A Virtual Prototyping Environment for Parallel Kinematic Machine Analysis and Design

Keywords: PKM, Multi-body Analysis, Virtual Prototyping

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Abstract

Industrial adoption of PKMs may be eased by availability of methodologies and integrated tools able to analyze in a short time PKMs of any architecture, providing the key data needed to design the machine. The proposed Virtual Prototyping Environment for PKM Analysis answers to these requirements, quickly estimating not only the reachable workspace, the Jacobian conditioning, but also the actuators' effort, internal loads in the mechanical structure and the effects of lumped structural compliances. A description of the developed VPE-PKM, based on a commercial Multi-body package, is given. Its effectiveness is shown presenting results obtained by ITIA-CNR during the design of a 3 dof translational PKM for light deburring operations.

1 INTRODUCTION

Parallel Kinematic Machines promise interesting performances, compared to serial machines mechanisms, under several aspects [Heisel, Moriwaki, Neugebauer et al., Pritschow, Sohlenius, Tönshoff et al, Weck et al. in 1; 2; 3] and in fact the industrial interest has been continually growing [4]. Nevertheless, industrial applications are still confined to a few domains. A possible motivation, in addition to the ones presented in [Koren in 1; 5], may be the difficulty, in the first steps of design, to find, among the quite infinite variety of possible configurations in terms of strut and joints typology and location, the most suitable one for the given application [2, 3]: to respond to current and future industrial requirements on PKM design, a methodology, supported by powerful, integrated software tools, is required.
Several works have been done toward this direction providing either a systematic methodology for the design of different PKMs' topologies [6], or software tools for the optimal design of a specific PKM class (typically, the Stewart platform like mechanisms) [7; 8; 9; Tsai, Ji et al. in 1].
The problem of developing an appropriate methodology and related 'Integrated Analysis & Design Tool' (IADT) has been tackled by ITIA-CNR, within several European and National Research Programs [10-14], as a fundamental part of studying new industrial applications of PKMs in different sectors. The effort produced to date has lead to the development of a methodological approach [15] and several software tools, among them the Mathematical Evaluation Environment (MEE) [16] and the Multi-body Virtual Prototyping Environment for Parallel Kinematic Machines Analysis and Design (Multi-body VPE-PKM) (Fig. 1), which have been used and tested during the whole design process, from the conceptual to the prototyping step, of different PKMs architectures.

Basically, the MEE systematizes the typical analysis steps followed when a new PKM architecture is being conceived: write by hand the kinematic equations, solve them either manually or by an analytic/numerical software tool, evaluate the workspace and identify singularities using computationally optimized software routines [Negri et al. in 1; 16] and about the kineto-static behavior of the machine. The developed routines are very effective in evaluating, in few minutes, several geometric variants of different machine architectures (topologies), but they require a considerable programming effort for each new machine topology and become very complex when it is required to evaluate the dynamic behavior, the internal loads in the machine structure or the sensitivity to manufacturing and assembly errors.

The VPE-PKM has been designed to overcome these limitations and to fulfill the following requirements:

1) **Generality**. Applicable to any existing or completely new topology of PKM.

2) **Completeness**. It should support the users in the key steps of mechanical design, given the application requirements: architecture selection, geometry optimization, actuator sizing, mechanical structure design.

3) **Quick response**. It should provide answers with the short timing typical of an industrial product development. In fact, it should be used in the first design phases, when it is necessary to rapidly configure and evaluate several architectures .

The VPE-PKM satisfies these requirements joining the power of a commercial multi-body software (ADAMS^{TM}, MDInc) with the efficiency of PKM-specific analysis routines (implemented in Matlab^{TM}, The MathWorks, Inc.).

The paper is structured in the following way: in Section 2 the VPE-PKM architecture is presented, in Section 3 the industrial application used as an example through the paper is described, in Section 4 the analyses performed by VPE-PKM are illustrated, explaining the key implementation issues, while in Section 5 the final remarks and conclusions are given.

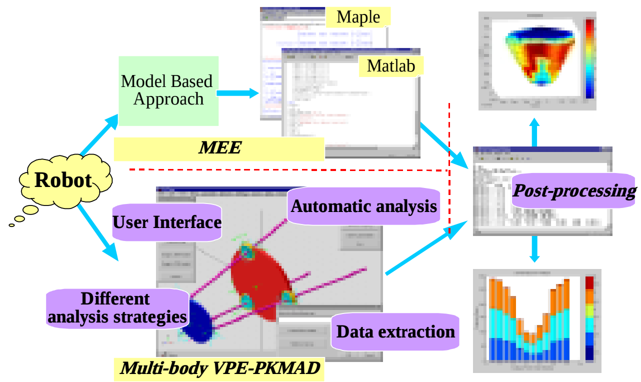

Fig.1. From the Conception Stage to the Prototyping and Industrial Application using the proposed Multi-body VPE-PKM and the MEE

2 VPE-PKM ARCHITECTURE

The kinematic analysis based on the evaluation of the Jacobian matrix (core of the MEE) is crucial for PKM design but it is not sufficient to complete the analysis of a real machine. In fact, actuators must not only counteract all external loads applied to the end-effector (as evaluated by the Jacobian), but also work to support the machine weight, balance the inertial forces and win unavoidable joint friction. It is also important to evaluate loads in critical points of the machine structure. This is particularly true for machines with less than six degrees of freedom, because in this case part of the forces applied to the end-effector «flows» to ground through the structure, without loading an actuator. It was thereafter decided to develop the VPE-PKM customizing a general purpose multi-body analysis software with a set of *"ad hoc"* routines and related user interfaces dedicated to the virtual prototyping of a PKM.

