Chapter 1
Introduction to Robotics and Digital Human Modeling

1.1 Robotics Evolution: The Past, Today and Tomorrow

Robotics research and technology development have been on the road to grow and advance for almost half a century. The history of expedition can be divided into three major periods: the early era, the middle age and the recent years. The official definition of robot by the Robot Institute of America (RIA) early on was:

"**A robot is a reprogrammable multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks**."

Today, as commonly recognized, beyond such a professional definition from history, the general perception of a robot is a manipulatable system to mimic a human with not only the physical structure, but also the intelligence and even personality. In the early era, people often remotely manipulated material via a so-called teleoperator as well as to do many simple tasks in industrial applications. The teleoperator was soon "married" with the computer numerically controlled (CNC) milling machine to "deliver" a new-born baby that was the **robot**, as depicted in Figure 1.1.

Since then, the robots were getting more and more popular in both industry and research laboratories. A chronological overview of the major historical events in robotics evolution during the early era is given as follows:

1947- The 1st servoed electric powered teleoperator was developed;
1948- A teleoperator was developed to incorporate force feedback;
1949- Research on numerically controlled milling machines was initiated;
1954- George Devol designed the first programmable robot;
1956- J. Engelberger bought the rights to found Unimation Co. and produce the Unimate robots;
1961- The 1st Unimate robot was installed in a GM plant for die casting;
1961- The 1st robot incorporating force feedback was developed;
1963- The 1st robot vision system was developed;

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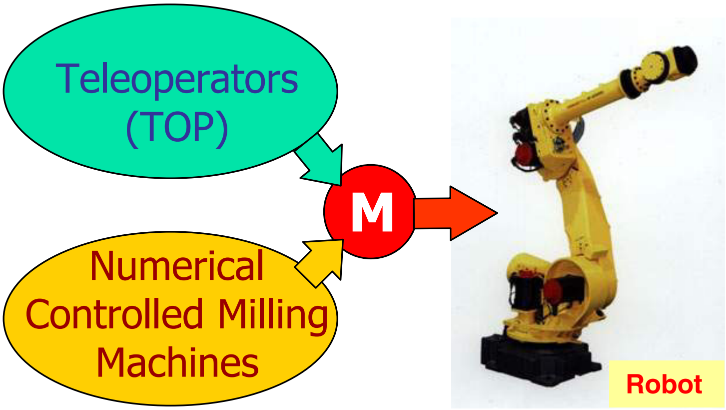

Fig. 1.1 Married with a child

1971- The Stanford arm was developed at Stanford University;
1973- The 1st robot programming language (WAVE) was developed at Stanford University;
1974- Cincinnati Milacron introduced the T3 robot with Computer Control;
1975- Unimation Inc. registered its first financial profit;
1976- The RCC (Remote Center Compliance) device for part insertion was developed at Draper Labs;
1978- Unimation introduced the PUMA robot based on a GM study;
1979- The SCARA robot design was introduced in Japan;
1981- The 1st direct-drive robot was developed at Carnegie-Mellon University.

Those historical and revolutionary initiations are unforgettable, and almost every robotics textbook acknowledges and refers to the glorious childhood of industrial robots [1, 2, 3]. Following the early era of robotics, from 1982 to 1996 at the middle age of robotics, a variety of new robotic systems and their kinematics, dynamics, and control algorithms were invented and extensively developed, and the pace of growth was almost exponential. The most significant findings and achievements in robotics research can be outlined in the following representative aspects:

- The Newton-Euler inverse-dynamics algorithm;
- Extensive studies on redundant robots and applications;
- Study on multi-robot coordinated systems and global control of robotic groups;
- Control of robots with flexible links and/or flexible joints;
- Research on under-actuated and floating base robotic systems;
- Study on parallel-chain robots versus serial-chain robots;
- Intelligent and learning control of robotic systems;

- Development of advanced force control algorithms and sensory devices;
- Sensory-based control and sensor fusion in robotic systems;
- Robotic real-time vision and pattern recognition;
- Development of walking, hopping, mobile, and climbing robots;
- Study on hyper-redundant (snake-type) robots and applications;
- Multi-arm manipulators, reconfigurable robots and robotic hands with dexterous fingers;
- Wired and Wireless networking communications for remote control of robotic groups;
- Mobile robots and field robots with sensor networks;
- Digital realistic simulations and animations of robotic systems;
- The study of bio-mimic robots and micro-/nano-robots;
- Research and development of humanoid robots;
- Development and intelligent control of android robots, etc.

