PROCEEDINGS

53. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

Faculty of
Mechanical Engineering

PROSPECTS IN MECHANICAL ENGINEERING

8 - 12 September 2008

www.tu-ilmenau.de

TECHNISCHE UNIVERSITÄT
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Published by
Impressum

Publisher Herausgeber	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor Redaktion	Referat Marketing und Studentische Angelegenheiten Andrea Schneider
	Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurz, Univ.-Prof. Dr.-Ing. habil. Rainer Grünwald, Univ.-Prof. Dr.-Ing. habil. Prof. h. c. Dr. h. c. mult. Gerd Jäger, Dr.-Ing Beate Schlütter, Dipl.-Ing. Silke Stauche
Editorial Deadline Redaktionsschluss	17. August 2008
Publishing House Verlag	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16, 98693 Ilmenau

CD-ROM-Version:

Implementation Realisierung	Technische Universität Ilmenau Christian Weigel, Helge Drumm
Production Herstellung	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

ISBN: 978-3-938843-40-6 (CD-ROM-Version)

Online-Version:

Implementation Realisierung	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=17534

53rd Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
08 – 12 September 2008

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The Simulation of Parallel Mechanisms in MATLAB/Simulink Development Environment

Abstract

The modern phase of science and technology evolution in the field of automatic and robotic systems is characterized by the use of multi-degree-of-freedom movement systems, realizing almost any spatial movements of an actuator or machining tool. Additional requirements for simultaneous implementation of all translational and angular motions are in increasing frequency demanded for new developed movement position devices. The multi-degree-of-freedom systems constructed on the basis of 6-DOF parallel mechanisms are among the most perspective solutions for such motions implementation. However, the task of rapid kinematic and dynamic analysis of such parallel mechanisms is one of the main difficulties in the sphere of robotics. Therefore the paper examines the simulation and analysis of two 6-DOF parallel mechanisms in MATLAB/Simulink development environment to present a productive and up-to-date way of similar robotic manipulators engineering.

The 6-Dof Parallel Mechanisms

The spatial mechanisms with the structures presented on Fig. 1 and Fig. 2 are referred to the class of parallel mechanisms. Such a definition of the class is connected with their structure which includes the mechanics of several parallel kinematic chains, confined to the executive element with the same or similar transformation laws of motion. Their ability to scaling, phase shift, different locations in space, independent management enables controllable electromechanical systems, implementing any movement of an executive element in space. Such movement can be specified by six independent laws of motion, for example, by three linear and three angular coordinates, characterizing the spatial, plane-parallel and rotational motion of an executive part.

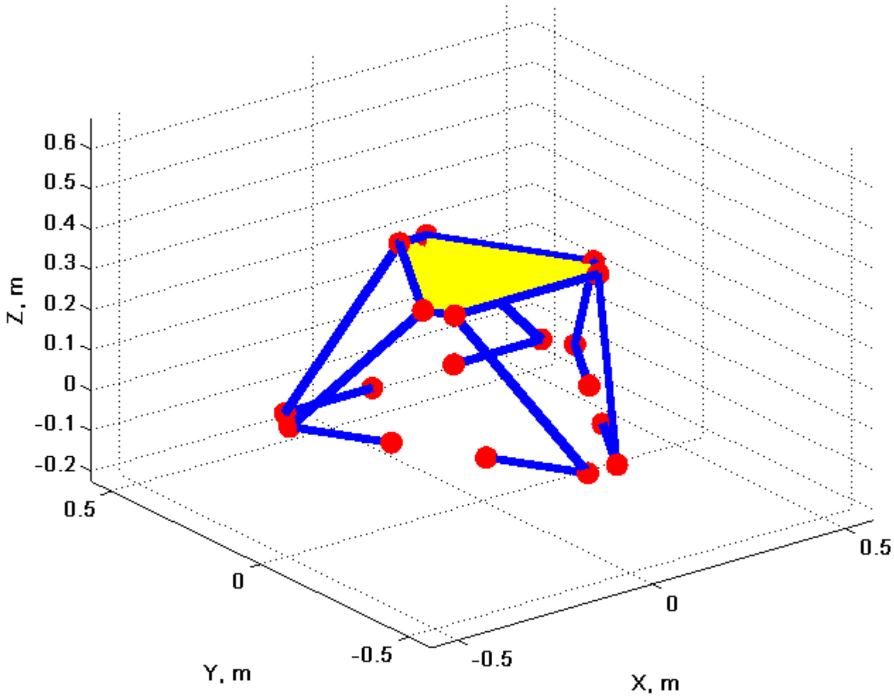

Fig. 1. The 6-DOF parallel mechanism (modification 1)

