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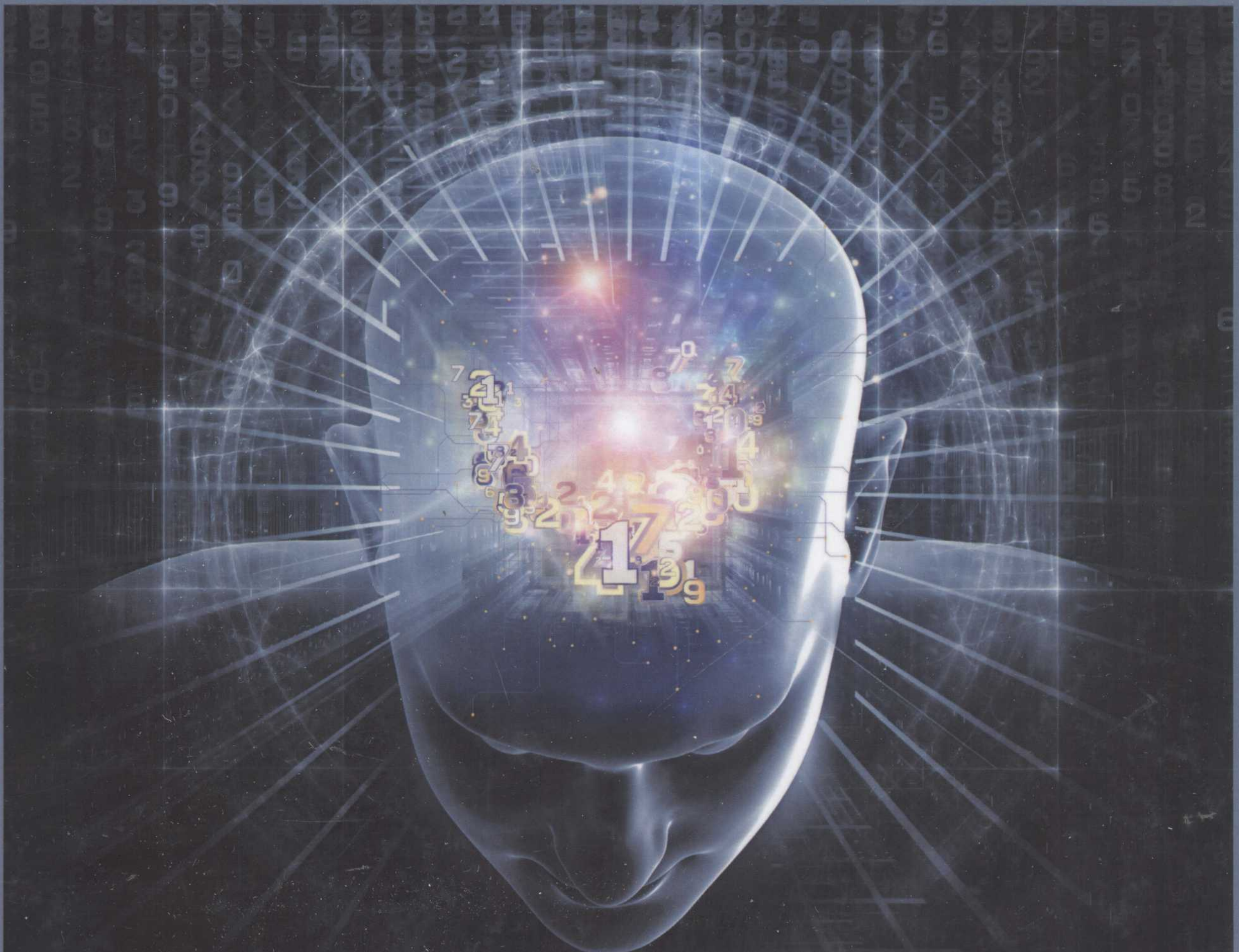
Advanced Engineering and Computational Methodologies for Intelligent Mechatronics and Robotics



