Interactive multimodal Path Planning in immersion

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***Abstract*—Recent studies have defined interactive path planners for simulations involving a human operator. Such path planners enable a human operator to share control with an automatic planner and are based on Robotics and Virtual Reality (VR) methods. This paper proposes a novel architecture for this interactive planner. It enhances interaction with the user by adding topological and semantic representations to the purely geometric model traditionally used.**

Keywords—Virtual reality; simulation in immersion; interactive path planning; shared control

INTRODUCTION

Virtual Reality allows the rapid and efficient validation of industrial processes (assembling, disassembling, maintenance). Industrial development process brings numerical models that are more available than physical ones. Robotic tools for path planning can also improve VR simulations to help the operator in achieving the task. Such tools must be adapted with shared control paradigms in order to integrate the operator in the loop. Few studies have been done for interactive planning using paradigms of these two fields.

The work presented here aims at improving collaboration between an automatic path planner and a human user immersed in a numerical model. The robotic community has studied this issue (moving on the road network, in building, assembling, disassembling or handling tasks), without including a human operator in the path finding process. In addition, while the aim of path planning in robotics is to avoid obstacles, human way to plan often uses contact such as for assembly tasks where geometries identified as slides are used to guide the movement and reach the goal position faster.

So, the objective here is to adapt planners from robotics and associate them with a supervisor module to analyze the planning task and the environment (set of notions that we call the planning context). To do so, we propose a high level environment representation. The supervisor module adapts the interactive planning method to capabilities and progress of the interacting user and to local environment characteristics. This interactive planner can be used in industry for task involving humans: path planning and operator training, for industrial tasks as assembling, disassembling or maintenance.

In this paper, after a state of the art in the section I, a high-level representation of the environment is given in the section II. It enhances the geometric model of the environment with semantics and topological data. Section III details how this high-level representation is used by the interactive planner to, on one hand, adapt assistance given to the user, and on the other hand interpret user's intentions through his actions (avoid an area, move in contact with a surface...). Finally, the section IV describes the implementation of the planner in progress on the VR platform before concluding in the section V.

I. STATE OF THE ART

A. Robotic path planning

Finding a path for a mobile object between an initial and a goal position in an environment that may contain obstacles has been largely investigated by roboticists. Pioneer studies in this field have formalized concepts such that configuration space introduced by Lozano-Perez in [1]. The configuration describes the overall geometry of the system (articulated or not) by specifying the value of its degrees of freedom. This concept reduces path searching for an articulated system to path searching for a point in a space of dimension equal to the number of degrees of freedom of the system.

The first proposed approaches using the notion of configuration space for path planning were deterministic. Three families of approaches have been particularly studied:

1) Potential fields: associate to each point of the configuration space a potential pushing toward the goal configuration while maintaining the distance to obstacles. In practice, several potential fields are calculated (attractive potential to the goal configuration, repulsive potential of obstacles,...) and then summed up (see Khatib [2]). Thus, adding new potential fields allows taking into account many constraints such as the presence of humans in the environment (see Sisbot [3]).

2) Cells decomposition: builds a total or partial representation of the environment using computational tools of geometry (regular, triangular, square cell decomposition...). The cell graph representing the free space is then explored to generate a path between the initial and goal configurations (see Brooks [4]).

3) Roadmaps: capture the connectivity of the free space through a network of edges connecting configurations. Once the network is built, the initial and goal configurations are connected to the roadmap. Finally, the graph is explored to determine a path between them (see Brooks and Nilson [5], [6]).

Probabilistic approaches introduced later by Kavraki [7] are based on a random exploration of free space. First, Probabilistic RoadMap (PRM) was inspired by the Roadmap approach (prior construction of a graph from a set of randomly drawn configurations in free space). Probabilistic methods were then freed from the prior construction of the Roadmap by randomly exploring free space propagating from given configurations (RRT (Rapidly exploring Random Tree) by LaValle [8] or RDT (Rapidly exploring Deterministic Tree) by Dalibard [9])

An overview of path planning methods can be found in the book of LaValle [10].

