Human interaction with Motion Planning Algorithm

Michel Taïx, David Flavigné, Etienne Ferré

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Michel Taïx, David Flavigné, Etienne Ferré. Human interaction with Motion Planning Algorithm. 2011. hal-00605850

HAL Id: hal-00605850
https://hal.science/hal-00605850

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hal-00605850, version 1 - 4 Jul 2011

Noname manuscript No.
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Human interaction with Motion Planning Algorithm

Michel Taïx · **David Flavigné** · **Etienne Ferré**

Received: date / Accepted: date

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Abstract This paper presents..... A
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Michel Taïx
CNRS; LAAS ; 7, av. du Colonel Roche, 31077 Toulouse, France, Université de Toulouse;
UPS, INSA, INP, ISAE ; LAAS ; F-31077 Toulouse, France
E-mail: taix@laas.fr

David Flavigné
ISIR
UPMC Univ Paris 06, UMR 7222, ISIR, F-75005, Paris, France
E-mail: flavigne@isir.upmc.fr

Etienne Ferré
Kineo CAM
Rue de la dcouverte, 31677 Labege, France
E-mail: ef@kineocam.com

Keywords Human-system interaction · Interactive device · Motion Planning · Assembly industrial task

1 Introduction

Manufacturing industries (automotive, aerospace, shipbuilding) take benefits from numerical simulations for several decades. The computer is used almost in all the stages of the product lifecycle: design, manufacturing, maintenance. One of the most recent applications of the numerical simulation is the digital mockup for assembly path definition. Thanks to the numerical model of the product, design engineers are able to build the manufacturing processes at the early stages of the product definition. This simulation avoids the building of a physical mockup, which is costly, and time consuming moreover the time needed to build a physical mockup makes the prototype always outdated as soon as it is available. Thanks to the numerical model, the engineers always have access to an up-to-date representation of the current product. Thus, by checking the assembly motion of the product while the design phase, the project team can minimize the risk induced by a non-feasible product. Indeed, an error in the feasibility of assembling a product leads to several months of delay and several hundreds of K$ of over costs. The engineers use various types of tools to define assembly paths. The goal of the study is the creation of a collision free motion of one part from a position outside the assembly to mounted position. The assembly problem inside the digital mockup can be solved generally by two approaches : manually or by algorithms. The user can manually create such a motion thanks to highly efficient collision detector warning of a clash while he/she moves the target component. Another solution is the automatic path planner. These algorithms use the numerical model to automatically calculate the collision free trajectory.

This work concerns the conception and the realization of a new approach to solve problems in mechanical assembly of numeric models (3D C.A.D) based on interaction between a user and a motion planning algorithm.

When the assembly is done manually, the user can be immersed in a virtual reality environment. Virtual reality allows him to have a better world perception and can use an haptic arm in order to interact with CAD software. Haptics is a recent enhancement that provides an additional perceptual modality in virtual environments [4]. A force feedback device allows the user to test collision-free paths in assembly tasks during the process of industrial design or benchmark maintenance [11]. The contribution of haptics can improve the use of Virtual Reality [31,5]. The use of a 3D mouse for interaction, is less expensive than a haptic device and can give very good results in many design processes with digital mockup [7,27]. Manufactured goods using such technology are already available in the market and are used in car and aeronautical industries. The main applications concern the operations of dis-assembly for maintenance checks as well as during final phase assembly.

But in complex scenes the user may get lost and need help in finding the solution easily. It is very easy to move a ball in a 3D environment with a haptic device because in that case the orientation of the object has no importance. But this is not the case with a real non-convex object in a complex scene.

Elsewhere, in robotics, a lot of work in motion planning [15] has been done to compute free paths in digital models for mechanical systems. With the recent results in random planning algorithm [18] it is possible to solve automatically problems for systems with many degrees of freedom. The algorithm computes a collision-free roadmap in a configuration space (*CS*) where the object is reduced to a point. This point represents the robot's model in

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the environment and the dimension of *CS* is equal to the number of degrees of freedom of the mechanical system. The algorithm searches a free path for a point in the roadmap. One example of applying motion planning techniques in real studies are in the maintenance and operation of nuclear power stations [25,24]. Now, companies uses automatic path planning to solve PLM applications [9,16].

There are mainly two families of methods for building a roadmap, the Probabilistic Roadmap (PRM) [13] and the Rapidly-exploring Random Tree (RRT) [19]. The RRT approach is more interesting to our study because it is faster in the single query case, when the roadmap computation must be limited in time. For really constrained environments [8], there are very effective methods to solve problem. But this is not always the case, especially when the object must pass through a narrow passage. It is difficult for the algorithm to find the passage entrance (see for example [3,30,1,28,26,20,22]). To do so it will have to investigate randomly all the *CS* dimensions. On the other hand when the algorithm finds the narrow passage entrance in the *CS*, it will quickly progress to find a solution. Random algorithms progress easily in narrow passage but have no global vision of the solution.

On the contrary, in the case of a free or low-constrained environment, a user will easily find a solution (for example, we quickly steer the key towards the keyhole). On the other hand, a user will have much more difficulties to progress in narrow passages. Thus, the user has a good global vision of the problem, but finds it difficult to make fine movements.

It is noticeable that the algorithm and a user with an interaction device, can both work in complementary fashion. The complementarity between user and algorithm is the essential idea of this work. The main contribution of the method is to allow simultaneously cooperation between the loop of roadmap search and the loop of interaction for the user. As the roadmap tree iteratively enlarges, it uses the directions of motion of the user device to favor the directions of search extensions.

In this paper, we choose to integrate the human into the planning loop via an interaction device, which can be a 3D mouse or a haptic arm. The user can thus act on the search, showing areas to explore or to go through. On the other side, the algorithm can gather information while exploring the scene (independently from the user's input) and display them visually and/or haptically. The purpose is to simultaneously accelerate the search of a solution, and to improve the operator guidance during an assembly task in a virtual environment with the help of an automatic path planning algorithm. These results are an extension of [10].

This algorithm can also propose other possible solutions to the user. For example, during the insertion of window glass in a car's door, it may be interesting to test the various solutions to insert the window. For this purpose, human and computer must cooperate in an efficient way along the process.

The paper is organized as follow. We begin by describing previous work in interactive motion planning. The following section describes the basic RRT algorithm and extensions that have been made to answer our problem. The interactive motion planning algorithm, I-RRT, and the main functions are presented in section 4. Simulation results with an industrial application device are presented in section 5. Finally, we analyse our results and concludes the paper.

2 Related works

We can find works where the main problem was to move a robot arm in a virtual environment for off-line programming industrial robot by means of interactive path planning

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method. In [12] the user selects critical robot configurations with an haptic interface to facilitate the automatic path planning research with PRM approach. The advantages of human's intuition are exploited to facilitate the robot path planning process. A virtual tele-operation system provides a convenient tool for manipulating a virtual robot arm. They defined a semi-automatic path planning without a real feedback loop between user's motion and motion planning method. [6] used potential field method to guide user's control on the virtual robot through haptic device. This approach provides little information to the user because of the many local minima induced by the force fields in complex environment. In these two works the motion planning issue is not the important point of the approach.