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Preface

The fields of mechatronics and robotics engineering have witnessed enormous progress in recent years. Unprecedented advances in computing hardware and software, sensor and actuator technology, and science of controls, signal processing, artificial intelligence, and computing have spurred the rapid growth of the applications of mechatronic and robotic systems. Application areas of these technologies span from advanced manufacturing systems in the automotive and microelectronic industries to the emerging fields of medical and personal care. Manufacturing processes have benefited from greater integration of new sensing and information processing technologies into more sophisticated and intelligent systems that can operate at scales considered impossible before. Medical and surgical robots have emerged as intelligent mechatronic devices that allow medical practitioners not only to improve existing procedures, but also to carry out operations that would have been unimaginable only a few years ago. Advances in robotics and mechatronics have led to new prosthetic and rehabilitative devices that help the injured and disabled to recover faster and regain some of their lost functionality. Robots also have gained popularity for personal and home care, in part due to the ageing population in the developed world.

Robots have proven effective in many other terrestrial applications. Unmanned remotely operated robotic vehicles are increasing used in disaster recovery and search and rescue operations, mining, underwater exploration, and military combat and intelligence operations. Remotely operated robots played a crucial role in assessing the damage to the nuclear power plants after the 2011 earthquake and tsunami in Japan. In recent years, the United States military has deployed an increasing number of unmanned mobile robots and aerial drones for combat and intelligence operations. In space, robotic rovers are exploring the surface of Mars to help gather critical scientific information about the planet that one day may lead to its colonization. Robotic manipulators carry out many of the critical assembly and maintenance operations on the International Space Station (ISS) in the hazardous space environment.

A cycle of sensing, perception, control, and action characterizes modern intelligent robotic and mechatronic systems. They incorporate core hardware and software processing and control elements to provide a desired functionality within a task environment. The essential hardware components of these systems are sensors, actuators, and computing machinery. Signal and image processing, state estimation and navigation algorithms, controls, and artificial and computational intelligence are examples of software elements. It is precisely because of this complexity that the mechatronics and robotics engineering builds on such a diverse set of disciplines as electrical and computer engineering, mechanical engineering, computer science, and system engineering, among others. Robotics scientists and engineers have often benefited from latest advances in these disciplines, but they have also had to contend with unique application and system dependent challenges that inevitably arise in the development and integration of complex robotic and mechatronics systems. To effectively utilize, maintain, and upgrade these systems, manufacturing professionals at all levels must have a comprehensive understanding of the mechatronic and robotic principles at work across multiple disciplines.

The chapters in this critical reference explore the emerging technologies and techniques used in manufacturing systems as well as additional topics in the fields of neural networks, assistive technologies, robotics, computer architecture, and 3D modeling, among others. In all, this book presents practitioners, researchers, developers, managers, and engineers with insight into the latest developments in modern intelligent mechatronics, robotics, and automation systems, combining theory and practice to develop innovations in, and enhance knowledge of, mechanical and electrical engineering.

Many robots and mechatronic devices, including some used in medical applications, have to operate in small workspaces, which severely constrains their size. Piezo-electric motor drives have become popular for use in applications requiring miniaturization since they can be made in very compact form factor compared to other types of actuators including conventional electric motors. In Chapter 1, "Open Loop Force Control of Piezo-Actuated Stick-Slip Drives," by Christoph Edeler and Sergej Fatikow, a new method for force generation in stick-slip piezo-electric actuators is presented. While stick-slip drives have been commonly used in motion drives, the literature on their force control is rather scant. The authors of this article demonstrate the feasibility of producing a variable output force with such actuators. A particular actuator studied in the article can output a force in the range of hundreds of mN, promising to expand applications of this type of actuators in micro- and nano-handling miniaturized robots. An interesting point is that the actuator force is produced in open-loop manner eliminating the need for any additional sensor. The authors discuss a model and its important parameters that can be helpful in calibrating the actuator.