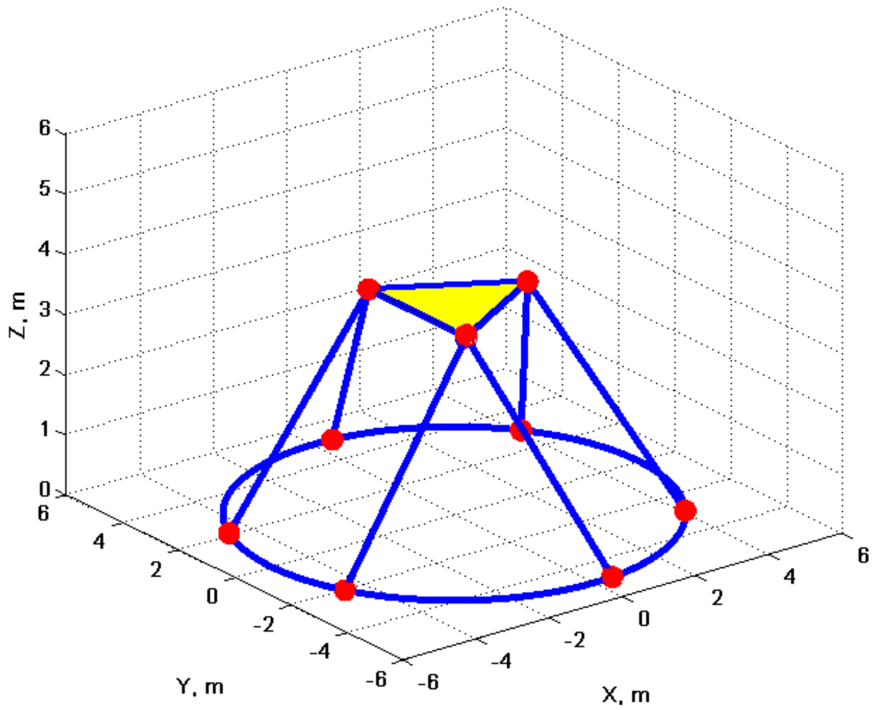

Fig. 2. The 6-DOF parallel mechanism (modification 2)

Both 6-DOF parallel mechanisms, presented on Fig. 1 and Fig. 2, support three coordinate axial displacements (x, y, z) and three angular rotations (ψ − yaw, θ − pitch, φ − roll) of the mobile platform about the appropriate coordinate axes respectively.

The general advantages of the investigated parallel mechanisms benefit from their parallel structures. Parallel robot structures can be designed which are specially tailored to handle heavy loads with accurate positioning [1]. Roughly, positioning errors in serial kinematic chains tend to propagate throughout the chain links. This is not the case with parallel manipulators, which are consequently capable of performing positioning tasks to a high degree of accuracy. Furthermore, the parallel structure inherently distributes the forces and torques by the actuators giving this class of robots high bandwidth dynamic characteristics. Typical applications include flight simulators, multicoordinate precision systems, shaking tables (used in simulation of the effects of earthquakes in building structures), support structures for the accuracy positioning of instrumentation, medical instrumentation and even entertainment devices.

Parallel mechanism, presented on Fig. 1, is composed of 6 independent legs connecting the mobile platform with the base. Each of these legs is a serial kinematic chain that is controlled by one motor which actuates one of the joints [2]. Each motor produces rotational motion of its shaft (axle) to put into action parallel mechanism. In parallel mechanism with structure chart, presented on Fig. 2, the mobile platform is directly connected to the planar motors (by six legs), which provide plane-parallel movements on a closed circle and thus put into action the whole mechanism.