After 1996, robotics research has advanced into its maturity. The robotic applications were making even larger strides than the early era to continuously grow and rapidly deploy the robotic technologies from industry to many different fields, such as the military applications, space exploration, underground and underwater operations, medical surgeries as well as the personal services and homeland security applications. In order to meet such a large variety of challenges from the applications, robotic systems design and control have been further advanced to a new horizon in the recent decades in terms of their structural flexibility, dexterity, maneuverability, reconfigurability, scalability, manipulability, control accuracy, environmental adaptability as well as the degree of intelligence [4]–[8]. One can witness the rapid progress and great momentum of this non-stop development in the large volume of internet website reports. Figure 1.2 shows a new Fanuc M-900iB/700 super heavy industrial robot that offers 700 Kg. payload capacity with built-in iRVision and force sensing integrated systems.

Parallel to the robotics research and technology development, virtual robotic simulation also has a long history of expedition. In the mid-1980's, Deneb Robotics, known as Dassault/Delmia today, released their early version of a robot graphic simulation software package, called IGRIP. Nearly as the same time, Technomatix (now UGS/Technomatix) introduced a ROBOCAD product, which kicked off a competition. While both the major robotic simulation packages impressed the users with their 3D colorful visualizations and realistic motions, the internal simulation algorithms could not accurately predict the reaching positions and cycle times, mainly due to the parameter uncertainty. As a result of the joint effort between the software firms and robotic manufacturers, a Realistic Robot Simulation (RRS) specification was created to improve the accuracy of prediction.

In the mid-1990's, robotic simulation technology was maturing. The capability of robotic simulation had also been extended to Product Lifecycle Management (PLM) [13, 14]. The robot arms, fixtures and workcells in a graphic simulation study were not only getting larger in scale, but also be-

Fig. 1.2 A Fanuc M-900iB/700 industrial robot in drilling operation. Photo courtesy of Fanuc Robotics, Inc.

came more capable of managing product design in association with the manufacturing processes from concept to prototyping, to production. Today, the status of robotic simulation has further advanced to a more sophisticated and comprehensive new stage. It has become a common language to communicate design issues between the design teams and customers, and also an indispensable tool for product and process design engineers and managers as well as researchers to verify and validate their new concepts and findings.

The new trends of robotics research, robotic technology development and applications today and tomorrow will possibly grow even faster and be more flexible and dexterous in mechanism and more powerful in intelligence. Due to the potentially huge market and social demand, robotic systems design, performance, and technology have already jumped into a new transitional era from industrial and professional applications to social and personal services. Facing the pressing competitions and challenges from the transition, robotics research will never be running behind. Instead, by keeping up the great momentum of growth, it will rapidly move forward to create better solutions, make more innovations and achieve new findings to speed up the robotic technology development in the years to come [9]–[12].

Figure 1.3 depicts a robotics research and robotic systems evolution tree. The innovation and continuous development of industrial robots in the early era are the main stem of the tree. The robotics research that was initiated, motivated and challenged by industrial robot development becomes the top of the tree stem before it branches. As the robotics research was rapidly