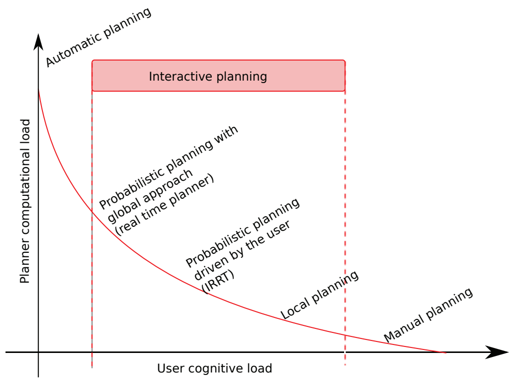


Fig. 1. Computational and cognitive load for interactive planners.

B. Interactive systems and sharing control

In parallel to these works on path planning, during and since the 80's, various problems due to automated systems and human operators collaboration were identified (operator's system misunderstanding, operator skill loss,...). These problems were first noticed in aviation by Wiener [11] but later also in all industrial processes by Bainbridge [12]. These problems persist, as can be seen in Abbink's synthesis in 2011 [13] on shared control between a human and a system through an haptic interface.

In this context, Flemisch described a principle for automation inspired from mounting horses. This principle is called H-Metaphor [14] and presents horses as an autonomous vehicle archetype. Flemisch clarifies the part of his metaphor dedicated to shared control (H-mode) in [15]. He describes how the horse and the rider share the authority. In fact, the rider takes control tightening reins and the horse becomes autonomous when the rider eases reins. Reins can be seen as a haptic interface through which horse can perceive driver involvement. Flemish proposes to use the same paradigm for semi-automated vehicle conception. The H-mode has been studied for an automated car driving through a haptic side stick in [16]

On a higher level, shared control aims at predicting the user's intents, as it has been done for example by Dragan in [17] for a robot teleoperation. In these works, the user's objective is predicted from a set of potential objectives. Two methods of prediction are studied. The first one is an "amnesic" method (only the current position is taken into account) which determines the user's objective thanks to a simple distance computation. The second one is memory based and takes into account previous trajectory and movement's direction to predict intent.

C. Interactive path planning

Thus, at the intersection of these fields (path planning and shared control), interactive path planning applications emerged. Among the interactive planners, there are those dedicated to teleoperation such as Tarault's [18] that aims to give some autonomy to the system in case of connection failure with remote operator. One can also observe planners in virtual environments. Such simulations reuse some features of automatic planners (such as collision detection) for exploration modes where the user directly control the movement [19]. User's movements can also progressively be constrained to help him assembling industrial systems [20]. Finally, interactive path planners through which the user and the planner collaborate to find a path also emerged [21], [22]. Thus, for the Flavigné's IRRT (Interactive Rapidly exploring Random Tree) [21], the diffusion direction of a RRT tree is influenced by the operator's action. Ladevèze [22] defines two different interactive planners. The first one, the local planner, pulls the user on a linear interpolation towards the goal configuration through a haptic interface. Planner ignores obstacles in the environment, so the obstacle avoidance remains the user's responsibility. The second one, the probabilistic planner with global approach, is based on an octree representation of the 3D environment. First an A* algorithm is used to find a free 3D path. Then an RDT algorithm determines a 6D path in the 3D path of A* algorithm. Finally, the 6D path is suggested to the user still through a haptic interface. During the trajectory execution, the user can move away from the path and thus restart the A*/RDT process to generate a new path.

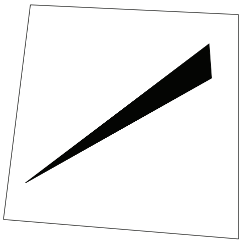
D. Limits of existing interactive planners

At the end of the last work, the three interactive planners were classified by Ladevèze [22] in Fig.1 representing the computation load for the automatic planner and user's cognitive load. The work presented here is therefore a continuation of these planners. Indeed, as a result of these works, it became clear that they implement different ways to share control (control of RRT algorithm diffusion, local path modification or global re-planning). They are suitable for various planning contexts (cluttered environment or not, task to do), but no method to choose or switch between these planners have been determined.