Parallel mechanisms (Fig. 1 and Fig. 2) have an exceptional range of motions and can be accurately and easily positioned and oriented. They provide a large amount of rigidity, or stiffness, for a given structural mass, and thus provide significant positional certainty. But the manipulator model is moderately complex, with a large number of mechanical constraints that require a robust simulation. Moreover the control system modeling cannot be implemented without complex kinematic analysis of the manipulator.

Direct Kinematic Problem Solving

In many applications it is necessary to determine the position and orientation of the mobile platform out of the input actuation from driving motors. For the first case of the investigated mechanism (Fig. 1) the direct kinematic problem solving implies the determination of the output variables (platform position x, y, z and orientation ψ, θ, φ) out of the input variables (rotary angles $\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6$ of motors shafts). The direct kinematic problem solving for second mechanism (Fig. 2) includes the determination of position and orientation of the platform which directly corresponds to angular positions of six planar motors.

As it came out of geometric analysis, carried out for both mechanisms, the direct kinematic problem is a difficult task to be solved only by analytical geometric approach. The more convenient way is to apply the optimization methods to solve the equations set which connects the input variables with the output.

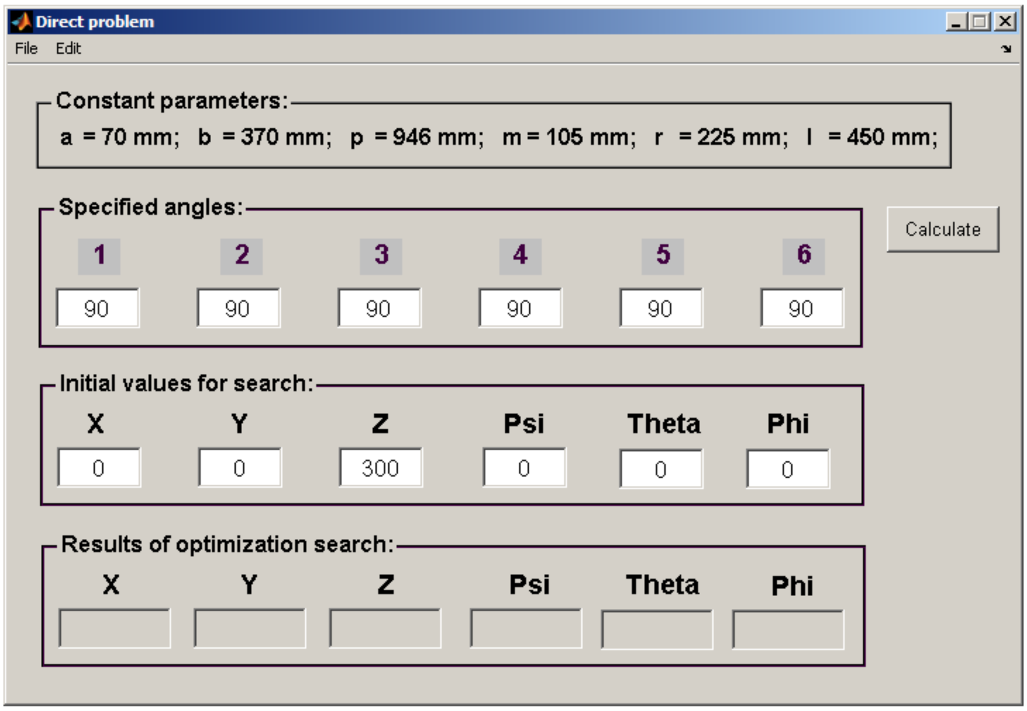

Fig. 3. Direct kinematic problem solving program

As a result the appropriate computing programs for direct kinematic problems solving have been implemented in MATLAB environment deploying the Optimization Toolbox. For instance, a new developed program with screenshot presented on Fig. 3 enables solving the direct kinematic problem for mechanism type proposed on Fig. 1. The optimization is based on Levenberg-Marquardt and Gauss-Netwton algorithms. The program enables to set the initial point of search, optimization algorithm and input values of rotary angles.