The key features of the multi-body analysis package exploited by VPE-PKM are:

- Complete and Customizable 3D Graphical User Interface for manipulator modeling and visualization
- Automatic generation of kinematic and dynamic equations of motion
- Static equilibrium computation
- Model linearization and generation of a State Space representation (ABCD matrices)

Commercial multi-body analysis softwares can be used directly to analyze a PKM performing standard simulations [17,23]; the VPE-PKM strongly increases the efficacy of such a solution adding the following PKM-specific capabilities:

- dedicated user interface for a quick and consistent model set-up (e.g. to define joint limitations)
- repetitive analyses automation for workspace identification and scanning (e.g. stiffness mapping on a selected grid of points)
- specific strategies for PKM analysis not implemented in the multi-body environment (e.g. Jacobian evaluation)
- post-processing of the raw data provided by the Multi-Body analyses, using efficient mathematical routines
- complete and intuitive 2D and 3D graphical representations of results

The VPE-PKM permits the following analyses:

- **Interference analysis**: actual workspace determination (considering active and passive joint's limits)
- **Jacobian analysis**: singularities and numerical conditioning
- **Actuator effort**: due to external forces, machine weight, inertial forces, joint friction
- **Loads in the structure** due to external forces and machine weight
- **Error analysis**: tool displacement due to structural deformations or manufacturing errors
- **Compliance at the tool** due to lumped compliances anywhere in the structure.

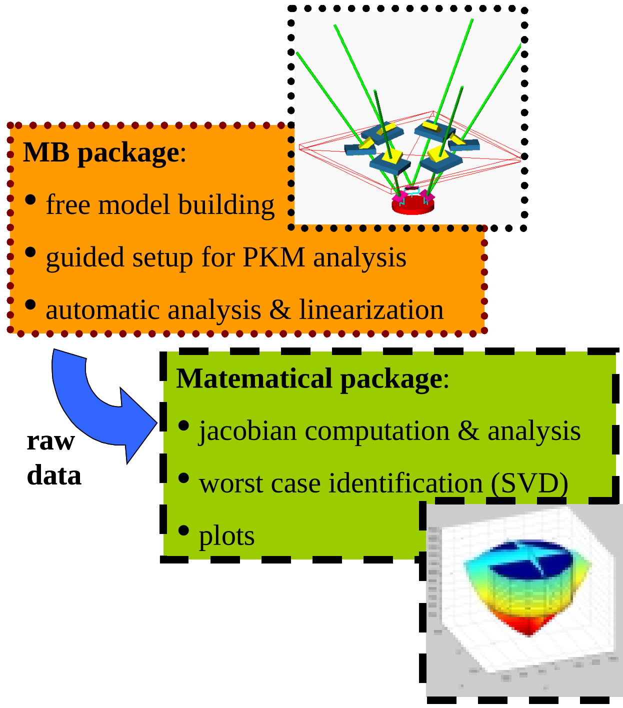

Fig.2. VPE-PKM architecture

3 INDUSTRIAL CASE STUDY

In order to clarify the functionality of the VPE-PKM, the design steps are illustrated using also numerical examples, all based on the analyses performed to design an industrial prototype for light deburring operations in shoe manufacturing, currently being built at ITIA-CNR. The process requirements asked for a 3 dof translational PKM, the orientations of the end effector being given by a serial wrist mounted on the mobile platform. The final layout of the optimized machine is shown in Fig.3. Other process requirements are summarized in Tab. 1.

Max. external force on E.E.	80 N
Max. external torque on E.E.	20 Nm
Max E.E. speed	0.5 m/s
Max E.E. acceleration	5 m/s^2

Max E.E. positioning error	0.1 mm

Tab.1. Process Requirements (E.E. : End Effector)

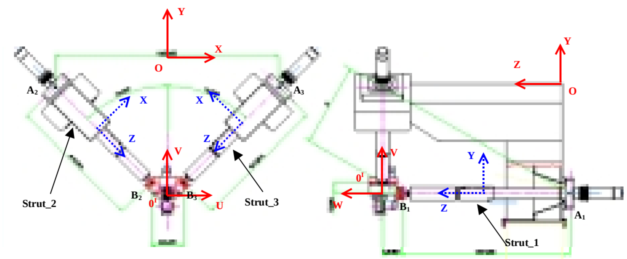

Fig.3. The 3 dof translational PKM designed and analyzed with the VPE – PKM

The proposed design has been evaluated analyzing the machine behavior over a grid of 105 points, covering the following ranges along the coordinate axes:

axis	N. of points	Range [mm]
X	5	-180 : 140
Y	3	-80 : 80
Z	7	-240 : 240

4 MODEL SETUP AND ANALYSIS

4.1 Model set-up

The Multi-body VPE-PKM has been developed with the idea of maintaining the generality of the multi-body simulation environment. For this reason the machine model has not to be chosen from a set of existing parametric families, but can be freely built using all the elements provided by the Multi-body environment.

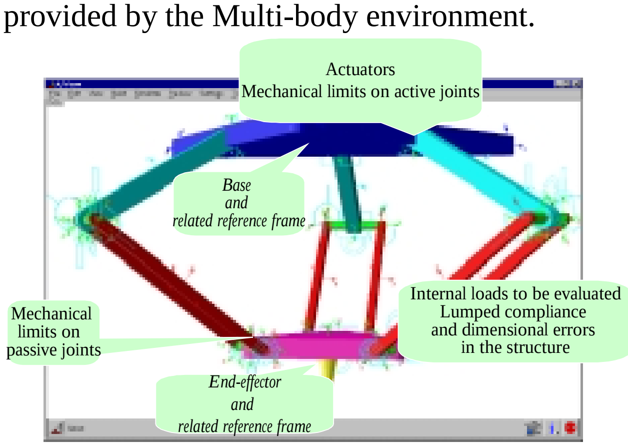

Fig.4. Standard objects that the user must define during the model set-up phase

In order to analyze a general machine with the VPE-PKM, the user must define, through the custom user interface, only a coordinate frame associated to the end effector and indicate which joints are actuated (Fig.4).

4.2 Workspace evaluation

In order to identify the machine workspace, the user have to define, for each joint, the allowed motion range (Fig.5): only local interference in joints are considered.

