Virtual Prototyping of a Parallel Robot actuated by Servo-Pneumatic Drives using ADAMS/Controls

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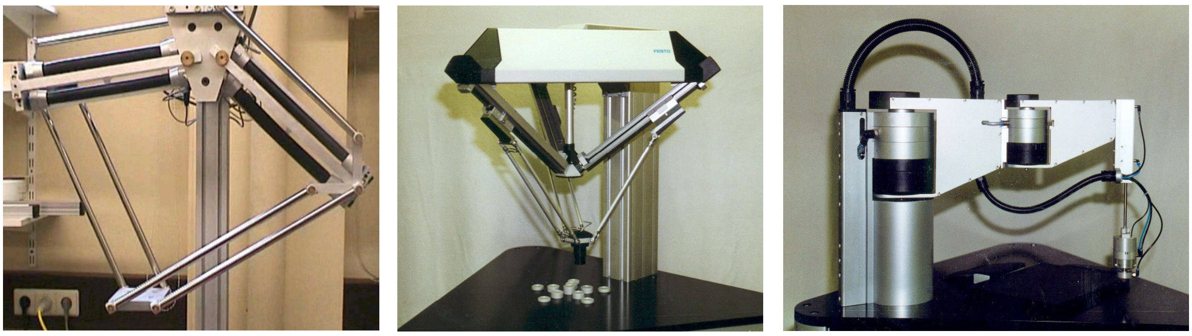
Summary

Advanced pneumatic drives for servo-pneumatic positioning allow for new generations of handlings and robots. Especially parallel robots actuated by servo-pneumatic drives allow the realization of very fast pick and place tasks in 3-D space. The design of those machines requires a virtual prototyping method called the mechatronic design [1]. The most suitable software tools are ADAMS for mechanics and Matlab/-Simulink for drives and controllers. To analyze the overall behavior the co-simulation using ADAMS/Controls is applied. The combination of these powerful simulation tools guarantees a fast and effective design of new machines.

1. Introduction

Festo is a supplier for pneumatic components and controls in industrial automation. The utilization of pneumatic drives is wide spread in industry when working in open loop control. It's limited however, when it comes to multipoint movement or path control. The development has been driven to servo-pneumatic drives that include closed loop control. Festo servo-pneumatic axes are quite accurate, thus they can be employed as drives for sophisticated tasks in robotics. The special advantage of these drives is the low initial cost in comparison to electrical and hydraulic drive systems. Servo-pneumatic driven parallel robots are new systems with high potentials in applications. The dynamical performance meets the increasing requirements to reduce the cycle times.

One goal is the creation and optimization of pneumatic driven multi-axes robots. This allows us to support our customers, and of course to create new standard handlings and robots (Fig. 1).



Two-axes machine with pneumatic muscles | Tripod | Scara

Fig. 1. Prototypes of servo-pneumatic driven multi-axes machines

The complexity of parallel robots requires the use of virtual prototyping methods.

Preferred applications are fast multipoint positioning tasks in 3-D space. Free programmable stops allow a flexible employment of the machine. The point to point (ptp) accuracy is about 0.5 mm. The continuous path control guarantees collision free movement along a trajectory.

1.1. Why parallel robots?

The main benefits using parallel instead of serial kinematics is shown in Fig. 2.

