KINEMATICAL SYNTHESIS AND DYNAMICAL ANALYSIS OF MULTILINK ROBOT USING MULTI-BODY APPROACH

Janusz Frączek
Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology
Nowowiejska 24, 00-665 Warsaw, POLAND
e-mail: jfraczek@meil.pw.edu.pl

1. Introduction.

Multilink robot 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 classical example of such manipulator is spine-type robot constructed in the late eighties. The arm of the multilink robot consists usually of great number of rigid links connected by kinematical pairs of different classes and its dynamical and kinematical analysis is not straightforward.

An example of a multilink robot is the one designed and built (prototype) recently in the Institute of Aeronautics and Applied Mechanics (IAAM) of Warsaw University of Technology [1]. For the control system synthesis purposes the classical robotics tasks like trajectory planning, direct and inverse kinematics and dynamics were investigated. Since the analytical solution of kinematics and dynamics is not available for that robot, the general multibody formalism implemented in ADAMS™ (DAE equations) [2] environment was used. It should be pointed out that in the robotics field, and in the specialised multibody robotics packages, the problem of direct and inverse kinematics and dynamics are distinguished in natural way (e.g. when the motion of the robot gripper is planned, and the inverse dynamics problem is considered- driving torque's must be found). In the multibody packages based on Lagrange equations with constraints (like ADAMS) both tasks are not treated separately and are solved using simple tricks.

In the paper the following issues are presented – solved in ADAMS environment:

- kinematical synthesis and trajectory planning of the multilink robot,
- the inverse kinematics solutions,
- the inverse dynamics solution.

The dynamical problem presented in the paper was solved using strong assumption that friction forces can be neglected. At present the results with friction modelled by ADAMS 10.1 algorithm are being calculated and will be discussed during oral presentation.

2. Kinematical and structural synthesis.

The multilink robot designed in IAAM consists of several sets of bodies called segments. The robot was primarily intended to weld car body in places, which are not easy to reach. Each segment is built of rigid parts and its kinematical scheme is given in the Fig.1. The segment consists of n rigid parts connected by spherical-translational (II- th class) and revolute joints. The i-th rigid body in the segment is connected with (i-3) body by spherical- translational joint and with (i-1) body by revolute joint. The mobility of the segment (Grubler number) does not depend on number of rigid bodies (see e.g. Fig.2) and is always equal to 2. The segment does not contain redundant constraints. The 2,3 4 (generally m) segments with different or equal number of bodies can be connected giving manipulator with Grubler count equal to 4,6 and 8 (2m) respectively. In the Fig.3 two different variants of multilink robots fixed to the base (ground) are shown – consisting 3 segments but with different number of bodies in each of the segments (equal to 6 in the first manipulator and equal to 10 in the other). In both cases the mobility of the manipulators is equal to 6.

For the industrial applications it is essential the robot should be capable of realising trajectory required by welding process with collision avoidance if necessary. This property depends significantly on kinematical properties of the robot. The simplest way of description of the robot kinematical properties is whole workspace analysis. Since in the multilink robot case solution to this task seems to be complicated the kinematical structure of the robot is investigated for different trajectories of the robot tip. The initial position of the robot is known.

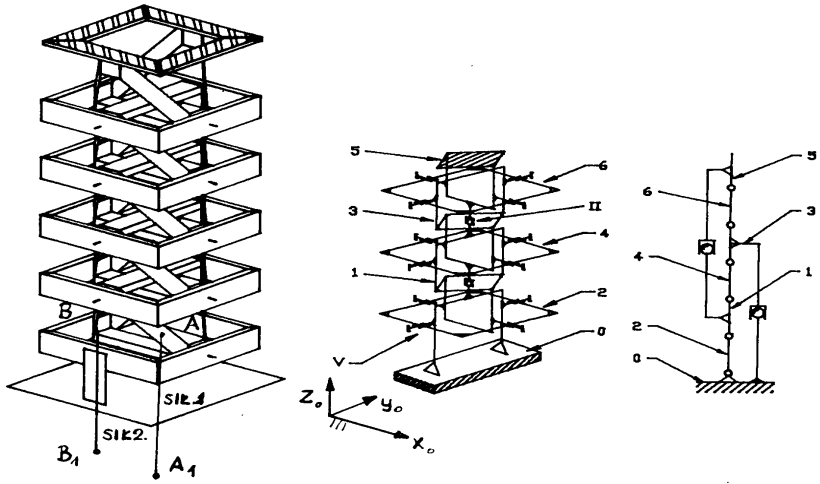


Fig. 1. The kinematical scheme of one segment of the multilink robot. The mobility (Grubler number) is equal to 2 and does not depend on number of rigid bodies.