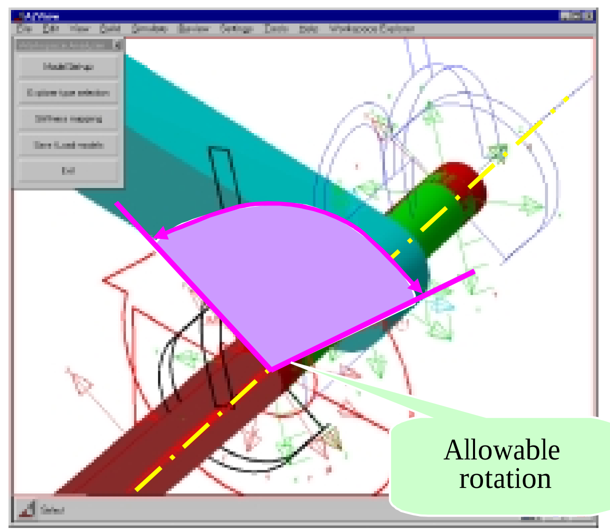

Fig. 5. Definition of the mechanical limits on active and passive joints

The space can be explored using different strategies, always based on space discretization:

1. Moving along a given sequences of machine poses (*Pose following:* Fig. 6). It is useful to verify the execution of point-to-point paths required by the application and also to quickly evaluate the machine at a restricted set of poses, before running more exhaustive searches. If a pose is not reachable the nearest reachable one is determined and the six dimensional distance evaluated.
2. Moving the machine in different directions, along a set of rays ordered following a spherical (*Spherical scanning*) or cylindrical (*Cylindrical scanning*) geometry, until an interference occurs (Figs. 7 and 8).

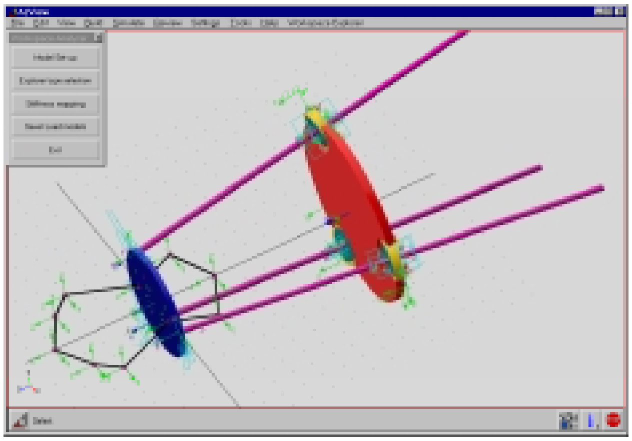

Fig. 6. Pose Following

The workspace exploration is performed exploiting the Multi-body simulation capabilities: for each limited joint, two “Impact” statements [18] are defined to reproduce the mechanical constraints. The machine is then pulled toward the desired pose or along the selected ray by a six dimensional spring (a “bushing” element). The reachable pose is obtained computing a simple static equilibrium. This approach is particularly useful for the pose following explorer, because we don’t want only to verify if the machine can be assembled in each required pose, but also if there exist a continuos path connecting all required poses (i.e. the workspace must be connected): the possible path is heuristically searched for simply pulling the machine by the end-effector from one pose to the following one.

For the interference analysis, the analyst must classify each end-effector dof in one of the following categories:

1) Fixed dof. These end-effector dof are kept fixed during the workspace exploration, e.g. to maintain a fixed end-effector inclination (for machines with angular dof).
2) Dof to be maximized. The space defined by these end-effector dof is explored moving the machine along rays. (e.g. XYZ can be inserted in this class to explore the 3D translational workspace of a PKM)
3) Free dof. Free end-effector dof are exploited to obtain a larger workspace (e.g. for a Stewart platform, defining as free the rotational dof about Z, redundant with respect to the spindle rotation, it simulates the effect of an optimizing NC strategy, able to rotate the moving platform around the spindle axis, in order to reach a larger workspace).

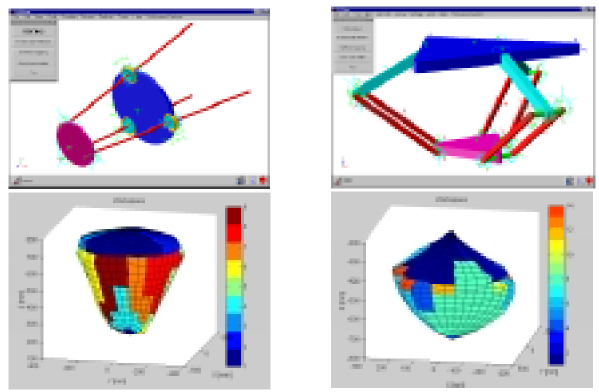

Fig. 7. Workspace representations of 3 dof PKMs. Colors identify the joint limiting the workspace because of interference.

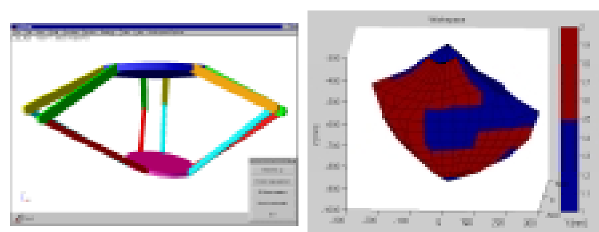

Fig. 8. Workspace representations of 6 dof PKMs. Colors are associated to the mobile platform orientation that limits the workspace.

4.3 Stiffness mapping

The stiffness mapping is performed in the classical way, using all the typical PKM kinematic performance indexes, localizing in particular all kinematic singularities. As it is well known [19 - 21], the analysis is based on numerical condition of the Jacobian matrix. Since ADAMS doesn’t explicitly provide this matrix, an indirect way to obtain it has been found, exploiting the linearized system representation supplied by the Multi-body package in standard state-space format (ABCD matrices) [22].

$$\begin{cases} \begin{Bmatrix} \dot{x}_{vel} \\ \dot{x}_{pos} \end{Bmatrix} = A \begin{Bmatrix} x_{vel} \\ x_{pos} \end{Bmatrix} + Bu_{act} \\ y = \begin{Bmatrix} vel_{act} \\ vel_{ee} \\ vel_{pass} \end{Bmatrix} = \begin{bmatrix} C_{act} & 0 \\ C_{ee} & 0 \\ C_{pass} & 0 \end{bmatrix} \begin{Bmatrix} x_{vel} \\ x_{pos} \end{Bmatrix} \end{cases}$$

The VPE-PKM automatically selects the internal states, keeping separate velocity (x_{vel}) and position (x_{vel}) information. Actuator forces are considered as input and, as output, the speed of all actuators (vel_{act}), of the end-effector (vel_{ee}) and the relative speed at all passive joints of interest (vel_{pass}).

