $\mathbf{v}_t$ is the vector that gives direction to the point-attraction primitive, from equation (2).
- $\mathbf{v}_f$ is the vector that gives direction to the segment-attraction primitive, from equation (3).
- $\mathbf{q}_u$ is the current user configuration.
- R_s is the force influence region of a segment-attraction primitive.
- R_p is the force influence region of a point-attraction primitive.

Even the Probabilistic Roadmap Methods based Haptic Guidance approach demonstrated to be reliable, it does not use the information (Configuration Space characterization) obtained by the Kautham Path Planner. The use of harmonic functions is a valuable feature of the Path Planner that can be exploited to haptically guide the user all over the regions of the $\mathcal{C}$-space model and is introduced in next sections.

4 Haptic Guidance based on Attracting Balls

This is a haptic guidance approach that uses the solution channel found with the Kautham Path Planner to generate the attractive forces that guide the user to accomplish a robotics task. In this approach, the user navigates the partitioned $\mathcal{C}$-space model, in order to go from the initial cell c_{ini} to the final cell c_{end} by descending the negated gradient of the harmonic function HF.

Previous work [8] deals with the problem of haptic guidance through Attracting-Balls, using the OpenHaptics HL



(a) Solution Channel cells (b) Balls used for haptic guidance

Figure 4: Attracting Balls guidance model

library, nevertheless, a new whole implementation is presented in this work by defining a set of primitives programmed with the OpenHaptics HD API, gaining speed and flexibility. Formally, the complete methodology, used to accomplish Haptic Guidance based on Attracting Balls is described below:

1. For a pair of cells, the current cell (i) and the next cell $(i+1)$, such that the width of the current cell is w_i and the width of the next cell is w_{i+1} (Fig. 4a), three balls B^i_{home}, $B^{(i+1)}_{home}$ and B^i_{next} are defined (Fig. 4b):

   - B^i_{home} is the ball inscribed into the current cell whose radius is: $r_i = \frac{w_i}{2}$. i.e. B^i_{home} is the ball with center $\mathbf{b}_i$ and radius r_i such that for any point $\mathbf{p} \in B^i_{home}$, $\|\mathbf{p} - \mathbf{b}_i\| \leq r_i$ holds.
     - $B^{(i+1)}_{home}$ is the ball inscribed into the next cell whose radius is: $r_{(i+1)} = \frac{w_{i+1}}{2}$. i.e. $B^{(i+1)}_{home}$ is the ball with center $\mathbf{b}_{(i+1)}$) and radius $r_{(i+1)}$ such that for any point $\mathbf{p} \in B^{(i+1)}_{home}$, $\left\|\mathbf{p} - \mathbf{b}_{(i+1)}\right\| \leq r_{(i+1)}$ holds.
     - B^i_{next} is a ball, centered on the next cell center and whose radius is $r_{i,(i+1)} = w_i + \frac{w_{i+1}}{2}$. i.e. B^i_{next} is the ball with center $b_{(i+1)}$ and radius $r_{i,(i+1)}$ such that for any point $\mathbf{p} \in B^i_{next}$, $\left\|\mathbf{p} - \mathbf{b}_{(i+1)}\right\| \leq r_{i,(i+1)}$ holds.
   - B^i_{next} is used as an attracting-ball haptic primitive. While the user is outside the ball $B^{(i+1)}_{home}$ but inside the ball B^i_{next}, a directed force that guides the user from its current configuration $\mathbf{q}_u$ to the center of the ball B^i_{next}, is generated.

2. If the user leaves the B^i_{next} ball, then, a force proportional to the distance of the user configuration $(\mathbf{q}_u)$ to the center of the ball is generated. Finally, equation 4 can be re-written in terms of the balls defined in step 1 to state the force $\mathbf{F}_b$ as in equation 9:

$$\mathbf{F}_b = \begin{cases} k_b\mathbf{u}_b + k_c\mathbf{v}_c \\ \qquad \text{if } r_{i,(i+1)} \geq \|\mathbf{v}_b\| > r_{i+1} \\ \left[k_b + k_o(\|\mathbf{v}_b\| - r_{i,(i+1)})\right]\mathbf{u}_b + k_c\mathbf{v}_c \\ \qquad \text{if } \|\mathbf{v}_b\| > r_{i,(i+1)} \\ 0 \\ \qquad otherwise \end{cases} \tag{9}$$

   where $k_c$is the damping constant and $\mathbf{v}_c$ is the probe velocity.