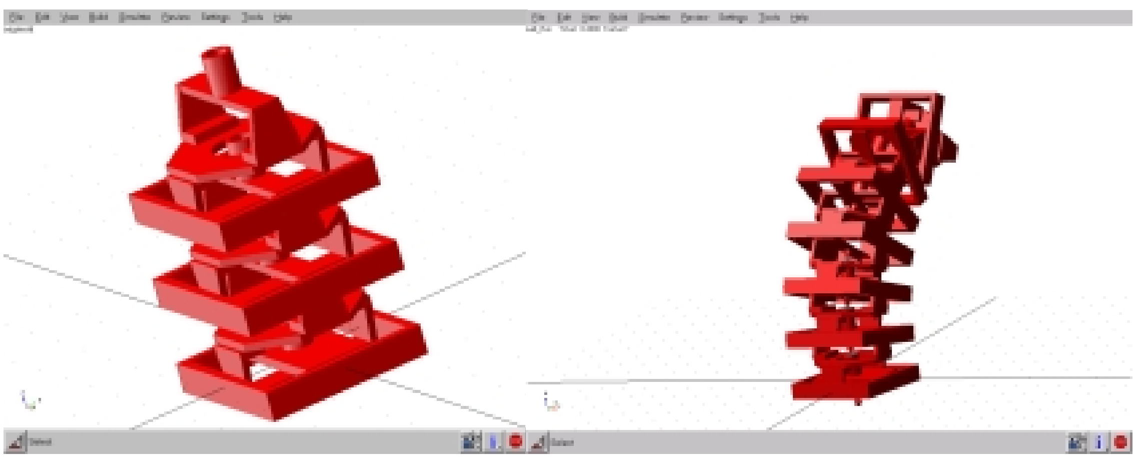


Fig.2. The general view of one segment consisting 6 and 14 rigid bodies (ADAMS view).

It is obvious that number of segments and number of bodies in each segment, relative positions of kinematical pairs and kinds of robot driving should be considered as the main factors that affect the kinematical properties of the robot.

Although different structures were investigated in the design process, it was assumed in this kinematical study that multilink robot was built of three segments (6 DOF total) with different number of bodies in each of the segment - equal to 6,8,10,12 and 14 respectively. Moreover robot is driven in revolute joints – two driving torques in the lowest revolute joints (at the base of the segment) for each segment. The relative positions of kinematical pairs of the segments are parameterised in certain range. It should be pointed out that in case the robot consists of more than 3 segments the number of degree of freedom is greater than 6 and manipulator becomes redundant. In such a case it can realise trajectories avoiding obstacles of different shapes depending on the degree on redundancy.

For kinematical and structural synthesis the one of the trajectories obtained from technical specifications of the welding process was chosen. The trajectory (shown in Fig. 3b as the white line) describes the position of the point on the top body (where robot gripper is placed) of the robot and orientation of the body (three angles) as the smooth (C^1 class) function of time in the inertial co-ordinate frame. In the Fig.4a and 4b the the x co-ordinate and orientation angle (around Y) of the marker fixed to the top body of the robot (identified with robot gripper), called gripper marker, along the planned trajectory are presented as a function of time. The trajectory is always defined in the inertial reference frame defined by initial position of gripper marker.

a) b)

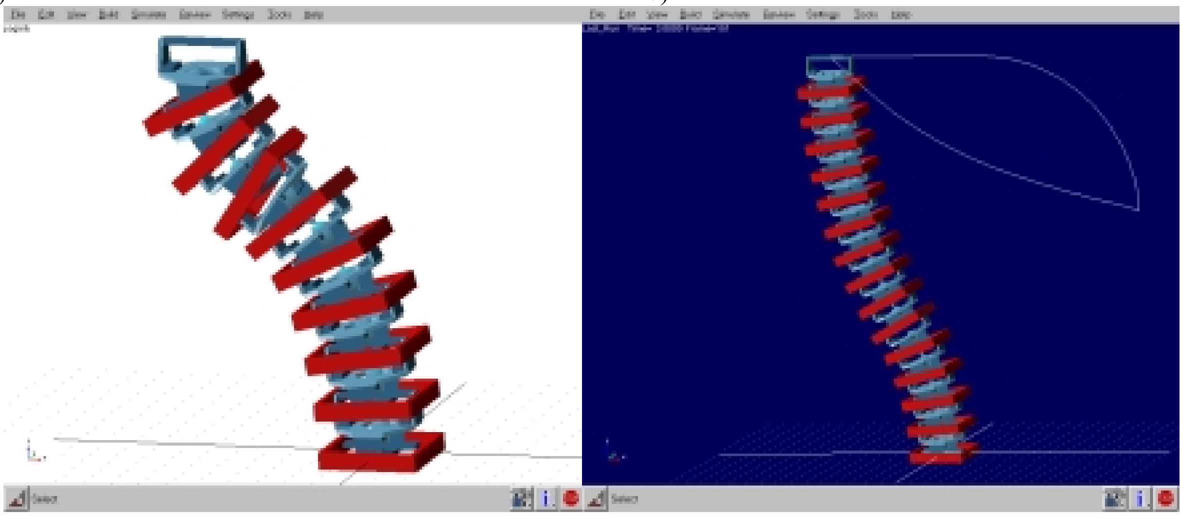


Fig.3. Three segment manipulators a) segment with 6 rigid bodies b) segment with 10 rigid bodies.