Through an elaboration of the ABCD matrices, instead of the usual Jacobian matrix, the joints Inverse Extended Jacobian (***IEJ$_{joint}$***) is obtained:

$$\begin{Bmatrix} vel_{ee} \\ vel_{pass} \end{Bmatrix} = IEJ_{\text{joints}}\, vel_{act} \equiv \begin{bmatrix} C_{ee} \\ C_{pass} \end{bmatrix} C_{act}^{-1}\, vel_{act}$$

A singular or badly conditioned $\mathbf{C_{act}}$ means that the machine motion is not fully defined by actuators speeds, i.e., the machine is near a singularity.

The $\mathbf{C_{act}}$ matrix is square if the number of internal states is twice the number of machine actuators (dof); as a consequence, the model must be iso-static and composed by rigid bodies.

4.4 Actuators sizing

A key step in machine design is to compute the actuators requirements, in term of maximum force and speed. The VPE-PKM evaluates the actuator effort due to:

- External forces on the end-effector;
- Machine weight;
- Inertial forces due to the maximum acceleration;
- Static friction in active and passive joints

For each load typology (inertial, gravitational and working loads), the software identifies automatically the load orientation that produces the maximum effort on each actuator.

In the present VPE-PKM release, the actuator effort due to inertial forces is approximated because the Multi-body software linearizes the system at zero speed, obtaining an ABCD system with actuator forces as inputs and actuators accelerations as outputs. The inertial matrix is extracted from the direct coupling matrix D, but this approach forces to zero the second order terms containing Coriolis and Centripetal forces, as expressed in the following Lagrange-Euler dynamic equilibrium equation:

$$f_{act} = D_{q(t)}\ddot{q}(t) + h_{q(t)}(\dot{q}(t)) + g_{q(t)}$$

where f_{act} is the actuator force, $D_{q(t)}$ the inertial matrix, $\ddot{q}$ the actuators acceleration, $h_{q(t)}$ contains the quadratic terms in the velocities (forced to zero in our case) and the subscript $\cdot_{q(t)}$ indicates the dependence from the machine pose q(t). The gravity term ($g_{q(t)}$) is directly evaluated computing the structural loads at the selected joints solving the model for a static equilibrium. Alternatives approaches are under evaluation; in the meantime, performing time simulations at the maximum speed, we can estimate the effect of this approximation.

To directly identify the most critical direction for loading and/or motion, almost all the analyses are based on Singular Values Decompositions ("SVD") of the linear matrix (M) that relates the generic inputs (v) and outputs (u):

$$u = M\,v$$

$$M \underset{SVD}{=} \left[\{U_1\}\cdots\{U_m\}\right] \cdot \begin{bmatrix} \sigma_{MAX} & 0 & 0 & 0 \\ 0 & \ddots & 0 \quad \cdots & 0 \\ 0 & 0 & \sigma_{\min} & 0 \end{bmatrix} \cdot \begin{bmatrix} [V_1^T] \\ \vdots \\ [V_n^T] \end{bmatrix}$$

The columns of the orthogonal matrices U and V can be interpreted as directions (in the output and input spaces respectively) corresponding to the gains expressed by the singular values σ_i . The maximum singular value (σ_1, U_1 and V_1) corresponds to the most critical loading direction.

In friction evaluation for actuator sizing, only Coulomb-like friction (i.e. $F_{\text{frict joint}} = A_{\text{joint}} \cdot sign(V_{rel})$) with a constant pre-load is considered. In this case, because of the problem non-linearity, the SVD approach cannot be used to identify the motion that requires the maximum actuator effort, but it can be shown that the worst case is required when all other actuators are standing still (in this case the active actuator must work against all related joints with friction).

Actuator sizing routines provide the following data for our test case:

Max. act. Speed	0.5 m/s
Max. act. Thrust	940 N

Tab.2. Actuator sizing

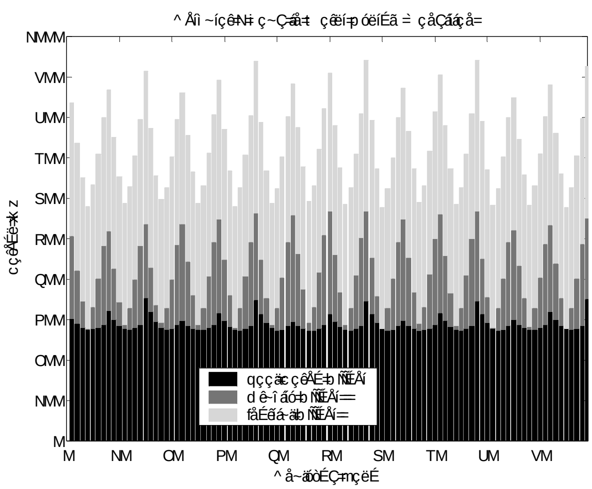

Fig. 9. Stacked bar chart of the maximum loads on strut 1 actuator.

The maximum required force is represented in Fig. 9, for strut 1 actuator, showing both the variability along the used mesh and the relative relevance of efforts due to external loads, inertial forces and machine weight. It can be seen, as common for high speed machines executing light operations, that the effect of external loads is not sufficient to correctly choose the actuator.

4.5 Internal Structural Loads

The internal loads analysis can be interpreted as a generalization of the actuator load analysis, thinking to have “fictitious actuators” located where the internal loads have to be computed. We can thereafter define an “ Internal Loads Extended Jacobian” (“EJ_{int}”), that links the forces on the end-effector with the loads on the fictitious actuators:

$$f_{\text{int}} = EJ_{\text{int}} f_{ee}$$

The EJ_{int} cannot be obtained from Multi-body package using the ABCD approach used before, because, at the moment, joint reactions cannot be defined as system outputs during linearization. The EJ_{int} matrix is therefore built by the VPE-PKM applying one at a time a force/torque on the end-effector (X, Y, Z, RX, RY, RZ) and computing the joint reactions (by a static equilibrium).

The EJ_{int} is used to find, for each reaction, the worst load case, by SVD.

The internal loads analysis is particularly important for the examined machine, because three degrees of freedom of the end-effector are passively constrained by the mechanical structure, provoking both bending and torsion in each strut.