Next, Yongmin Zhongm et al. present a new methodology based on neural dynamics for optimal robot path planning in static and dynamic environments in their chapter "Optimal Robot Path Planning with Cellular Neural Network." This new method builds on concepts in Cellular Neural Networks (CNN) by proposing a new network in which the local connectivity of neurons is a nonlinear harmonic function as opposed a linear distance function in the exiting neural network models. The dynamics of this modified cellular neural network ensure that the target and obstacle remain at the top and bottom of the activity landscape for the network. The result is an algorithm that not only produces real-time smooth and collision free paths for a mobile robot, but it also can respond to dynamic changes in the task environment and take into account safety considerations. This is all achieved without any prior knowledge of target and obstacle movements, learning procedures, and explicit searching over the global work space or searching collision paths.

"Impedance Control of a Spherical Parallel Platform" by Luca Carbonari et al. presents an impedance control method for a 3DOF parallel manipulator with purely rotational motion at the end-effector. Instead of using a conventional Euler angles representation, the proposed controller employs the axis/angle of representation of the rotation. This new impedance control approach for an orientation only manipulator yields a smoother and more natural motion and decouples the impedance along different rotational degrees of freedom.

In "Stiffness Modeling and Analysis of Passive Four-Bar Parallelogram in Fully Compliant Parallel Positioning Stage," X. Jia et al. explore the role of a prismatic pair on the overall stiffness of a 3DOF compliant positioning stage. Parallel manipulators with compliant mechanisms can be useful in applications requiring high precision capabilities in a compact package. They can provide higher stiffness and response bandwidth than serial mechanisms and are compatible with operation in vacuum and clean room. Replacing conventional joints with flexure hinges allows for miniaturization of the manipulator structure and can eliminates backlash, friction and accumulation of error. The analysis based on the compliant matrix method and matrix transformation in this article sheds light on the impact of various design parameters of a flexure-based parallelogram on the overall compliance/stiffness of the 3DOF manipulator. A comparison between the results of analytical model with those from finite-element simulations reveals that the compliance of the connecting bars and the constraints need be taken into account for accurate modeling.

In "Computation of the Output Torque, Power, and Work of the Driving Motor for a Redundant Parallel Manipulator" by Yongjie Zhao, inverse dynamic analysis of the 8-PSS redundant parallel manipulator is carried out in the exhaustive decoupled way. The required output of the torque, the power and the work of the driving motor are achieved. The whole actuating torque is divided into four terms which are caused by the acceleration, the velocity, the gravity, and the external force. It is also decoupled into the components contributed by the moving platform, the strut, the slider, the lead screw, the motor rotor-coupler, and the external force. The required powers contributed by the component of torque caused by the acceleration term, the velocity term, the gravity term, the external force term, and the powers contributed by the moving platform, the strut, the slider, the lead screw, and the motor rotor-coupler are computed respectively. For a prescribed trajectory, the required output work generated by the i^{th} driving motor is obtained by the presented numerical integration method. Simulation for the computation of the driving motor's output torque, power, and work is illustrated.

Chapter 6, "Random Weighting Estimation of One-Sided Confidence Intervals in Discrete Distributions," by Yalin Jiao et al., presents a new random weighting method for estimation of one-sided confidence intervals in discrete distributions. It establishes random weighting estimations for the Wald and Score intervals. Based on this, a theorem of coverage probability is rigorously proved by using the Edgeworth expansion for random weighting estimation of the Wald interval. Experimental results demonstrate that the proposed random weighting method can effectively estimate one-sided confidence intervals, and the estimation accuracy is much higher than that of the bootstrap method.