The kinematical and structural synthesis consist in:

- deciding whether the trajectory can be realised for given structures and dimensions of the robot (detection of lock-up positions),
- detection of singular positions of the robot and particularly positions where kinematical parameters of robot links are not continuos function of time,
- determining the relative angles in the revolute joints with actuators as the function of time (inverse kinematics).

a) b)

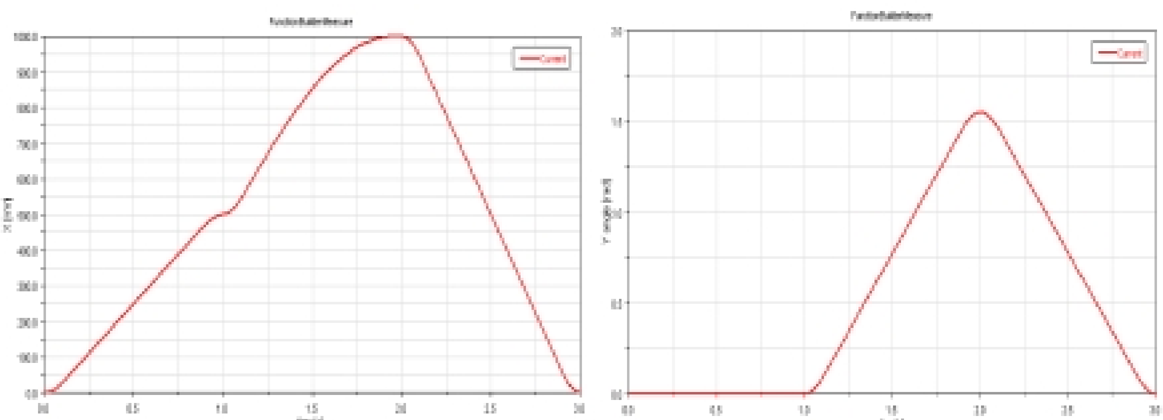


Fig.4. Trajectory of the multilink robot a) x co-ordinate of the marker placed on the robot gripper with reference to initial (ground) reference frame b) angle of the marker around the Y axis.

The kinematics of the robot is simulated using multibody model developed in ADAMS (Fig.2, Fig.3). The distances between axis of revolute joints (and simultaneously distance between spherical- translational joints) were parameterised using design variables.. Moreover the analysis was automated i.e. the model is built automatically if the number of segments, number of bodies in each of the segment and initial position of the robot is known.

Many simulations using ADAMS were carried out for different structures of multilink robots (here only three-segment manipulator with various number of bodies in each segment is analysed). The two typical configurations that can be detected with ADAMS package are shown in the Fig.4. and Fig.5. Figure 4 presents results of simulation of kinematical analysis for robot consisting 6 bodies in each segment. The planned trajectory is not accessible for that structure of robot due to the lock-up configuration detected for time of simulation equal approximately to 1.5 s. Although ADAMS does not communicate lock-up position, it can be verified that euclidean norm of generalised velocities and acceleration converges to infinity in lock-up position (fig.5 b) [3] i.e.

$$\lim_{time \to timelock} \|\dot{\mathbf{q}}\| = infinity$$

a) b)