These loads have been computed for each strut, at the position where the actuator is located (represented by a prismatic joint. See the reference frames associated to each strut in Fig. 3). Adding the external load and the inertial forces, an equivalent force of 275 N has been applied (inertial forces have to be approximated by equivalent external loads).

The bar plot represented in Fig. 10 shows the torsional load for strut 2 (in this case the joint friction has not been considered).

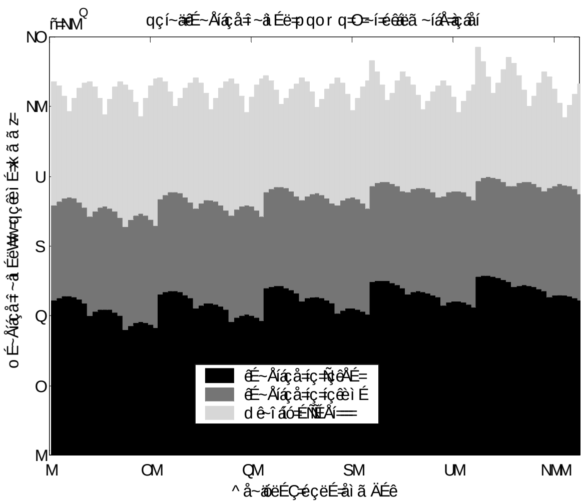

Fig. 10. Stacked bar chart of the maximum torsional load on strut 2

The complete computation is synthesized in Tab. 3; these data have been used to verify the expected life of the employed bearings.

Strut	Bending ar. X	Bending ar. Y	Torsion ar. Z
1	65÷75 Nm	10 ÷ 13 Nm	55 ÷ 80 Nm
2&3	8 ÷ 16 Nm	30 ÷ 60 Nm	100÷120 Nm

Tab. 3. Internal loads

4.6 Effect of Manufacturing errors and deformation

Using the same EJ_{int}, the dual analysis on error propagation is performed, giving useful hints on required manufacturing accuracy for each critical component.

In this case the fictitious error of 1 *rad* for both bending and torsion in each strut has been considered, in order to quantify the error amplification. Fig. 11 shows for example the end-effector translation in the Y (vertical) direction, due to the defined errors.

We can summarize such analysis saying that, for the Y direction, strut 1 bending and strut 2&3 torsions are most significant and, if we keep the hypothesis of uniform errors, we need to limit all these errors in the milli-radiant range, in order to limit the end-effector under 0.1 mm.

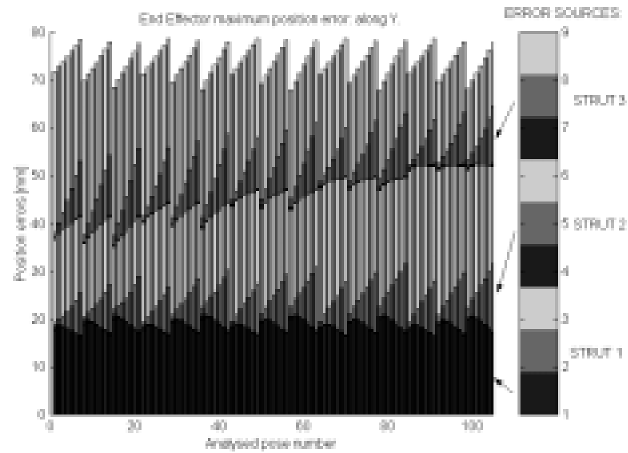

Fig. 11. Y Stacked bar chart of the End Effector motion due to struts bending and torsion.

4.7 Lumped structural compliances

The internal loads and manufacturing errors analyses are well synthesized introducing an estimate of corresponding structural compliance, considered as lumped in the same locations.

The computation is again based on the EJ_{int}, exploiting the duality between forces and virtual displacements (δ):

$$\delta_{ee} = EJ_{\text{int}}^T \delta_{\text{int}}$$

The lumped structural compliance are described by the diagonal C_{int} matrix:

$$\delta_{\text{int}} = C_{\text{int}} f_{\text{int}}$$

that can be transformed into corresponding End-Effector compliance:

$$\delta_{ee} = EJ_{\text{int}}^T C_{\text{int}} EJ\, f_{ee} \Leftrightarrow C_{ee} \equiv EJ_{\text{int}}^T C_{\text{int}} EJ_{\text{int}}$$

The analysis is completed identifying by SVD the translational and rotational directions corresponding to the maximum compliance and the compliance value. A sensitivity analysis is also performed, indicating the contribution of each structural compliance to the end effector compliance.

For our three dof machine, the effect of torsional strut deformation has been evaluated, considering the global compliance due to the two universal joints and the prismatic joint at the actuator.

Case B in next table shows the criticality of the torsional strut compliance (unitary stiffnesses are considered).

Case A: strut bending stiffness	1 Nm/mrad
Min Translational Stiffness at E.E.	149 N/mm
Min. Rotational Stiffness at E.E.	5 Nm/mrad
Case B: strut torsional stiffness	1 Nm/mrad
Min Translational Stiffness at E.E.	33 N/mm
Min. Rotational Stiffness at E.E.	0.44 Nm/mrad

Tab. 4 Effect of structural compliances.

5 CONCLUSIONS

The VPE-PKM developed and presented in this paper contributes to improving and speeding up the process of conceiving and optimizing PKMs in the numerous industrial domains where the special features of PKMs are needed.

The developed VPE-PKM is applicable to any PKM, modeled by rigid bodies; it enables quick analysis set-up and execution (typically one day is sufficient to analyze a completely new machine) performing a full set of analyses (workspace, Jacobian conditioning, actuator sizing, structural loads and compliance) fundamental in order to design a high quality industrial machine.

The research carried out has proved that, by using the developed Multi-body VPE-PKM approach, an optimized PKM configuration may be obtained within few days.