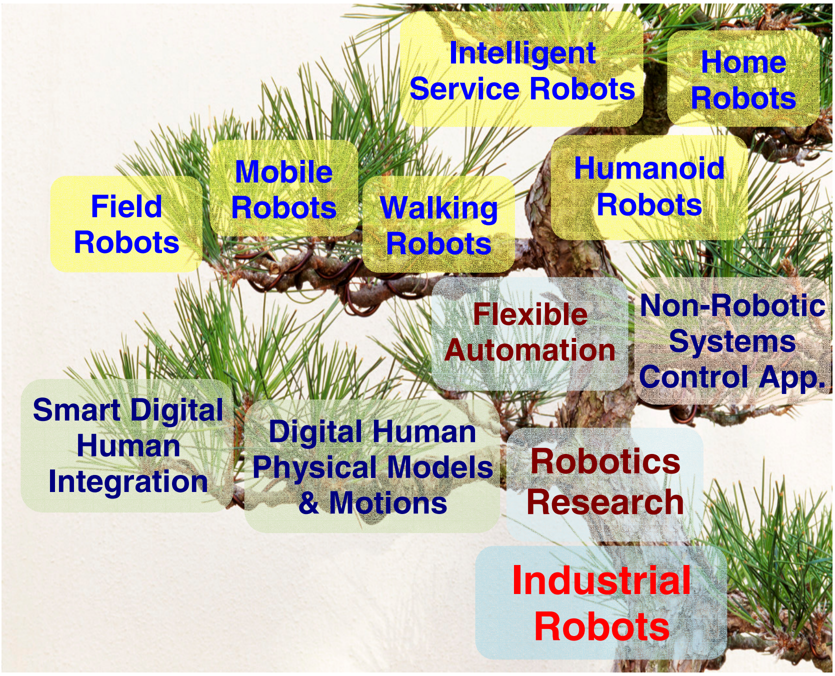

Fig. 1.3 Robotics research and evolutions

growing and getting mature, it became more capable of helping new robotic systems creation and fueling new research branches to sprout and grow. In addition to creating and developing a variety of service robots, a number of new research and application branches have also been created and fed by the robotic systematic modeling approaches and control theories, which benefited their developments. One of those beneficiaries is digital human modeling and applications. The others may include many non-robotic systems dynamic modeling and control strategy design, such as a gun-turret control system for military vehicles, helicopters and platforms, and a ball-board control system that will be discussed in Chapter 8.

While a large number of new service robots and humanoid robots are taking over today's performing stage of robotics, the development of industrial robotic technologies has never slowed down. Instead, they are gaining even more momentum to continuously innovate new robot models and systems to enhance their flexible automation in better serving manufacturing and production lines. A task that used to be operated by a single robot arm is now automated by two-robot coordination, or even by a large number of robots in a group. A typical example of recent applications is to employ a group of more than 20 industrial robots to be globally controlled by an Ethernet/wireless communication-based PLC (Programmable Logic Controller) to weld and fabricate car bodies in an automotive body-in-white assembly station.

One of the most remarkable achievements that deserves celebration is the development of humanoid robots, which underlies an infrastructure of various service robots and home robots. The history of the humanoid robot development is even longer than the industrial robots [15]. An Italian mathematician/engineer Leonardo da Vinci designed a humanoid automaton that looks like an armored knight, known as Leonardo's robot in 1495. The more contemporary human-like machine Wabot-1 was built at Waseda University in Tokyo, Japan in 1973. Wabot-1 was able to walk, to communicate with a person in Japanese by an artificial mouth, and to measure distances and directions to an object using external receptors, such as artificial ears and eyes. Ten years later, they created a new Wabot-2 as a musician humanoid robot that was able to communicate with a person, read a normal musical score by his eyes and play tones of average difficulty on an electronic organ. In 1986, Honda developed seven biped robots, called E0 (Experimental Model 0) through E6. Model E0 was created in 1986, E1-E3 were built between 1987 and 1991, and E4-E6 were done between 1991 and 1993. Then, Honda upgraded the biped robots to P1 (Prototype Model 1) through P3, as an evolutionary model series of the E series, by adding upper limbs. In 2000, Honda completed its 11th biped humanoid robot, known as ASIMO that was not only able to walk, but also to run.

Since then, many companies and research institutes followed to introduce their respective models of humanoid robots. A humanoid robot, called Actroid, which was covered by silicone "skin" to make it look like a real human, was developed by Osaka University in conjunction with Kokoro Company, Ltd. in 2003. Two years later, Osaka University and Kokoro developed a new series of ultra-realistic humanoid robots in Tokyo. The series initial model was Geminoid HI-1, followed by Geminoid-F in 2010 and Geminoid-DK in 2011.

It is also worth noting that in 2006, NASA and GM collaborated to develop a very advanced humanoid robot, called Robonaut 2. It was originally intended to assist astronauts in carrying out scientific experiments in a space shuttle or in the space station. Therefore, Robonaut 2 has only an upper body without legs for use in a gravity-free environment to perform advanced manipulations using its dexterous hands and arms [16, 17].