On the other hand, idea of taking into account user input has been studied by various authors specialized in motion planning. In [2] the authors use user-input to work with automatic motion planner. They show that randomized techniques are quite useful to transform an approximate user-input path with collisions into a collision-free path. The idea is to push approximate user path to free space in *CS*. The use of a path planning technique based on harmonic functions to generate guiding forces that aid a user in a virtual environment is introduced in [29], [23]. The idea is to compute a solution channel by cell decomposition that connects the initial and the final configuration and then two harmonic functions are computed over the *CS* to find a guiding path. RRT Algorithm including heuristics based on a study of the workspace are presented in [14], [21]. The idea is to discretize the workspace using an unbalanced octree decomposition and generate a free continuous volume between initial and final configuration using A^*. In a second time a free path for the object is computed by using RRT approach.

In all these studies, it is necessary to note that the interaction between the automatic search by motion planning algorithm and the user is simplified by a decomposition in two stages.

New kinds of peripheral devices that allow users to interact in a more natural way with machines were developed. These various devices such as space mouse or haptic arm (figure 1) can be used to improve motion planning algorithm with a natural user input, thus speeding-up path computation. A space mouse is a kind of mouse that can move in three dimensions, and even with orientation, the drawback is that the user has no feedback from the machine. This is done by haptic arms, which can send back forces and torques to the user. The Virtuose 6D Desktop includes three articulated branches whose end is fixed on the sphere of seizure. This haptic interface has a kinematics with 6 degrees of freedom (dof), and the return of effort is exerted on the 6 degrees.

Fig. 1 The Virtuose6d and the space mouse

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The main contribution of this work is to allow simultaneously cooperation between the loop of roadmap search and the loop of interaction for the user. In our work we do not separate the two stages. We define a framework of cooperation among algorithm and users's intuition or experience. As the roadmap tree iteratively enlarges, it uses the directions of motion of the user device to favor the directions of search extensions.

3 RRT Path Planning

We present the principles of the RTT that we modifie thereafter to take into account the interaction with the user. The Rapidly-exploring Random Tree (RRT) was introduced in [17] as an efficient sampling method to quickly search in hight dimensional spaces for single query motion planning.

The RRT algorithm is shown in Algorithm 1 and the development is illustrated in figure 2 Starting at a given initial configuration, RRTs incrementally search the configuration space for a path connecting the initial and the goal configuration. At each iteration a new configuration, q_{rand}, is sampled ($RANDOM_CONFIG$) and the extension from the nearest node, q_{near}, in the tree ($NEAREST_NODE$) toward this sample is attemped. If the extension succeeds ($CONNECT$) a new node, q_{new}, and an edge in the roadmap are created.

Algorithm 1 The RRT-CONNECT algorithm

```
T(q_init)
for i = 0 to N do
    q_rand ← RANDOM_CONFIG()
    q_near ← NEAREST_NODE(q_rand, T)
    if CONNECT(T, q_rand,q_near,q_new) then
        Add_Vertex(T, q_new)
        Add_Edge(T, q_near,q_new)
    end if
end for
```

By definition the RRT tends to grow rapidly in the unexplored regions of the CS and the probability to find a path (if exist) approaches one as the number of RRT nodes increases to infinity. Many different planners exploits the exploration properties of the basic RRT and tries to increase the rapidly exploring property.

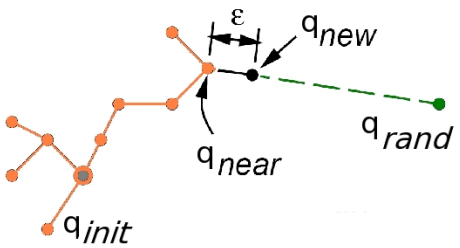

Fig. 2 RRT Agorithm

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RRT planner performs well in many application but gives unsatisfactory results when narrow passages are far from both initial and goal configuations. To improve performances it is necessary to guide exploration by leveraging available information. In our case it is necessary to take into account the interaction with the user.

The main modifications of the basic RRT are to be made on the following stages:

- By definition, the state of the node is binary. If the node is free and the connection path is also collision free, the node/edge is created in the roadmap, otherwise, any information is memorized. It is interesting to memorise information for the user when the CONNECT function return false.
- The sampling area in RANDOM_CONFIG is a crucial point to extend efficiently the roadmap. User's interaction must be taken into account in the definition of the sampling area.
- The NEAREST_NODE function has not only to take into account the Euclidian distance but also the most interesting nodes with regard to the task of the user.
- At each iteration, the new I-Device position must be taken into account to compute these differents steps

To take into account these various points we propose a new algorithm called Interactive Rapidly-exploring Random Tree, I-RRT, which is presented in the next section.

4 Interactive RRT

In this section, the I-RRT algorithm is described. The first part gives an overview of the method and the second part details each step of the algorithm.

We note that I-Device stands for Interaction device which can be a 3D-mouse or a haptic device. If I-Device is an haptic device the method uses force through the haptin feedback, in the case of a 3D-mouse, the motion of the mouse is transformed in a pseudo-force.

4.1 Approach Overview

The idea behind the I-RRT algorithm is to take advantage of both a human operator and the RRT algorithm capacities to solve a motion planning problem. Motion planning methods that include a human in the loop are focusing on two steps approaches that separate user input from algorithm execution. Our main contribution is to gather these two steps in a single general loop, shown on Fig. 3.

The goal is to improve the user guidance using motion planning algorithms. The principle is to let the user move an object (the avatar) in the virtual scene to guide the RRT exploration by introducing a bias toward the avatar during the planning phase. The operator uses an interactive device to move the virtual object. Such algorithm has to take 2 constraints into account :

- The operator movement has to lead the roadmap extension.
- The planning algorithm has to provide useful information to the user concerning environment, obstacles and exploration status.

The proposed planning method is based on a RRT algorithm and can be divided into 2 distinct parts, represented on Fig. 3 by two loops running in parallel :

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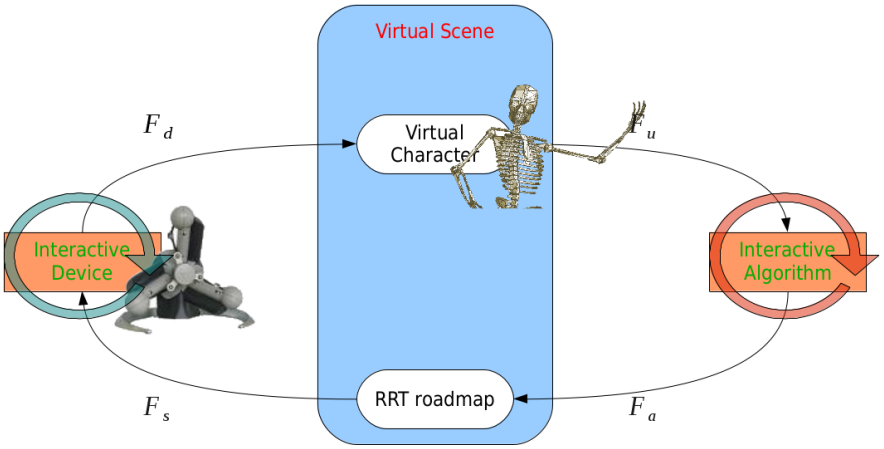

Fig. 3 General interaction loop between the algorithm and the user (represented by the interactive device) through the virtual scene

1. In the first loop ("interactive algorithm"), the planner explores the configuration space in an automatic way, looking for a collision-free path between start and goal configurations. The sampling and the extension steps are different from the original RRT algorithm, in order to take the user input into account. The user interaction is represented by the pseudo-force F_u on Fig. 3. Using this pseudo-force, the planner extends its roadmap and gathers data on the virtual scene. This data is sent back to the user through another pseudo-force called F_a. This pseudo-force is also used in the next iteration of the general loop, along with F_u, to extend the roadmap.
2. In the second loop ("interactive device"), the operator moves the avatar in the virtual scene. A pseudo-force F_s is applied to the interactive device if it is possible (haptic device) or directly on the avatar otherwise. This pseudo-force may be interpreted as a disturbance by the operator but is intended to act as a guide towards a better area to explore in the configuration space. The device interaction with the virtual scene is interpreted as a pseudo-force F_d, which can include F_u in the case of a non-haptic device.