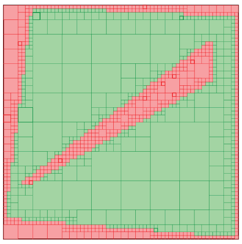
The purpose of the work presented here is to take advantage of the interacting user to simplify planning algorithms. To do this, we use interactive planners strongly inspired from Flavigné [21] and Ladevèze [22] works. We use a novel high level representation of the environment to switch between these planners and also to interpret the user intent.

II. Representation of the Environment

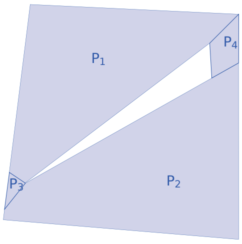
To improve 3D immersive simulation realism and shared control with human user smoothness, a novel environment representation architecture is proposed. This representation is more adapted to the presence of a human operator in the interactive simulation than purely geometrical representations



a. 2D environment.

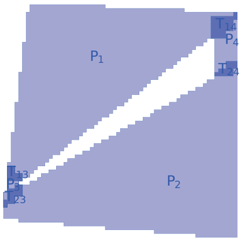


b. Planner representation.

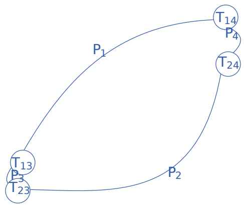


c. User representation.

Fig. 2. Different perceptions of environment for user and planner.



a. Semantic representation.



b. Topological representation.

Fig. 3. High-level environment representation for interactive path planning.

usually used for path planning. To illustrate the basic concepts involved in this innovative approach, a 2D environment is used as an example. All concepts are easy to generalize to the case of a 3D environment.

Consider the simple example in Fig.2.a. This 2D environment is composed of an obstacle of elongated shape separating two large empty places P_1 and P_2 and allowing passage between P_1 and P_2 through two narrow places P_3 and P_4.

Whereas traditional purely geometrical approaches lead to representations like the one presented by Fig.2.b (case of a quadtree decomposition) a human being would have a very different perception of this same environment when executing an action (e.g. walk around the obstacle in this environment). A human being first deals with semantic and topological information. The geometries of the environment (especially of the obstacle and the passage places) are needed more locally (e.g. for collision avoidance), see Fig.2.c.

Thus, to improve automatic planner and user collaboration, it seems essential to make them work in a quite similar environment model. To do this, a semantic and a topological representation are available for the planner to split the planning task into sub-tasks (steps) that can be processed with the geometrical representation.

A. Semantic representation

The semantic representation (Fig.3.a) of the environment provides the automatic planner with semantic information

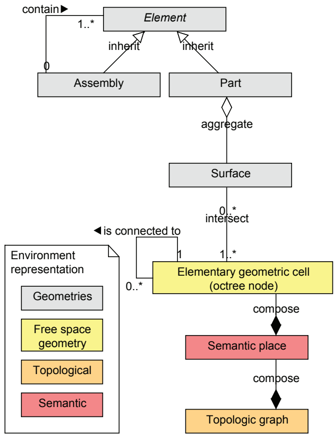


Fig. 4. Environment representation for interactive path planning.

associated to different free spaces and environmental obstacles enabling him to interpret user actions with whom it interacts.

The semantic representation of the environment for the planner (Fig.3.a) is built to match the human being one (Fig.2.c). This representation is made of a set of four places (two free places P_1 and P_2 and two passage places P_3 and P_4).

For now, we consider that this representation of the environment is known a-priori and is built to be used by the interactive planner.

B. Topological representation

Topological information attached to a given environment deals with the concept of places and the topological relation between them (e.g. connectivity). So, the topological representation (Fig.3.b) of the environment consists of a graph that describes the connectivity of the environment. Neighbors places defined in the semantic representation overlap on their common border that define transition areas (T_{13}, T_{14}, T_{23} and T_{24}). The nodes of the graph represent transition areas and are connected by edges representing the path between the transition areas topologically connected. Thus, the use of places as edges and transition areas as nodes in the topological graph allows to easily specify, for each connected pair of transition areas, what place connect them and the distance between them.

The transition areas are automatically computed thanks to a overlaying of places on their common border.

C. Geometric representation

The geometric representation of the environment consists of a set of obstacles and a representation of free space thanks to an octal unbalanced tree (octree) developed during previous work of the laboratory [22]. In the example given on Fig.2.b, a quadtree is used as an equivalent of octree for a 2D environment.