Inverse Kinematic Problem Solving

The output position and orientation of the platform directly corresponds to the input actuation from motors. Therefore, the parallel manipulators control system modeling often starts with the inverse kinematic problem solution, that implies the determination of the input variables (rotary angles of motors shafts – for the first parallel mechanism, angular positions of planar motors for the second parallel mechanism) out of the output variables (platform position x, y, z and orientation ψ, θ, φ).

The input variables are connected with the output variables by the appropriate equations. The initial equations analysis showed that the inverse kinematic problem doesn't always have general solution. The reason is, that for a given set of output variables there are several valid sets of input variables. A new developed program with implementation in MATLAB environment enables inverse kinematic problem solution for mechanism type proposed on Fig. 1. The inverse kinematic problem computing program screenshot is presented on Fig. 4.

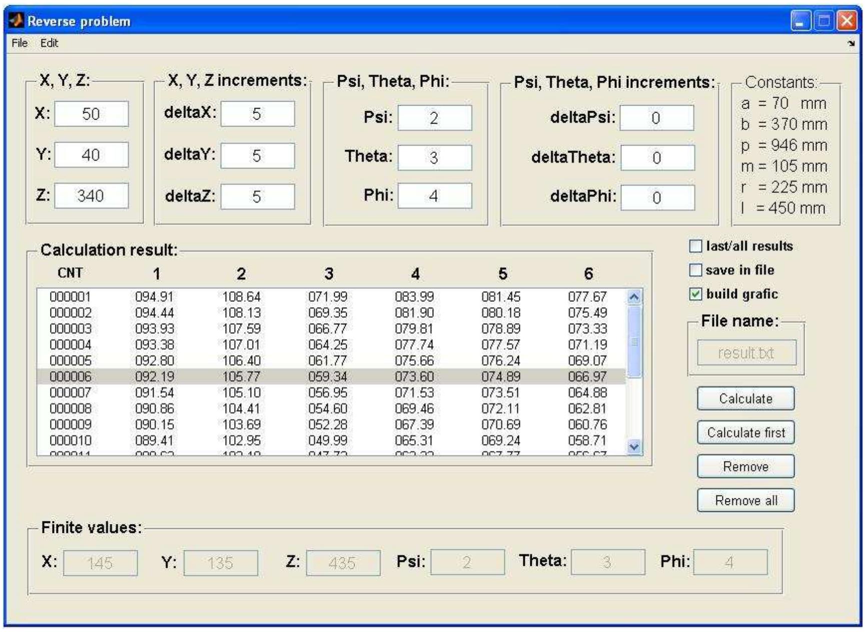

Fig. 4. Inverse kinematic problem computing program

The program provides both immediate and step-by-step solution of the inverse kinematic problem for parallel mechanism. The step-by-step mode enables consecutive computing of the inverse kinematic problem for specified incremental changes of output variables on every step. The inverse kinematic problem computing program also provides possibility for building up graph of function that represents the changes of motors shafts rotary angles according to platform movement from initial to final position and orientation (Fig. 5). The curves on Fig. 5 are obtained by the inverse kinematic problem solution for specified incremental changes of $x, y, z, \psi, \theta, \varphi$ variables on every step. As it can be seen the curves have nonlinear trajectories and different total angular changes. This proves the fact that all six motors to actuate the parallel mechanism must be controlled independently, bringing the demand of six regulators implementation in future control system [2].

As the research revealed while developing mechanotronic systems it is sometimes necessary and useful to visualize the inverse kinematic problem solution.

Having the opportunity of spatial parallel mechanism movements visualization according to the specified law of motion enables to eliminate inverse kinematic problem algorithm errors.

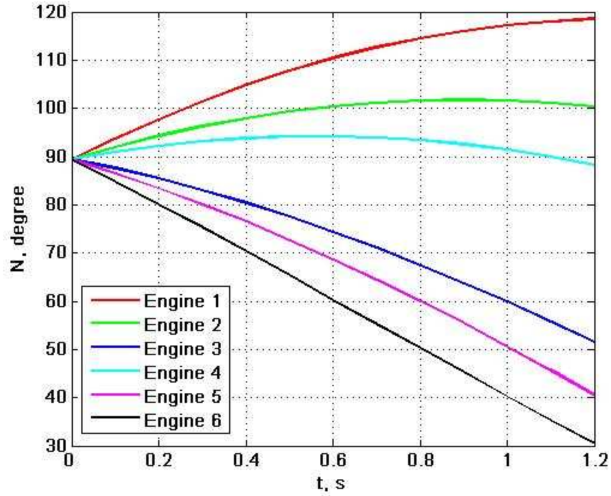

Fig. 5. Changes of motors shafts rotary angles

Specially for this purpose the inverse kinematic problem visualization program has been implemented in MATLAB environment (Fig. 6).