These 2 loops are interacting through the virtual scene. First, the user uses the interactive device to move the avatar (F_d). The avatar movement is used to generate F_u (which includes F_s either directly or applied to the interactive device if possible). Then, the algorithm builds a RRT roadmap using data gathered during previous iterations (F_a) and F_u. This roadmap is used to gather data for next iterations and give feedback to the user (F_s).

The different nature of the 2 parts of the algorithm allows us to distinguish 3 different modes of working for the I-RRT algorithm :

– The user is moving the interactive device faster than the algorithm builds its roadmap because he knows where to go to get closer to the goal configuration. In this case, the algorithms tracks the avatar position in the virtual scene. The user's intention is considered predominant. If the solution is obvious to the user, the algorithm follows his movements.
– The user does not move the device. The algorithm keeps exploring the configuration space to gather data on the environment and to give visual and/or (depending on the device) haptic hints to the user. This happens if the user is stuck and does not know how to move the avatar. This mode is close to the original RRT algorithm.

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– The user slowly moves the device. In this case, the algorithm extends the roadmap around the user's position while still exploring other part of the configuration space, without the user's influence, to gather more data on the environment.

These 3 different modes of working are not 3 separate states of the algorithm, but rather 2 extremities and the middle of a behaviour line (Fig. 4).

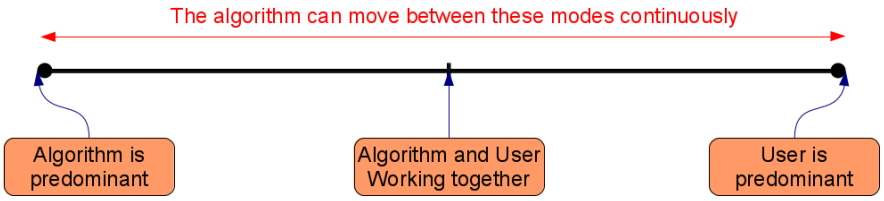

Fig. 4 Behaviour line of the algorithm. The algorithm state can be anywhere between fully automatic behaviour (left) and fully manual behaviour (right)

Each loop is running at its own speed. The interactive device loop is faster than the algorithm loop (which can vary due to the increasing number of nodes). This is not a problem since they are non-blocking. Only pseudo-forces are shared between each loop. In the next section we detail each step of the algorithm that is different from the original RRT.

4.2 Interactive Motion Planning System

This section is divided into 2 main parts, each of them describing one of the 2 loops involved in the interactive motion planning system.

4.2.1 The interactive device loop

This loop is simple as its only purpose is to deal with the interactive device data. It computes necessary pseudo-forces for feedback from and to the user.

Algorithm 2 Interactive device algorithm

```
loop
  F_s ← ALGORITHM_FEEDBACK()
  if USING_HAPTIC() then
    APPLY_FEEDBACK(F_s)
    Q_device ← RETRIEVE_DEVICE_STATE()
    F_d ← COMPUTE_DEVICE_PSEUDO_FORCE(Q_device)
  else
    Q_device ← RETRIEVE_DEVICE_CONFIG()
    F_d ← COMPUTE_DEVICE_PSEUDO_FORCE(Q_device,F_s)
  end if
end loop
```

The algorithm 2 shows the principle of the interactive device loop. First, it starts by retrieving information from the algorithm to guide the user in the virtual scene (ALGORITHM_FEEDBACK()). This information is represented by the pseudo-force F_s, which points to areas to explore according to the algorithm. Then, it handles 2 different cases:

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1. The interactive device is a haptic device. F_s is sent to the device to provide the user with a feedback from the algorithm (APPLY_FEEDBACK()). The state of the device resulting from this feedback and the user's action is retrieved (RETRIEVE_DEVICE_STATE()) and used to compute a pseudo-force F_d (COMPUTE_DEVICE_PSEUDO_FORCE()) that is used by the algorithm as user input.
2. The interactive device does not have haptic features. In this case the state of the device Q_{device} is mixed with F_s to compute F_d (COMPUTE_DEVICE_PSEUDO_FORCE()).

4.2.2 The interactive algorithm loop

The algorithm loop is based on the RRT motion planning algorithm. It is shown on algorithm 3. The main steps of interactive RRT (I-RRT) are :

- Configuration sampling using computed pseudo-forces (F_u,F_a). We are looking for an efficient way of combining user movements with the algorithm automatic search.
- Choosing the nearest neighbour in the roadmap.
- Extending the roadmap.
- Updating node data given the result of the roadmap extension.
- Computing a pseudo-force F_a aimed at attracting the user to relevant areas to explore. It is computed using data contained in the roadmap nodes.
- Computing a pseudo-force F_u from the motion of the avatar in the virtual scene. This motion is generated by the user interaction with the device (F_d) and the virtual scene (obstacles may stop the movement).
- Sending back some useful information to the user by using haptic feedback or visual hints.

Algorithm 3 I-RRT algorithm

$T \leftarrow q_{init}$,q_{goal}
while !PATH(q_{init},q_{goal}) **do**
  $q_{rand} \leftarrow$ SAMPLING(F_a, F_u)
  $q_{near} \leftarrow$ NEAREST_NODE(q_{rand}, T)
  if CONNECT(T, q_{rand}, q_{near}, q_{new}) **then**
    $T \leftarrow q_{new}$,EDGE(q_{near}, q_{new})
  end if
  GATHER_DATA(T, q_{near}, q_{new})
  F_a,$F_u \leftarrow$ COMPUTE_PSEUDO_FORCES(T, q_{user})
end while

Algorithm 4 COMPUTE_PSEUDO_FORCES(T, q_{user})

$L_{near} \leftarrow$ NEAREST_NEIGHBORS(q_{user}, T)
$B \leftarrow$ Compute_Barycenter(L_{near})
$F_a \leftarrow$ Compute_FAlgo($Bary$, q_{user});
$F_u \leftarrow$ Compute_FUser(q_{user});
$F_r \leftarrow$ Compute_FResult(F_a,F_u);

In a first time, the pseudo-forces computation are described because they are the basis of interaction in the method and are used in other parts of the algorithm. Then, the part of

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the original RRT algorithm that were modified for our algorithm is explained. Finally, the data gathering and storage and the haptic feedback are described.