Almost every year, a large number of new humanoid robots are reported to show up worldwide. While the degree of intelligence and the realistic dynamic motion may still be two major challenges to the humanoid robot research and development, their appearance and motion speed have made a revolutionary breakthrough and climbed to a new height. We are quite optimistic that sooner rather than later, a smart humanoid robot would come to reality, and a true intelligent home robot would be a family addition to serve and assist in daily housework and to entertain family members and guests, and even replace a desktop or laptop computer to do every computation and documentation work in the home. However, to achieve this goal, only making a technological development effort is not enough. Instead, it must also rely on more new findings and solutions in theoretical development and basic research to overcome every challenging hurdle.

As a summary, in the recent status of basic research in robotics, there is a number of topics that still remain open:

1. Adaptive control of under-actuated robots or robotic systems under non-holonomic constraints;
2. Dynamic control of flexible-joint and/or flexible-link robots;
3. The dual relationship between open serial and closed parallel-chain robots;
4. Real-time image processing and intelligent pattern recognition;
5. Stability of robotic learning and intelligent control;
6. Robotic interactions and adaptations to complex environments;
7. Perceptional performance in a closed feedback loop between robot and environment;
8. Cognitive interactions with robotic physical motions;
9. More open topics in robot dynamic control and human-machine interactions.

In conclusion, the robot analysis part of this book is intended to motivate and encourage the reader to accept all the new challenges and make every effort and contribution to the current and future robotics research, systems design and applications. The robotics part of the book will cover and focus primarily on the three major fundamental topics: kinematics, dynamics, and control, along with the related MATLAB^{TM} programming. Specifically, Figure 1.4 illustrates the formal definitions in the covered topics of robotics. However, the book does not intend to include discussions on robotic force control, learning and intelligent control, robotic vision and recognition, sensory-feedback control, and programmable logic controller (PLC) and human-machine interface (HMI) based networking control of robotic groups. The reader can refer to the literature or application documents to learn more about those application-oriented topics.

1.2 Digital Human Modeling: History, Achievements and New Challenges

Dr. Don Chaffin from HUMOSIM Research Laboratory in the University of Michigan has made a comprehensive review in 2008 [19]. At the beginning of this review, he emphasized that many human factors/ergonomics specialists have long desired to have a robust, analytic model that would be capable of simulating the physical and cognitive performance capabilities of specific, demographically defined groups of people. He also referred to a 1990 report from the U.S. National Research Council on human performance modeling that highlights the following benefits of such models:

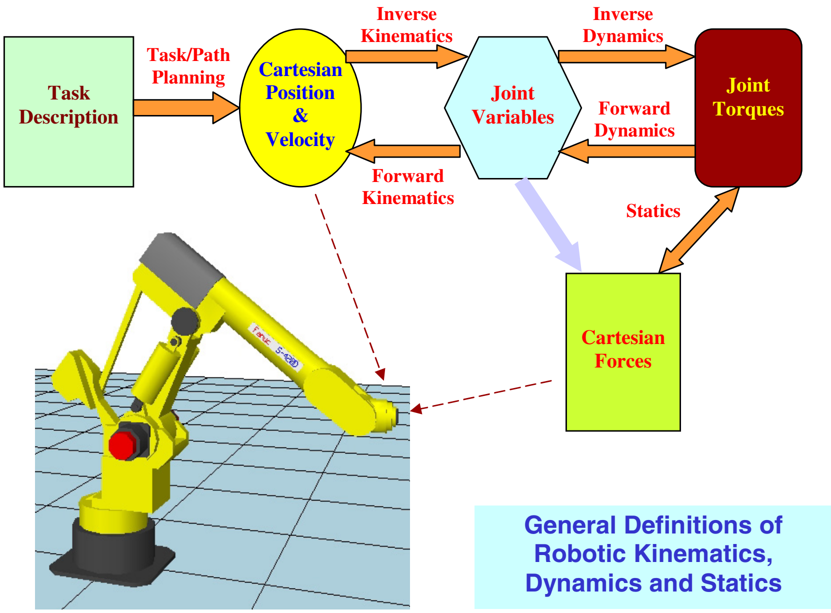

Fig. 1.4 Important definitions in robotics

1. Experts in ergonomics can simulate and test various underlying human behavior theories with these models, thus better prioritizing areas of new research;
2. Experts can use the models to gain confidence about their own knowledge regarding people's performance under a variety of circumstances;
3. The models provide a means to better communicate human performance attributes and capabilities to others who want to consider ergonomics in proposed designs.

