Motion Planning and Autonomy for Virtual Humans
Class Notes

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Part 3

Biographies

Julien Pettré is Chargé de Recherche at INRIA-IRISA since 2006. He received B.S., M.S. and Ph.D. degrees in Mechanical Engineering and Computer Science in 1998, 2000 and 2003. Prior to joining the Bunraku team at IRISA, he was postdoctoral fellow at the EPFL-VRlab of Pr. D. Thalmann. His research interests include robotics and computer graphics. His works focused on motion planning for virtual humans: locomotion, manipulation and crowd navigation planning.

Marcelo Kallmann is Assistant Professor and Founding Faculty in the Engineering School at the University of California, Merced. He is also currently affiliated as adjunct faculty to the Computer Science Department of the University of Southern California (USC). Prior to joining UC Merced, Prof. Kallmann was a researcher working on Autonomous Virtual Humans at the USC Institute for Creative Technologies (ICT). Before that he did postdocs on humanoid robotics at the USC Robotics Lab and on virtual human animation at the Virtual Reality Lab of the Swiss Federal Institute of Technology (EPFL), where he completed his Ph.D. in 2001. His main areas of interest are motion planning, computer animation and robotics.

Ming C. Ling received her Ph.D. in EECS from UC Berkeley. She is currently Beverly Long Distinguished Professor of Computer Science at UNC Chapel Hill. She received several honors and six best-paper awards. She has authored over 170 refereed publications in physically-based-modeling, haptics, motion planning, and geometric computing. She has served as the chair of over 15 conferences and steering committee/board member of IEEE VR, ACM/EG SCA, and IEEE TC on Haptics and on Motion Planning. She is also the associated EIC of IEEE TVCG and serves on 4 editorial boards. She has given many lectures at SIGGRAPH and other conferences.

James Kuffner is an Assistant Professor at the Robotics Institute, Carnegie Mellon University. He received a B.S. and M.S. in Computer Science from Stanford University in 1993 and 1995, and a Ph.D. from the Stanford University Dept. of Computer Science Robotics Laboratory in 1999. From 1999 to 2001, he was a Japan Society for the Promotion of Science (JSPS) Postdoctoral Research Fellow at the University of Tokyo. He joined the faculty at Carnegie Mellon University's School of Computer Science in 2002. He has published over 80 research papers in topics ranging from computer graphics and animation, robotics, and geometric motion planning.

Michael Gleicher is an Associate Professor in the Department of Computer Sciences at the University of Wisconsin, Madison. Prof. Gleicher is founder and leader of the Department's Computer Graphics group. Prof. Gleicher's current research falls into three categories: character animation, particularly the synthesis of human motion from examples; automated multimedia processing and production; and visualization and analysis tools for structural biology. Prior to joining the university, Prof. Gleicher was a researcher at The Autodesk Vision Technology Center and at Apple Computer's Advanced Technology Group. He earned his Ph. D. in Computer Science from Carnegie Mellon University, and holds a B.S.E. in Electrical Engineering from Duke University.

Claudia Esteves is an Associate Professor in the Faculty of Mathematics at the University of Guanajuato, México. She received her Ph.D. in Computer Science from the National Polytechnic Institute of Toulouse in 2007. Her Ph.D. research was conducted at LAAS-CNRS under the supervision of J-P. Laumond on motion planning for virtual characters and humanoid robots. Her research interests include mainly motion planning of human-like mechanisms and motion planning with dynamics.

Jean-Paul Laumond is Directeur de Recherche at LAASCNRS in Toulouse, France. He got the M.S. degree in Mathematics, the Ph.D. and the Habilitation from the University Paul Sabatier at Toulouse in 1976, 1984 and 1989 respectively. In Fall 1990 he has been invited senior scientist from Stanford University. He is currently co-director of the joint French-Japanese laboratory JRL on humanoid robotics. He has been coordinator of several European projects dedicated to robot motion planning technology. In 2001 and 2002 he created and managed Kineo CAM, a spin-off company from LAAS-CNRS devoted to develop and market motion planning technology (third IEEE-IFR prize for Innovation and Entrepreneurship in Robotics and Automation in 2005). His current research is devoted to human motion studies. He teaches Robotics at ENSTA and Ecole Normale Supérieure in Paris. He publishes papers in Computer Science, Automatic Control, Robotics and Neurosciences. He is IEEE Fellow and Distinguished Lecturer.

Part 4

Overview

4.1 Objectives

An enormous amount of Motion Planning techniques has been developed in the past decade specifically targeting applications in Computer Animation. Going beyond the traditional path planning for navigation, recent techniques address challenging problems in cluttered environments ranging from crowd navigation among obstacles to multi-agent cooperative manipulation and to whole-body manipulation and locomotion planning. Given these recent advances, Motion Planning has already become a main tool for controlling autonomous virtual characters and will become crucial for empowering the next generation of Virtual Humans with the *Motion Autonomy* that will be needed in increasingly complex, interactive and realistic Computer Games and Virtual Reality Applications.

These notes present for the first time a systematic and comprehensive exposition of the main Motion Planning techniques that have been developed for applications in Computer Animation, in particular for the animation of Virtual Humans (VHs). These notes comprehensively document the class "'Motion Planning and Autonomy for Virtual Humans"' delivered at SIGGRAPH 2008.