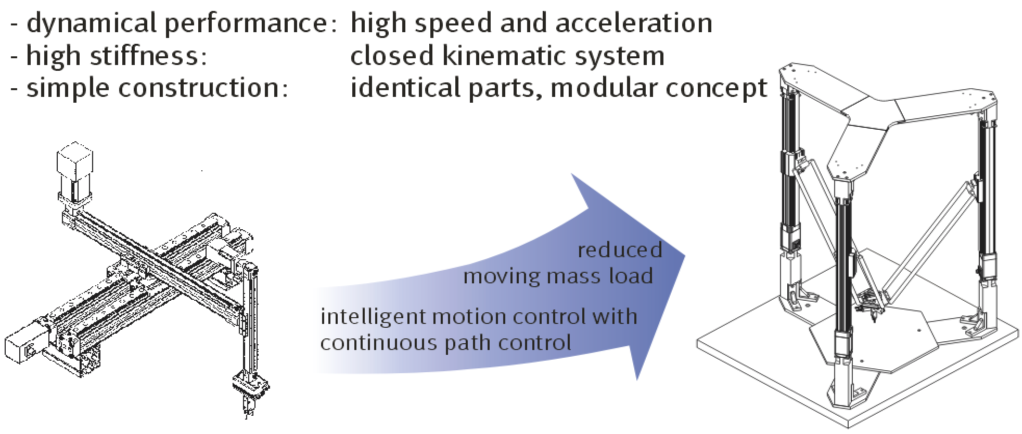


Fig. 2. Benefits of robots with parallel kinematics

High dynamical performance is achieved due to the low moved masses. While in serial robots the first axis has to move all the following axes, the axes of a parallel robot can share the mass of the workpiece. Furthermore serial axes are stressed by torques and bending moments which reduces the stiffness. Due to the closed kinematics the movements of parallel robots are vibration free for which the accuracy is improved. Finally the modular concept allows a cost-effective production of the mechanical parts. On the other hand there is the higher expense related to the control.

1.2. Why Pneumatic Drives?

The advantages of servo-pneumatic drives are:

- direct drives → high accelerating power
- compact (especially rodless cylinders with integrated guidance)
- robust and reliable
- cost-effective

Direct drives imply a high acceleration power due to the low equivalent mass in relation to the drive force. With pneumatic drives the relationship is particularly favorable.

Festo has already built up some system solutions, predominantly parallel robots (see Fig. 1), to demonstrate the technical potential of servo-pneumatics. Which performance can be reached is shown in Fig. 3. This prototype is equipped with an advanced model based controller that makes use of the computed torque method [3].

Technical Data:		
Frame space	800x750 h = 1100	[mm]
Workspace (cylindrical)	d = 400 h = 200	[mm]
Max. acceleration (5 bar, 0.3 kg load)	50	[mm/s²]
Max. velocity	3.5	[mm/s]
Absolute accuracy	0.5	[mm]
Repetition accuracy	0.1	[mm]
Load	≤ 1	[kg]

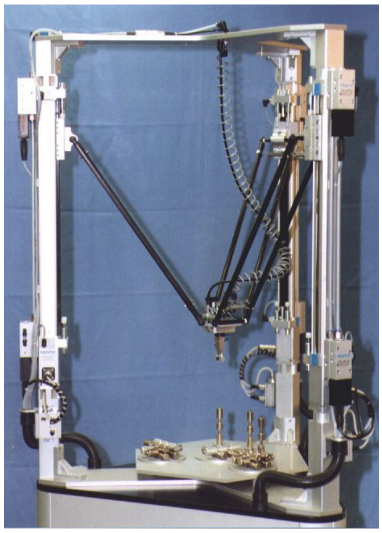


Fig. 3. Performance of the Tripod

2. Design Method

The system design, where several engineering disciplines are involved in, requires a holistic approach. This method is the so-called mechatronic design. The components of a mechatronic system are the mechanical supporting structure, the servo drives as well as the control. All these components are mapped into the computer and optimized with respect to the mutual interaction. This procedure can be used to analyze and improve existing systems as well as to create new systems. The two main steps of the mechatronic design are first building models in each discipline, and secondly the analysis and synthesis of the whole system. These steps are done in a cycle for the optimization.

The modeling can be carried out in two ways: Either you apply one tool to build up models in all disciplines, but with restrictions. The other way is to use powerful tools in each discipline and to analyze the whole system via co-simulation. In this case you have to consider some specials of the solving method like communication step size or direct feedthrough behavior.

2.1. Why Co-Simulation?

Co-simulation is used because of the powerful tools, each specialized in its own discipline. ADAMS is an excellent tool for the mechanical part and Matlab/Simulink[1] is the suitable tool for controller development and simulation of pneumatics.

The behavior of the mechanical part is modeled at best using ADAMS/View. The advantages of ADAMS are:

- fast physically modeling of rigid and elastic bodies
- extensive features for parameterization
- animation of simulation results
- solving inverse kinematics by “general point motion”

[1] Matlab and Simulink are registered trademarks of the MathWorks, Inc.