Due to the limitation of computer power, the early attempt of digital human physical modeling was undertaken only conceptually until the late 1970's. With the exponential growth of computational speed, memory and graphic performance, a mannequin and its motion could be realistically visualized in a digital environment to allow the ergonomics specialists, engineers, designers and managers to more effectively assess, evaluate and verify their theoretical concepts, product designs, job analysis and human-involved pilot operations.

One of the earliest efforts of computerized human performance models in history, according to Chaffin's review, was done by K. Kilpatrick in 1970. He made a 3D human graphic model to demonstrate how the model reaches and moves in a seated posture. After the 1970's, a number of sophisticated digital human models emerged. SAMMIE (System for Aiding Man-Machine

Interaction Evaluation) was developed in the United Kingdom at that time and is now one of the leading packages in the world to run digital human simulations. During the late 1980's, Safework and Jack were showing their new mannequins with real-time motions as well as their unique features and functions. In the early 1990's, a human musculoskeletal model was developed in a digital environment by AnyBody Technology in Denmark to simulate a variety of work activities for automotive industry applications [18].

One of the most remarkable achievements in recent digital human modeling history was the research and development of a virtual soldier model: Santos in Center for Computer Aided Design at the University of Iowa, led by Dr. Karim Abdel-Malek during the 2000's [22, 23, 24]. It is now under continuous development in a spin-off company SantosHuman, Inc. Not only has the Santos mannequin demonstrated its unique high-fidelity of appearance with deformable muscle and skin in a digital environment, but it has also made a pioneering leap and contribution to the digital human research community in borrowing and applying robotic modeling theories and approaches. Their multi-disciplinary research has integrated many major areas in digital human modeling and simulation, such as:

- Human performance and human systems integration;
- Posture and motion prediction;
- Task simulation and analysis;
- Muscle and physiological modeling;
- Dynamic strength and fatigue analysis;
- Whole body vibrations;
- Body armor design and analysis;
- Warfighter fightability and survivability;
- Clothing and fabric modeling;
- Hand modeling;
- Intuitive interfaces.

To model and simulate dynamics, one of the most representative software tools is MADYMO (Mathematical Dynamic Models) [20]. MADYMO was developed as a digital dummy for car crash simulation studies by the Netherlands Organization for Applied Scientific Research (TNO) Automotive Safety Solutions division (TASS) in the early 1990's. It offers several digital dummy models that can be visualized in real-time dynamic responses to a collision. It also possesses a powerful post-processing capability to make a detailed analysis and check the results against the safety criteria and legal requirements. In addition, MADYMO provides a useful simulation tool of airbag and seat-belt design as well as the reconstruction and analysis of real accidents.

While all the achievements after three decades of extensive investigations in digital human modeling for design and engineering applications are quite encouraging [20, 21], there are still many big challenges ahead, and they can be summarized as follows:

1. Although the realism of digital human appearance has made a breakthrough, the high-fidelity of digital human motion may need more improvements, especially in a sequential motion, high-speed motion and motion in complex restricted environments;
2. Further efforts need to be made for modeling human-environment interactions in a more effective and adaptive fashion;
3. More work must be done to enhance the digital human physical models in adapting to the complex anthropometry, physiology and biomechanics, as well as taking digital human vision and sound responses into modeling consideration;
4. Develop a true integration between the digital human physical and non-physical models in terms of psychology, feeling, cognition and emotion.

1.3 A Journey from Robot Analysis to Digital Human Modeling

After screening the history and evolution of research and technology development in both robotics and digital human modeling, it is foreseeable that all progresses and cutting-edge innovations can always be mirrored in leading commercial simulation software products. However, most of such graphic simulation packages render a small "window" as a feature of open architecture to allow the user to write his/her own application program for research, testing or verification. When the user's program is ready to communicate the product, it often requires a special API (Application Program Interface) in order to acknowledge and run the user's application program. Thus, it becomes very limited and may not be suitable for academic research and education. Therefore, it is ideal to place the modeling, programming, modification, refinement and graphic animation all in one, such as MATLAB^{TM}, to create a flexible, user-friendly and true open-architectural digital environment for future robotics and digital human graphic simulation studies.