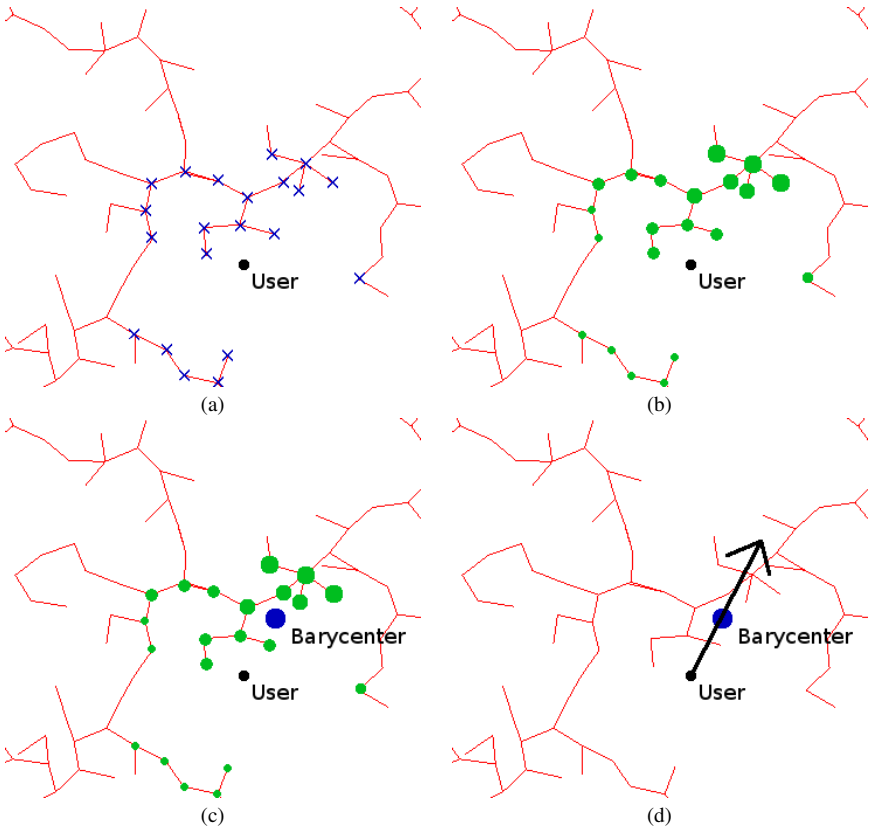

Fig. 5 Computing F_a pseudo-force.

Attractive pseudo-force computation

Interaction being the basis of the I-RRT, the contribution of each interacting part (the user and the algorithm) has to be defined. These contributions has to be flexible and has to reflect the planning constraints (obstacles, goal, ...). This means that they vary continuously during the planning, according to the virtual scene. This is achieved through computation of pseudo-forces which are aimed to represent each interacting part influence over the path searching process.

The contribution of the algorithm part is defined by the computation of the attractive pseudo-force F_a (Compute_FAlgo() in algorithm 4). This computation is illustrated on Fig. 5. First, the p nearest neighbours of the user position q_{user} are retrieved from the RRT roadmap (NEAREST_NEIGHBORS() and Fig. 5-a). The barycenter B of these nodes is then computed (Compute_Barycenter()). The data contained in the nodes are used as weights during this computation (Fig. 5-b et 5-c). The computation of weights is detailed below in the

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paragraph "Node Labelling". F_a is the vector starting from q_{user} and directed towards the barycenter (Fig. 5-d).

User pseudo-force computation
The other interacting part of the system is the user. Its contribution is defined by the pseudo-force F_u (Compute_FUser()). F_u results from the avatar movements in the virtual scene and its interaction with obstacles. As the avatar movements are controlled by the user and the pseudo-force F_d, F_u can be deduced directly from F_d most of the time ($F_u = F_d$). However, if the avatar is not allowed to collide with obstacles during the path search, F_u can be different from F_d when there is a contact with an obstacle. The user will apply a force on the device ($F_d \neq 0$), but the avatar will not move if it implies a collision with the obstacle ($F_u = 0$).

Resulting pseudo-force computation
As the path search has to reflect both part of the interaction, the 2 previously computed pseudo-forces are mixed into a resulting pseudo-force called F_r (Equ. 1 and Fig. 6-a). F_r takes into account the user's intention and the algorithm suggestions for the path search. We can retrieve the 3 modes of working illustrated on Fig. 4 by studying the variations of F_r :

- The user moves fast : $F_u > F_a$. In this case, F_a is negligible compared to F_u and then F_r is almost equivalent to F_u. The user is predominant and leads the path search.
- The user doesn't move : $F_u = 0$ and $F_a > 0$. In this case, $F_r = F_a$. The algorithm is predominant.
- The user moves slowly : The user and the algorithm are working together.

$$F_r = \alpha \cdot F_u + (1 - \alpha) \cdot F_a \tag{1}$$

In equ. 1, α can be used to modify manually the influence of each part. If $\alpha = 0$, the algorithm is equivalent to an RRT algorithm. If $\alpha = 1$, the algorithm is only tracking the user position.

Sampling method
The resulting pseudo-force F_r is computed in order to guide the sampling of the RRT algorithm. The sampling is the heart of probabilistic methods. If the sampling can be controlled, the path planning is controlled as well.

The F_r pseudo-force computed in the previous step is used by the sampling method to guide the path search (Fig. 6). The sampling method is a gaussian sampling along F_r direction. If the user does not move or move slowly, the sampling is equivalent to a gaussian sampling around the user position but if he is moving fast the sampling anticipates the user's movements. This sampling method can be seen as a position tracking method. The standard deviation σ of the gaussian sampling is used to tune the influence of the algorithm on the search.

But this sampling method has some drawbacks. If the user moves too fast, the RRT algorithm may not be able to link newly sampled nodes to the existing roadmap due to obstacles. To deal with this problem, 3 other sampling methods were investigated.

- The first method allows creation of several local trees rooted at nodes that cannot be linked directly to the main tree. It is useful in the case of I-RRT method to keep track of user's movements even if the connection with the main tree was lost (this is the drawback of the original sampling method). The missing connection is made by the algorithm part of the interactive motion planner.

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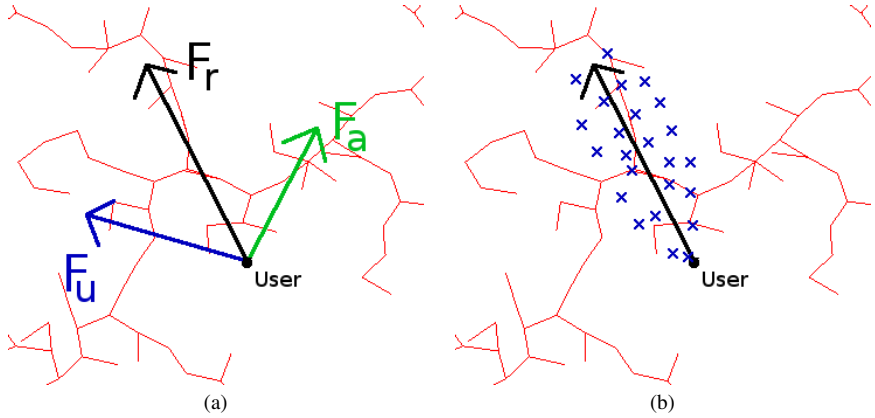

Fig. 6 Sampling a new configuration using user and algorithm interaction.

- The second method stores the path traveled by the user and samples around this path (gaussian sampling). The advantage is that the connection to the main tree is never lost, but it slows down the resolution. In this method, the influence of the algorithm can also be tuned using σ.
- The third method adds a uniform sampling in the configuration space. This method allows a global exploration of the virtual scene, independently of the user's position, and then the data gathering is also more global compared to the original sampling method. To preserve the interactivity, the uniform sampling should be used with one of the other methods. A parameter β indicates the ratio between the usage of the two used methods.

