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Robots for the Human and Interactive Simulations

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Abstract: A new field of robotics is emerging. Robots are today moving towards applications beyond the structured environment of a manufacturing plant. They are making their way into the everyday world that people inhabit. The article discusses models, strategies, and algorithms associated with the basic capabilities needed for robots to work, assist, and cooperate with humans. In addition to the capabilities they bring to the physical robot, these models and algorithms and more generally the body of developments in robotics is today making a significant impact on the virtual world. Haptic interaction with an accurate dynamic simulation provides unique insights into the real-world behaviors of physical systems. The potential applications of this emerging technology include virtual prototyping, animation, surgery, robotics, cooperative design, and education among many others.

Keywords: Operational Space Control, Dynamic Simulation, Multiple Contacts, Mobile Manipulation, Real-Time Path Modification, Haptics, Whole-body control

1 Introduction

The successful introduction of robotics into human environments will rely on the development of competent and practical systems that are dependable, safe, and easy to use. To work, cooperate, assist, and interact with humans, the new generation of robots must have mechanical structures that accommodate the interaction with the human and adequately fit in his unstructured and sizable environment. Human-compatible robotic structures must integrate mobility (legged or wheeled) and manipulation (preferably bi-manual), while providing the needed access to perception and monitoring (head camera) [5,11]. Such diverse requirements can only be fulfilled by rather complex mechanisms, posing various challenges for algorithms in modeling, perception, programming, motion planning and control.

As advances are made in methodologies and techniques to address these challenges, it is becoming more and more apparent that their impact is going beyond the physical robot. Models and algorithms in robotics are providing the foundations for developments in many of the application areas found at the intersection of the physical and virtual worlds. These are areas where physical models are simulated and interacted with, such as virtual prototyping, haptics, molecular biology, training, games, collaborative work, and haptically augmented teleoperation [4,9,10]. A large number of ongoing efforts in robotics have resulted in significant advancements in these areas of application; in this article we will survey only some of the developments we have pursued in our laboratory that have contributed to this progress.

The new emerging applications in robotics share the requirement of simulating and controlling physical models with sufficient sophistication to recreate a complicated, physically consistent world and at speeds which allow user interaction. One example is the haptic display of virtual environments, where a robotic device permits the haptic interaction with a virtual environment. The potential applications of this technology include, among others, virtual prototyping, teleoperation, training, and games. The developments in the area of advanced control and simulation methods are discussed in Section 2.

For haptic interaction to appear realistic to the user, the virtual object must exhibit the same simulated physical properties as the real object. These properties include the dynamics of rigid and articulated bodies and their mutual influences like those created by the impact forces during contact. To resolve the physical constraints arising in these situations and to simulate the dynamic behavior of complex objects in a cluttered environment, we have developed fast algorithms, which are presented in Section 3.

Both the virtual and the real world can be populated by complex, articulated and actuated mechanisms. Creating motions for these mechanisms with the purpose of performing a task, performing a command specified by the user in a haptically simulated world, or reacting to interaction with other objects in the environment is a difficult task. In Section 4 our approach to whole-robot modeling and control is presented. It applies equally well to humanoid robots as to complex articulated bodies simulated in the virtual world.

In increasingly complex virtual and physical environments robots or objects can exhibit autonomous behavior: rather than being passively interacted with by a user, they themselves pursue an objective and can initiate interaction with other objects or the user. Section 5 discussed our approach to supporting the interactions resulting from independently and autonomously operating objects.

2 Interactive Haptic Simulation

To address the compexities of programming robots to perfrom tasks in human environments, haptic simulation can play a pivotal role as a user interface or programming environment. The efficient dynamic algorithms, originally applied to robots, are also making a significant impact on the haptic simulation and interaction with the virtual world. The computational requirements associated with the haptic interaction with complex dynamic environments are quite