Wheeled mobile rovers are being used in various missions for planetary surface exploration. In Pushpendra Kumar and Pushparaj Mani Pathak's chapter, "Dynamic Modeling, Simulation, and Velocity Control of Rocker-Bogie Rover for Space Exploration," a six-wheeled rover with rocker-bogie structure has been analyzed for planar case. The detailed kinematic model of the rover was built and the dynamic model was derived based on bond graph. The simulation studies were performed for obstacle climbing capability of the rover. It was observed from the study that the rover can pass through plane surface, inclined surface, and inclined ditch without any control on the actuators of the rover. However, it fails to cross a vertical ditch so a velocity controller was designed. It consists of a Proportional Integral (PI) controller and reduced model of the rover. It is found from simulation and animation studies that with the proposed velocity controller the rover is able to cross the vertical ditch.

Robotics and mechatronics engineers often have to deal with the problem of processing of unstructured raw sensory data into a structured form that is more suitable for analysis and decision making. In "Processing of 3D Unstructured Measurement Data for Reverse Engineering," Yongmin Zhong looks at a particular interesting problem in which the sensor outputs unstructured data in the form of a cloud of points in the 3-Dimensional (3D) space. Examples of such sensors are 3D dimensional surface scanners or computed tomography machines, which generate a large set of vertices in the 3D coordinate system. While a careful choice of scanning directions for objects with well-structured shapes can help avoid unstructured data, this may not be possible for objects with complex shapes. The article presents a solution for transforming such unstructured data points into a structured form suitable for application of the Non-Uniform Rational B-Splines (NURBS) surface modeling tools. Example applications of the proposed method for surface reconstruction of the aircraft component and a mold demonstrate its effectiveness.

In the next chapter, by Majid Habibi and Alireza B.Novinzadeh, is "Modeling and Simulation of Digital Systems Using Bond Graphs." Bond graphs are suitable tools for modeling many types of dynamical systems and can model these systems consisting of mechanical, electrical, fluidic, and pneumatic sub-systems. The advantage of a bond graph is that it can model non-linear systems and combinational systems. In this chapter, the authors utilize bond graphs for modeling mechatronics systems. Mechatronics systems consist of mechanics, electronics, and intelligent software. Many of these systems have digital sections that are constructed by logical circuits (hardware by transistors and now mostly by chips). The authors present a methodology to implement these mechatronics systems by bond graphs.

"Modeling, Simulation, and Motion Cues Visualization of a Six-DOF Motion Platform for Micro-Manipulations" by Umar Asif and Javaid Iqbal examines the problem of realizing 6-DOF motion platform by proposing a closed loop kinematic architecture that benefits from an anthropological serial manipulator design. In contrast to standard motion platforms based on linear actuators, a mechanism with actuator design inspired from anthropological kinematic structure offers a relatively larger motion envelope and higher dexterity, making it a viable motion platform for micromanipulations. The design consists of a motion plate connected through only revolute hinges for the passive joints, and three legs located at the base as the active elements. In this hybrid kinematic structure, each leg is connected to the top (motion) plate through three revolute hinges and to the bottom (fixed) plate through a single revolute joint forming a closed-loop kinematic chain. This chapter describes the mathematical modeling of the proposed design and demonstrates its simulation model using SimMechanics and xPC Target for real-time simulations and visualization of the motion cues.

The combination of a rigid and a flexible link in a space robot is an interesting field of study from a modeling and control point of view. "Bond Graph Modeling and Computational Control Analysis of a Rigid-Flexible Space Robot in Work Space" by Amit Kumar et al. presents the bond graph modeling and overwhelming trajectory control of a rigid-flexible space robot in its work space using the Jacobian-based controller. The flexible link is modeled as Euler Bernoulli beam. Bond graph modeling is used to model the dynamics of the system and to devise the control strategy by representing the dynamics of both rigid and flexible links in a unified manner. The scheme has been verified using simulation for a rigid-flexible space manipulator with two links.