Nearest neighbour
The choice of the nearest neighbour q_{near} for extension is made using the distance d (Equ. 2) between the newly sampled node and each node of the tree (NEAREST_NODE()). This distance is also used for the choice of the nearest neighbours of the user's position (NEAREST_NEIGHBORS()) during barycenter computation.

$$d = \sqrt{\sum i = 1n\alpha \cdot (dof_{i_{sample}} - dof_{i_{node}})^2} \tag{2}$$

Extend method
The extension step of the I-RRT is the same as a RRT-Connect algorithm : the nearest neighbour in the tree is extended towards the new sample until it reaches this sample or collide with an obstacle. Given the result of this extension, the extend method can return 3 different states :

- Collision : the extension failed because q_{near} was near an obstacle. No new node is added to the tree.
- Obstacle : the extension was partially done because an obstacle was between q_{rand} and q_{near}. A new node q_{new} is added to the tree.
- Success : q_{near} and q_{rand} were successfully connected. q_{rand} is added to the tree.

For the original RRT algorithm, this is the last step of an iteration. For the I-RRT algorithm, we need to define the feedback for the user. This feedback is computed as hints that can be either haptic hints or visual hints (or both). With this feedback, the interaction loop is closed. The steps needed for this are detailed in the following paragraphs.

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Node Labelling
The first type of feedback is visual. The algorithm uses data stored in nodes to display visual hints for the user. These visual hints are modeled as a coloring of nodes and edges according to labels computed from return states of the extend step. These labels are the data stored in the nodes. In the original RRT algorithm, configuration are sampled randomly and the only piece of information returned is their collision state with the scene obstacles. In the I-RRT, these collision tests are used to label roadmap nodes. 2 types of labels were defined for visual feedback :

- The distance label is a function to guide towards the goal. It is the distance from the current node to the goal node.
- The collision label is a function of the covered distance during the extension, the number of extension of the current node and the number of collisions resulting from extension attempts. It is computed using the return states of the extend method.

Haptic feedback computation
The second type of feedback is the haptic feedback. A pseudo-force is inserted in the interaction loop to give a more intuitive guidance for the user and to avoid cluttering the screen with visual artifacts. To compute this pseudo-force F_s, the previously computed attractive force is used :

$$F_s = k \times F_a \tag{3}$$

In equ. 3, k is a scale factor set by the user before algorithm execution.

In the case of the operator using a haptic device, F_s is sent directly to the device. The user constantly feels an effort from the device which guides him towards areas to explore, according to the algorithm. In other cases, the haptic feedback is applied to the avatar movements in the virtual scene. The user does not feel the feedback directly but will be able to see the perturbations due to F_s on the movements of the avatar.

F_s also allows the user to stay within range of the algorithm roadmap and thus limit the problems mentioned in paragraph *Sampling method*.

5 Results

5.1 System implementation

The algorithm was developed in C++ using the HPP (Humanod Path Planner) platform developed at LAAS and based on the KineoWorks software. Experiments were made on a dual-core PC, 2,1GHz and 2GB RAM.

In practice, using a local trees sampling method mixed with a uniform sampling method minimizes the user's influence on the path search. The main idea behind the interactive RRT methodis to make user and algorithm interact equally, for this reason these two methods will not be used together in most of the cases. In the following experiments, the uniform sampling method will be used with the sampling method centered on the user's position (along F_r) and with the sampling method along the user's path. In each case, $\beta = 3$. The pseudo-forces F_u and F_a have the same influence on the search ($\alpha = \frac{1}{2}$). The nearest neighbours search is made by comparing each node of the tree. The number of nodes p used to compute F_a is five. For this computation, all the neighbours should remain in the same connected component.

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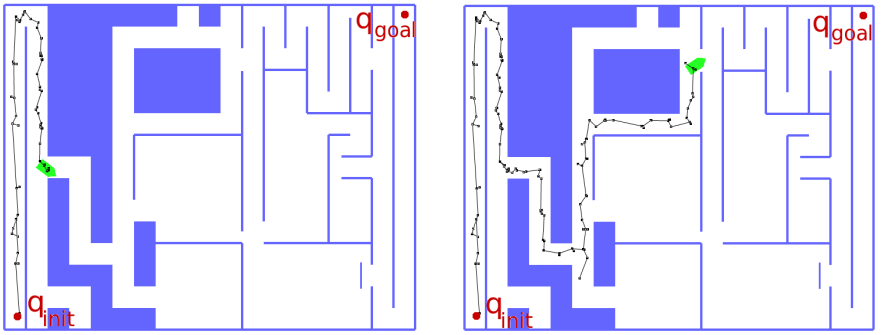
The required time to solve the path planning is dependent on the user's ability to manipulate the interactive device. If he does not move or is stuck in a dead-end, the planning time can increase and the algorithm will not benefit from the user's guidance. In the following case, we decided to let the user go through obstacles (contact forces are not considered) so that user's movements will not be limited, and he will still be able to guide the algorithm. The F_s pseudo-force replaces the contact forces to inform the user of obstacles limiting the exploration capacity of the algorithm in the current area. With this, even if the user path is in collision with the environment, the algorithm can still find a collision-free solution.

5.2 Simple 2D case

The main goal of this first case is to illustrate the principle of the interactive algorithm, and the different modes that can be observed during a planning query. In this case, the user moves the avatar with a 6D mouse in the virtual scene shown in Fig. 7, 8 and 9. The coloring of nodes was not activated for this example.



(a) Few nodes are created (b) The user has a dominant influence on the search

Fig. 7 The user is leading the search and the algorithm is tracking his position

The user has to reach q_{goal} from q_{init}. The avatar (the green block) has three degrees-of-freedom : x, y, θ. The first part of the environment is simple and user and algorithm can both find easily find the path. The user being faster, he leads the search during this part. Then, the environment becomes tighter and there is crossroads (Fig 7-a). The way is obvious for the user, but in a non-interactive case the algorithm would have difficulties to find the narrow passage. The user is predominant and leads the search into the narrow passage.

After the narrow passage, the environment has two room with no exit. These rooms would have required a large amount of time to be explored in a non-interactive case. Instead, the user avoids them and leads the search in the right direction (Fig. 7-b). The algorithm is not predominant but can initiate a slow exploration towards regions left out by the user (small branch are developped towards the rooms).

On Fig. 8-a, the exploration made by the algorithm part is more visible. Meanwhile, the user saw a possible passage and tries it. The passage is too narrow for the user to find a solution here. While the user is trying to develop nodes in this passage, the algorithm continues exploration in other parts of the environment (uniform sampling), as shown on Fig. 8-b. The algorithm finds a solution left out by the user because it seemed to be too

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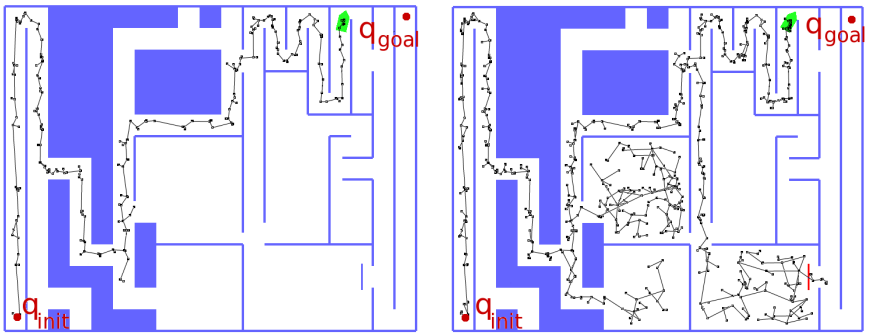
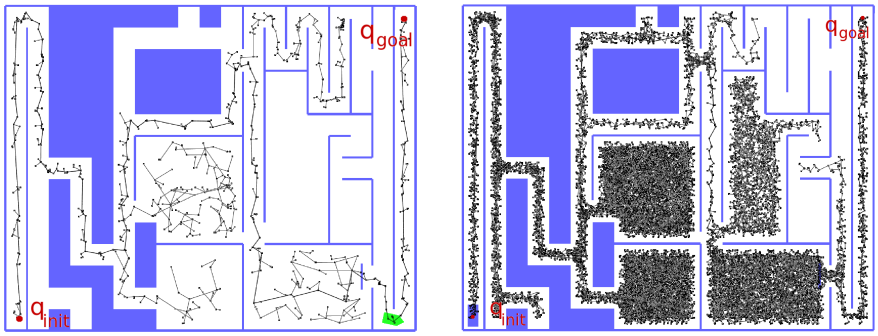


(a) The user leads the search to a dead-end (b) The algorithm explores other possibilities

Fig. 8 The user is stuck in a dead-end, the algorithm is searching other possibilities to reach the goal

narrow for the robot (red obstacle on Fig. 8-b). The user mistake is due to his point of view of the virtual scene. The red obstacle is placed below the plan in which the robot can move. This trap may seem artificial but it illustrates perfectly problems that can be met in complex 3D environments.