We start with the basic concepts of Motion Planning and then present techniques for increasingly complex problems: ranging from the navigation of single and multiple VHs to object manipulation and synchronization of manipulation and locomotion. We also explain how Motion Planning techniques can handle challenging problems involving underactuated and redundant skeletal structures of Virtual Humans and show examples of complex motions planned in high-dimensional configuration spaces subjected to geometric and kinematic constraints. The advantages of configuration-space Motion Planning are in particular emphasized, for instance in contrast with common approaches based on executing end-effector trajectories with Inverse Kinematics. The described techniques expose the pluridisciplinary aspects of Computer Graphics and Robotics, from the Motion Planning origins in Robotics to its continuous development relying on Graphics tools, to the current increasing need of motion autonomy in Computer Animation. After reading these notes, the reader will obtain a clear understanding of the potential of Motion Planning and the new dimension of motion autonomy that is being achieved by its variety of techniques.

4.2 Intended Audience

These notes are designed both for researchers and developers willing to learn more about the use of advanced Motion Planning techniques for applications in Virtual Reality, Video Games or Computer Animation Systems. The class also discusses practical implementation aspects and several examples and demonstrations are presented and discussed.

4.3 Prerequisites

This class addresses two different domains: Computer Animation and Motion Planning. An overview of basic Motion Planning concepts will be presented but basic Computer Animation concepts are considered to be prerequisites.

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Part 5

Motion Planning and Autonomy for Virtual Humans Syllabus

5.1 Introduction

A motion planning problem occurs every time a mechanical system has to reach a destination with a collision-free motion within an environment containing obstacles. Humans unconsciously solve motion planning problems every time they are moving: walking in streets or buildings, grasping objects, transporting them, scratching their head, driving their car, shaking hands, etc; an infinity of other examples could be enumerated here. In several situations humans are able to plan in few milliseconds some incredibly complex motions with almost no effort. However in other situations, humans require help from maps for deciding on a direction or are even unable to solve a maze or a puzzle for hours.

Robotics historically first formulated the motion planning problem and raised the foundations of motion planning algorithms. Indeed, this domain is motivated by the crucial need of giving robots the required autonomy of motion in order for them to achieve tasks without colliding with obstacles in their environment. Simple formulations were first proposed, such as the Piano Movers Problem, with deterministic solutions [39]. But the problem was rapidly extended in many different directions due to the variety of situations the Robotics domain is facing and the increasing complexity of the Robots' mechanics. Indeed, robots may evolve in different kinds of environments: inside buildings, streets, natural environments, air, water, and even on other planets. Robots may also be very different in their design: from simple mobile platforms (as the Roomba vacuum cleaner) to many degrees of freedom in the case of humanoid robots. However, among the multitude of solutions developed, some major classes of motion planning algorithms can be distinguished. These notes are organized according to these classes.

Looking from the Computer Animation side, it is also clear that several major developments were achieved in the past decades. This class focuses on techniques dedicated to Virtual Human (VH) animation both in the context of interactive applications (where VHs behave autonomously) and of off-line applications (applications for content production, motion editing, etc) where an animator drives the VH's motion according to a scenario. Creating animations for VHs is a challenging task for many reasons. Among them, two are in particular critical to motion planning. First, the Human mechanics is complex: hundreds of degrees of freedom articulate our skeleton. And Second, Human motion is multi-modal, organic, and unique: therefore not all the feasible motions look natural or even correct.

As a result, in the context of media production applications, animators have to combine technical and artistic skills in order to synthesize VHs' motions. Early techniques required key-postures to be defined and interpolated as keyframes. Defining postures for VHs is time consuming and producing natural motion requires many parameter tuning and expertise. Progressively, many new techniques have been proposed to simplify this task or to make part of them automatic: Inverse Kinematics, Motion Editing, Dynamic filtering, etc. In particular motion capture technologies are changing the animation practice significantly. For instance animators can now produce realistic motions by specifying elementary actions, which are automatically computed. This is especially true for the most common actions such as walking, running, etc.

In the context of interactive applications, motion capture based animation is even more important: it does not raise high computation costs and it results in highly-believable motions. It is possible to create a corpus of captured motions and to reuse them for achieving desired actions. However, the main limitation is that the VH capacity of action is limited to the motion capture content, even if great efforts have been proposed in order to slightly modify the content and adapt the motion data to specific situations. As a result, many different techniques are available for obtaining the needed flexibility in data-based animation: motion warping, blending, concatenation, retargetting, parameterized motion graphs, etc.

In conclusion, a first level of motion autonomy has been already reached. It is already possible to achieve VHs performing elementary actions autonomously and with convincing motions. However such animation techniques generally do not take into account the environment where the action takes place. The risk of not taking into account obstacles is serious: in most cases VHs need to perform their motions in realistically constrained environments and collisions with the environments are not acceptable. A second level of autonomy is therefore still required for providing VHs with spatial reasoning abilities, which has been the main goal of the Robotics motion planning domain.

