Course 5: Mechatronics - Foundations and Applications

The Virtual Prototyping of Robots Dynamics

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Abstract

Virtual prototyping of robots dynamics is a very interesting and ordinary tool nowadays to simulate mechanical systems, such as robots etc. Simulating is the first step to design,identify and control robots and it's a powerful technique to improve quality and productivity of researchers work.

Using software environment, one can visually design and model systems by means of simulating separate parts of these systems and investigating its behavior under conditions that are close to real ones.

In this paper virtual prototyping concept is introduced. Most known simulating packages of robots dynamics' prototyping with examples are presented.

Contents

1 Introduction

Modern computer technology achievements allow to develop robotic system by means of creating a computer model [1]. It allows to simulate systems' separate unit functioning, to present systems' 3D shape on a monitor screen and to investigate its behavior under conditions that are close to real ones. That is why technology of complex systems and units development calls virtual prototyping. It plays a very important role in modern robotic and mechatronic systems development.

Any modern automatic machine can be considered as mechatronic system (aircraft, automobiles, HDD-drives, robots, trains, washing machines, etc). They consist of mechanical parts, drives, sensors, microcontrollers and microprocessors, and software for automatic control of its work.

Nowadays, there is a tendency to increase motion speed of the system mechanical parts. It leads to necessity of mechanical systems' dynamics simulation because the inertia forces role increases. Mobile robots move on surfaces and contact surrounding objects. This one requires dynamics simulation, too.

Mechanical system complications require to consider executive bodies, drives and control systems dynamics in common. That is why the problem of complex mechanical systems modeling has become actual at the beginning of the twentieth century. Thanks to modern CAD/CAE software the simulation has changed from pure-scientific problem into a mere component of many projects.

The virtual prototyping now is an ordinary tool for aircraft, cars, engines, pumps, reducers, robots, trains, transfers, turbines development - there is an endless list. Simulation with use of computers allows mimicking of a real life or potential situation.

Computer modeling has always been one of the most interesting and diversified areas of modern science. At present modeling represents the basic scientific tool applied for pure-theoretical and practical purposes. With simulation, one can study a problem that is not often subject to direct experiment. It allows researchers to build system models, based on real world data collected from many studies, and then test a model under conditions when time and materials are not available. It is a powerful tool for designing and analyzing complex and dynamic systems, for predicting their behavior under different conditions on time scale. Simulation is a highly cost-effective method of testing new processes without having to carry out actual experiments. It can save enormous amount of money, which could be spent on pilot programs, and it can produce better results much faster.

Simulation should be used when it is expensive or dangerous to run real systems. With simulation, one can

- gain better understanding how a system works;
- identify problems prior to their implementation;
- test potential effects of changes;
- identify areas for resource deployment;
- design efficient and cost-effective systems.

2 Modern Virtual Prototyping Packages

From mechanical point of view robot represents a system of connected solid bodies. The system is subject to some external influences. Bodies can be connected among themselves by means of various joints. Its motions can be limited by stationary and non-stationary constrains. That is why in the initial design stage we need in determining forces and movement trajectories of all bodies.

There are several ways to do it and the best one is to make a dynamic model and to produce it with a help of some modeling programs. If there are few bodies in the system and constrains are deterrent, the direct dynamic model can be carried out without any difficulties. But it is a more complicated task when there is a great amount of bodies or system constrains are non-deterrent.

The other peculiarities of robotic system are control system and various drives that demand tools and primitives for their modeling.

Creating a model that is a close approximation to reality is a very important step. It is a logical description of how a real life system works, with all its defined inputs, outputs and interactions. Starting with a basic model one can go on improving it as his own understanding of this model clarifies. For more complicated problems, user can run the mimic of a real life process by means of computer to generate uncontrollable events.

The modern design process suggests the permanent transfer from sketches to 3D model, from 3D model to virtual prototype and from virtual prototype to real production. There are a lot of systems that can give us an opportunity to simulate robots dynamics. They are MSC.Adams, Universal Mechanism, MatLab, DyMoLa, Webots, RobSim, Simbad, ThreeDim-Works, RoboWorks, etc. Some of them can support the whole path from design to production stages. Let's have a closer look at some of them.

2.1 MatLab

MatLab (Matrix laboratory) [2]is an interactive software system for numerical computations and graphics.

It has provided an excellent environment for thousand experts and researchers to carry on calculations in various industrial branches.