3. Finally, transitions from cell to cell are managed in the following way: if the user is inside the B^i_{home} ball within the cell (i), an attracting-ball haptic primitive generates a force that guides the user to the center of the B^i_{next} ball by means of a force $\mathbf{F}_b$.

   This force is kept as a constant inside the B^i_{next} ball until the user enters the $B^{(i+1)}_{home}$ ball, within cell $(i+1)$. Notice that B^i_{next} and $B^{(i+1)}_{home}$ are concentric balls, so a continuous guidance is offered.

   When the user enters the ball $B^{(i+1)}_{home}$, it automatically becomes the ball B^i_{home} and steps 1, 2 and 3 are applied again.

The Haptic Guidance based on Attracting Balls approach is not as restrictive as the PRM based approach since it uses a channel of cells to guide the user. Nevertheless, only the Solution Channel is used in this guidance approach, in the next section, a complete method that uses all the $\mathcal{C}$-spacemodel is presented.

5 Haptic Guidance based on Local Channels and Local Paths

The Haptic Guidance based on Local Channels and Local Paths is a combination and improvement of the two previous approaches, fist presented in [10]. The $\mathcal{C}$-space model characterization is fully exploited allowing the user to navigate all through the free space, by tracking the current user configuration using an improved Finite-State Machine instead of a Petri Net, as in previous works, and rendering the correct feedback forces depending on the current cell transparency and its Harmonic Function value.

5.1 Force feedback

The guiding force $\mathbf{F}_G$ results from the sum of the following forces:

- $\mathbf{F}_g$ is the force that guides the user from the current cell c_c to the next cell c_n.

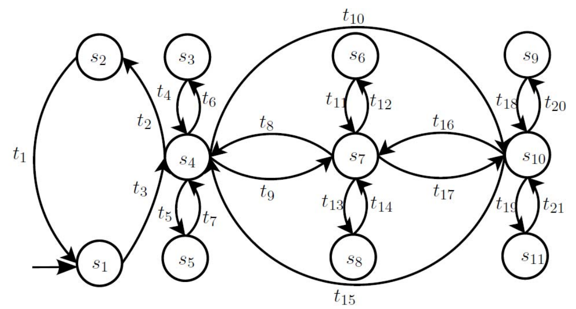


Figure 5: Finite State Machine for Channel Navigation

- $\mathbf{F}_c$ is the force that attracts the user to the local path segment τ_l.
- $\mathbf{F}_r$ is the force that repels the user from the neighbor cell c_j when the user tries to leave the current cell c_c and such a neighbor cell is different from the next cell (c_n).
- $\mathbf{F}_v$ is the damping force, it is a force proportional to user movements velocity that avoids oscillations during the guidance.

The force to be rendered depends on the current user configuration, which can be obtained from the Finite State Machine depicted in figure 5.

6 Results

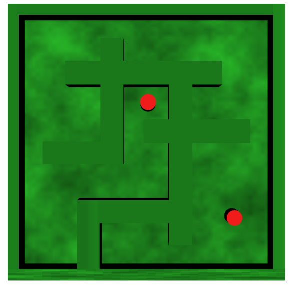
Figure 6a depicts a $\mathbb{R}^2$ maze problem. The problem consists on moving the red cylinder from the center of the maze to the bottom-right corner, without colliding. This experiment is presented to illustrate a low clearance task, with narrow-bend corridors.

For haptic guidance tests, a right-handed user moved the robot using his/her right hand as fast as possible, but trying not to collide with the obstacles. Figure 6b depicts the haptic guidance setup, where the Phantom Omni is used as the force feedback device.