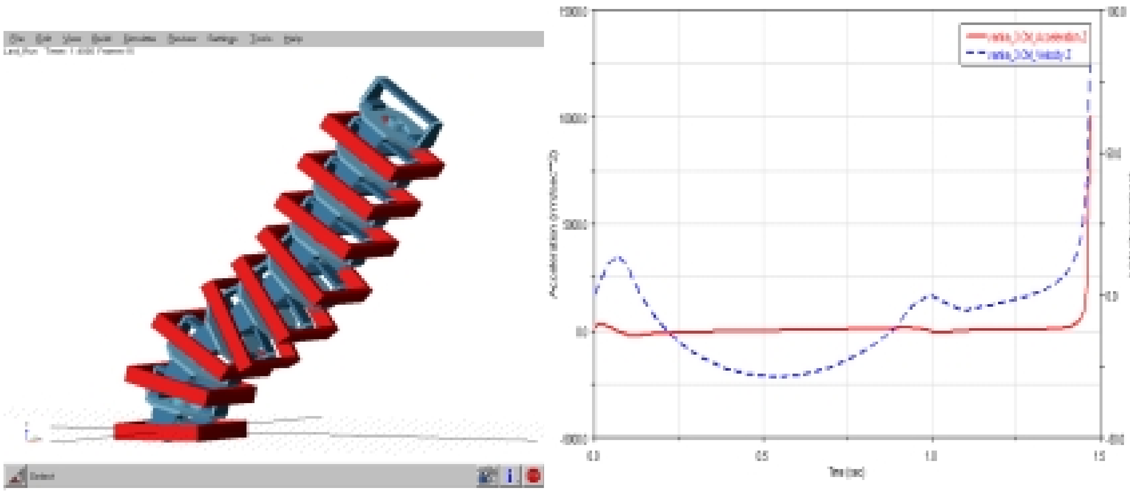


Fig.5. The results of simulation for robot with 3 segments consisting 6 bodies. Lock-up detection.
a) Robot position in lock-up configuration b) Diagrams of velocities and acceleration of cm marker of one of the robot body (3rd segment). In the lock-up positions they become unlimited.

In Figure 6 the results of simulation of robot with 8 bodies in each segment are shown. The diagram of velocities (Fig.6c) indicates that in time of simulation equal to 2.54 s solution of the kinematical task switches discontinuously form one branch of the solution to the another. Figures 6a and 6c show two consecutive positions of the robot confirming discontinuity of the solution obtained form simulation with ADAMS package. In case the robot with segments built from 10 bodies is analysed the planned trajectory can be realised without any “mathematically pathological” behaviour. It was checked with ADAMS if robot consists of more than 10 bodies in each segment the trajectory can be accessed by robot gripper as well.
For the case of robot structure with 10 bodies in segment the inverse kinematics task was solved with driving actuators attached to revolute joints at the bases of segments. The driving constraints imposed on the revolute joints, to realise required trajectory by robot gripper can be found using measure tool implemented in ADAMS. During kinematical simulation the relative angles in six revolute joints were measured and saved as functions of time in sufficient number of points. In case the smooth function of time is required the spline or FFT function can be used to make motion continuous. It was checked that robot gripper repeats planned trajectory with sufficient accuracy when the motion in driven joints is given by calculated splines.
Figure 7 presents the relative angles in driven joints obtained from numerical simulations.
Finally it should be pointed out that graphical representation of the multilink robot in ADAMS proved to be valuable tool for collision detection and is useful to plan trajectories to avoid any obstacles encountered in the workspace. As an example figure 6a presents configuration of the robot that is acceptable from kinematical point of view and is not permissible from geometrical point of view since rigid bodies of the robot cannot intersect.

3. Dynamical analysis of the multilink robot.

The typical tasks that are solved in robotics applications are known in the mechanics field as the direct and inverse dynamics. The first one consists in evaluating kinematical parameters of the robot if the driving forces are known and the other applies to determining driving forces when the trajectory of the robot gripper is given. Consequently, direct dynamics must be investigated during simulation of the robot motion under various driving forces, and inverse dynamics is usually solved when driving forces should be found for given trajectory of the robot. In ADAMS direct task can be solved in straightforward manner, however the inverse task requires solving inverse kinematics first. Here only inverse dynamics solution useful during control system synthesis is discussed.

a) b)