- visualization of eigenmodes (ADAMS/LINEAR)
- export of linear models (A,B,C,D)

A big advantage is the automatic calculation of the direct and inverse kinematics. The direct kinematics of parallel structures often cannot be solved analytically. Furthermore different kinematics can be compared to each other very easily when you define a trajectory of the end-effector via “general point motion”.

Applying these two software tools guarantees a high flexibility regarding the design of new systems. It is very important to analyze the closed loop behavior at an early stage. This makes a big difference between the mechatronic design and the conventional design. Furthermore the visualization of the mechanical system makes the discussion within a team very easy.

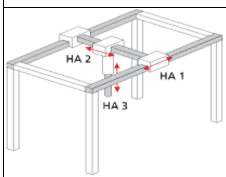
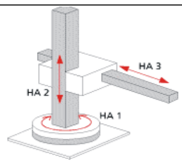
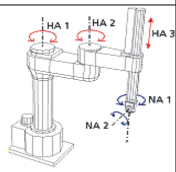
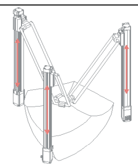
2.2. Restrictions

A disadvantage is that the model of the mechanics is purely numerically available. However some symbolic code of the mechanical system is needed for the control hardware when the system becomes realized. In general we have to derive the equations of the inverse kinematics, which are used in the feed forward control. For specific robot types a controller with decoupling structure is necessary in order to fulfill the requirements. Then the symbolic code of the dynamics is needed. For this we have to pull up further tools to complete the task.

2.3. What has to be analyzed?

For the design of new robots it is important to know about the effect on the system stability and accuracy. The main properties that influence stability and accuracy are opposed in Table 1 for different kinematical structures.

Table 1: Properties of different kinematical configurations

Robot Type:	serial robots			parallel robot
	 cartesian	 cylindrical	 articulated	
Position dependency on inertia	none	minor	strong	medial
Position dependency on gravity forces	none	none	medial (scara: none)	existing
Coupling between axes	none	none	strong	medial
Gyroscopic forces	none	minor	strong	medial

With respect to the control the cartesian type is the best one. But the main disadvantage of a serial robot compared with a parallel one is the lower dynamics and the lower stiffness (see Fig. 2).

Depending on the requirements with regard to dynamics and accuracy different control approaches must be applied. As mentioned above we prefer to employ a standard controller SPC200 for a single axis. Due to the coupling of the axes the stability of the closed loop system must be checked.

3. Model of the Tripod

The model of the Tripod consists of three parts: the mechanics, the pneumatic drives, and the controller.

3.1. Mechanics (ADAMS)

We apply the so-called delta-kinematics which causes a purely translational movement of the tool center point (tcp). An additional rotary drive allows the orientation of the gripper in the horizontal plane. Together with the rotary drive the machine has four degrees of freedom.