The first type of motion planning problem that comes to mind is probably related to entities navigating autonomously in video games. Path planning is a classical and very important problem, however, it does not expose several important abilities of motion planning algorithms. Indeed, in this case, the motion planning part is reduced to producing paths which are clearly separated from the animation process.

Seminal works that closely combine motion planning with animation techniques appeared in the 90's [22], where a motion planner decides and parametrizes a sequence of elementary actions in order to achieve a high-level task. In such a solution, VHs are truly equipped with spatial reasoning. The obtained results demonstrates that motion planning can be used both for:

1. giving motion autonomy to VHs and allowing them to behave autonomously in interactive applications,
2. getting fast motion prototyping from high level directives in the context of production of animation content.

This seminal work also demonstrates the difficulty of the problem and that a closer integration of motion planning and computer animation methods is required. Indeed, Robotics obviously did not consider the Computer Animation demands. Human-like constraints or expressiveness in motions, at least in the beginning, have not been considered important aspects from a Robotics point of view.

In this class, our main objectives are:

1. To present an overview of existing motion planning techniques in order to give to the audience a clear view on the importance of the capabilities of motion planners, and in particular for addressing specific classes of problems in computer animation.

2. To describe the main techniques that were developed specifically for answering Computer Animation demands: human-like motions and constraints, believability, performance, realism of motions, etc. We will focus on three major case studies: autonomous navigation for VHs in their environment, autonomous navigation for crowds of VHs, and autonomous manipulation of objects.

5.2 Motion Planning Basics
James Kuffner

5.2.1 Introduction: Problem Statement and Useful Concepts

The goal of Motion Planning (MP) is to compute a continuous sequence of collision-free robot configurations connecting given initial and goal configurations. A robot configuration is a specification of the positions of all robot points relative to a fixed coordinate system. Usually, a configuration is expressed as a vector of generalized coordinates including position and orientation parameters.

Historically, the MP problem appeared in the Robotics field in the 60's, as part of the Artificial Intelligence topic. MP was modeled in a discrete manner and solved using Search algorithms (Dijkstra's, A*, etc.). No clear distinction was made between the Action Planning Problem and the Motion Planning problem until continuous representations has been introduced in the early 80's using the Configuration-Space Concept (noted $\mathcal{C}$) introduced by Lozano-Perez in [31], and giving rise to new MP problems formulations.

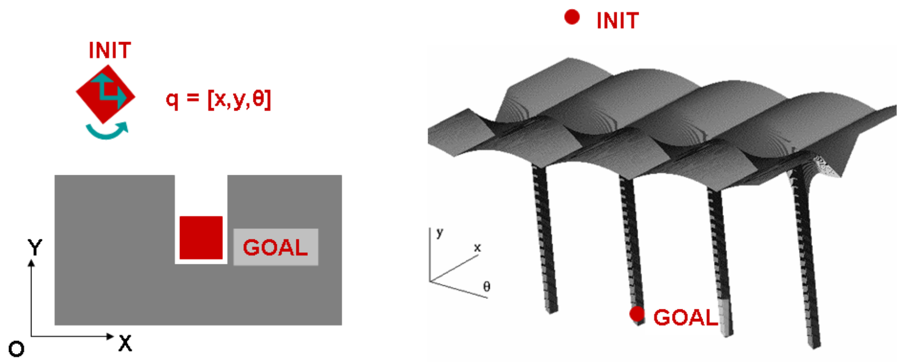

Figure 5.1: Representations of a single motion planning problem (moving the square into the hole) using the workspace representation (left) and the configuration space representation (right). The workspace is 2-dimensional as the red square moves into a plan, whereas the configuration space is 3-dimensional as the square has 3 degrees of freedom (two translations and one orientation.

The Configuration-space or $\mathcal{C}$ is the set of all the possible configurations that a mechanism can attain. Since then, this has been a key concept in motion planning for it allows to translate the problem of moving a body in a space $\mathcal{W} \subset \Re^2$ or $\Re^3$ into the problem of moving a point in another space $\mathcal{C} \subset \Re^n$. The dimension of the manifold $\mathcal{C}$ is equal to the number of independent variables or degrees of freedom (DOF) whose values at an instant t specify a configuration. The obstacle region $\mathcal{C}_{obst}$ in the configuration space corresponds to the configurations where the robot intersects with an obstacle in $\mathcal{W}$. $\mathcal{C}_{free}$ is defined as the collision-free space in the configuration space, i.e. $\mathcal{C}_{free} = \mathcal{C} \backslash \mathcal{C}_{obst}$. In this context, a motion planning problem is re-stated as the problem of computing $\mathcal{C}_{obst}$ and finding a continuous curve or path, $\tau : [0, 1] \rightarrow \mathcal{C}_{free}$, that connects an initial configuration $\tau(0) = q_{init}$ to a final configuration $\tau(1) = q_{end}$. A path exists if and only if q_{init} and q_{end} belong to the same connected component of $\mathcal{C}_{free}$.