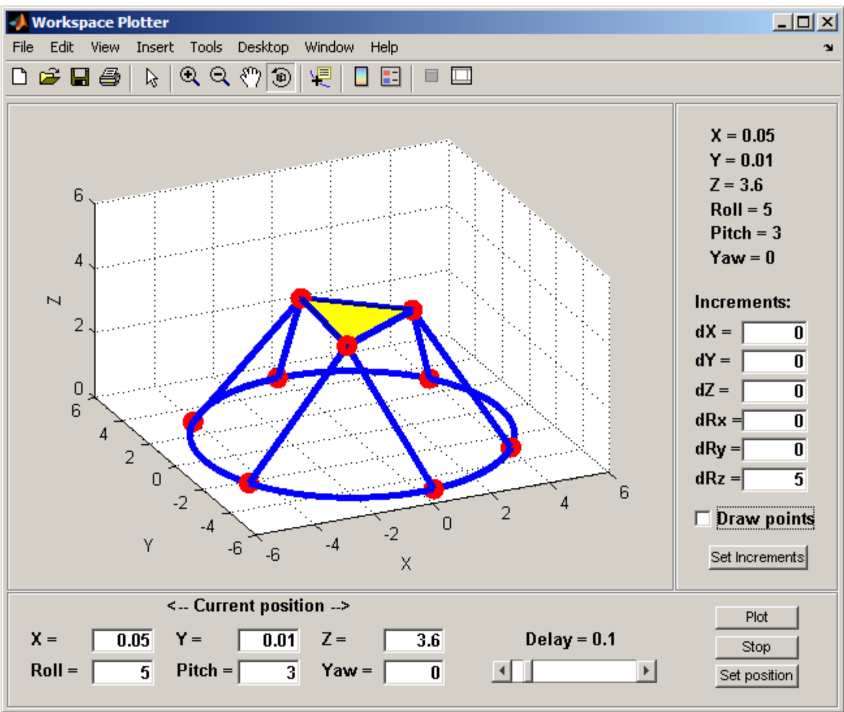

Fig. 6. Inverse kinematic problem visualization program

The program provides both immediate and step-by-step solution of the inverse kinematic problem for parallel mechanism presented on Fig. 2. The basic feature of this program is that it enables visualization of mechanism state on every step to provide possibility of inverse kinematic problem solution verification.

Dynamics Modeling

Developing mechanical motion systems demands the necessity to choose the appropriate actuators to put into action the manipulator or mechanical execute part of the system [3]. The choice of that or another actuator is based on the output forces/torques required to produce a specified motion in a mechanical system. The required forces and torques can be found by solving equations that represent the dynamics model of the whole system. Dynamics equations such as Newton's laws of motion relate cause and effect. In mechanics, the cause is a set of forces and torques applied to the bodies of a mechanical system; the effect is the set of resulting motions. Dynamical equations allow analyzing motion in either direction:

▪ Forward dynamics deals with a given set of forces/torques to the bodies to produce accelerations. Integrating the accelerations twice yields the velocities and positions as functions of time. A set of initial conditions is needed to specify the initial positions and velocities and produce a complete solution for the motion;

▪ Inverse dynamics starts with given motions as functions of time and differentiates them twice to yield the forces and torques needed to produce the given motions.