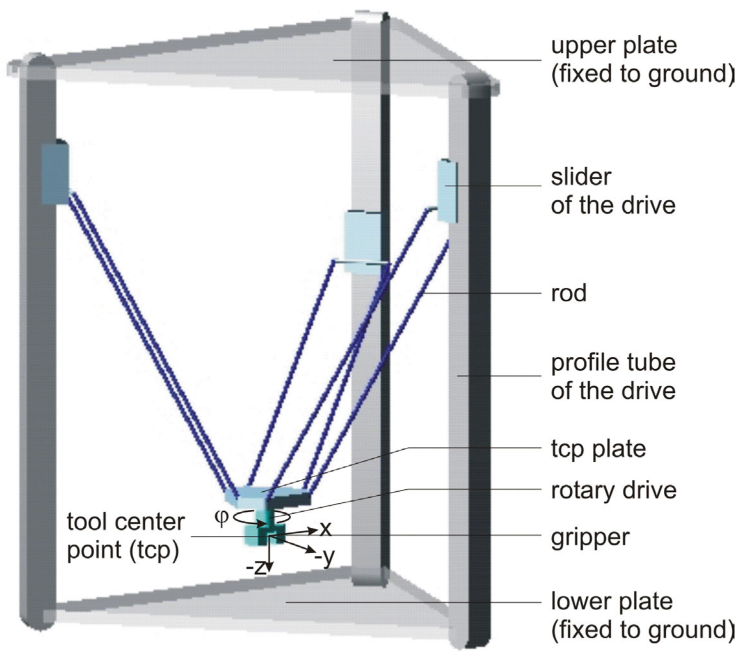


Fig. 4. Degrees of freedom and structure of the Tripod

The tripod is modeled using rigid body parts what is often sufficient for the present type of parallel structure. The upper and lower plates are fixed to ground. The profile tubes are connected to these plates via fixed joints. Each slider has one translational degree of freedom. Both ends of a rod are connected to the neighbored parts by universal joints. Including the rotary drive, the model verification results in four Gruebler counts and there are no redundant constraints. The model is parameterized in such a way that different kinematical configurations can be generated very easily by means of design variables. The most important parameters are the radiuses of the plates (see Fig. 4) and the distances to each other. For instance the following configurations can be achieved just by variation of these parameters or design variables.

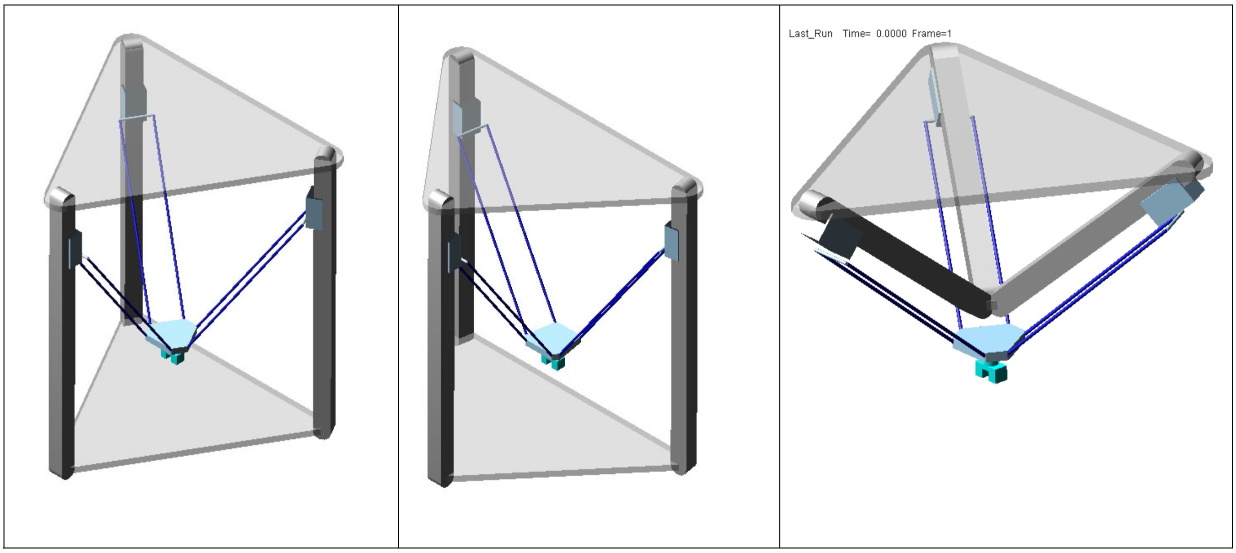


Fig. 5. Variation of kinematics by “design variables”

3.2. Servo-Pneumatic Drives (Simulink)

The models of the servo-pneumatic drives are developed by means of Matlab/Simulink. Depending on the requirements several controller models were developed. It is common to all that they are highly non-linear. Mainly the compressibility of air makes a more complex control system necessary. All controller models including the standard controller SPC200 are available as C-coded s-functions. This allows to use the same code in the simulation as well as on the target hardware.

A survey of the control scheme is shown in Fig. 6. For this contribution it is important to know about the interface for the co-simulation. The calculated forces of the servo-pneumatics are the inputs to the mechanics. The slider positions are the outputs of the mechanics. Detailed information on the controllers can be found in [2] and [3].