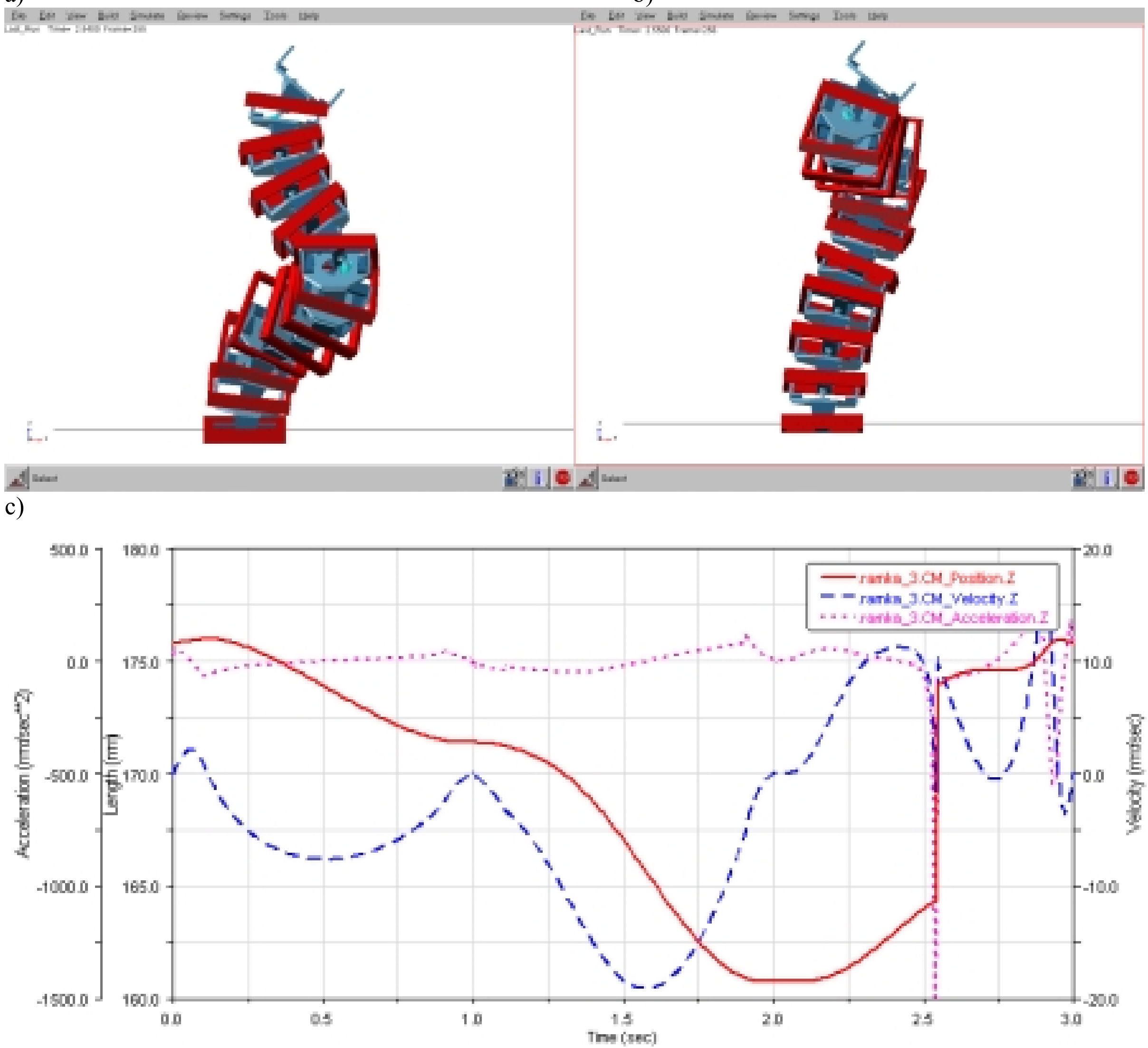


Fig. 6. The results of simulation of multilink with 3 segments consisting 8 bodies. At time=2.54 s singular position and switch of the solution from one branch to the another can be observed.
a),b) The animation sequences of robot in turn , time=2.54s and time=2.55s. c) diagrams of position, velocity and acceleration of cm marker (z axis) on one of the robot body (in 3 rd segment).

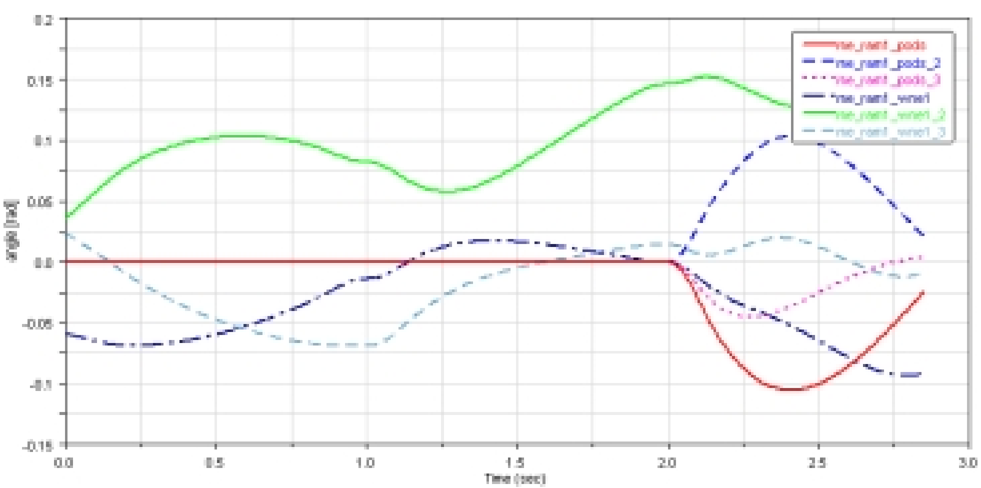


Fig.7. Relative angles in the driven joints as a function of time (spline representation).

The solution to inverse dynamics task was found for multilink robot with 3 segments consisting 10 bodies for the gripper trajectory the same as in the kinematical synthesis. The solution to inverse dynamics is understood here as determining torques time function necessary to drive robot along the desired trajectory. 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.