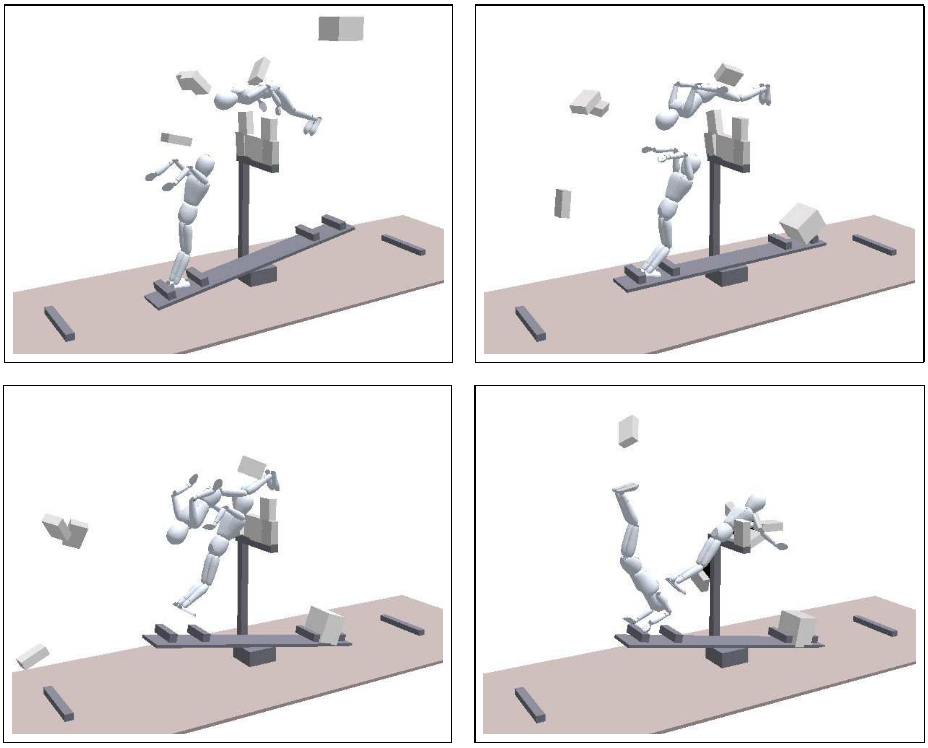

Figure 1: The sequence shows the simulated dynamic interaction between two figures and a number of objects. The dynamics, contacts, and control are computed in interactive time. The ability to simulate complex interactions is a prerequisite for the simulation of sophisticated haptic environments.

challenging. In addition to the need for real-time free-motion simulation of multi-body systems, contact and impact resolution and constrained motion simulation are also needed to convey a sense of physical realism.

Building on the operational space formulation, we developed a general framework [12] for the resolution of multi-contact between articulated multi-body systems. A contact point is treated as an operational point and a contact space is defined. Similarly to the operational space inertia matrix, a contact space inertia matrix Λ is introduced to provide the effective masses seen at all the contact points and to characterize the dynamic relationships between them. Computing the contact space inertia matrices Λ for a number of m contact point on a branching mechanism is achieved with an efficient $O(nm + m^3)$ recursive algorithm.

The contact space representation allows the interaction between groups of dynamic systems to be described easily without having to examine the complex equations of motion of each individual system. As such, a collision model can be developed with the same ease as if one was considering interaction only between simple bodies. Impact and contact forces between interacting bodies can then be efficiently solved to prevent penetration between all the objects in the environment. An example of an interaction between a large number of articulated and rigid bodies is shown in Figure 1. Using our contact space inertia formulation, interactive-timer performance can be achieved, even for scenes with a large number of degrees of freedom. The fast dynamic methods used to compute this dynamic interaction are discussed in more detail in Section 3.

This framework was integrated with our haptic rendering system to provide a general environment for interactive haptic dynamic simulation. Figure 2 shows a user haptically interacting with a simulated humanoid robot. The haptic device serves as a 3D position input and force output device. By moving the end-effector of the haptic device, the user is able to specify a manipulation task for the humanoid robot in real time. At the same time the force output of the device is used to reflect the inertial properties of the manipulated object. Force feedback can also be used to prevent the human operator from approaching configurations with actuation limitations and to avoid singularities, for example.

3 Efficient Operational Space Algorithms

Early work on efficient operational space dynamic algorithms has focused on open-chain robotic mechanisms. An efficient $O(n)$ recursive algorithm was developed using the spatial operator algebra and the articulated-body inertias [3]. A different approach that avoided the extra computation of articulated inertias also resulted in an O(n) recursive algorithm for the operational space dynamics. Building on these early developments, our effort was aimed at algorithms for robotic mechanisms with branching structures that also address the issue of redundancy and dynamics in the null space.