As the name suggests, MatLab is designed especially for matrix computations: solution solving of linear equation systems, computing eigenvalues, eigenvectors and matrices, and so on.

The present MatLab is a highly effective language of engineering and scientific calculations. It supports mathematical calculations, visualization and programming. The most known MatLab scopes:

- mathematics and calculations;
- algorithm development;
- computing experiment, imitating modeling, prototyping;
- data analysis and result researches;
- scientific and engineering visualizations;
- application development, including the graphic interface of the user.

MatLab is the interactive system, where a file with implicit specified dimension is its basic object. It allows to solve many computing problems connected with vector-matrix formulations and it reduces time which could be required for programming in scalar languages C or Fortran.

MatLab system is an environment and programming language at the same time. User can write specialized functions and programs at his discretion that is one of MatLab's characteristic features.

In addition, it has a variety of graphical capabilities, and can be extended through programs written in its own programming language. A lot of programs like these come with the system; these programs extend MatLab's capabilities to non-linear problems, such as solution of initial value problems for ordinary differential equations.

One of those programs is Simulink. It is an interactive tool for dynamics system modeling and analysis. With Simulink help modeling is performed by means of visual programming. User creates device model by means of standard blocks and carries out calculations. In difference with classical modeling ways, it is not necessary to investigate programming language and numerical mathematics' methods. Computer and subject knowledge required to work are enough.

Simulink is an independent MatLab component and you don't need to know MatLab itself to work in Simulink. On the other hand MatLab means can be employed in Simulink. There are also additional blocks libraries for different scopes (e. g., SimPowerSystems - electrotechnical devices modeling, SimMechanics - mechanical devices modeling, Digital Signal Processing Blockset - a digital device development, etc.).

Any Simulink-model can have hierarchical structure, that is, it can consist of lower level models.

There is an opportunity to keep up system processes during modeling with a help of special supervision devices which are a part of Simulink library. System characteristics can be presented both in numerical and graphic forms.

Besides, Simulink is an open system: library structure can be added up due to own blocks development (by means of MatLab's internal language, C++, FORTRAN).

MatLab is designed to solve problems numerically, but arithmetic precision is finite. Therefore it produces approximate rather than exact solutions. One shouldn't confuse it with the other symbolic computation system (SCS) such as Mathematica or Maple. Its characteristic features don't make MatLab better or worse than an SCS; these tools were designed for different purposes and it is worth to compare them directly.

Designing an automatic suspension system for a bus turns out to be an interesting control problem that can be solved by means of MatLab. When the suspension system is designed, a bus model is used to simplify the problem to a one dimensional spring-damper system. A diagram of this system is shown in Figure 1:
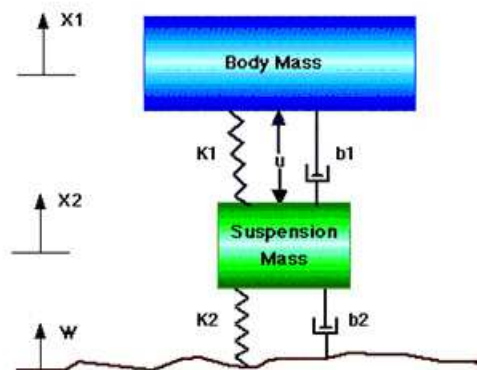

Figure 1: Model of bus suspension system(1/4 bus)

By means of SimMechanics we can consider mechanic system as a block of functional diagrams. Besides, such software packages allow to visualize the motion of mechanical system in 3D virtual space.

In SimMechanics one can find the example of a detailed dynamic model of Siemens Manutec r3 robot. All of important physical effects were modeled there by means of SimMechanics:

the multibody dynamics, Coulomb friction, elasticity and damping in the gear-boxes, the dynamics of the motors including the current controller and the tachogenerators, and the cascade controllers.