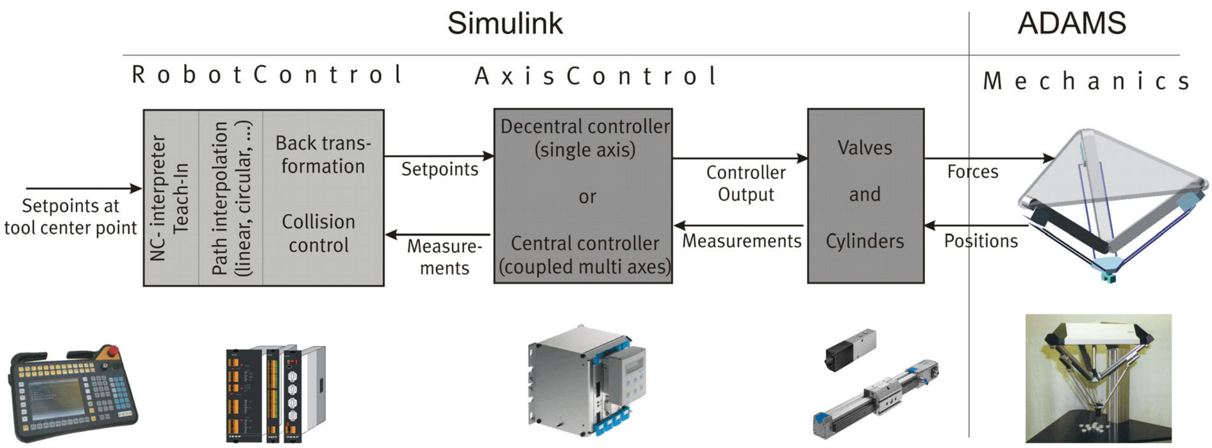


Fig. 6. Control structure

4. Analyzing the behavior of the whole system

When the modeling is done we can go on with the second step of the mechatronic design. In the following it is assumed that the SPC200 controller always controls the machine. The task is the analysis and synthesis of different parallel kinematics relative to stability, dynamics, and accuracy for a given workspace.

Some studies, e.g. concerning the workspace, can be made exclusive using ADAMS. Others such as feedback analysis are carried out by means of co-simulation.

The workspace can be determined by varying all drive positions in all combinations. After simulation the end-effector positions are traced using the feature “create trace-spline”.

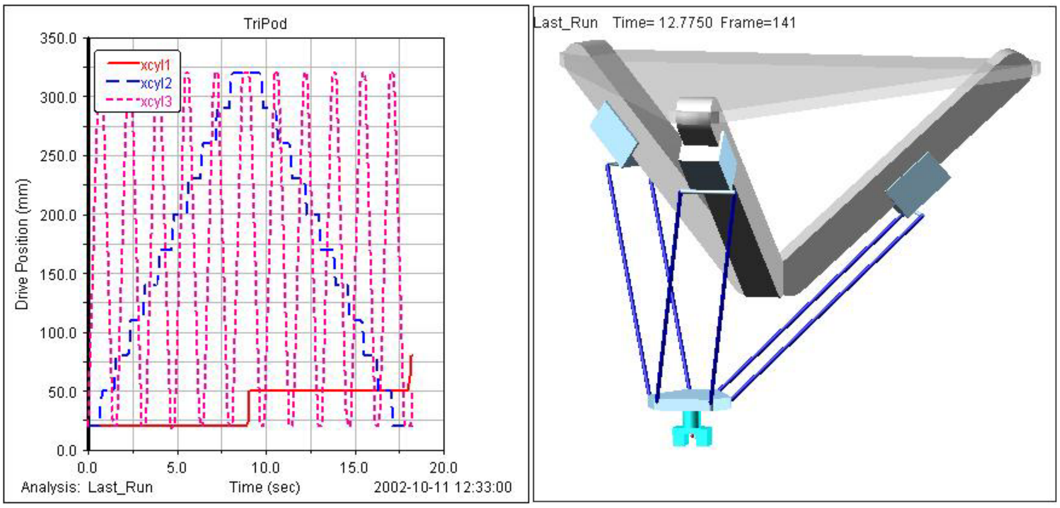


Fig. 7. Drive motions for the workspace calculation

The data can be visualized in ADAMS or any other graphics tool. As an example the workspace of the Tripod configuration of Fig. 7 is represented in Fig. 8