General concept of dynamic analysis starts with the model representation of the physical structure of a machine, the geometric and kinematic relationships of its component bodies on a detailed level to be considered in equations of forward and inverse dynamics. But the problem is that many mechanotronic systems, like the investigated, have a complex mechanical structure that is very hard to describe directly by ordinary dynamical equations. At the same time MATLAB/SimMechanics modeling package grants a very convenient environment for the engineering design and simulation of rigid body machines and their motions, using the standard Newtonian dynamics of forces and torques. SimMechanics is part of Simulink Physical Modeling, encompassing the modeling and design of systems according to basic physical principles. Physical Modeling runs within the Simulink environment and interfaces seamlessly with the rest of Simulink and with MATLAB. SimMechanics toolbox enables modeling and simulating of mechanical systems with a suite of tools to specify bodies and their mass properties, inertia tensors, their possible motions, kinematic constraints, and coordinate systems, and to initiate and measure body motions.

A SimMechanics model differs significantly from other Simulink models in how it represents a machine. An ordinary Simulink model represents the mathematics of a machine motion, the algebraic and differential equations that predict the machine future state from its present state. The mathematical model enables Simulink to simulate the machine. By contrast, a SimMechanics model represents the physical structure of a machine, the geometric and kinematic relationships of its component bodies [4]. SimMechanics converts this structural representation to an internal, equivalent mathematical model. This saves a great amount of time and effort of developing the mathematical model.

Forward dynamics problem solution implies the determinations of motion (position, velocity, acceleration) corresponding to a given set of specified forces/torques to the bodies. In order to solve the forward dynamics problem for the investigated 6-DOF parallel mechanism, presented on Fig. 1, an appropriate mechanical model has been implemented in MATLAB/SimMechanics environment (Fig. 7).

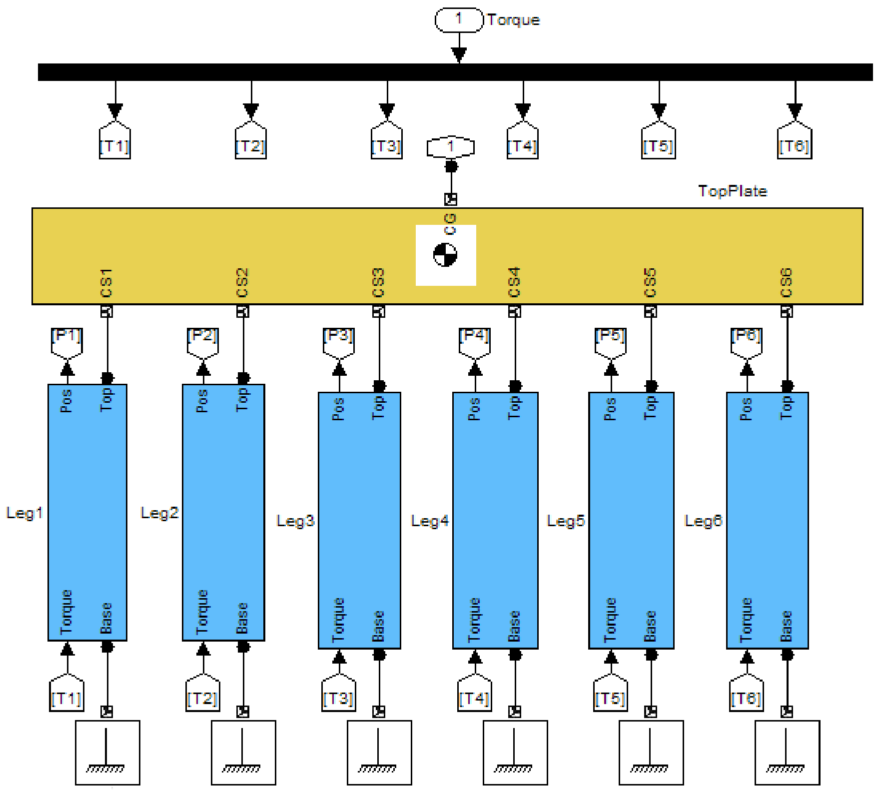

Fig. 7. SimMechanics model of the 6-DOF parallel mechanism

The model itself represents a set of blocks that determine the physical structure of a machine, the geometric and kinematic relationships of its component bodies on a detailed level. Each serial kinematic chain of the 6-DOF parallel mechanism (Fig. 1) can be represented in MATLAB/SimMechanics by appropriate blocks (rigid bodies, joints, grounds, actuators and so on). The implementation of one serial kinematic chain in MATLAB/SimMechanics with simple blocks explanation is presented on Fig. 8.