The driving constraints imposed in the driven joints presented in Fig.7 were briefly discussed in the previous item. The reaction forces of the motions representing driving torques can be found automatically in ADAMS with reference to the co-ordinate frames fixed to the robot links. Fig. 8 presents driving torques found in ADAMS for multilink robot provided that segments consist of 10 bodies each.

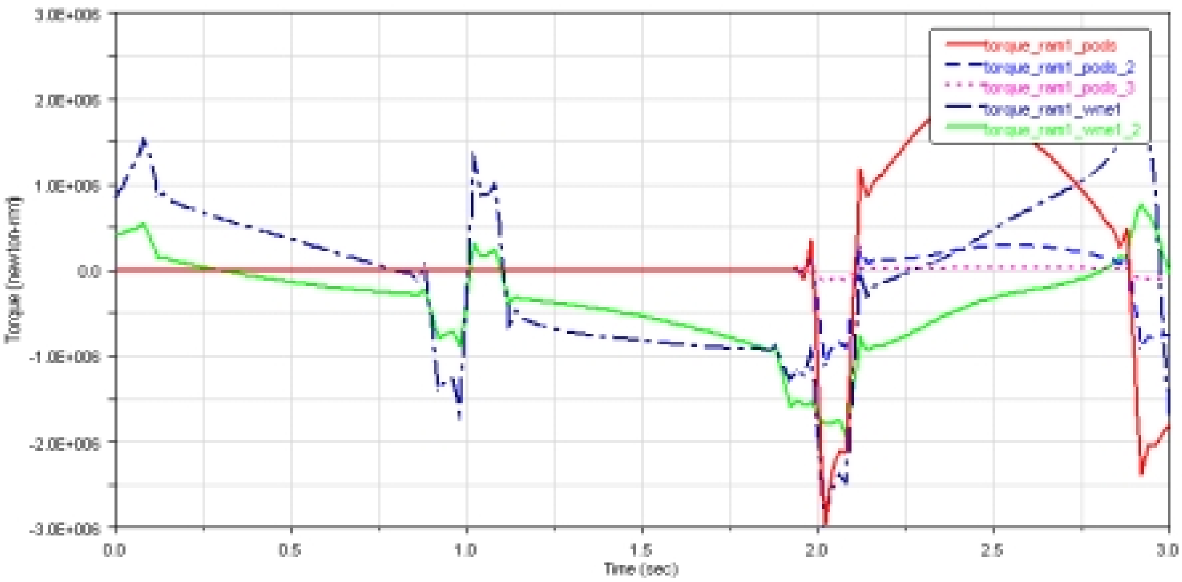


Fig. 8. The torques driving manipulator along planned trajectory obtained from ADAMS simulation.

4. Concluding remarks.

The ADAMS model of multilink robot was developed. The kinematical analysis and synthesis was carried out using ADAMS tools. The graphical representations of the robot during simulation were used to detect collision with obstacles. The problem of inverse dynamics, being usually solved in the control system synthesis was studied basing on ADAMS simulations.

5. References.

1. Frączek J.: Kinematics and Dynamics of Multlink Robots. Proceedings of the 23 rd IsiR. Barcelona Spain, 6-9th October 1992, pp.249-253.
2. ADAMS – ver. 10.1 Manuals (ADAMS View User's Guide, ADAMS Solver etc. MDI, USA 2000.
3. - Haug, E.J.,Computer-Aided Kinematics and Dynamics of Mechanical Systems, Volume I: Basic Methods, Allyn and Bacon, (1989).

KINEMATICAL SYNTHESIS AND DYNAMICAL ANALYSIS OF MULTILINK ROBOT USING MULTI-BODY APPROACH

Janusz Fraczek

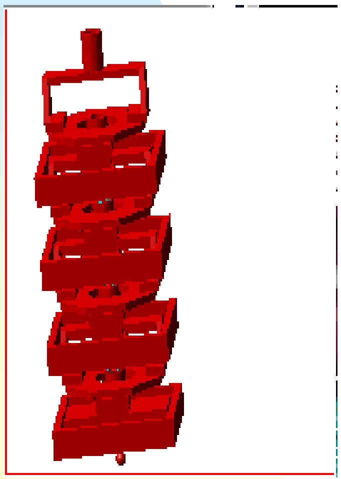
Institute of Aeronautics and Applied Mechanics,
Warsaw University of Technology
Nowowiejska 24, 00-665 Warsaw, POLAND

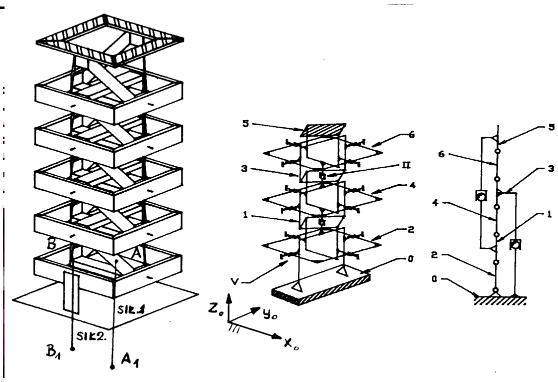
ADAMS Conference, Roma 2000

- **Multilink robot 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 consists usually of great number of rigid links connected by kinematical pairs of different classes and its dynamical and kinematical analysis is not straightforward.**
- **The classical example of such a manipulator is spine-type robot constructed in the late eighties.**

Example: Multilink robot designed and built (prototype) recently in the Institute of Aeronautics and Applied Mechanics (IAAM) of Warsaw University of Technology.