(a) The IRRT roadmap after the solution was found (b) A Bi-RRT roadmap

Fig. 9 Comparison between the roadmap obtained after using the IRRT algorithm and after using a Bi-directionnal RRT algorithm

On Fig. 9, we can compare the roadmap built by the IRRT algorithm with the roadmap of a bi-directionnal RRT algorithm. The interaction between the user and the algorithm allows a lower number of nodes and a faster exploration (few minutes) than a RRT algorithm. The RRT algorithm made a dense exploration and covered the maximum of the space. This kind of exploration requires a lot of time and resources (>2 hours).

5.3 Simple 6D case

In this example, shown on Fig. 10-a, the user has a haptic arm to manipulate a S-shaped object in order to cross a wall through a hole in its center. The wall dimensions are $700 \times 700 \times 20$ and the hole's are 80×80. The object is composed of three sticks assembled along three edges of a virtual cube. The nodes of the roadmap represent the position of the center

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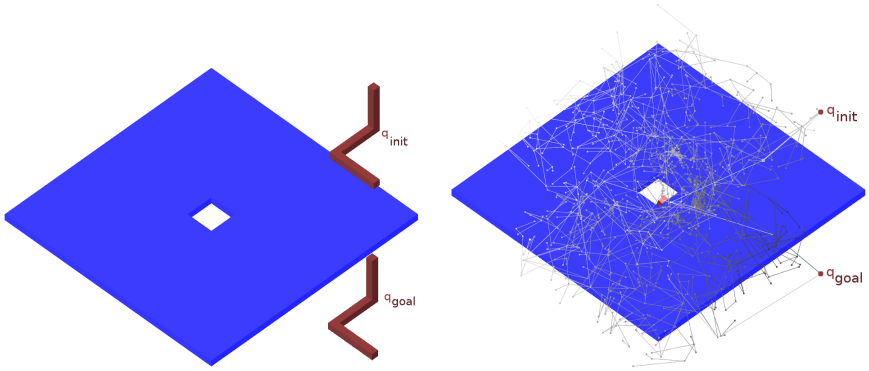
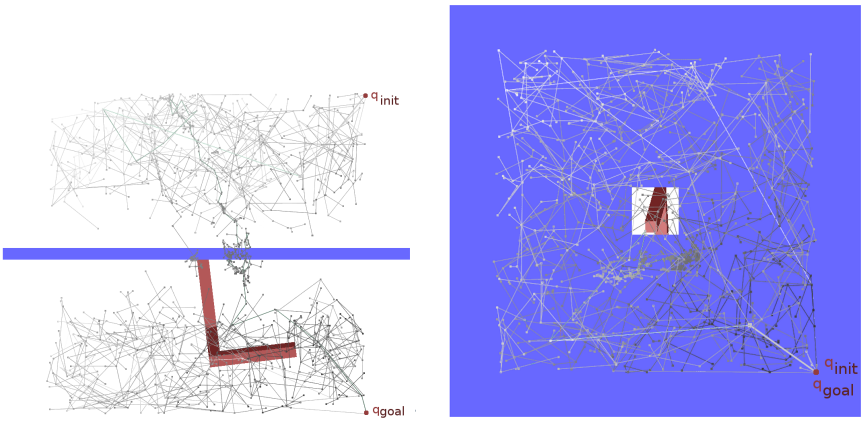
of this cube (and thus are not a point on the object itself). Each stick is $20 \times 20 \times 100$. The environment has only one difficult passage which requires the help of the user. The sampling method used are user tracking (using F_r) and local trees are allowed. The node coloring is activated. The configuration space is bounded to force the user to go through the hole, and the object has six degrees-of-freedom.



(a) (b)

Fig. 10 A case with a 6-dimensional configuration space.

Solving this planning query requires that the user has a good ability to manipulate the interactive device, the passage being really narrow. The user has to slowly guide the search through the hole in order to improve the search. On Fig. 10-b and Fig. 11, the developed roadmap is displayed with nodes colored according to the labelling. Nodes that are closer to the goal are displayed in a darker color than others. The algorithm part covered both part of the wall (due to the local trees) so that the user has only to guide the part in the narrow passage. The roadmap density can testify to the dexterity of the user. Here, the roadmap is not dense nor sparse, which shows that the user has an average dexterity.



(a) (b)

Fig. 11 The roadmap is developed on both sides of the wall

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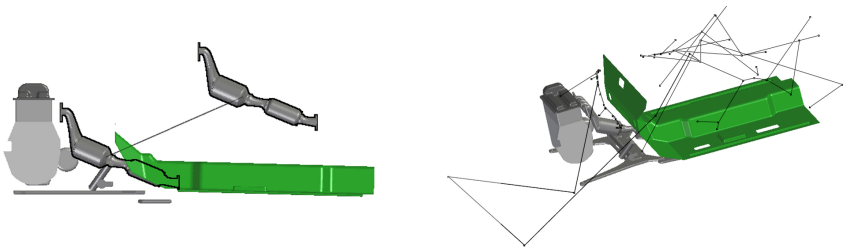
5.4 Industrial case

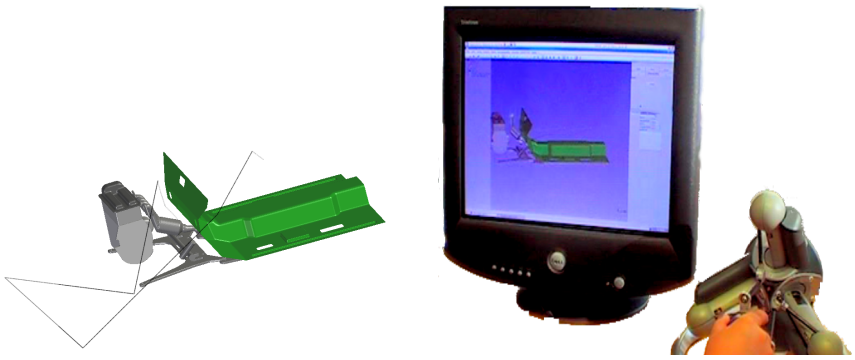
The following example is based on a real automotive case. The goal is to find a disassembly path for a car silencer. In this example, the configuration space is bounded. The user is using a haptic arm (Fig. 13) to move the silencer and extract it from its location. The extension of a tree from the goal configuration is allowed, because it does not modify the interaction user-algorithm : the goal configuration is in a large free space, easily accessible after the silencer is removed.