The r3 is an industrial robot designed in the early eighties. It is shown in Figure 2. Its dynamic model, shown in Figure 3, consists of rigid bodies that are connected by ideal revolute joints. Every joint is driven by a torque, which is produced by the electro-magnetic motor field.
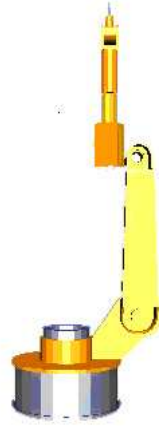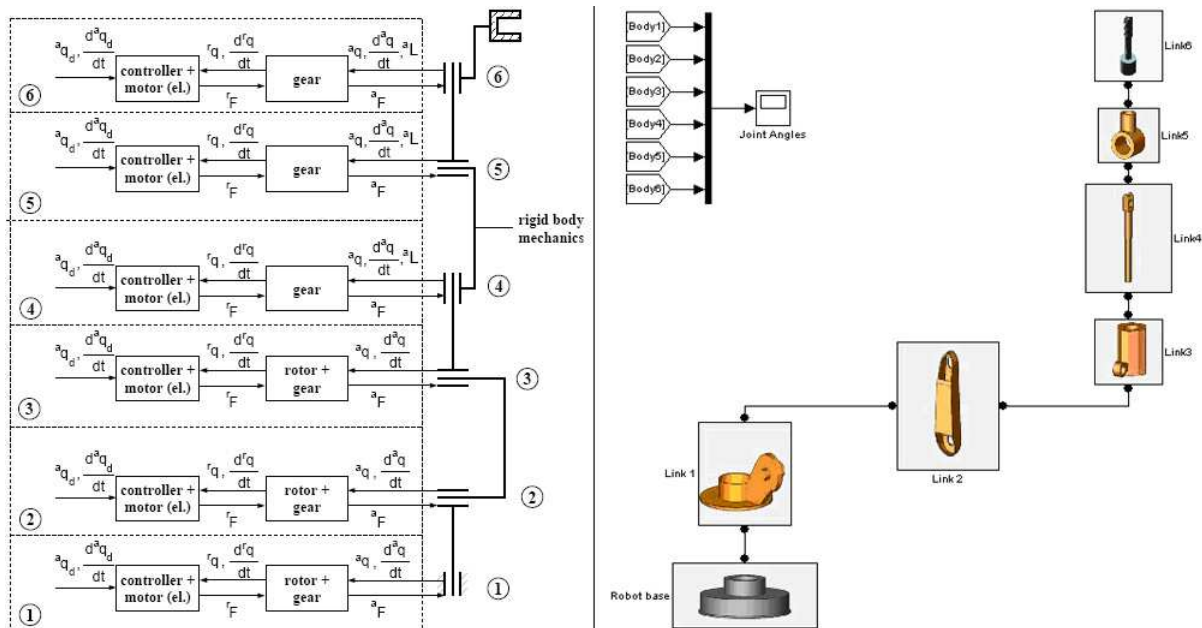

Figure 2: Industrial robot r3

Figure 3: Dynamics model structure

Electrical part of motor together with it tachogenerator, current-, rate- and position controller is represented by a block "controller + motor". Block "rotor + gear" contains mechanical part of motor and of its gear-box.

The torque in the air gap drives rotor to the motor. The angular rate of the rotor is transformed to lower speed by means of the gear-box, which drives the joint of the next arm.

Robot bodies, joints and rotors are modeled as a rigid multibody system. Reference trajectories for the simulations have been determined by multi-objective trajectory optimization.

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2.2 DyMoLa

DyMoLa (Dynamic Modeling Laboratory) [3]is a complete tool for modeling and simulation of integrated and complex systems for use within automotive, aerospace, robotics, process and other applications.

The unique multi-engineering capabilities presents new and revolutionary solutions for modeling and simulation as it is possible to simulate the dynamic behavior and complex interactions between systems of many engineering fields, such as mechanical, electrical, thermodynamic, hydraulic, pneumatic, thermal and control systems. This means that DyMoLa users can build more integrated models and have simulation results that better depict reality.

Its graphical editor and the multi-engineering libraries make modeling easy. The libraries include elements corresponding to physical devices which are simply dragged-and-dropped to build the model. Interactions between the components are conveniently described by graphical connections that model physical coupling of the components. This means that models are intuitively organized in the same way as the physical system is composed.

The DyMoLa environment is completely open in contrast to many modeling tools that have a fixed set of component models and proprietary methods for introducing new components. The open and flexible structure makes DyMoLa an excellent tool to simulate new or alternative designs and technologies. DyMoLa is based on Modelica, which is an object-oriented language for physical modeling, and that gives unique access to libraries developed by leading experts around the world.

Figure 4: DyMoLa examples

DyMoLa has unique and outstanding performance for solving differential algebraic equations (DAE). The key to high performance and robustness is symbolic manipulation which also handles algebraic loop and reduced degrees-of-freedom caused by constraints. These techniques together with special numerical solvers enable real-time hardware simulations.