6 AKNOWLEDGEMENTS

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A Virtual Prototyping Environment for PKM Analysis and Design

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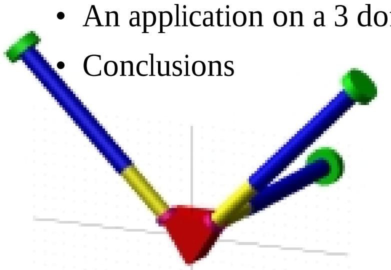
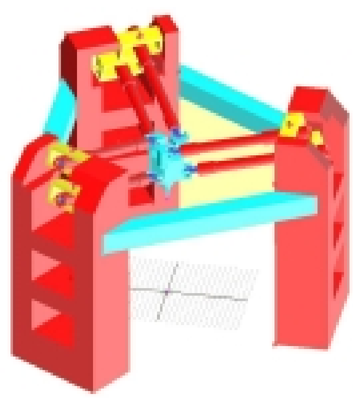
• Conclusions





Motivations for a VPE-PKM tool

Most existing PKMs have been designed independently of their final use: they are more “concept-machines” than “industrial solutions”. Many of the design tools developed reflect this approach.

A number of interesting approaches to the design and analysis of a PKM can be found in literature but almost all of them are specific configuration solutions and are mathematically oriented tools dealing with simplified geometry and mechanical properties (i.e. the Robotool CAC Tool).

Performance evaluations and parameter optimisations can be carried-out with commercially available CAE-tools but there's a lack of a specific user interface

Characteristics

Generality. Applicable to any existing or completely new topology of PKM.

Completeness. It should support the user in the key steps of mechanical design, given the application requirements: architecture selection, geometry optimization, actuator sizing, first mechanical structure design.

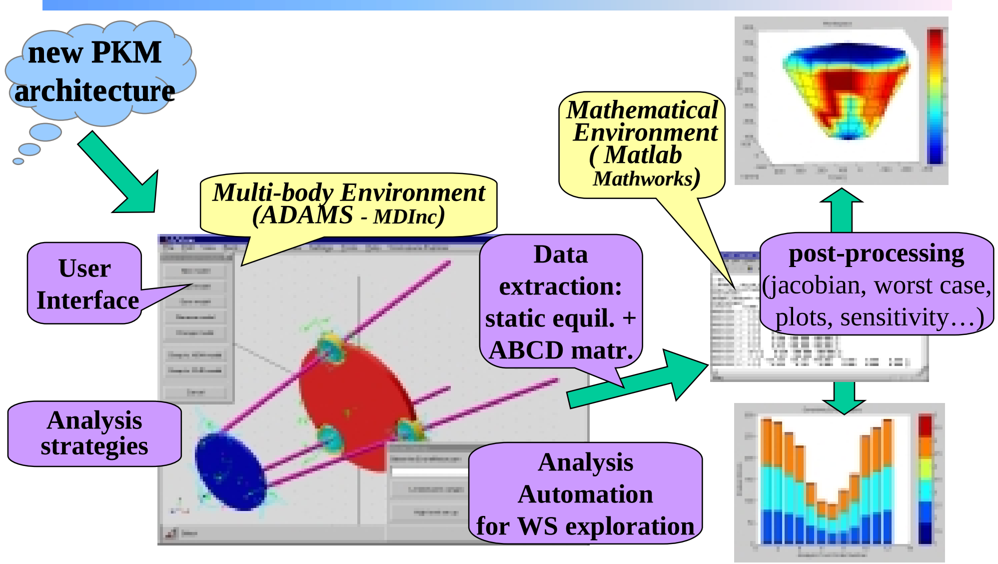
Quick response. It should provide answers with the short timing typical of an industrial product development. In fact, it should be used in the first design phases, when it is necessary to rapidly configure and evaluate several architectures.

Objectives

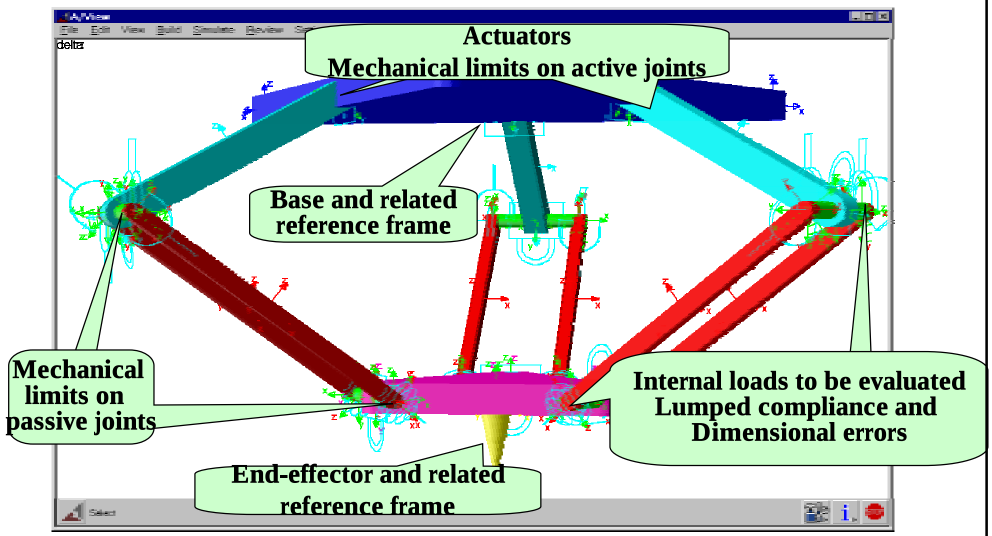
The VPE PKM should allow the following analyses:

- Actual workspace determination, taking into account active and passive joint's limits)
- Kineto-static performance evaluation
- Actuator forces determination (considering external forces, machine weight, inertial forces, joint friction)
- Internal structural loads evaluation (bending and torsional effects in the struts)
- Sensitivity analysis: tool displacement due to structural deformations or manufacturing/assembly errors
- Evaluation of the compliance at the tool due to lumped compliances within the structure