(a) The planning query (b) The IRRT roadmap

Fig. 12 The silencer has to be remove from bottom to be placed on the top.

The query is solved in few minutes by the user (Fig. 12). The main difficulty is to extract the silencer from the start area, under the green part. This disassembly query can be solved more quickly by specific automatic algorithms [8]. This problem does not favor interaction between user and algorithm but, in the context of guiding the user, the IRRT method is still valid because the interactivity allows to control the solution and to take into account constraints imposed by the user. On Fig. 12-b, we can see that the roadmap around the goal configuration is developed mainly by the algorithm part and the roadmap around the start configuration by the user part.



(a) The solution path (b) Manipulating the haptic device

Fig. 13 Extracting the silencer using an interactive device and The IRRT algorithm

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6 Analysis

Due to its dual nature, the interactive RRT performances are strongly dependent on several parameters. First, on the user side, are the user capacities to visualize the virtual scene and the potential solutions and his skills at manipulating the interactive device. Then, on the algorithm side, the choice of the sampling method to use is determinant. Last, the parameters needed for exchanges between each part of the I-RRT are also to take into account (k for the haptic feedback and α for computing F_r). The standard deviation used for gaussian sampling methods is also important for exchanges.

The settings of the algorithm parameters will influence its performances and the aspect of the resulting path. They can be used to adapt the algorithm to the user skills.

In this section, we analyze the influence of 3 of these parameters on the algorithm. We choose the parameters that seemed to be the most representative of each type of parameters:

- The user dexterity for the user part.
- The sampling method for the algorithm part.
- The standard deviation for the exchange part.

For testing purposes, we choose a simple environment. This environment is shown on Fig. 14.

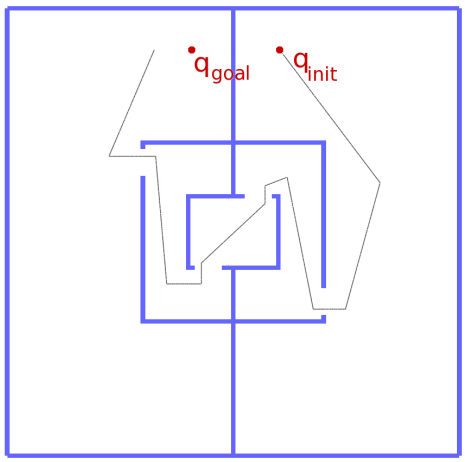

Fig. 14 Testing environment. The user's path is displayed in black.

The user dexterity is a parameter difficult to model. In the tests, it is represented by the user speed along a predetermined path $path_p$(Fig. 14). For each iteration of the algorithm part (each time a new configuration is sampled), the user's position is moved by a step ε_v along this path. ε_v is used as equivalent of the user speed. The tests were run for 4 differents values of ε_v.

4 different sampling methods were chosen for the tests:

- *POS*: Gaussian sampling around the user's position.
- $POS + CS$: Gaussian sampling around the user's position and uniform sampling in the configuration space.

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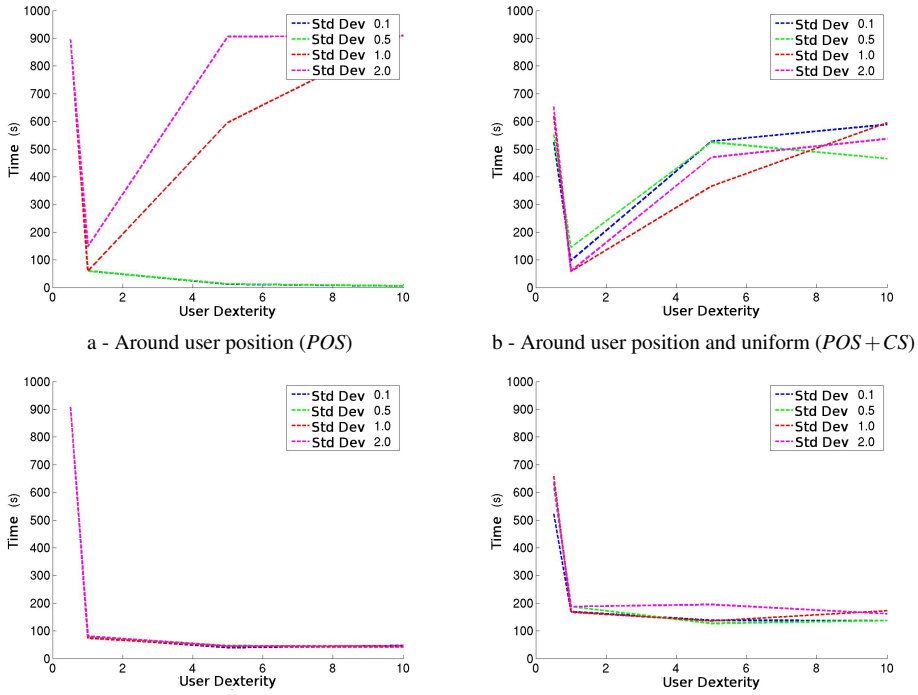
- $PATH$: Gaussian sampling around the user's current path (path part along $traj_p$ between start position and user's position).
- $PATH+CS$: Gaussian sampling around the user's current path and uniform sampling in the configuration space.

The sampling method defines how to use the user input to gain information, explore the environment and find the solution. All the methods are based on gaussian sampling as it allows randomness to be guided (by user input in our case). The standard deviation σ is the parameters that defines the influence of the guide on the gaussian sampling. 4 different values of standard deviation were chosen for the tests.

Visual and haptic feeback are not considered during the tests. The results shown are average over 50 runs. The time limit for each test was fixed to 900 seconds.

6.1 Sampling

Fig. 15 shows the computing time given the user speed for each values of the standard deviation. Curves (a) to (d) shows the results for each particular sampling method.



a - Around user position (POS)

b - Around user position and uniform ($POS+CS$)

c - Around user path ($PATH$)

d - Around user path and uniform ($PATH+CS$)

Fig. 15 Comparing the standard deviation effect on resolution time given the user speed for different sampling methods.

On each curve, we can observe that the computation time is higher (almost reaching the time limit) for lowest user speed values. This is due to the fact that in this case, the user is

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not fast enough to find a solution before the time limit. When a uniform sampling method is used, however, the problem can be solved within time limit.

The curve (a) shows the results for the *POS* sampling method. In this case, high values of σ (red and magenta on Fig. 15-a) shows the worst performances because the user position tracking is less efficient, and the narrow passages of the environment reduce the probability of linking a new sampling to the existing roadmap for this method. On the contrary, if the sampling is precise enough when following the user (low values of σ, blue and green), the increase of the user speed will benefit to the algorithm.

The curve (b) shows the results for the $POS + CS$ sampling method. In this case, a uniform sampling in the configuration space is added to the gaussian sampling around the user position. (1 sampling of 3 is chosen with the uniform method). We observe on the curve that it introduces a latency in computation time for low σ values, but speeds up the resolution for high values. The addition of the uniform method reduces significantly the dependence of the algorithm to the standard deviation.

The curve (c) shows the results for the $PATH$ sampling method. In this case, σ has no influence over the path planning process. The resolution time always benefits from the increasing user speed. The memorization of the user path allows to deal with narrow passages and problems of link between the samples and the existing tree.

The curve (d) shows the results for the $PATH + CS$ sampling method. The computation time increases a little bit compared to the $PATH$ sampling method, and the differences due to σ are visible, but the addition of the uniform sampling has no significant influence on the planning.