German automotive manufacturers, DaimlerChrysler, BMW, Audi and Volkswagen, have jointly decided to use Dymola and the new AirConditioning Library (Figure 5)as a tool for model exchange and simulation of automotive air conditioning systems. After an extensive benchmark study Dymola was chosen in competition with several other modeling and simulation tools.

Figure 5: Model of an air-conditioning system

Dymola and the AirConditioning Library allow you to optimize and verify the design of an air conditioning system from the early design phases through control design and implementation.

The AirConditioning Library features an open, object-oriented architecture with access to the model source code in Modelica.

2.3   Universal Mechanism

The program package "Universal Mechanism" (UM) [4]is a Russian development. It has been designed to automate the analysis of mechanical objects, which can be represented as rigid body systems (or multibody systems - MBS) with the bodies connected by means of kinematical and force elements. An automobile, a locomotive, a railway car, robot and excavator manipulators, different mechanisms and devices are the examples of such systems.

UM operates a majority of systems which theoretical and applied mechanics deal with. With the help of UM a user can solve direct and inverse problems of kinematics, dynamics, and control. A mechanical system with two or three dimensions can be analyzed successfully. As a matter of fact, there are no limits to the number of bodies in a particular system.

For complex mechanical systems with large number of bodies not only analysis of equations and their generation as well as description of the object's structure are difficult. UM makes it possible to automate these procedures, which raises productivity of the designer's work. If an object consists of more than dozens of bodies, it takes much time to enter usual data for inertial and kinematical properties description. If you have to model a train (Figure 6) consisting of a locomotive and twenty similar cars, it is only necessary to enter data for the locomotive and one car. In its turn, the locomotive and the car can also be divided into separate subsystems, some of which might turn out to be alike or kinematically identical, roughly. For similar subsystems you have to describe only one. This spares your time and helps you to avoid number of errors.

Figure 6: Rail vehicle dynamics simulation

UM widely applies update methods of computer graphics both to display the 3D motion of the system in the process of numerical motion equations and to analyze the obtained results.

The motion equations are generated by a special procedure of the software in a completely symbolic form. For some problems, the number of equations is so large that it is virtually impossible to obtain them with a pencil and paper, although there is not much sense in obtaining them analytically. E.g., if one had to write down the motion equations for a robot with six rotational degrees of freedom (d.o.f.), it would take several pages. Therefore, it makes no sense to analyze them visually. So, the user just describes his system according to a set of certain simple rules, and the rest part of the task is performed automatically.

The program is oriented to all people who are involved into problems of dynamics of machines and mechanisms. There are lots of measurable dynamical performances of mechanical systems: linear and angular coordinates, velocities and accelerations, active forces and moments, reaction forces etc that can help us to model an engine,shown in Figure 7, e.g.
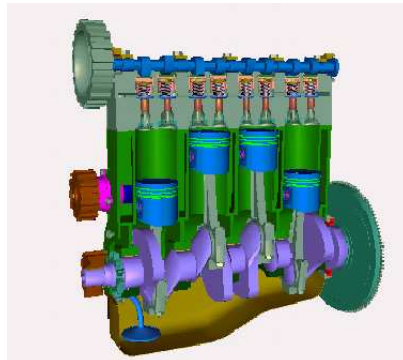
Figure 7: Engine model

2.4 MSC.ADAMS

MSC.ADAMS [5] is powerful universal mean for virtual modeling of complex system. It has a possibility of 3D model import from so widely known CAD systems as Catia, ProEngineer, SolidWorks, SolidEdge, etc. The other possibility of MSC.ADAMS is connection of its model as the control object to MSC.Easy5 and MatLab/Simulink.

To design a mechanical system such as an automotive suspension or an aircraft landing gear, you need to understand how various components (pneumatics, hydraulics, electronics, and so on) interact as well as what forces (noise, vibration, and harshness) those components generate during operation. ADAMS is the world's most widely used mechanical system simulation software. It is a motion simulation solution for analyzing complex behavior of mechanical

assemblies. Adams allows you to test virtual prototypes and optimize designs for performance, safety, and comfort, without having to build and test numerous physical prototypes.

