Human-Centered Robotics and Haptic Interaction: From Assistance to Surgery, the Emerging Applications

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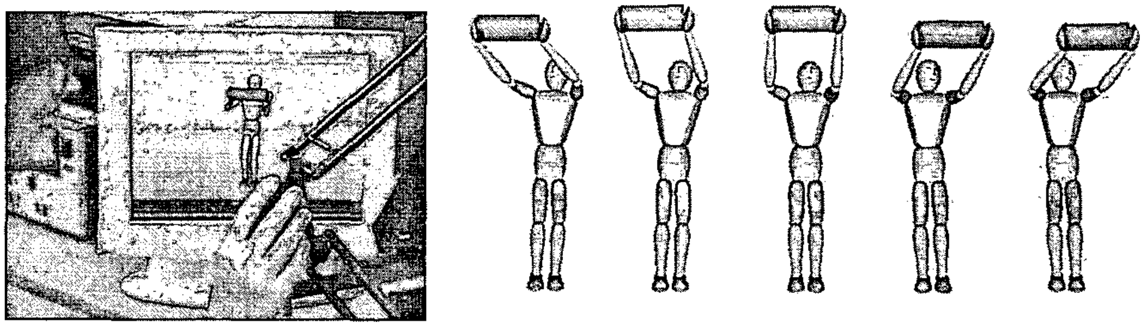
SUMMARY: Robots are moving towards applications beyond the structured environment of a manufacturing plant, making their way into the everyday world that people inhabit. The discussion focuses on the models, strategies, and algorithms associated with the basic capabilities needed for robots to work, interact, and cooperate with humans. In addition to the new capabilities they bring to the physical robot, these models and algorithms and more generally the overall body of developments in robotics is making a significant impact on the virtual world. Tactile or 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, teleoperation, cooperative work, and education among many others.

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, and interact with humans, the new generation of robot require mechanical structures that accommodate the interaction with the human and adequately fit in his unstructured and sizable environment.

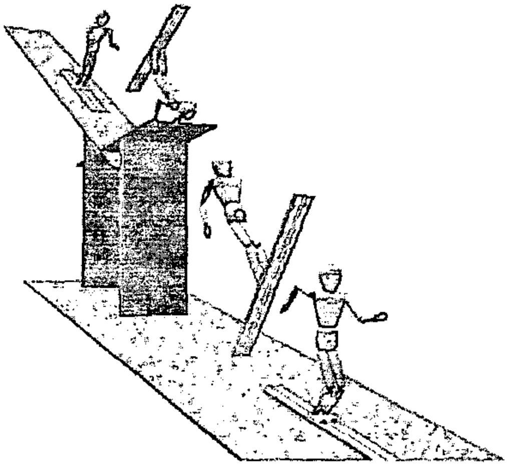
Human-compatible robotic structures must integrate mobility (legged or wheeled) and manipulation (preferably bi-manual), while providing the needed access to perception and monitoring (head camera). These requirements imply robots with branching structures - tree-like topology involving much larger numbers of degrees of freedom than those usually found in conventional industrial robots. The substantial increase in the dimensions of the corresponding configuration spaces of these robots renders the set of fundamental problems associated with their modeling, programming, planning, and control much more challenging.

As advances are made in robotic methodologies and techniques, it is becoming increasingly apparent that the effect of these developments goes beyond the physical robot. Models and algorithms in robotics provide the foundations for developing many of the application areas involving interactive simulation with a physically-consistent virtual world. These applications include virtual prototyping, training, games, animation, collaborative work, and surgery.

For robots with human-like structures, tasks are not limited to the specification of the position and orientation of a single



Interactive Haptic Simulation: The user haptically direct the motion of the manipulated object, while the posture is automatically adjusted according to a simple posture energy.



The sequence shows motion and contact simulation of a controlled figure. The sliding motion and subsequent jump and landing are dynamically simulated in interactive time.