D. Environment model implementation

Fig.4 shows the environment model built for the object-oriented implementation of the environment representations (semantic, topological and geometric). This figure shows how the different representations are associated. The topological graph points toward places to which semantic information can be attached, and describe their connectivity. Semantic places point toward their geometric models: surfaces are represented using analytic equations or meshes, free space is typically represented using an octree.

III. Interactive planning

The interactive planner provides the user with an assistance specifying a preferred direction of movement in the configuration space. This assistance can be used in different ways depending on the platform hosting the interactive simulation capabilities.

A. Various planners

The calculation of the assistance involves four separate planners, each one dedicated to a given representation of the environment.

1) Semantic planner: is responsible for the supervision of the planning, it is linked with the semantic representation of the environment. It allows the semantic planner to configure other planning levels according to the planning context. Thus, it is up to the semantic planner to interpret the planning query to extract the meaningful elements of the semantic representation for each planning context. It is also up to it to interpret the user's action during interactive path planning.

2) Topological planner: manages the progress in the topological graph. To do this, it defines a path consisting of steps (places to cross) and milestones (transitions between two locations) used as goal configurations for each step. Then it monitors progress in the topological graph and measures the gap with the calculated path. If necessary, it seeks a new path better suited to user's wishes.

3) Geometric planner: links the geometric representation of the free space to interactive planner. It associates elementary geometric cells to the different configurations taken, and thus allows other planners to monitor the progress of the path search. The geometric planner can also perform an A* algorithm on the octree portion corresponding to a specific place in order to provide a smaller workspace to local planners described below.

4) Local planner : provides local assistance to the user. It is the planner part allowing user to interact at the geometric level of path planning. The local planner is chosen by the semantic planner according to user's previous progression rate and the current place. Thus, the semantic planner is provided with different local planners adapted to places with different properties (contact or not, geometrically constrained places,...). These planners are strongly inspired from those described at the end of section I-C. Semantic planner activates local planner according to the context.

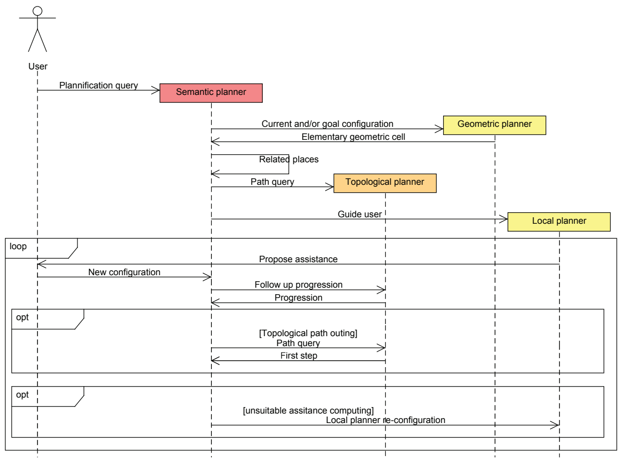
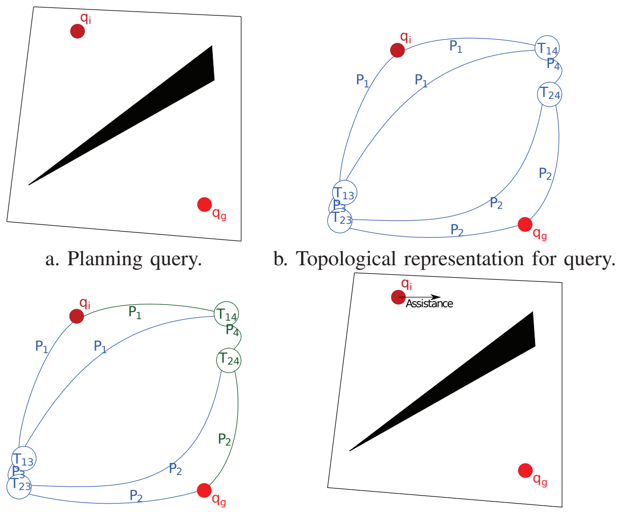


Fig. 5. UML Sequence Diagram of planners collaboration for interactive path planning.