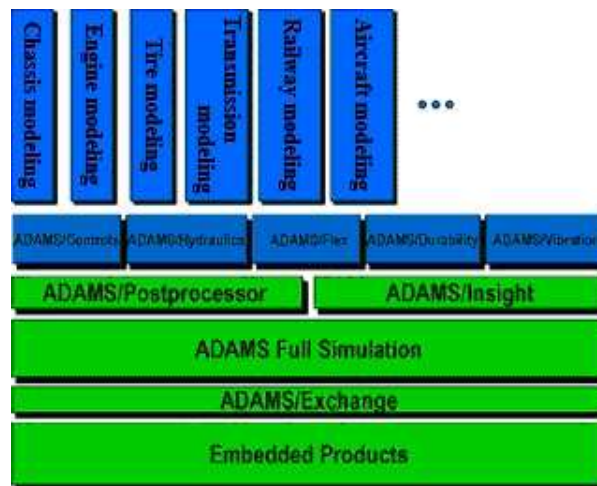Adams is a family of interactive motion simulation software.

Figure 8: Software package structure

A core package in Figure 8(Adams/View, Adams/Solver, and Adams/PostProcessor) allows you to import geometry from most major CAD systems or to build a solid model of a mechanical system from scratch. A full library of joints and constraints is available for creating articulated mechanisms. Once the virtual prototype is complete, Adams checks the model and then runs simultaneous equations for kinematic, static, quasi-static, and dynamic simulations. Results are viewable as graph, data plots, reports, or colorful animations that you easily can share with others. You can use the results (loads created from different types of motion) of Adams simulation studies to provide loads for many different programs including Nastran to optimize the structure of a design.

In other words, it lets you build and test virtual prototypes, realistically simulating on your computer, both visually and mathematically, the full-motion behavior of your complex mechanical system designs. With ADAMS, you can quickly and easily create a complete, parameterized model of your mechanical system, building it from a scratch or to import parts' geometry from your preferred CAD system. You apply then forces and motions and run this model through a battery of physically realistic 3D motion tests.

Adams benefits are:

- work in a secure virtual environment, without the fear of losing critical data;
- reduce risk by getting better design information at every stage of the development process;
- analyze design changes much faster and at a lower cost than physical prototype testing requires;
- improve product quality by exploring numerous design variations in order to optimize full-system performance;
- vary the kinds of analyses being performed without having to modify physical instrumentation, test fixtures, and test procedures.

There is a wide range of extension modules, including ADAMS/Control to analyze control systems, such as hydraulics, electronics, pneumatics, and so on; ADAMS/Flex to examine the impact of flexible parts; ADAMS/Linear to calculate natural frequencies and mode shapes of large systems. ADAMS also offers a range of modules tailored especially for automotive,

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aerospace, and rail industries. These modules include templates to build design simulation. Several CAD interface modules allow you to explore the motion of CAD designs without having to leave a familiar CAD interface or transfer data into Adams.

There are a lot of purposes this package can be used for. There are such operations as listed in Figure 9 and a lot of other ones:
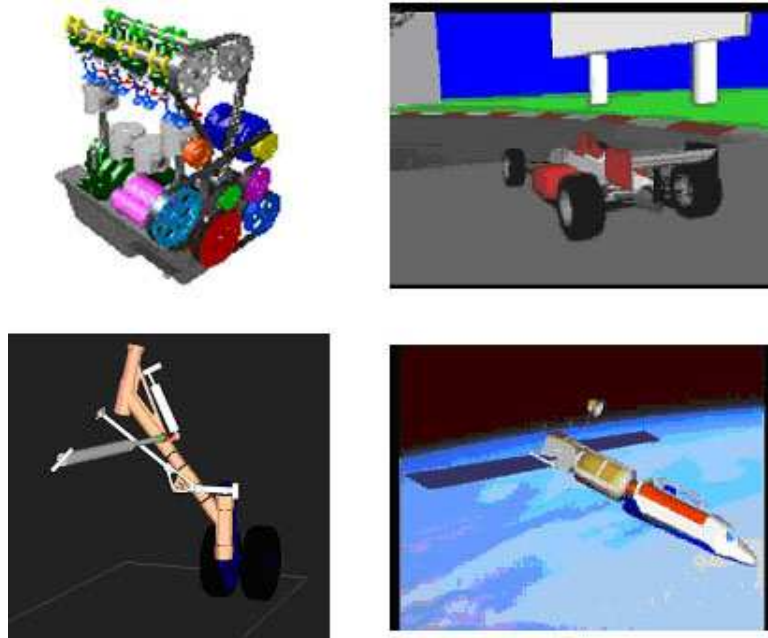