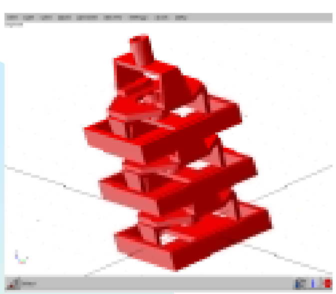
- ***Kinematical scheme***



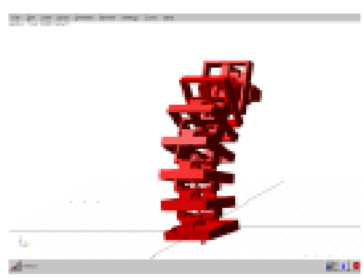


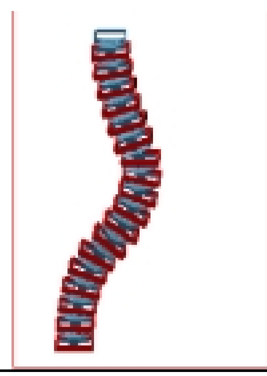
- ***Grubler count = 2***
- ***no redundant constraints***

- 3 body segment

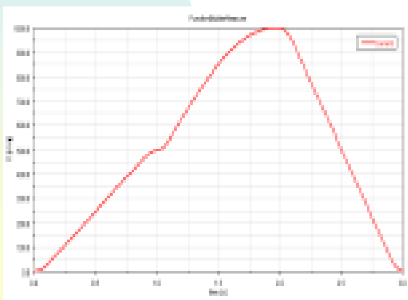


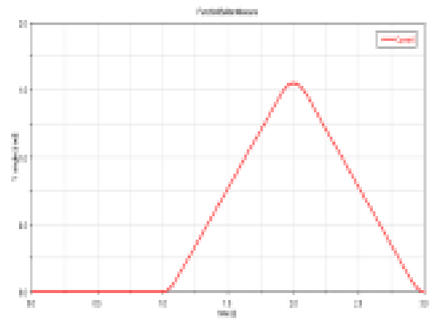
- 7 body segment





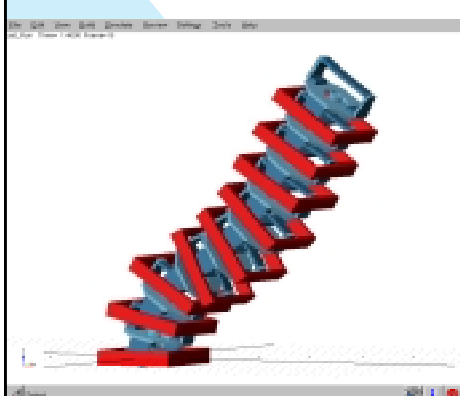
- **The kinematical and structural synthesis consists in:**
- **deciding whether the trajectory can be realised for given structures and dimensions of the robot (detection of lock-up positions),**
- **detection of singular positions of the robot and particularly positions where kinematical parameters of robot links are not continuous function of time,**
- **determining the relative angles in the revolute joints with actuators as the function of time (inverse kinematics).**