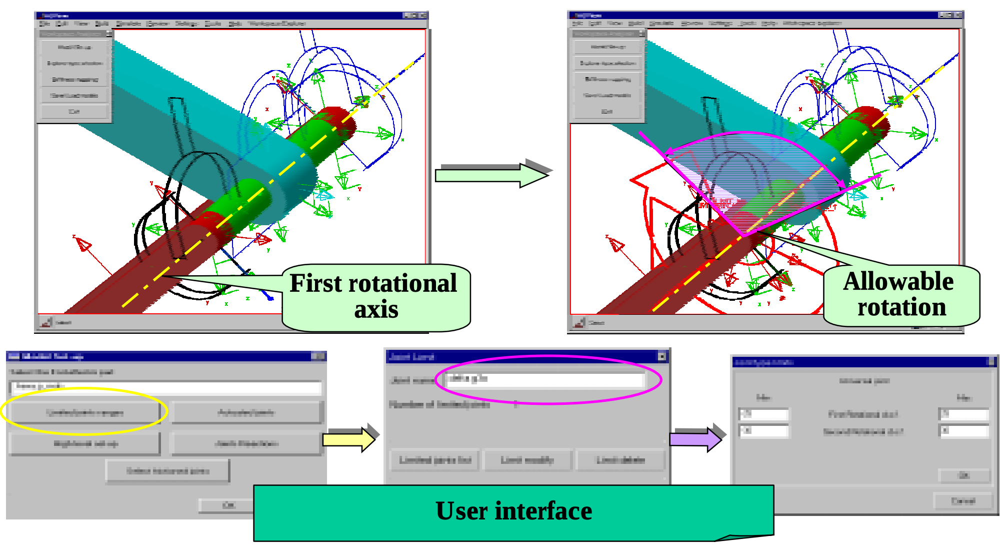
The VPE-PKM Integrated Approach

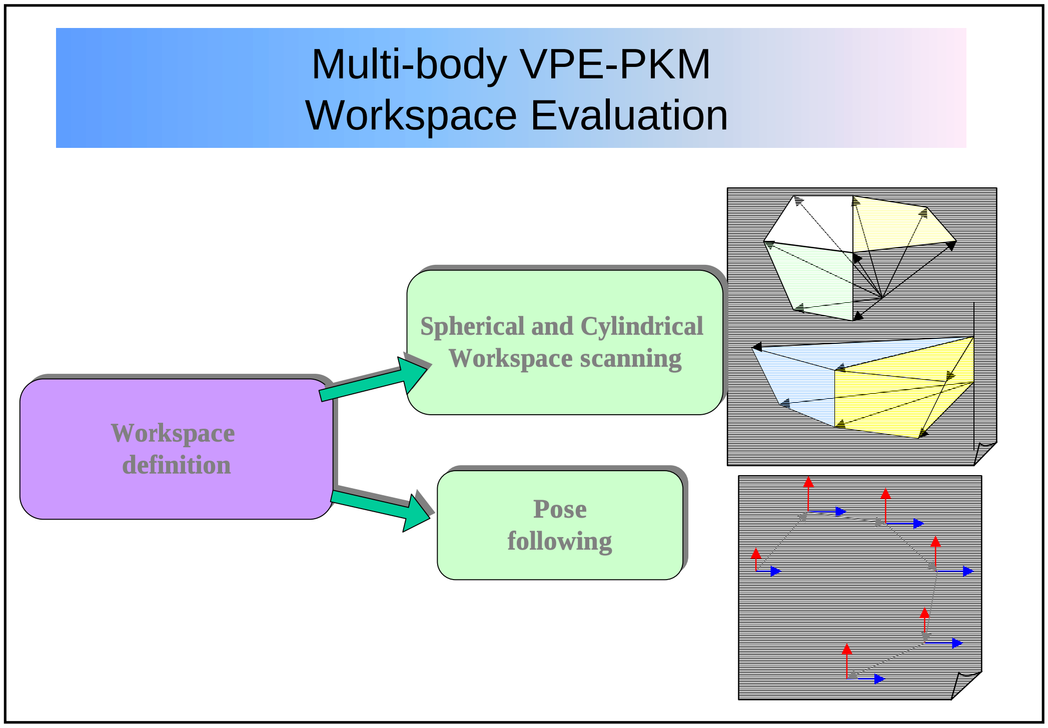


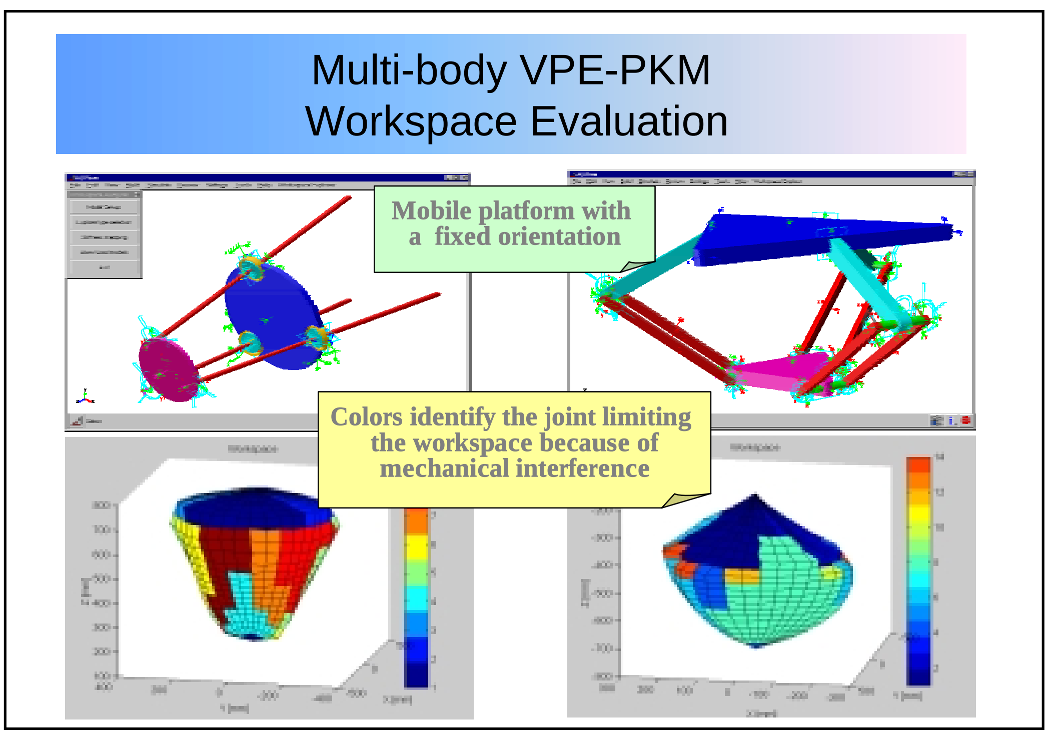
Multi-body VPE-PKM
Pre-processing Model Set Up