Figure 9: MSC.ADAMS examples

The ADAMS example is the Multilink robot. It is a kind of manipulator with its arm constructed in such a way that by taking appropriate shapes it can avoid obstacles encountered in the workspace. The arm of the multilink robot, shown in Figure 11, consists usually of great number of rigid links connected by kinematical pairs of different classes and its dynamical and kinematical analysis is not straightforward.
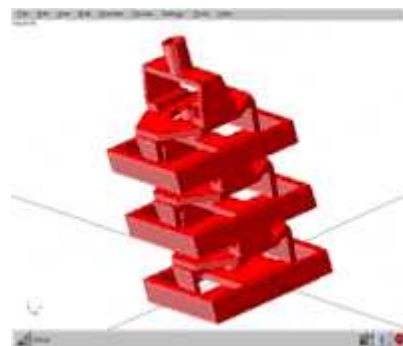
Figure 10: General view of a segment

The classical example of such a manipulator is spine-type robot constructed in the late eighties.

The solution to inverse dynamics is understood here as determining torques time function necessary to drive robot along the desired trajectory.
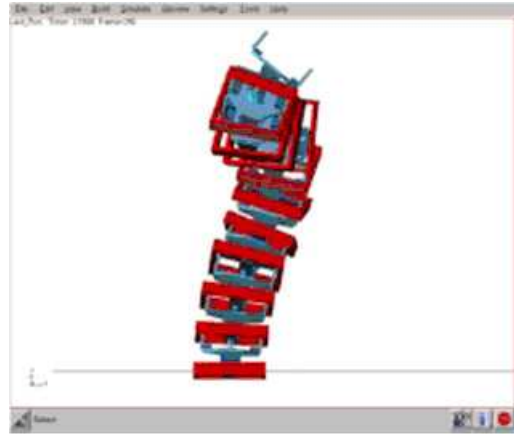
Figure 11: Multilink robot arm

In real construction the driving torques come from the motors placed on the segments and their mass and dynamics should be included in the model.

The driving torques for the multilink robots can be found in ADAMS in two stages:

- inverse kinematics should be solved;
- driving toques can be determined as the reaction forces of the driving constraints.

3 MSC.ADAMS Virtual Prototype Examples

The following part of the report will be about examples of my teachers and colleagues virtual prototyping in MSC.ADAMS.

3.1 The Snakelike Robot ZmeeLoc

The existing prototypes of snakelike robots are developed by various firms and universities of Russia, Europe, Japan, China and USA [6]. They have reached a significant progress in imitating snake ways of movement, but there are still difficulties with maneuverability, carrying capacity, speed and autonomy (i.e. abilities to long work without use of external power supply).

We have a special interest in snakelike robot ZmeeLoc that was developed in CRDI RTC. Figure 12 shows it physical view.

Figure 12: Snakelike robot ZmeeLoc

This device represents an iterative system that consists of 16 parts. These parts are connected with each other by means of Hook's two-sedate hinges. In each part there are two servo-drives. These drives provide rotation in two degrees of freedom.

For model construction of this snakelike robot software package has been used, because it allows to analyze complex mechanical and mechatronic systems dynamics, to create a reasonable and economic basis in designing new machines and mechanisms. Mechanical system model, created in this software product, is described in mechanics' terms, like bodies, connections and forces and it's very easy to compare dynamics' simulation results with physical experiments results.

Virtual ADAMS-model of the snakelike robot ZmeeLoc (Figure 13)is an assembly that contains 31 firm bodies. It was created in the software package SolidWorks and exported to MSC.ADAMS.
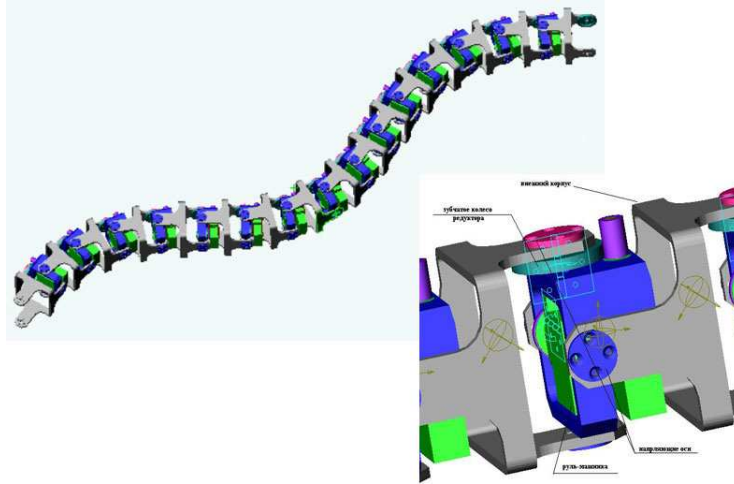
Figure 13: ZmeeLoc ADAMS-model