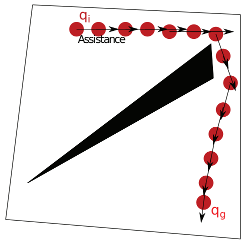
a. Planning query. b. Topological representation for query. c. Topological path. d. User assistance.

Fig. 6. Environment representation for interactive path planning.

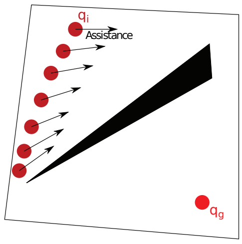
B. Path planning

Fig.5 represents communications between planners for interactive path search. These interactions are discussed in the following paragraphs and illustrated in Fig.6 and 7 where interaction modes for planner and operator are presented.

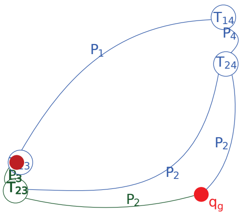
1) Interactive path planning initialization: a planning query (Fig.6.a) creates an instance of the semantic planner that manages the whole path planning process. The semantic planner creates an instance of geometric planner that allows him to localize start and goal configurations in the octree and then in the semantic representation of the environment. The query is then transmitted to the topological planner when instancing. Topological planner, thus, recovers the topological representation of the environment and complement it with planning query data (Fig.6.b). The topological planner compute a path in the topological graph. Each edge constituting this topological path represents a step of the whole trajectory. The first step is thus used by the semantic planner to instantiate properly the local planner.



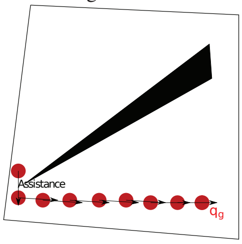
a. User following assistance.



b. User against assistance.



c. Topological re-planning.



d. User intent used for re-planning.

Fig. 7. Environment representation for interactive path planning.

2) Monitoring progress: it is performed on two levels. First by the topological planner which monitors progress in the topological graph and thus detects the transition to a new step. Such transition means a new geometric and semantic context requiring local planner re-configuration (Fig.7.a). Topological planner may also perceive if user runs off pre-computed path (Fig.7.b) and hence detects the need for a new topological planning (Fig.7.c) to define new path (Fig.7.d). For now, a topological re-planning is done only when the user leaves a place to a new one which is not in the pre-computed topological path. Further, prediction methods inspired from [17] could be used to evaluate this gap between the topological path and the performed trajectory. To do so, the set of potential objectives considered must be constituted of the transition areas linked to the current place.

The semantic planner also evaluates the recent configuration evolution in order to adapt, if necessary, the local planner and therefore the calculation of the proposed assistance.

3) Planning methods: They are different for each planner. As mentioned earlier in section III-A4, the planners used as local planners are those defined by Ladevèze and Flavigné. The geometric planner can perform an A* algorithm on the octree part constituting a place to reduce the workspace of the local planner. The topological planner explore the topological graph thanks to a Dijkstra algorithm [23] in order to determine the topological path. Finally, semantic planner does not strictly plan, but uses the semantic representation of the environment to weigh distances of topological graph according to place and planning query characteristics and user's progression. This weighting allows topological planner to chose a path from a set of possible paths. Place and planning query characteristics are also taken into account for to chose the local planner.

IV. Implementation

The proposed planning architecture implementation is in progress on the VR platform of the Laboratoire Génie de Production (LGP) illustrated in Fig.8. This platform consists of an immersive stereo display, a motion capture system and a haptic arm. The implementation structure is shown in Fig.9

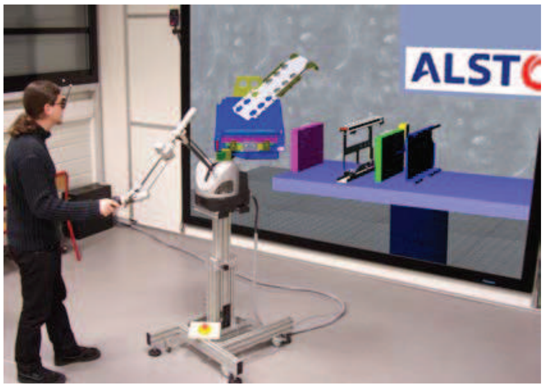


Fig. 8. Assembling simulation on LGP VR platform.

where it is clear that interactive planner is independent of real-time simulation developed with Virtools. This modular implementation allows using the interactive planner in different 3D simulation development environments (3DVIA Studio, Unity 3D, ...). Currently, an UML analysis of the desired system is in progress for a C++ implementation. The object oriented characteristic of this language will be used to define distinct objects for each representation of the environment and for each planner.