Umesh Bhagat et al.'s "Experimental Study of Laser Interferometry Based Motion Tracking of a Flexure-Based Mechanism" presents an experimental study of laser interferometry-based closed-loop motion tracking for flexure-based four-bar micro/nano manipulator. To enhance the accuracy of micro/nano manipulation, laser interferometry-based motion tracking control is established with experimental facility. The authors present and discuss open-loop control, model-based closed-loop control, and robust motion tracking closed-loop control for flexure-based mechanism. A comparative error analysis for closed-loop control with capacitive position sensor and laser interferometery feedback is discussed and presented. Model-based closed-loop control shows improvement in position and motion tracking over open-loop control. Robust control demonstrates high precise and accurate motion tracking of flexure-based mechanism compared to the model-based control. With this experimental study, this chapter offers evidence that the laser interferometry-based closed-loop control can minimize positioning and tracking errors during dynamic motion, hence realizing high precision motion tracking and accurate position control.

Visually impaired people are faced with challenges in detecting information about terrain. "Analysis and Implementation for a Walking Support System for Visually Impaired People" by Eklas Hossain presents a new walking support system for the blind to navigate without any assistance from others or using a guide cane. In this research, a belt, wearable around the waist, is equipped with four ultrasonic sensors and one sharp infrared sensor. Based on mathematical models, the specifications of the ultrasonic sensors are selected to identify optimum orientation of the sensors for detecting stairs and holes. These sensors are connected to a microcontroller and laptop for analyzing terrain. An algorithm capable of classifying various types of obstacles is developed. After successful tests using a laptop, the microcontroller is used for the walking system, named "Belt for Blind," to navigate their environment. The unit is also equipped with a servo motor and a buzzer to generate outputs that inform the user about the type of obstacle ahead. The device is light, cheap, and consumes less energy. However, this device is limited to standard pace of mobility and cannot differentiate between animate and inanimate obstacles. Further research is recommended to overcome these deficiencies to improve mobility of blind people.

In Chapter 14, Kazi Mostafa et al. ask "Which is Better? A Natural or an Artificial Surefooted Gait for Hexapods." Natural multiped gaits are believed to evolve from countless generations of natural selection. However, do they also prove to be better choices for walking machines? This chapter compares two surefooted gaits, one natural and the other artificial, for six-legged animals or robots. In these gaits four legs are used to support the body, enabling greater stability and tolerance for faults. A standardized hexapod model was carefully examined as it moved in arbitrary directions. The study also introduced a new factor in addition to the traditional stability margin criterion to evaluate the equilibrium of such gaits. Contrary to the common belief that natural gaits would always provide better stability during locomotion, these results show that the artificial gait is superior to the natural gait when moving transversely in precarious conditions.

The next chapter, "Design and Validation of Force Control Loops for a Parallel Manipulator" by Giuseppe Carbone et al., addresses problems for design and validation of force control loops for a 3-DOF parallel manipulator in drilling applications. In particular, the control design has been investigated for a built prototype of CaPaMan2bis at LARM (Laboratory of Robotics and Mechatronics of Cassino). Two control loops have been developed, each one with two types of controllers. The first one is a Constrained Control Loop, which limits the force that is applied to an object to stay below a given value. The second one is a Standard Control Loop with external force feedback, which keeps the force at a given value. The control loops have been implemented on CaPaMan2bis by a Virtual Instrument in LABVIEW Software. CaPaMan2bis has been attached to a serial robot to make dynamic tests. The results of the experimental tests show the effectiveness and quick response of both algorithms after a careful calibration process.

Next, "High Performance Control of Stewart Platform Manipulator Using Sliding Mode Control with Synchronization Error" by Dereje Shiferaw et al. presents the design and analysis of a high performance robust controller for the Stewart platform manipulator. The controller is a variable structure controller that uses a linear sliding surface which is designed to drive both tracking and synchronization errors to zero. In the controller, the model based equivalent control part of the sliding mode controller is computed in task space and the discontinuous switching controller part is computed in joint space; hence, it is a hybrid of the two approaches. The hybrid implementation helps to reduce computation time and to achieve high performance in task space without the need to measure or estimate 6DOF task space positions. Effect of actuator friction, backlash, and parameter variation due to loading have been studied, and simulation results confirmed that the controller is robust and achieves better tracking accuracy than other types of sliding mode controllers and simple PID controller.