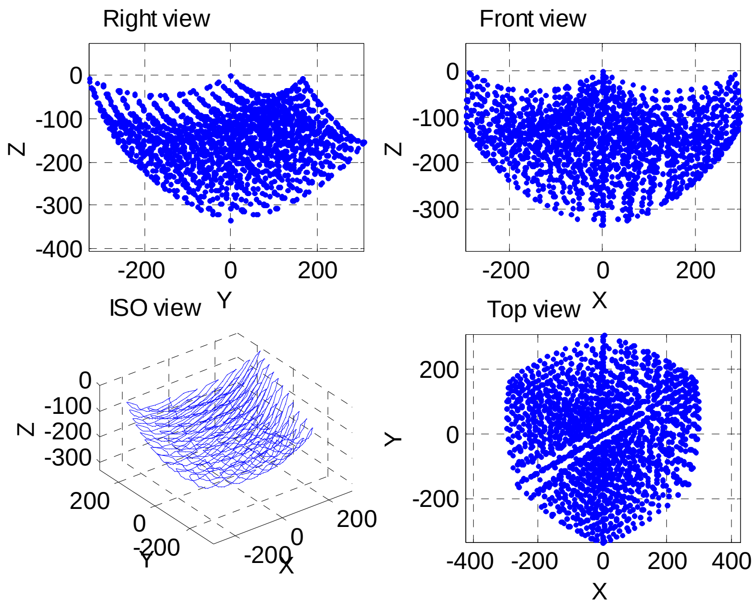


Fig. 8. Workspace of the Tripod (configuration as in Fig. 7)

Measuring the velocity of the end-effector at the same time delivers the gear ratios of all drives over the workspace.

To examine the behavior of the closed loop system ADAMS/Controls is used to couple ADAMS and Simulink. Before the model can be exported some inputs and outputs of the plant must be defined by state variables. The inputs of the Tripod are the drive forces. Though the controller makes only use of the drive position some additional signals are defined as outputs: The drive velocities are needed for solving the differential equations of the pressures in the pneumatics model. Furthermore we need the velocity of the tool center point to calculate the non-linear gear ratios. Finally the drive accelerations serve for the calculation of the equivalent moved masses. The whole system is shown in Fig. 9.

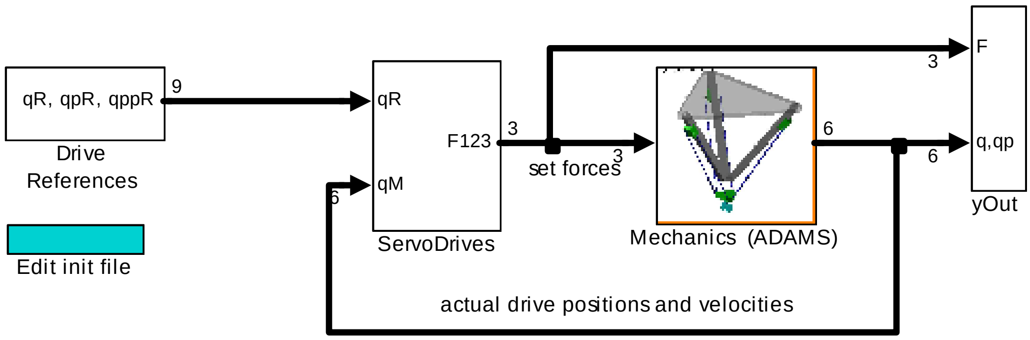


Fig. 9. Model of the whole system

The model of the mechanics is embedded in Simulink. ADAMS/Controls makes the interface available by means of s-function.

The equivalent moved masses depend on the positions of drives. The non-linearity of the robot grows with the strength of this dependency. As shown in Table 1 with the parallel kinematics there is a medium strong coupling of the dynamics. This coupling is neglected, if we use the standard SPC200 controller. Nevertheless there is an influence on the stability of the closed loop system. To initialize and parameterize this controller we need the following information from the mechanics model:

- equivalent moved mass of each drive (depends on slider positions)
- gravity forces in initial position
- Coulomb and viscous friction

The controller is designed for a single axis with a constant mass. Due to the position dependency of the equivalent moved masses of the robot we have to choose an average value for each drive. Unfortunately with ADAMS there is no easy way to calculate the equivalent moved masses along a trajectory. We tried to apply different methods such as dividing a drive force by its acceleration during a slow motion, but this method yielded not in satisfying results. The best method found is the linearization of the system. However this requires ADAMS/Linear. When we define the drive accelerations as plant outputs in ADAMS/Controls the direct feed through matrix **D** of the exported linear system delivers the mass matrix in the defined operating point as

$$\mathbf{M}(\mathbf{q}) = f \cdot \mathbf{D}(\mathbf{q})^{-1} \qquad (1)$$

Corresponding to the three degrees of freedom of the rigid body system the size of the mass matrix **M(q)** is three by three. It depends on the vector of the generalized coordinates of the drives. The non-diagonal elements cause the coupling between the axes. The factor *f* depends on the units chosen for the inputs and outputs. When the forces are given in [N] and the accelerations are given in [mm/s^2] *f* is 0.001.