The haptic arm of the platform have been chosen to exploit the assistance generated by the local planner through Flemish's shared control paradigm (H-mode). This paradigm is used to give autonomy to the user when he feels able to perform the planning task. The adaptation of authority is obtained by modulating the magnitude of the force pulling the operator. This implementation of H-mode being closely related to our hardware platform, its implementation is hosted in the real-time simulation developed with Virtools. Methods needed are developed with the SDK (Software Development Kit) of this software and update existing library dedicated to haptic arm control.

The interactive planner is developed in a dedicated library, independent from Virtools, but also implies the development of a new library for interfacing the planner to Virtools.

V. Conclusion

The work presented in this paper proposes a way to increase the realism of interactive simulations in immersive 3D environment by supplementing purely geometric models by semantic and topological models. In our application, this information is used by an interactive path planner to adapt planning technique to the task and to the environment. This interactive path planning relies on different planners dedicated to the different representations of the environment (semantic, topological, geometric).

Another way to increase the realism of simulations is to enrich the mesh representation of obstacles surfaces with their analytic models. These new information allows implementing algorithms for collision detection between continuous surfaces (not sampled) and path planning with contacts between geometries.

Then, the proposed interactive path planning pays particular attention to shared control with the implementation of

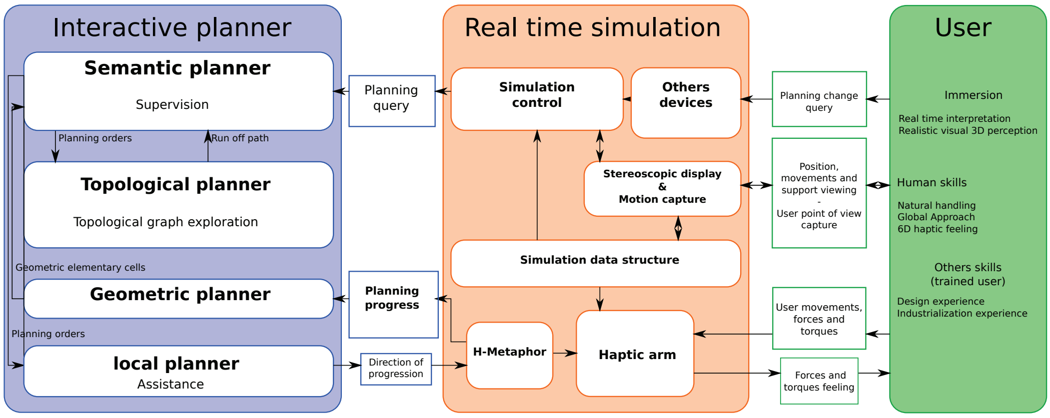


Fig. 9. Structure of a path planning simulation.

the H-mode through the haptic interface of VR platform. This metaphor allows the user to take all the autonomy he needs and increases the ergonomics of simulations. The shared control functionality could also be improved thanks to prediction of user's intents in the topological model of the environment.

Finally, it seems clear that the proposed interactive planner could not be evaluated only with indicators traditionally used in robotics (computation time, nodes created for RRT,...). Indeed, the strong implication of the operator in path planning needs to be taken into account. So, robotics indicators can be used for nominal scenario, but more psychological indicators must be provided to evaluate the interactivity of the planner. For interactivity, two things can be evaluated: the planner efficiency to assist the operator, and the planner acceptability by the operator. About 10 different operators will be invited to test the interactive planner. The operator's task performances with and without interactive planner will be compared to evaluate planner's efficiency. The planner ergonomics will be assessed by asking operators about their feelings during simulations.

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