The most computationally expensive element in the operational space whole-body control structure is the posture control, which involves the explicit inversion operation of the $n \times n$ joint space inertia matrix A, which requires $O(n^3)$. We have developed a computationally more efficient operational space control structure that eliminates the explicit computation of the joint space inertia matrix and its inverse. This elimination was achieved by combining

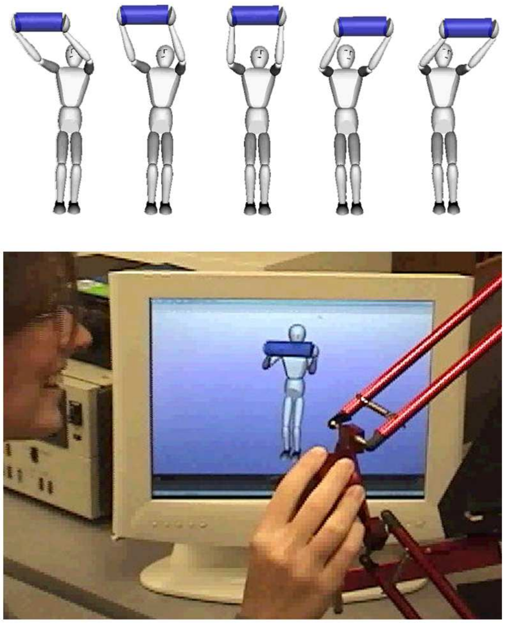

Figure 2: A user commands a virtual robot to move the manipulated object using a haptic device. The device permits the user to interact and control the manipulation task, while the humanoid robot autonomously adjusts its posture according to simple posture energies.

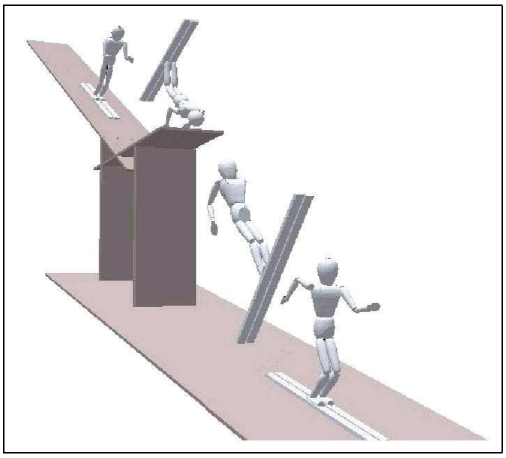

Figure 3: The image shows intermediate snapshots of a motion during a dynamic simulation involving contacts and impulses between an articulated body and its environment. The sliding motion and subsequent jump and landing are dynamically simulated in interactive time.

the dynamically consistent null space control and the operational space control in a computationally more efficient dynamic control structure.

Using this control structure, we have developed a recursive algorithm for computing the operational space dynamics of an n-joint branching redundant articulated robotic mechanism with m operational points [2]. The computational complexity of this algorithm is $O(nm + m^3)$, while existing symbolic methods require $O(n^3 + m^3)$. Since m can be considered as a small constant in practice, this algorithm attains a linear time $O(n)$ as the number of links increases. This work was extended for the dynamics of closed-chain branching mechanisms with an efficient $O(nm + m^3)$ algorithm.

The application of this algorithm to a complex dynamic scene are shown in Figure 3. The sequence of overlayed images illustrates how complex dynamic interactions for articulated bodies, as well as various contact types can be modeled and simulated efficiently.

4 Whole-Robot Control: Task and Posture

For robots with human-like structures tasks are not limited to the specification of the position and orientation of a single effector, or operational point. For these robots, task descriptions may involve combinations of coordinates associated with one or both arms, the head-camera, and/or the torso. The remaining freedom of motion is assigned to various criteria related to the robot's posture and its internal and environmental constraints in the form of posture energies.

Conventionally robot dynamics are described in terms of the robot joint motion. The operational space formulation [7] provides an effective framework for dynamic modeling and control of branching mechanisms in terms of their operational points or end effectors. As a consequence, the desired behavior at an operational point can be described directly in terms of its motion, rather than in terms of the joints causing its motion. In other words, the operational space framework allows the direct control of the task, implicitly accounting for the dynamics and kinematics associated with the manipulator.