6.2 Standard deviation

Fig. 16 shows the computing time given the user speed for each sampling method. Curves (a) to (d) shows the results for each value of σ.

This figure allows us to compare each sampling method directly given a single value of standard deviation. On curves (a) and (b) (low standard deviation values), we can observe that the addition of a uniform component to the sampling method increases the computation time (green and magenta). But while the $PATH + CS$ method follow the same kind of path as $PATH$ and POS (due to the memorization of the user path), the method $POS + CS$ has worse results as the user speed increases. This is due to the slow down caused by the uniform sampling and the linking problem when appraoching narrow passages. The POS method gives the best performances: this method benefits from the user speed more than others.

On curves (c) and (d), we can see that the 2 *POS* based methods are giving worse results because of the increase of the standard deviation. We can observe on curve (d) that, without the supply of a uniform component, the *POS* method cannot resolve the problem within the time limit (blue).

6.3 User dexterity

Fig. 17 shows the computing time given the standard deviation for each sampling method. Curves (a) to (d) shows the results for each value of ε_v.

On curve (a), we can observe that computation time are high for every sampling method. As said earlier, this is due to the user speed being to low to reach the goal before the time

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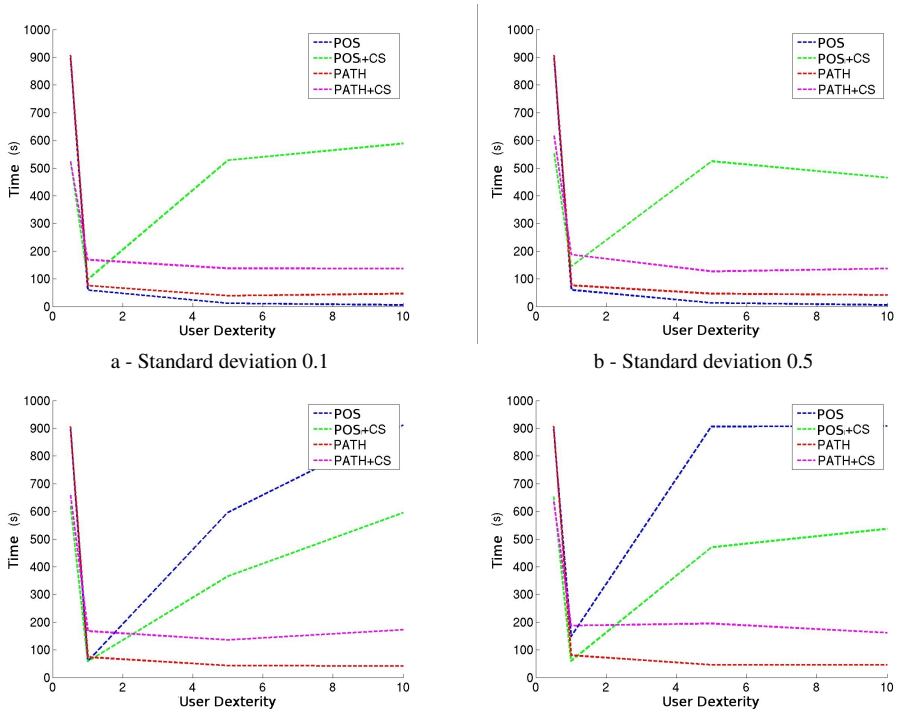

a - Standard deviation 0.1 b - Standard deviation 0.5

c - Standard deviation 1.0 d - Standard deviation 5.0

Fig. 16 Comparing the sampling method effect on resolution time given the user dexterity for different standard deviation values.

limit. Sampling methods without a uniform component cannot resolve the path planning problem in this case, but we can see that other methods can do it before the time limit.

On curve (b), we can observe that no matter the σ value and the sampling method, the performances are similar when $\varepsilon_v = 1.0$.

On curves (c) and (d), we see that $PATH$-based sampling methods are not affected either by the user speed or the standard deviation. The $POS+CS$ method is affected by the user speed but not by the standard deviation (green). This is due principally to the uniform sampling because if we look at the POS method, the computation time increases with the standard deviation (narrow passages and linking problem). However, for low values of σ and high user speed, this method is the most performant.

6.4 Discussion

In this section, 3 parameters of the I-RRT algorithm were analyzed. The results showed that each of these parameters are important and modifies the performances of the algorithm. They must be adapted to the user capacities and the problem environment.

Sampling methods without a uniform component (POS,$PATH$) are more adapted for an experienced user that can move the avatar in the virtual scene fast and with precision. They can take full benefit from the user guidance. Sampling methods with a uniform component ($POS+CS$,$PATH+CS$) are more efficient when the user is inexperienced (slow user speed)

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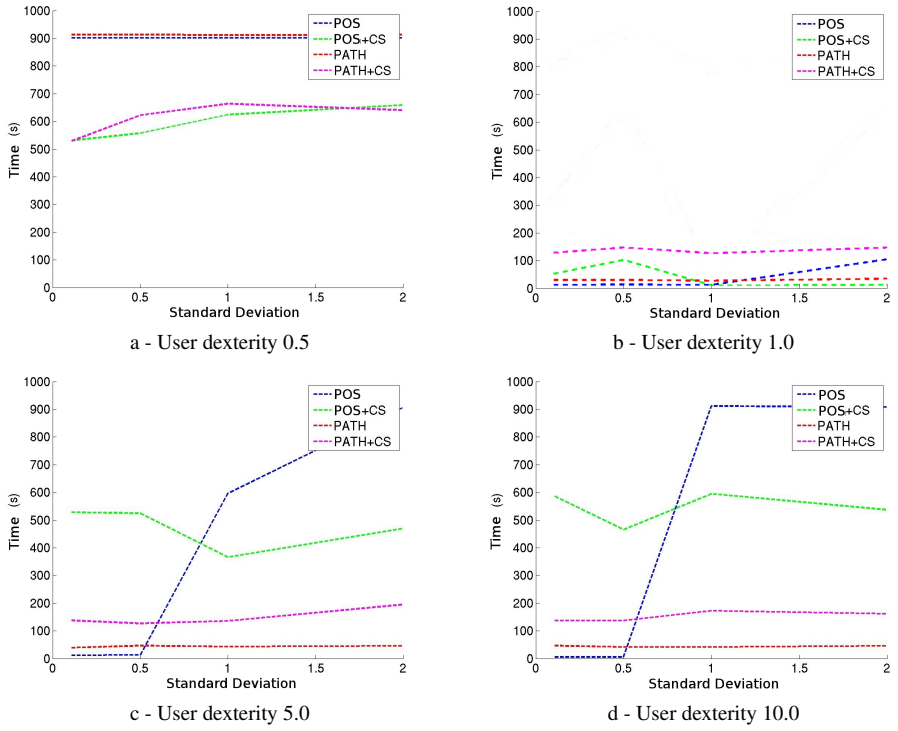

a - User dexterity 0.5 b - User dexterity 1.0

c - User dexterity 5.0 d - User dexterity 10.0

Fig. 17 Comparing the sampling method effect on resolution time given the standard deviation for different user dexterity values.

or cannot find the solution. They ease the problem resolution, but require more time. Path tracking methods ($PATH$,$PATH+CS$) are very little affected by user speed or standard deviation. They consitute a good compromise for unknown user capacities or environment.

7 Conclusion = 1 page

8 ACKNOWLEDGMENTS

Thanks to E Ferré for discussion and to make available the Haption haptic Device in Kineo-CAM Company.

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