5.2.2 Problem Representations: discrete vs. continuous

Some of the earlier algorithms for complete motion planning compute an exact representation of $\mathcal{C}_{free}$ or capture its connectivity using a roadmap. These include criticality-based algorithms such as exact free-space computation for a class of agents [2, 12, 32, 21], roadmap methods [5], and exact cell decomposition methods [39]. However, no efficient implementations of these algorithms are known for high DOF robots. Recently, a star-shaped roadmap representation of $\mathcal{C}_{free}$ has been proposed and applied to low DOF robots [46].

In theory, these methods are general. However, due to the exponential complexity to compute the exact representation of $\mathcal{C}_{free}$, most of these approaches are inefficient, difficult to implement, and limited for robots with low degree of freedom. As a result, many variants have been proposed to deal with special cases of motion planning problems [27].

One of the more commonly used approach is based on Voronoi diagrams. The Voronoi diagram is a fundamental proximity data structure used in computational geometry and related areas [33]. Generalized Voronoi diagrams (GVD) of polygonal models have been widely used for motion planning [7, 27]. The boundaries of the generalized Voronoi diagram represent the connectivity of the space. Moreover, they can be used to compute paths of maximal clearance between a robot and the obstacles. They have been combined with potential field approaches [14], or used to bias the sample generation for a randomized planner [10, 11, 47].

5.2.3 Sampling-Based Planning

The aim of these approaches is to capture the topology of $\mathcal{C}_{free}$ in a roadmap RM without requiring an explicit computation of $\mathcal{C}_{obst}$. The roadmap is used to find collision-free paths. A roadmap can be obtained mainly by using two types of algorithms: sampling and diffusion. These methods are said to be probabilistic complete, which means that the probability of finding a solution, if one exists, converges to 1 as the computing time tends to infinity. The main idea of the sampling technique, introduced as PRM or Probabilistic Roadmaps by Kavraki et al. [20] is to draw random collision-free configurations lying in $\mathcal{C}_{free}$ and to trace edges to connect them with its k-neighbor samples. Edges or local paths should also be collision-free and their form depends on the kinematic constraints of the robot or moving device.

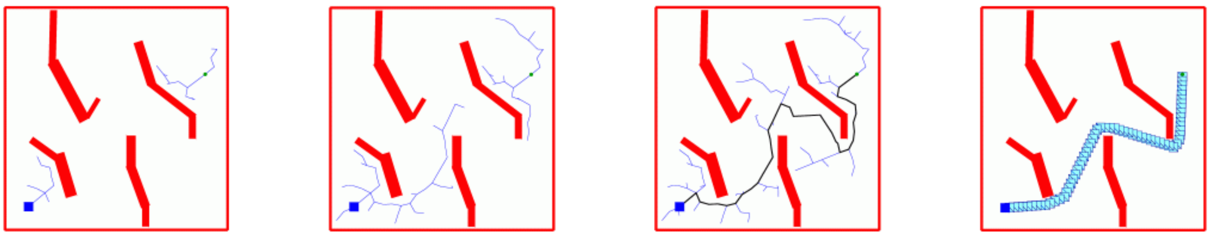

Figure 5.2: The sequence of images shows snapshots of two RRTs during the planning process for a simple 2D example. The final image shows the computed path after optimization.

The principle of diffusion techniques, usually referred to as Expansive-Space Trees (EST) [15] or Rapid-Random Trees (RRT) [29, 25], consists of sampling $\mathcal{C}_{free}$ with only a few configurations called roots and to diffuse the exploration in the neighborhood to randomly chosen directions until the goal configuration can be reached. Motion planners using this methods, are called single-query because they are specific to the input configurations.

When using PRM-like methods, a path is found by using a two-step algorithm consisting of a learning phase and a query phase. In the learning phase, random configurations are drawn within the range allowed for each degree of freedom of the mechanism in order to build a probabilistic roadmap. In the query phase, the initial and final configurations are added as new nodes in the roadmap and connected with collision-free edges. Then, a graph search is performed to find a collision-free path between the start and goal configurations. If a path is found, then it is smoothened to remove useless detours. Finally, it is converted into a time-parameterized path or trajectory $\tau(t)$ by means of classical techniques [41, 3, 42, 26].

5.2.4 Notes

Recommended Readings: [27], [8], [30].

5.3 Case Study 1: Autonomous Navigation for a Virtual Human - Part I Michael Gleicher

5.3.1 The applications of planning and the challenges of synthesis for animated human characters

Navigation is a crucial activity for Animated Human Characters. Thus, autonomous navigation is one of the major challenge when Applying Motion Planning Techniques to Computer Animation. But, Computer Animation has specific demands. We will detail these specific demands in terms of Motion Quality, Path Quality, Controllability and Responsiveness.

5.3.2 Example-Based Synthesis

Motion Capture technologies record the motions of real humans and allow virtual characters to imitate their performance; high-quality motions are intrinsically produced. But, using this technique, potential actions of Virtual Characters are limited to the content of motion captures. The main motivation of example-based techniques is consequently to synthesize high-quality motion from - but not strictly limited to - examples. Three classes of approaches appeared in the literature to answer this demand: editing based, blending based or concatenation based synthesis techniques. We will give an overview of such techniques and detail particularly the concatenation approaches which are to be divided into two categories: the unstructured or the structured approaches producing respectively large or reactive motion graphs.