Hamoon Hadian et al.'s chapter, "Kinematics and Dynamics Modeling of a New 4-DOF Cable-Driven Parallel Manipulator," addresses the kinematics and dynamics modeling of a 4-DOF cable-driven parallel manipulator with new architecture, and a typical Computed Torque Method (CTM) controller is developed for dynamic model in SimMechanics. The novelty of kinematic architecture and the closed loop formulation is presented. The workspace model of the mechanism's dynamic is obtained in an efficient and compact form by means of Natural Orthogonal Complement (NOC) method which leads to the elimination of the nonworking kinematic-constraint wrenches and also to the derivation of the minimum number of equations. To verify the dynamic model and analyze the dynamical properties of novel 4-DOF cable-driven parallel manipulator, a typical CTM control scheme in joint-space is designed for dynamic model in SimMechanics.

In Chapter 18, "Kinematic Isotropic Configuration of Spatial Cable-Driven Parallel Robots," Hamoon Hadian and Abbas Fattah study the kinematic isotropic configuration of spatial cable-driven parallel robots by means of four different methods, namely (1) symbolic method, (2) geometric workspace, (3) numerical workspace and Global Tension Index (GTI), and (4) numerical approach. The authors apply the mentioned techniques to two types of spatial cable-driven parallel manipulators to obtain their isotropic postures. These are a 6-6 cable-suspended parallel robot and a novel restricted three-degree-of-freedom cable-driven parallel robot. Eventually, the results of isotropic conditions of both cable robots are compared to show their applications.

G. Satheesh Kumar and T. Nagarajan continue with "Experimental Investigations on the Contour Generation of a Reconfigurable Stewart Platform." Reconfiguration of Stewart platform for varying tasks accentuates the importance for determination of optimum geometry catering to the specified task. They propose a solution using the variable geometry approach through the formulation of dimensionless parameters in combination with generic parameters like configuration and joint vector. The methodology proposed provides an approach to develop a complete set of design tools for any new reconfigurable Stewart platform for two identified applications, contour generation and vibration isolation. This chapter details the experimental investigations carried out to validate the analytical results obtained on a developed Stewart platform test rig and error analysis is performed for contour generation. The experimental natural frequency of the developed Stewart platform has also been obtained.

Finally, there is considerable scientific and commercial interest in understanding the mechanics of mastication. In "Parallel Architecture Manipulators for Use in Masticatory Studies," Madusudanan Sathia Narayanan et al. develop quantitative engineering tools to enable this process by (1) designing a general purpose mastication simulator test-bed based on parallel architecture manipulator capable of producing the requisite motions and forces and (2) validating this simulator with a range of test-foods, undergoing various mastication cycles under controlled and monitored circumstances. Such an implementation provides a test bed to quantitatively characterize the mastication based on "chewability index." Due to the inherent advantages of locating actuators at the base (ground) in terms of actuator efforts and structural rigidity as well as benefits of using prismatic sliders compared to revolute actuators, the 6-P-U-S system was chosen. A detailed symbolic kinematic analysis was then conducted. For the practical implementation of the test-bed, the analytical Jacobian was examined for singularities and the design was adapted to ensure singularity free operation. A comprehensive parametric study was undertaken to obtain optimal design parameters for desired workspace and end effector forces. Experiments captured jaw motion trajectories using the high speed motion capture system which served as an input to the hardware-in-the-loop simulator platform.

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In this paper a new method to generate forces with stick-slip micro drives is described. The forces are generated if the runner of the stick-slip drive operates against an obstacle. It is shown that the generated force can be varied selectively without additional sensors and that virtually any force between zero and a limiting force given by certain parameters can be generated. For the investigated micro actuator this force is typically in the range up to hundreds of mN. For this reason, the method has the potential to expand the application fields of stick-slip positioners. After the presentation of the testbed containing the measured linear axis, measurements showing the principle and important parameters are discussed. Furthermore, it is shown that the force generation can be qualitatively simulated using state-of-the-art friction models. Finally, the results are discussed and an outlook is given.