With a slider mass of 2 kg and an end-effector mass of 2 kg the mass matrix for the three positions shown in Fig. 10 are:

pos. 0	pos. 1	pos. 2
$\mathbf{M} = \begin{bmatrix} 4.13 & -0.3 & -0.3 \\ -0.3 & 4.13 & -0.3 \\ -0.3 & -0.3 & 4.13 \end{bmatrix}$	$\mathbf{M} = \begin{bmatrix} 5.01 & -1.03 & -1.05 \\ -1.03 & 5.01 & -1.04 \\ -1.05 & -1.04 & 5.01 \end{bmatrix}$	$\mathbf{M} = \begin{bmatrix} 5.14 & -0.32 & -2.42 \\ -0.32 & 4.10 & -1.17 \\ -2.42 & -1.17 & 6.80 \end{bmatrix}$

The gravity forces can be calculated very easily by static simulation. Likewise it is easy to model the friction in ADAMS. Nevertheless the parameters can differ very strong from one application to another one.

With the parameterized controller the stability should be checked in several operating points by means of eigenvalues and the dynamics of the closed loop system can be analyzed by means of frequency responses.

Of course with a robust controller you can start with a simulation in time domain. This gives information about the accuracy and system limits. For this we need the references for the drives. For a reference trajectory of the tool center point ADAMS applying the “general point motion” can generate the drive positions.

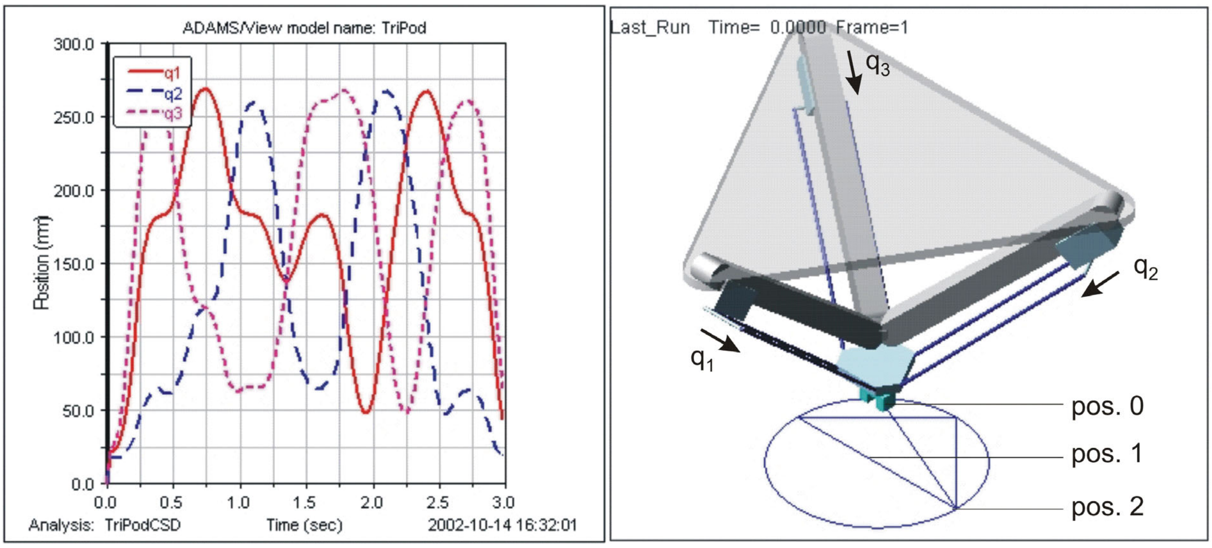


Fig. 10. Solving inverse kinematics by feature "general point motion"

In the following the simulation results are presented for a tripod configuration shown in Fig. 10. The workspace of this machine is illustrated in Fig. 8.