Sixteen rigid cases are connected with 15 Hook's hinges by means of one-sedate cylindrical hinges that provides two degrees of mobility. Hinges are produced with the help of the ADAMS's basic working tools package (Main Toolbox) in the form of one-sedate rotation hinges.

When the model was exported from SolidWorks, the weights-inertial characteristics of its bodies were transferred into ADAMS, too.

Produced version shows us the virtual model of a robot movement on a plane. The interaction of system's bodies with the given plane is carried out by means of contact forces, which were entered with the help of standard tools of MSC.Adams.

If we want to operate the virtual model, then it is necessary to set the rotation law. It is set in each cylindrical hinge by means of moments operated by PD-regulators.

At the stage of a control system construction, the factors of a PD-regulator were picked up empirically.

Simulation of dynamics movement during the modeling time has shown a solvency of the work done. Nowadays, the ZmeeLoc model, using the offered control system, has overcome the distance equal to its half length. The recount of its movement has borrowed 6 minutes of real time on the test system.

Visual materials of the mentioned above control system illustrate movement of the snakelike robot model on a plane, using the direct and lateral courses.

3.2 Mobile Multifunctional Platform SEPTOPOD

Among other interesting devices, developed in our institute, is robotic device SeptoPod. It represents a mobile multifunctional platform, capable of carrying various gauges and devices. Its primary application is to carry out investigation in remote or dangerous places, on blocked places and failures.

Septopod consists of heptagonal aluminum basic platform and seven legs, from technical point of view. Each leg is equipped with two servo-drives in order to perform two degrees of mobility.

Septopod's operating system is performed with the use of feedback and genetic algorithm at stage of current development. Movement in servo-drives of hinges is set in the form of harmonious function equations. Selection of factors for these equations (amplitudes, phases and frequencies of fluctuations) is carried out by the special computer program. The received laws of movement act on servo-drive controllers, where these laws are fulfilled. As the result of it the robot changes its position in space.

Its virtual model (Figure 14)has been designed for development of a real breadboard model. It has been made to fulfill operating algorithms and to avoid risk of prototype damage.
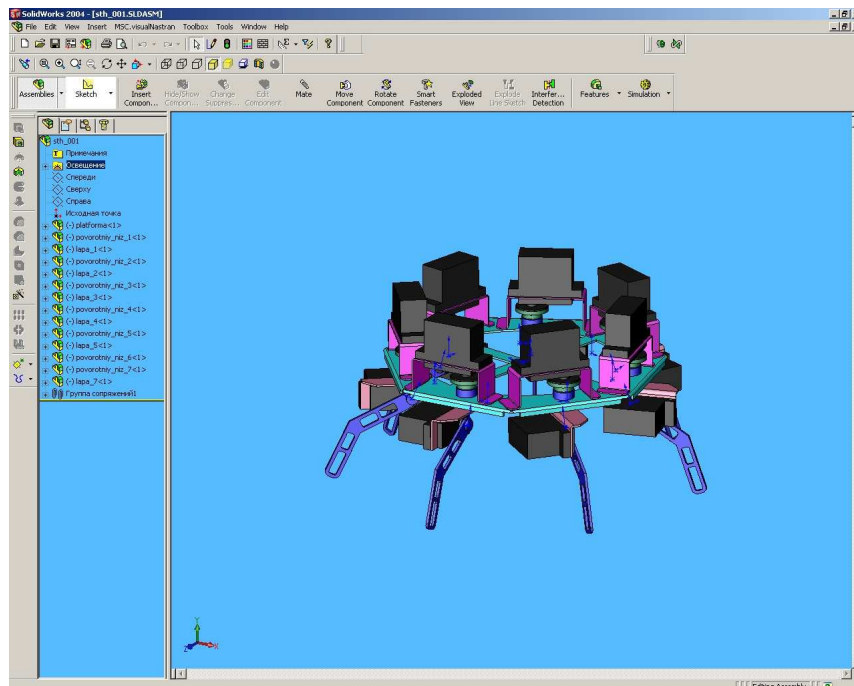