5.3.3 The limitations of synthesis by concatenation

In practice, concatenation-based motion synthesis techniques have some limitations. We will discuss them in terms of: search space dimension explosion, required path quality trade-offs, lack of reactivity and issues with inexactness.

5.3.4 Using concatenation in practice

At the opposite, we will define define precisely the limits of application domains where motion graphs behave and produce results as expected. We will summarize recent extensions of concatenation techniques and analyze where they are bringing us to. Finally, we will discuss the cases where reactive approaches or hybrid approaches are most suitable.

5.3.5 Notes

Class slides are provided Section 6.1.

Annotated Bibliography is provided Section 7.1.

See also Appendix 8.1, 8.2.

5.4 Case Study 1: Autonomous Navigation for a Virtual Human - Part II Claudia Esteves

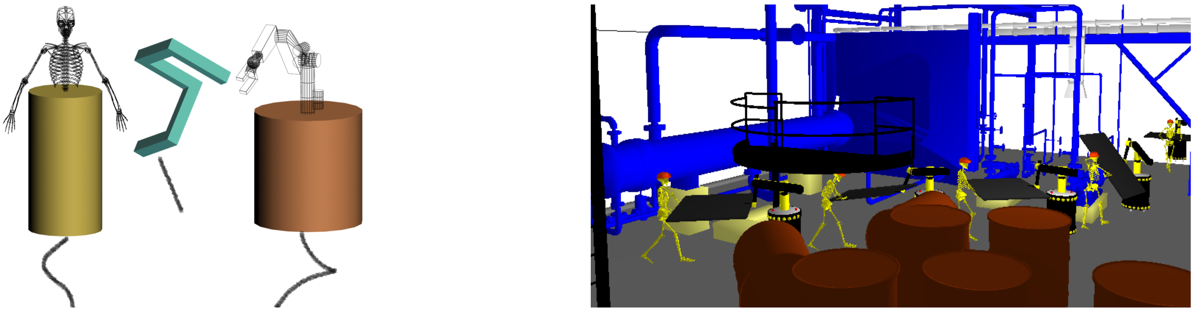

Figure 5.3: (a) Reduced model used for planning purposes in the second approach. (b) Example of an animation obtained with a 3-stage planner.

5.4.1 Abstract

When considering autonomous navigation of virtual characters, we need to design strategies that take the environment and the character's constraints into account. In this course we intend to present some of the works that have been done to automatically produce trajectories for the navigation of human-like figures in 3-dimensional cluttered environments.

Because a virtual character typically has many degrees of freedom, these works fall into the probabilistic motion planning framework.

We divide the presented planners into two categories, knowing that all of them account for the same difficulties:

- dealing with obstacle avoidance,
- generating eye-believable human-like motion,
- dealing with timing constraints for the sake of interactivity.

These two approaches are,

1. Planners where the trajectory is determined in one stage using a complete model of the character or the character's motions, and
2. Planners that rely on a reduced model of the system when determining a trajectory and use two or more stages to synthesize the whole-body motion of the character.

Among the former planners, we consider those based on footprint computation or those based on finite state machines. Among the latter we include those where a bounding volume is used in order to obtain a trajectory and then the motions are synthesized to follow this trajectory. We discuss the advantages and disadvantages of both of these approaches and the pertinence of them when considering specific problems such as having rough terrains, combining behaviors, etc.

5.4.2 Notes

Class slides are provided Section 6.2.

Recommended readings: [4],[23],[24],[6],[38],[28],[37],[9].

See also Appendix 8.3.

5.5 Case Study 2: Autonomous Navigation for crowds of Virtual Humans Part I: Interactive design of virtual population using Navigation Graphs Julien Pettré

5.5.1 Abstract

Figure 5.4: Large Crowds can execute a planned motion using some Levels of Simulation as introduced in [36]

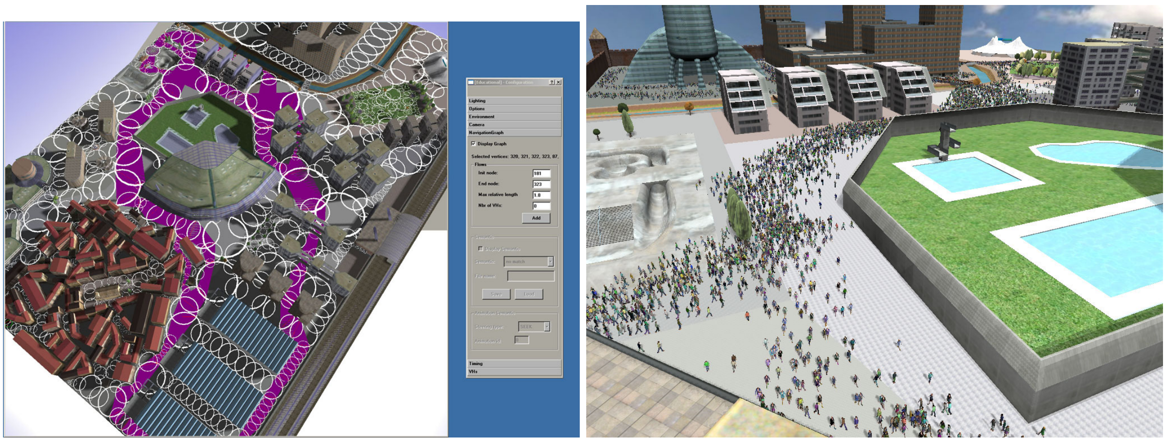

Figure 5.5: Design of a virtual population in a large scale scene using Navigation Graphs [35]