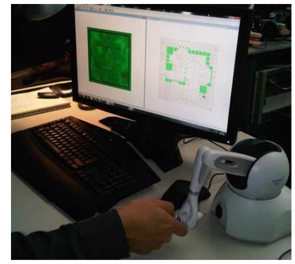
Figure 6c depicts a path that a user traced after achieving the task without haptic guidance. Notice that collisions occurred when the user went through constrained areas of the maze, as depicted with the yellow marks in the same figure.

Figure 6d shows the results of the Haptic Guidance based on Probabilistic Roadmap Methods. The figure depicts a comparison of the Solution Path (blue) versus the path that the user followed (red) using the haptic guidance based on PRM. Notice that this guidance highly constrains the user to the path, nevertheless, no force is felt outside the path.

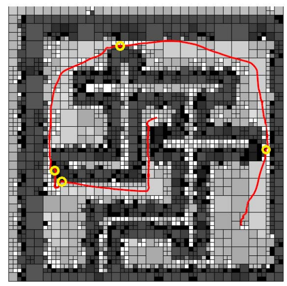
Figure 6e shows an example of the Haptic Guidance approach based on Attracting Balls. This figure depicts the solution channel in which the user is guided, the centers



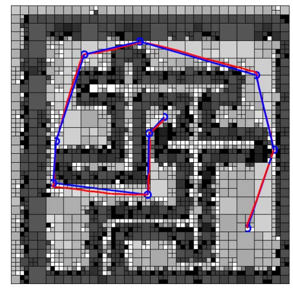
(a) Top View



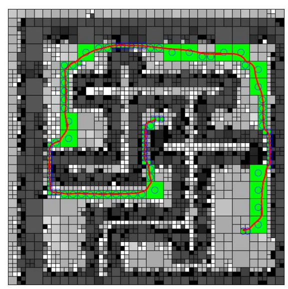
(b) Haptic Guidance Setup



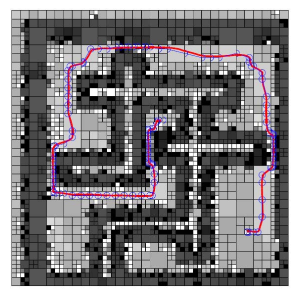
(c) User Path



(d) Solution Path vs. User Path



(e) Solution Channel vs. User Path



(f) Local Channels/Paths vs. User Path

Figure 6: Maze Experiment Results

of the cells are marked with a blue circle. Therefore, each circle represents the center of the attractive ball in the guidance process. Furthermore the path the user traced within the $\mathcal{C}$-space model, after using the Haptic Guidance based on Attracting Balls, is depicted in red. This guidance has a high clearance, nevertheless, collision with the obstacles may occur.

Figure 6f shows an example of the haptic guidance based on Local Channel and the Local Path. This Local Channel begins at center of the maze and ends close to the bottom-right corner. This figure depicts a comparison of the Solution Path (blue) versus the path that the user followed (red).

This approach combines the best features of the previous approaches, by constraining the user to the local paths, with a higher clearance given by the local channel.

Guidance Method	Num. Collisions	Num. Samples	Time to complete the task $[sec]$
Without Guidance	3	359	11.85
Solution Path	0	273	9.01
Attracting-Balls	0	191	6.3
Local Channels & Local Paths	0	187	6.17

Table 1: Haptic Guidance Collisions and Times.

6.1 Comparatives

Table 1 summarizes the results of the Haptic Guidance process. Good results were obtained using the Local Channels and Local Paths Haptic approach, because the guidance was smooth and the force suggestion was easy to follow, nevertheless, as cells are small the completion time increases. The fastest guidance was offered by the PRM based approach, this approach it is the most constrained and overshooting is likely to happen if the user moves too fast. Haptic Guidance based on the attracting balls approach is easy to follow, nevertheless, as it is the less constrained, the user can graze or penetrate obstacles easily.

7 Conclusion and Acknowledgment

The development of three reliable methods based on haptic primitives to guide the user into the adequate movement to achieve a selected task without collisions has been presented. The proposed system, based on a path planner is able to find a solution channel to support haptic guidance and to achieve a selected task within a virtual reality scenario.

The proposed methodologies are able to construct the local paths on the fly, so there is no need to have pre-defined paths to perform the haptic guidance. Furthermore, a visual aid is offered so the system feedback is complete and reliable.

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