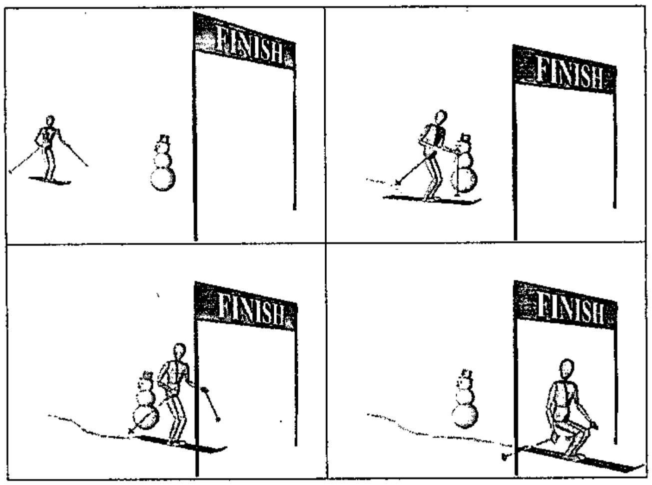
effector. For these robots, task descriptions may involve combinations of coordinates associated with one or both arms, the head-camera, and/or the torso among others. The remaining freedom of motion is assigned to various criteria related to the robot posture and its internal and environmental constraints. Our effort in this area has resulted in a *task-oriented* framework for the whole-robot modeling, motion coordination, and dynamic control. Addressing the computational challenges associated with the simulation and control of these complex structures, we developed efficient algorithms for computing their dynamics and resolving their interaction with the world. Our effort has also addressed the motion planning problem and resulted in an elastic planning framework for efficient modification of collision-free robot path in a task-consistent manner.

An important consideration in the development of posture behaviors is the interactions between the posture and the task. It is critical for the task to maintain its responsiveness and to be dynamically decoupled from the posture behavior. The posture can then be treated separately from the task, allowing intuitive task and posture specifications and effective whole-robot control. This is accomplished by a control structure that is dynamically consistent. The dynamic consistency enables task behavior and posture behavior to be specified independently of each other, providing an intuitive control of complex systems. In addition, complex posture behaviors can be obtained by combining various posture energies. 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.

The computational requirements associated with the haptic interaction with complex dynamic environments are quite 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. Building on our task-oriented formulation, we developed a general framework for the resolution of multi-contact between articulated multi-body systems. A contact point is treated as a controlled task point and a corresponding contact space is defined. Similarly to the task inertia matrix, a contact space inertia matrix 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 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. This framework was integrated with our haptic rendering system to provide a general environment for interactive haptic dynamic simulation.

Motion planning is another computationally challenging problem for robots with large numbers of degrees of freedom. Motion planners generally perform a global search in configuration space to determine a collision-free motion accomplishing a given task. Due to the high dimensionality of the configuration space of those robots, planning operations cannot be performed in real



The sequence shows the real-time elastic modification of trajectory of the figure, as the snowman moves into its path and the finished banner is lowered.

time. As a consequence, motion in dynamic environments cannot adequately be generated by those planners. The elastic band framework was developed to allow real-time modification of a previously planned path, effectively avoiding a costly planning operation in reaction to changes in the environment.

The elastic strip framework augments the representation of a path computed by a planner with a description of free space around that path. Collision avoidance can be guaranteed, if the work space volume swept by the robot along its path is contained within the free space. Real-time path modification is implemented by subjecting the entire path to an artificial potential field, keeping the path at a safe distance from obstacles. The modification of the path in accordance with those potentials is performed while ensuring that the volume swept by the robot along the path is always contained within the representation of local free space. This results in "elastic" paths, which deform in reaction to approaching obstacles, while maintaining the global properties of the path.

In addition to the repulsive, external potential, we also apply internal forces to consecutive configurations of the robot along the path. This shortens and smoothes the path. The overall behavior of of a path represented in the elastic strip framework can be compared to a string of elastic material: as obstacles approach, the path is locally modified or "stretched" by repulsive forces; once the obstacle moves further away, internal forces shorten and smoothen the path. The elastic strip framework scales to robots with many degrees of freedom and with many operational points, as it avoids a costly search for collision-free motion in configuration space. Instead, it employs simple work space-based potential fields in conjunction with aforementioned control structures to modify a previously planned motion in real time.

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. We focused on various methodologies for whole-robot modeling and control, interactive haptic simulation with contact, and real-time modification of collision-free path to accommodate changes in the environment, and their applications in the physical and virtual worlds.

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