Designers can create easily and quickly their own virtual world, but no much tools exist to design a virtual population. Goal of Navigation Graphs is to provide designers a tool for designing interactively a virtual population from few and simple high level directives. Navigation Graphs is a structure capturing the geometry and the topology of potentially complex and large scenes in a compact manner. Such a structure is computable automatically for many kind of environments from few parameters manipulable by non-experts. Navigation Graphs finally allow to solve path planning queries for large populations very efficiently and answer queries with a variety of solutions, allowing the re-use of planned paths without repeated patterns appearing in the crowd motion.

A secondary problem when a large number of entities is considered at the same time is to execute the planned motion and maintain up to date all the entities positions. Moreover, in this case, the environment is mainly dynamic and modifications to the planned trajectories are required. We will present

Figure 5.6: Using a motion capture system, we recorded and analyzed hundreds of pairs of participants having interacting trajectories. A well-defined protocol allowed us to understand some key factors during reactive navigation tasks executed by Humans.

a solution to scale the real time simulation of virtual crowds: the key-idea is to reuse the environment decomposition that was computed to build Navigation Graphs. Considering the current user's point of view, it is possible to execute the planned motion more or less precisely with respect to the centrality of virtual humans into the display. This allow us to lower considerably required computation times and to reach real-time simulation rates for very large crowds composed by up to tens of thousands of people.

Reactive Navigation is a key functionality for simulating crowds of pedestrians. In this section, we will focus on recent works attempting to give Virtual Humans the ability to react in a realistic manner to the presence of others Virtual Humans navigating in their vicinity. We will detail solutions exploiting database of examples of real people interacting during navigation tasks. We will present two kind of such solutions: firsts attempt to find similar examples in the dataset and reuse their content with maximum preservation, whilst the seconds try to extract a reactive navigation model from an analysis of the set of examples.

5.5.2 Notes

Slides are provided Section 6.3.

Recommended Readings: [35], [36], [34], [43], [44], [45].

See also Appendix 8.4.

5.6 Case Study 2: Autonomous Navigation for crowds of Virtual Humans Part II: Motion Planning Techniques for Large-Scale Crowd Simulation Ming Lin

5.6.1 Real-Time Path Planning for Virtual Agents using MaNG

We introduce a new data structure, Multi-agent Navigation Graph (MaNG), which is constructed from the first - and second - order Voronoi diagrams. The MaNG is used to perform route planning and proximity computations for each agent in real time. We compute the MaNG using graphics hardware and present culling techniques to accelerate the computation. We show in this part how Voronoi diagrams can be used as a practical tool for path planning and navigation of a large crowd.

5.6.2 Navigation of Independent Agents Using Adaptive Roadmaps

First we give a formal definition of roadmaps. We then show how to compute adaptive roadmaps to perform global path planning for each agent simultaneously. We take into account dynamic obstacles and inter-agents interaction forces to continuously update the roadmap by using a physically-based agent dynamics simulator. We also introduce the notion of ”link bands” for resolving collisions among multiple agents. We present efficient techniques to compute the guiding path forces and perform lazy updates to the roadmap.

5.6.3 Interactive Navigation Using Reciprocal Velocity Obstacles

A novel approach for interactive navigation and planning of multiple agents in crowded scenes with moving obstacles. Our formulation uses a precomputed roadmap that provides macroscopic, global connectivity for wayfinding and combines it with fast and localized navigation for each agent. At runtime, each agent senses the environment independently and computes a collision free path based on an extended ”Velocity Obstacles” concept. Furthermore, our new algorithm ensures that each agent exhibits no oscillatory behaviors.

5.6.4 Notes

Slides are provided Section 6.4.

See also Appendix 8.5, 8.6.

5.7 Case Study 3: Autonomous Object Manipulation for Virtual Humans Marcelo Kallmann

In this section of the course, several motion planning approaches for synthesizing animations of autonomous virtual humans manipulating objects will be presented. The topic will be exposed in three main parts. First an overview of the basic approaches for planning arm motions around obstacles for the purpose of reaching and object relocation will be presented. Second, approaches for addressing more complex planning problems involving manipulation and locomotion will be presented. Finally, learning strategies used to optimize the performance of motion planners will be discussed. The topics addressed by these three main subsections are detailed below.

Recommended readings: [17], [18], [16]. See Appendix (Sections 8.7, 8.8).