This book aims to take a journey from robot to digital human by providing the reader with a means to build a theoretical foundation at the beginning. Then, the reader will be able to mock up a desired 3D solid robot model or a mannequin in MATLAB^{TM} and drive it for motion. It will soon be realized that writing a MATLAB^{TM} code may not be difficult, because it is the highest-level computer language. The most challenging issue is the necessary mathematical transformations behind the robot or mannequin drawing. This is the sole reason why the theoretical foundation must be built up before writing a MATLAB^{TM} program to create a desired digital model for animation. Since MATLAB^{TM} has recently added a Robotics toolbox into the family, it will certainly reinforce the conceptual understanding of robotic theories and help for learning numerical solutions to robotic modeling procedures and motion algorithms.

Therefore, to make the journey more successful and exciting, this book will specifically focus on the basic digital modeling procedures, motion algorithms and optimization methodologies in addition to the theoretical fundamentals in robotic kinematics, statics, dynamics, and control. Making a realistic appearance, adapting various anthropometric data and digital human cognitive modeling will not be the emphasis in this book. Instead, once a number of surfaces are created to be further assembled together, more time can always be spent to sculpture each surface more carefully and microscopically to make it look like a real muscle/skin as long as the surface has a sufficient enough resolution. Moreover, one can also concatenate the data between the adjacent surfaces to generate a certain effect of deformation. For this reason, this book will introduce a few examples of basic mathematical sculpturing and deforming algorithms as a typical illustration, and leave to the reader to extend the basic algorithms to more advanced and sophisticated programs.

Furthermore, in the digital human modeling part of the book, each set of kinematic parameters, such as joint offsets and link lengths for a digital mannequin is part of the anthropometric data. They can be easily set or reset from one to another in a modeling program, and the parameter exchange will never alter the kinematic structure. For example, when evaluating the joint torque distribution by statics for a digital human in operating a material-handling task, it is obvious that the result will be different from a different set of kinematic parameters. However, once entering a desired set of parameters, the resulting joint torque distribution should exactly reflect the person's performance under the particular anthropometric data. There is a large number of anthropometry databases available now [20], such as CAESAR, DINED, A-CADRE, U.S. Army Natick, NASA STD3000, MIL-STD-1472D, etc. The reader can refer to those documents and literature to find appropriate data sets for high-credibility digital assessment and evaluation.

It is quite recognizable that in terms of real human musculoskeletal structure, the current rigid body-based digital human physical model would hardly be considered an accurate and satisfactory model until every muscle contraction and joint structure of real human are taken into account. Nevertheless, the current digital human modeling underlies a framework of the future targeting model. With continuous research and development, such an ideal digital human model with realistic motion and true smart interaction to complex environments would not be far away from today.

On the other hand, due to the maturity of robotics research, developing a digital human model and motion can be harvested by borrowing the systematic robotic modeling theories and motion algorithms. Therefore, this book is organized to trace the journey from robot analysis to digital human modeling. Chapters 2 and 3 introduce all the useful and relevant mathematical fundamentals. Chapter 4 starts a robotic modeling procedure and kinematic formulation. Chapter 5 will study the robots with redundancy, as well as the forward and inverse kinematics for serial/parallel hybrid-chain robotic systems. Once the foundations of robotics are built up, Chapter 6 will describe and illustrate the major steps to create parts and assemble them to mock up a complete robotic system with 3D solid drawing in MATLAB^{TM}. The robotic dynamics, such as modeling, formulation, analysis and algorithms, will then be introduced and further discussed in Chapter 7. It will be followed by an introductory presentation and an advanced lecture on robotic control: from independent joint-servo control to global dynamic control in Chapter 8. Some useful control schemes for both robotic systems and digital humans, such as the adaptive control and backstepping control design procedure, will be discussed in detail as well.

Starting from Chapter 9, the subject will turn to digital human modeling: local and global kinematics and statics of a digital human in Chapter 9, and creating parts and then assembling them together to build a 3D mannequin in MATLAB^{TM} as well as to drive the mannequin for basic and advanced motions in Chapter 10. The hand modeling and digital sensing will also be included in Chapter 10. The last chapter, Chapter 11, will introduce digital human dynamic models in a global sense, and explore how to generate a realistic motion using the global dynamics algorithm. At the end of Chapter 11, two typical digital human dynamic motion cases will be modeled, studied and simulated, and finally, it will be followed by a general strategy of interactive control of human-machine dynamic interaction systems that can be modeled as a k-cascaded large-scale system with backstepping control design.

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