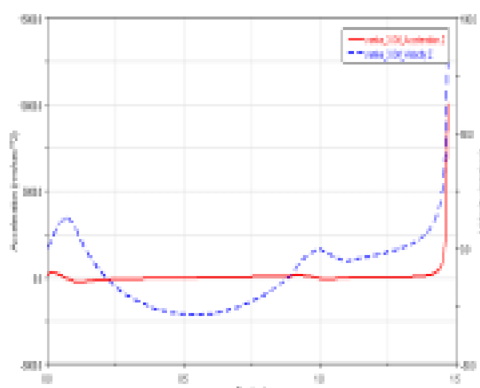




- **X co-ordinate** **Y angle**

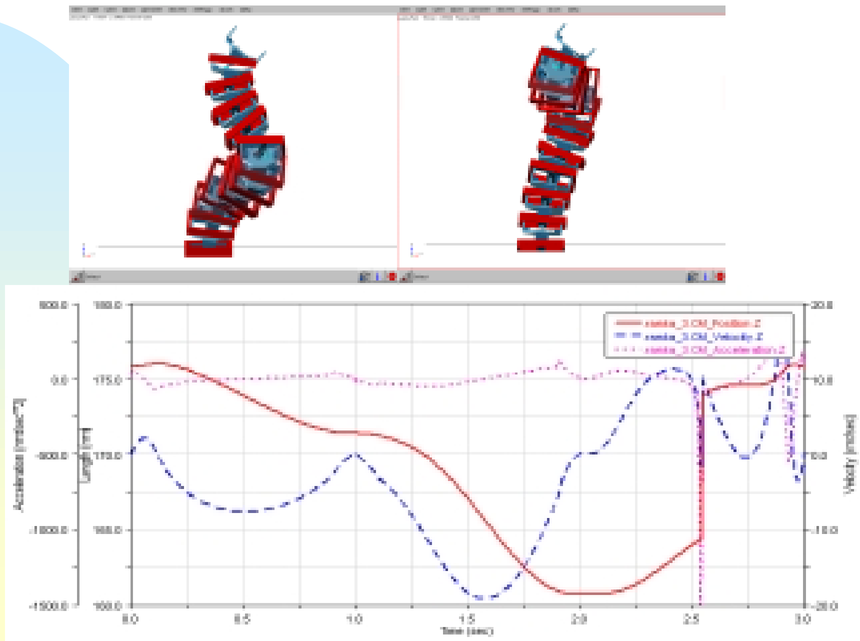
Lock-up configuration



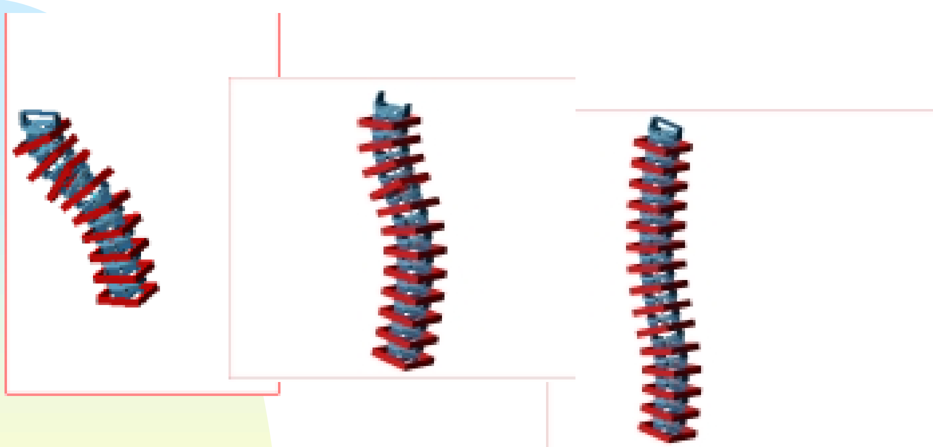


$$\lim_{time \to timelock} \|\dot{\mathbf{q}}\| = infinity$$

Solution switching



ADAMS Animations



Lock-up

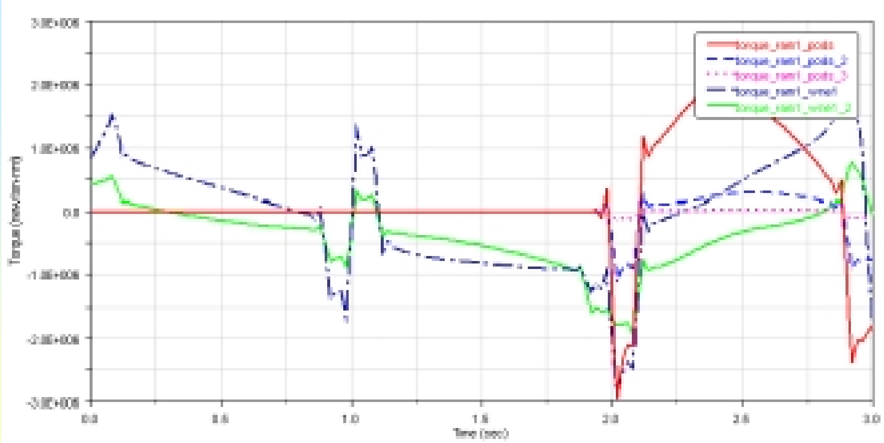
solution switching

without pathological solutions

Inverse dynamics

- solution to inverse dynamics is understood here as determining torques time function necessary to drive robot along the desired trajectory. 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.

Diagrams of driving torques



Concluding remarks.

The ADAMS model of multilink robot was developed. The kinematical analysis and synthesis was carried out using ADAMS tools. The graphical representations of the robot during simulation were used to detect collision with obstacles. The problem of inverse dynamics, being usually solved in the control system synthesis was studied basing on ADAMS simulations.