This paper presents a new methodology based on neural dynamics for optimal robot path planning by drawing an analogy between cellular neural network (CNN) and path planning of mobile robots. The target activity is treated as an energy source injected into the neural system and is propagated through the local connectivity of cells in the state space by neural dynamics. By formulating the local connectivity of cells as the local interaction of harmonic functions, an improved CNN model is established to propagate the target activity within the state space in the manner of physical heat conduction, which guarantees that the target and obstacles remain at the peak and the bottom of the activity landscape of the neural network. The proposed methodology cannot only generate real-time, smooth, optimal, and collision-free paths without any prior knowledge of the dynamic environment, but it can also easily respond to the real-time changes in dynamic environments. Further, the proposed methodology is parameter-independent and has an appropriate physical meaning.

This article describes the impedance control of an in-parallel actuated orientation platform. The algorithm is based on a representation of platform orientation which exploits the equivalent axis of rotation: this approach is more intuitive and easier to visualize than conventional methods based on Cardan or Euler angles. Moreover, since for small angular displacements the Mozzi's axis lies very close to angular velocity, impedance control algorithms based on such representation provides better performances and smoother motions. Results of numerical simulations and experimental tests are shown and commented with reference to the spherical parallel machine.

In order to investigate the influence of the stiffness of the compliant prismatic pair, a planar four-bar parallelogram, in a fully compliant parallel mechanism, the stiffness model of the passive compliant prismatic pair in a compliant parallel positioning stage is established using the compliant matrix method and matrix transformation. The influences of the constraints and the compliance of the connecting rods on the flexibility characteristics of the prismatic pair are studied based on the developed model. The relative geometric parameters are changed to show the rules of the stiffness variation and to obtain the demands for simplification in the stiffness modeling of the prismatic pair. Furthermore, the finite element analysis has been conducted to validate the analytical model.

Inverse dynamic analysis of the 8-PSS redundant parallel manipulator is carried out in the exhaustive decoupled way. The required output of the torque, the power and the work of the driving motor are achieved. The whole actuating torque is divided into four terms which are caused by the acceleration, the velocity, the gravity, and the external force. It is also decoupled into the components contributed by the moving platform, the strut, the slider, the lead screw, the motor rotor-coupler, and the external force. The required powers contributed by the component of torque caused by the acceleration term, the velocity term, the gravity term, the external force term, and the powers contributed by the moving platform, the strut, the slider, the lead screw, and the motor rotor-coupler are computed respectively. For a prescribed trajectory, the required output work generated by the ith driving motor is obtained by the presented numerical integration method. Simulation for the computation of the driving motor's output torque, power and work is illustrated.

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One of the most difficult problems in reverse engineering is the processing of unstructured data. NURBS (Non-uniform Rational B-splines) surfaces are a popular tool for surface modeling. However, they cannot be directly created from unstructured data, as they are defined on a four-sided domain with explicit parametric directions. Therefore, in reverse engineering, it is necessary to process unstructured data into structured data which enables the creation of NURBS surfaces. This paper presents a methodology to processing unstructured data into the structured data for creating NURBS surfaces. A projection based method is established for constructing 3D triangulation from unstructured data. An optimization method is also established to optimize the 3D triangulation to ensure that the resulted NURBS surfaces have a better form. A triangular surface interpolation method is established for constructing triangular surfaces from the triangulation. This method creates five-degree triangular surfaces with C1 continuity. A series of segment data are obtained by cutting the triangular surfaces with a series of parallel planes. Finally, the structured data is obtained by deleting repetitive data points in each segment data. Results demonstrate the efficacy of the proposed methodology.