5.7.1 Sampling-Based Motion Planning for Object Manipulations

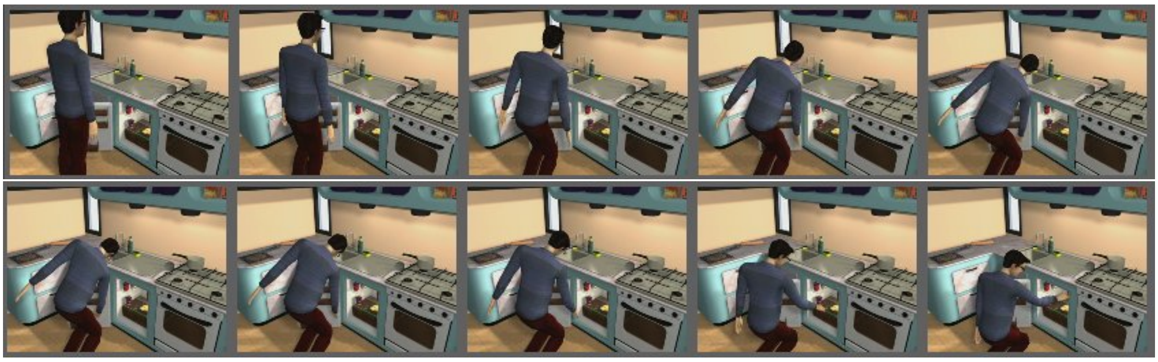

Figure 5.7: Whole-body reaching motion planned for a 22-DOF kinematic model in a kitchen scenario [17].

We will start by summarizing the main approaches taken for synthesizing manipulation motions for human-like characters. The focus will be on the main proposed extensions to sampling-based motion planners, including previous work published at SIGGRAPH.

Then, human-like constraints which can be efficiently implemented for sampling human-like postures for motion planning will be discussed. We will present suitable anatomically-plausible joint parameterizations based on the swing-twist decomposition and joint range limits based on spherical ellipses. Another important factor to take into account when using sampling-based planners is how to sample whole-body configurations which are coupled. As an example, it is not meaningful to extend the arm toward a high object and at the same time bend the knees. Sampling strategies for generating whole-body postures with spine, leg flexion and arm poses coupled in meaningful ways will be presented for the purpose of motion planning. Examples of motions obtained with extensions to traditional probabilistic roadmap methods will be also presented.

Finally we will compare the trade-offs between using precomputed roadmaps and on-line bidirectional search for object reaching and relocation. The focus will be on configuration space approaches and the integration with fast analytical inverse kinematics will also be discussed. Several results will be presented to illustrate the approaches (see Figure 5.7).

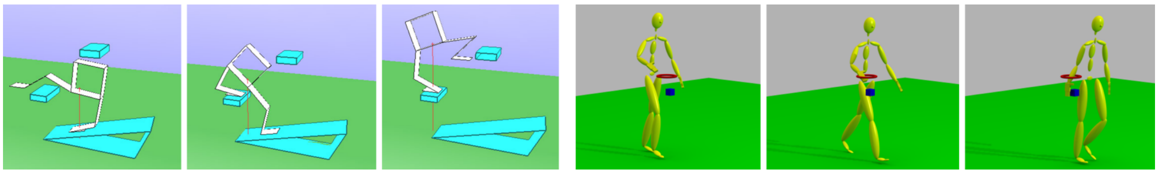

Figure 5.8: Sequencing leg motions for climbing and overcoming obstacles (left) [18] and coordinating walking with reaching (right) [40, 19].

5.7.2 Planning Whole-Body Coordinated Motion

Coordinated whole-body motions are critical for achieving movements that look realistic. The main challenge faced here is that, unlike simple reaching motions, a whole-body coordinated motion is actually a multi-mode planning problem which is usually addressed as a combination of continuous-space planning within a given mode, added to the discrete planning problem of deciding mode change. For instance walking can be planned by considering the motion of each individual leg as an independent motion planning problem, and at the same time considering the choice of which leg to move as an addition discrete planning step. The same framework can be applied to coordinate different human-like primitive skills, as for example parameterized locomotion with reaching and grasping tasks.

In this part of the class we will present approaches for addressing some of these challenges, in particular for achieving coordinated stepping motions with arm reaching motions. Two main aspects of this problem will be presented: (1) the sequencing of movement primitives for planning the precise coordination of legged structures, and (2) the synchronization of concurrent primitives for simultaneous locomotion and object manipulation using locomotion sequences from motion capture (see Figure 5.8).

5.7.3 Improving Planning Performance with Learning

In this part different approaches for improving the motion planning performance will be discussed, both in terms of computation time and quality of results. The approach of pre-computing roadmaps will be revisited but now considering techniques for updating the roadmaps according to obstacle changes. Several experimental results will be presented and compared with on-line bidirectional search approaches. Finally latest results with learning attractor points will be presented and discussed as a feature-based approach for learning motion strategies (see Figure 5.9). The idea is to use succinct indicators (or attractors) able to guide the planning exploration phase in order to achieve a solution much more efficiently. The challenge of this approach is how to associate attractor points with the obstacles in the environment in order to allow the efficient re-use of learned attractors across similar environments and similar tasks. Examples and first results will be presented.