Figure 14: SEPTOPOD's virtual model

The virtual model has been created in software package SolidWorks and exported to MSC.Adams. All features of a design, like setting communications, hinges and materials, were transferred into it. The laws of movement of foot drives are carried out with the use of tables, which are read from a file. According to this data the construction of cubic splines, which are the rotation laws of Septopod's hinges, is made. Nowadays, research based on connection between Septopod virtual model and genetic algorithm program is being carried out in MSC.Adams. It is necessary for carrying out virtual experiments.
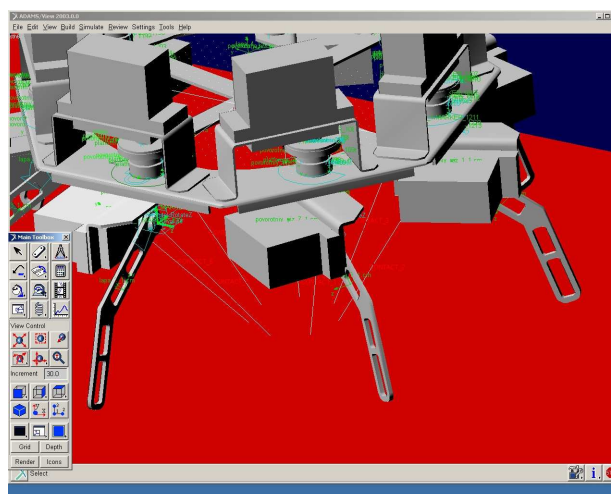

Figure 15: Rotary paw view

The program of genetic algorithm generates the laws of movement for virtual model. Then they are read out by the software package MSC.Adams and the virtual experiment starts. Coordinates of our robot's center of mass are written down into the file in the course of experiment. These data are read by genetic algorithm program which corrects factors of equations. Then process repeats.

3.3   Humanoid Robot

Its virtual model is shown in Figure 16 [7]. It was developed in SolidWorks and exported to MSC.ADAMS by "New Era" designers. It is equipped by all necessary mechatronic systems' attributes and it was a prototype of orthograde models development.
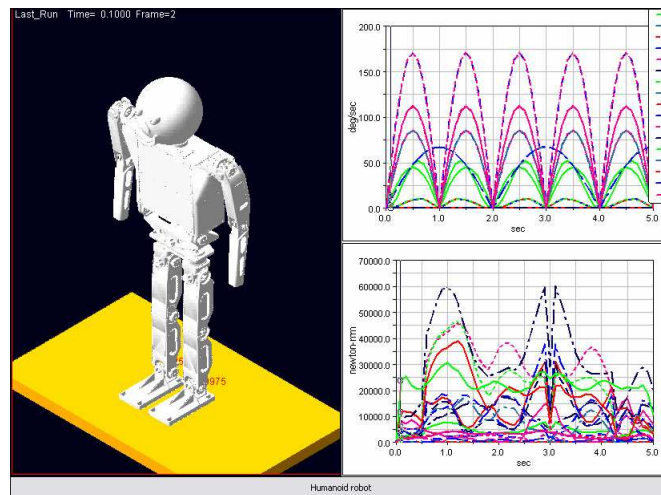

Figure 16: Humanoid robot

All the constructional and technological features pawned at the designing stage, have found reflection in mechanical virtual model.

Then the model was modified. Contacting forces, hinges and connections were added. The control system model which was developed by means of MatLab/Simulink package has been added. It is intended for real physical model control. Robot electromechanical model was developed by means of ADAMS/View and joined operating contour as a control object.

Interface between MatLab and ADAMS was provided by means of ADAMS/Control module.

Series of numerical experiments to find out robot's stability and limits of its parts corners have been led.

Model movement is represented in Figure with simultaneous corners change. Limits of corners change and angular speeds are picked up so that reactions in reference points are positive. The right side diagram represents dependence of the angular speed, operating moment and drive capacity in ankle joint.

4 Conclusions

Modeling is the first step to design, identify and control robots and it's a powerful technique to improve quality and productivity. Most efficient algorithms proposed for these applications are based on good study of robot model parameters. These operations need to be carefully planned.

Modern virtual prototyping tools have possibility to project dynamic and mechanic systems and allow to reach greater success in designing.

The successful coordination and interaction of robots and software will require new system designs, communication protocols and interfaces.

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