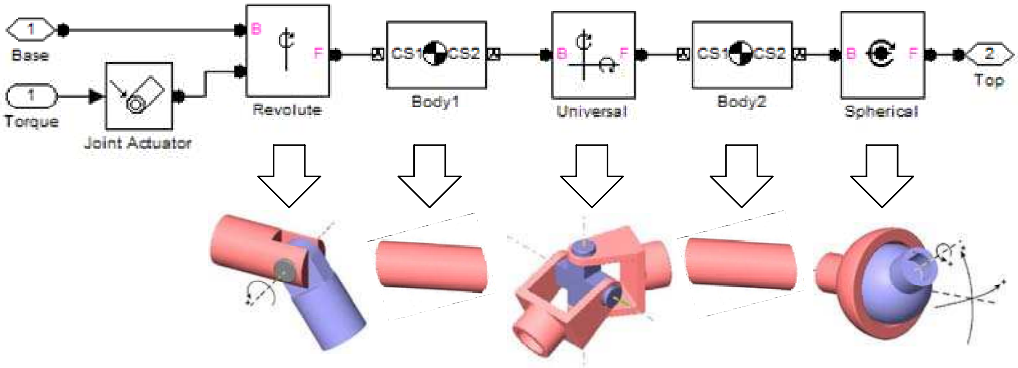

Fig. 8. Kinematic chain of the 6-DOF parallel mechanism

To simulate the motion of parallel mechanism the Joint Actuator element is used (Fig. 8), which is fed by entry control signal. The entry control signal represents a functional dependence of torque over time.

The realized dynamic model can also be automatically represented by visual dynamic 3D model in MATLAB/SimMechanics environment (Fig. 9). Each structural part of the mechanism is evaluated by equivalent ellipsoid according to its inertia tensor.

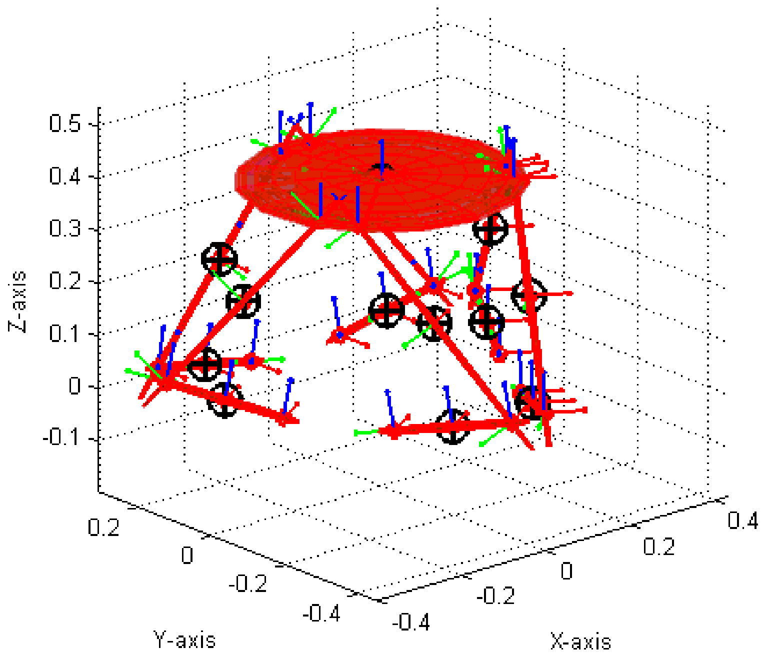

Fig. 9 Visual dynamic model of parallel mechanism

The forward dynamics model computes the platform position, orientation, velocity and acceleration in response to applied torques. The model can be used to determine motion dependence of the specified torques and thus provide possibility for the investigation of dynamics.

Conclusion

The 6-DOF parallel mechanisms kinematics and dynamics have been outlined in the paper. It covers the direct and inverse kinematic problems solving as well as forward dynamics problem. The proposed methods of kinematics and dynamics simulation can be immediately involved in developing similar mechanotronic systems.

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