A generalized torque/force relationship [7,8] provides a decomposition of the total joint torque command acting on the robot into two dynamically decoupled command torque vectors: the torque corresponding to the task behavior and the torque that only affects posture behavior. The former is used to command motions at the operational points of the robot, whereas the latter performs motion using the redundant degrees of freedom of the robot with out affecting task behavior. This framework extends very easily to robots with branching structures of m effectors or operational points.

Dynamic consistency is the essential property for the task behavior to maintain its responsiveness and to be dynamically decoupled from the posture behavior. This is illustrated in Figure 4 (left), where a robot (a 24-degree-of-freedom humanoid system) was commanded to keep the position of both hands constant (task behavior) while moving its left and right arm (posture behavior). Notice that dynamic consistency enables task behavior and posture behavior to be specified independently of each other, providing an intuitive control of complex systems. In Figure 4 (right) the robot posture can be controlled to maintain the robot total center-of-mass aligned along the z-axis of the reference frame. This resulting behavior is task execution at the operational points, while redundant degrees of freedom are used to maintain balance constraints to prevent tipping. More complex posture behaviors can be obtained by combination of simpler behaviors. We are currently exploring the generation of human-like natural motion from motion capture of human and the extraction of motion characteristics using human biomechanical models.

In addition to control methods to generate task and pos-

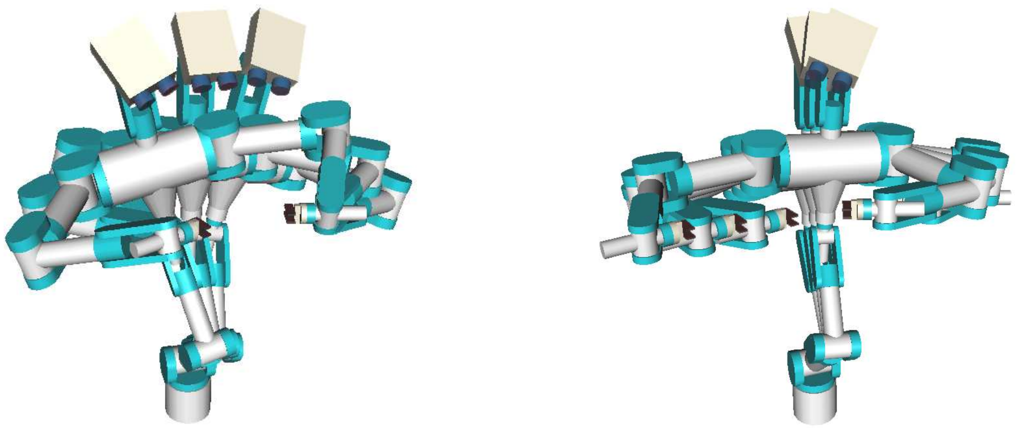

Figure 4: Dynamic Consistency and Posture Behaviors: a sequence of snapshots from the dynamic simulation of a 24-degree-of-freedom humanoid system. On the left, the task is to maintain a constant position for the two hands, while achieving hand-eye coordination. The posture motion has no effect on the task. On the right, the task also involves hand-eye coordination and motion of the common hand position. This position is interactively driven by the user. The posture is to maintain the robot total center-of-mass along the z-axis.

ture behavior for a single robot, effective cooperation strategies are needed both for the cooperation of multiple robots and for the interaction between robots and humans. Several cooperative robots, for instance, may support a load while being guided by the human to an attachment, or visually following the guide to a destination. Our approach to these problems is based on the integration of virtual linkage [9] and the augmented object model. The virtual linkage characterizes internal forces, while the augmented object describes the system's closed-chain dynamics. This approach has been successfully implemented on the Stanford robotic platforms for cooperative manipulation and human-guided motions.

5 Task-Consistent Elastic Plans

A robotic system must be capable of sufficient level of competence to avoid obstacles during motion. Even when a path is provided by a human or automatic planner, sensor uncertainties and unexpected obstacles can make the motion impossible to complete. Our research on the artificial potential field method [6] has addressed this problem at the control level to provide efficient real-time collision avoidance. Due to its local nature, however, reactive methods are limited in their ability to deal with complex environments. Our investigation of a framework to integrate real-time collision avoidance capabilities with a global collision-free path has resulted in the elastic strip approach [1], which combines the benefits of global planning and reactive systems in the execution of motion tasks.