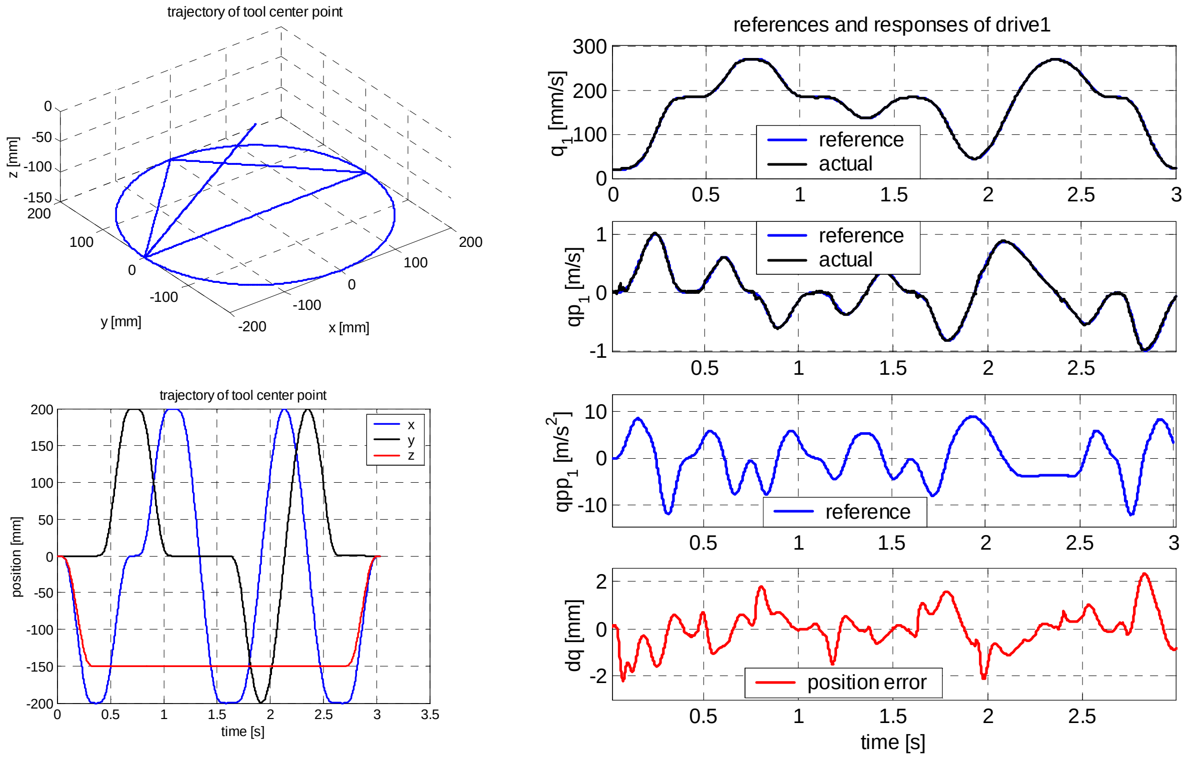


Fig. 11. Left: Trajectory of the tool center point. Right: Drive references and measures

5. Conclusion

The coupling of the software tools ADAMS and Simulink via co-simulation is a powerful method of virtual prototyping. This method enables an efficient design and optimization of servo-pneumatic driven robots. Especially robots with parallel kinematics can be analyzed very fast using ADAMS. Due to the potential of the linear analysis the use of ADAMS/Linear is meaningful. Particularly with controlled systems the linear analysis is required.

Literature

[1] Kuhlbusch, W., Moritz, W., Lückel, J., Toepper, St., and Scharfeld, F.: TRIPLANAR - A New Process-Machine Type Developed by Means of Mechatronic Design. Proceedings of the 3rd International Heinz Nixdorf Symposium on Mechatronics and Advanced Motion Control, Paderborn, Germany, 1999.

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[3] Neumann, R., Leyser, J., Post, P.: Simulationsgestützte Entwicklung eines servopneumatisch angetriebenen Parallelroboters. Tagungsband SIM2000 - Simulation im Maschinenbau, Dresden, Germany, 2000, p. 519-536.