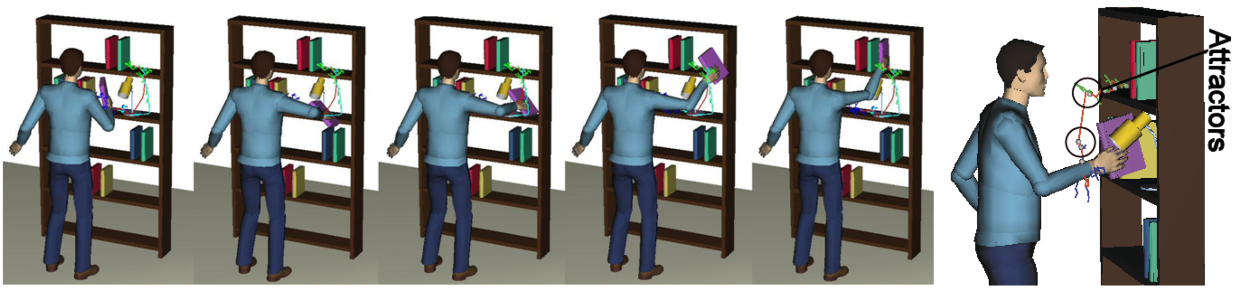

Figure 5.9: The planned motion for a book relocation is learned by extracting and reusing meaningfull attractor points (right-most image) [16].

5.7.4 Notes

Slides are provided Section 6.5.

Annotated Bibliography is provided Appendix 7.2.

See also Appendix 8.7, 8.8.

5.8 Digression: Back to Real?
Jean-Paul Laumond

This last part presents two current synergetic openings to Robotics and Neuroscience in the study of anthropomorphic systems.

5.8.1 Artificial Motion for Humanoid Robots

The goal is to endow humanoid robots with an autonomy of action by using automatic motion planning and execution control systems. The physical interactions between robots and the environment require that the dynamics of the systems be taken into account, wheras motion planning techniques traditionnaly solve these problems by using geometrical and kinematic approaches. We see how controls techniques for dynamics balance (e.g. ZMP approaches) should be integrated in motion planning schemes to combine tasks as manipulation while walking.

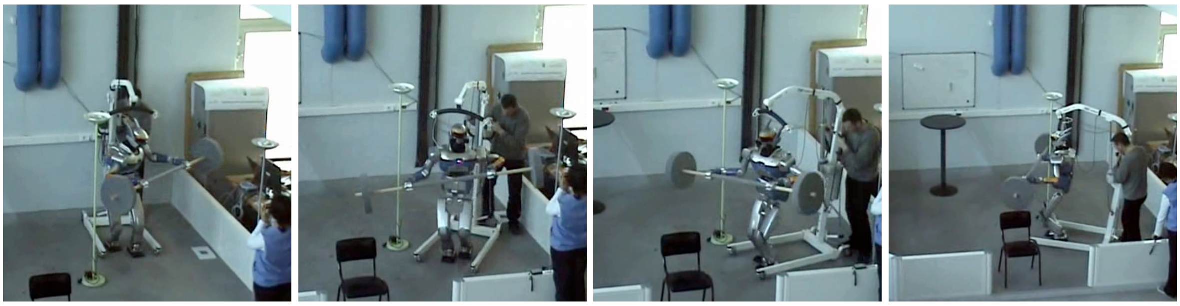

Figure 5.10: Humanoid robot HRP-2 carries a barrel without falling down.

Figure 5.11: Teleoperated by an operator located in Lyon through natural language interaction, the HRP-2 robot in Toulouse looks for a ball with its vision system and grasps it autonomously

5.8.2 Natural Motion for Human Beings

The goal here is to introduce the current multidisciplinary researches (robotics and neuroscience) aiming at exploring the sensori-motor basis of human motions. The human body is a highly redundant mechanical system with many degrees of freedom: a challenge is to understand how the brain solves the redundancy problems by exhibiting invariants in different tasks (e.g., locomotion, grasping). Locomotion will be taken as a worked out example : we will see how robotics models and optimal control methods recently allowed to prove that the shape of human locomotion trajectories obeys an optimality principle : the variation of centrifugal forces is minimized upon orientation changes.

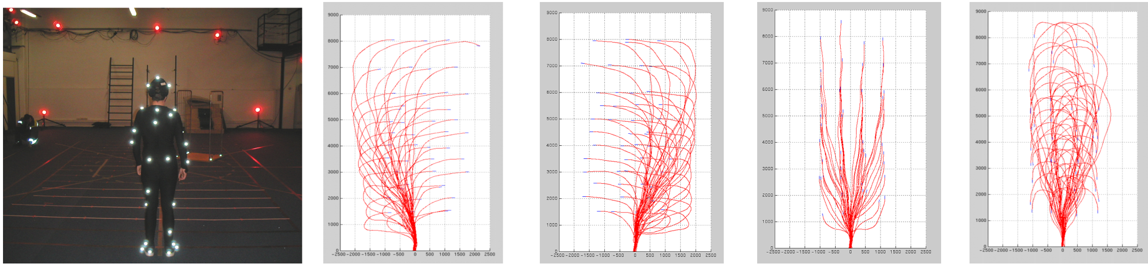

Figure 5.12: The basis of the study is a recording of more than 1.500 trajectories performed by six different subjects using a motion capture system

5.8.3 Notes

Slides are provided Section 6.6.

Recommended Readings: [49], [48], [13], [1].

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