The elastic strip framework modifies a specified path in real time to accommodate potential interactions with other robots or objects in the environment. This enables goal-directed motion in environments that change unpredictably. Due to the fact that the entire path is modified, the problem of local minima exhibited by purely local methods, is avoided. In order to satisfy the real-time requirements of the targeted applications, the efficiency of the elastic strip framework is of great importance. Real-time performance is achieved by the use of efficient free space computation and representation techniques.

The elastic strip framework exploits the decomposition of a robot's motion into task and posture, as described in Section 4, to enable task-consistent real-time path modification. This allows robots to perform desired behavior without interrupting task execution. The overall behavior can consist of a combination of various simple behaviors, such as maintaining a desired posture or avoiding collisions with obstacles. When the physical limitations of the robot render the simultaneous execution of task and additional behavior inconsistent, task execution can be automatically suspended; it is resumed when task-consistency can be achieved.

An example of a real-time path modification in interaction with the environment is shown in Figure 5, where a skiing humanoid avoids a moving snowman and crouches under the lowering finish banner. The snowman is avoided by performing a detour, but also by moving the ski pole closer to the body. The crouching behavior of the skier as it passes under the banner is the result of posture control. The ability to combine task execution with obstacle avoidance and posture behavior, as well as the ability to suspend and resume tasks, provide an important foundation for complex mechanical systems to operate autonomously in virtual or real worlds.

6 Conclusions

Advances toward the challenge of robotics in human environments depend on the development of the basic capabilities needed for both autonomous operations and human/robot interaction. In this article, we have presented methodologies for interactive haptic simulation with contact, relying on efficient dynamic algorithms; we also presented a whole-robot coordination and control scheme, and a framework for real-time modification of collision-free paths to address unpredictable changes in the environment during motion execution. These developments provide some of the basic foundations in the effort to create robots with the advanced capabilities needed for human environments. The real-time capability shared among these developments is a key characteristic for providing the computational tools for a variety of applications at the intersection of the physical and the virtual world.

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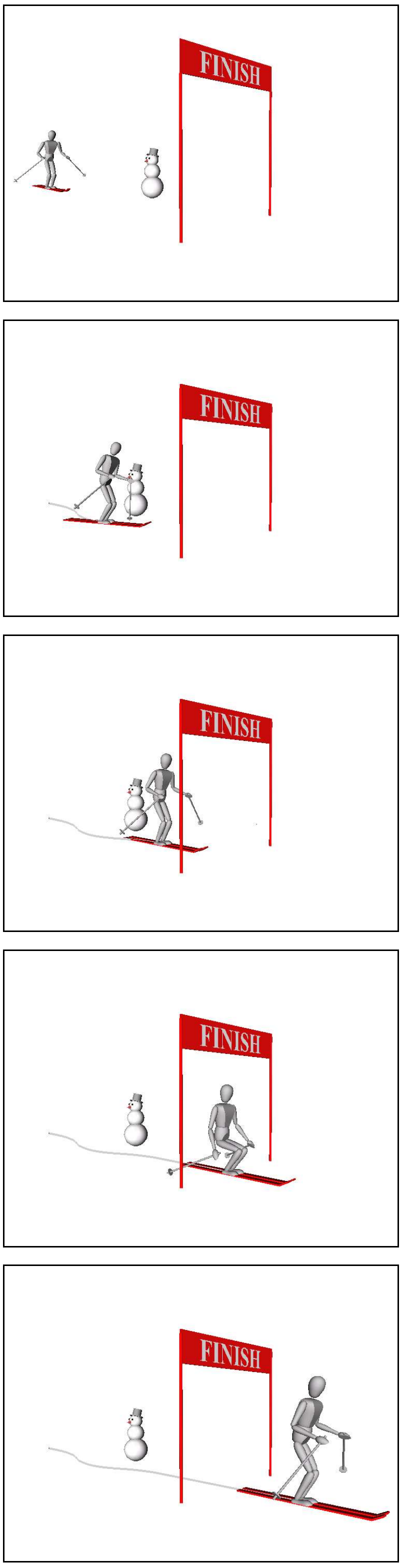

Figure 5: A human figure skies around an approaching snowman and passes through a gate, while the banner is being lowered. Note how all degrees of freedom of the robot are used to avoid collision in real time, as indicated by the ski poles moving closer to the body when passing the snowman and the gate. Posture energy causes the skier to maintain a human-like posture.