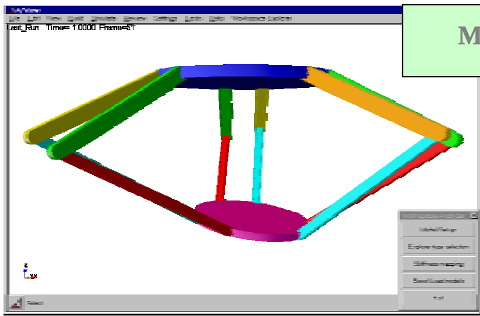
Multi-body VPE-PKM
Pre-processing Model Set Up



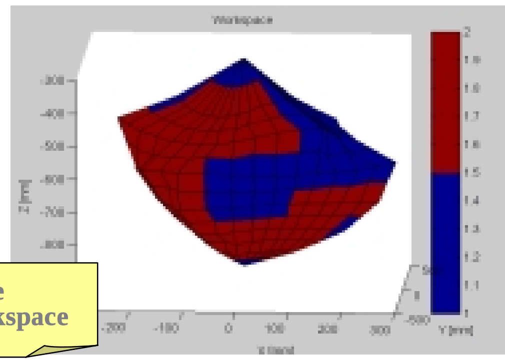

Multi-body VPE-PKM
Workspace Evaluation
Workspace definition
Spherical and Cylindrical Workspace scanning
Pose following


Multi-body VPE-PKM
Workspace Evaluation
Mobile platform with a fixed orientation
Colors identify the joint limiting the workspace because of mechanical interference

Multi-body VPE-PKM
Workspace Evaluation

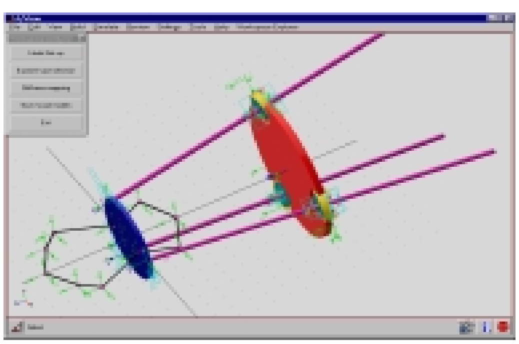


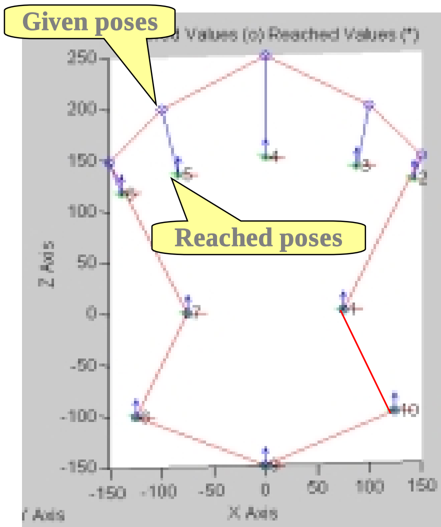
Mobile platform with free orientation



Colors are associated to the mobile platform orientation that limits the workspace

Multi-body VPE-PKM
Workspace Evaluation: Pose Follower





Given poses

Reached poses

Multi-body VPE-PKM
Kineto-static Performances Evaluation

All the typical PKM kinetostatic performance indexes are used. The so called **Joints Inverse Extended Jacobian** (IEJ_{joints}) matrix is obtained exploiting the linearized system representation supplied by ADAMS™ in standard state-space format (ABCD matrices):

The VPE-PKM automatically selects the internal states, keeping separate velocity (x_{vel}) and position (x_{vel}) information. Actuator forces are considered as input and, as output, the speed of all actuators (vel_{act}), of the end-effector (vel_{ee}) and the relative speed at all passive joints of interest (vel_{pass}).

Through an elaboration of the ABCD matrices, instead of the usual Jacobian matrix, the Joints Inverse Extended Jacobian (IEJ_{joints}) is obtained

Multi-body VPE-PKM
Sensitivity Analysis and Compliance at the Tool

- Using the same EJ_{int}, the dual analysis on error propagation is performed.

$$\delta_{ee} = EJ_{\text{int}}^{T} \delta_{\text{int}}$$

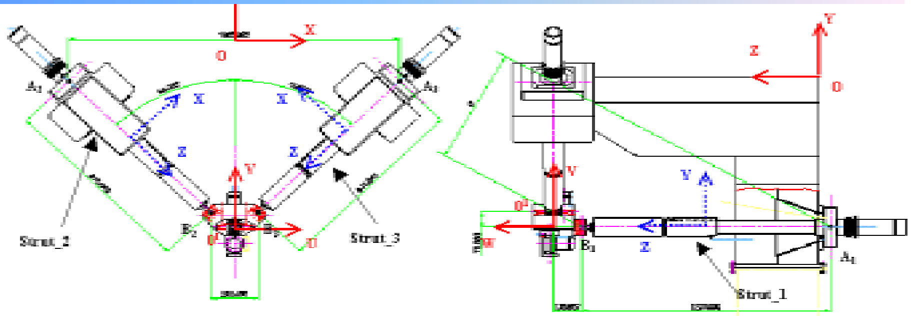
- The two previous analyses are well synthesized introducing an estimate of corresponding structural compliance, considered as lumped in the same locations.
- The lumped structural compliance is described by the diagonal C_{int} matrix:

$$\delta_{\text{int}} = C_{\text{int}} f_{\text{int}}$$

- that can be transformed into corresponding End-Effector compliance:

$$\delta_{ee} = EJ_{\text{int}}^{T} C_{\text{int}} EJ\, f_{ee} \Leftrightarrow C_{ee} \equiv EJ_{\text{int}}^{T} C_{\text{int}} EJ_{\text{int}}$$

Multi-body VPE-PKM: Industrial Requirements



Specifications:

- **workspace: 400 x 200 x 100 mm^3**
- **A axis : +/- 180°; B axis: +/- 90°**
- **max. speed: 30 m/min**
- **max acceleration: 5 m/s^2**
- **deburring force : 50 N**
- **precision: compliant tool support …**

Other applications

- **deposition, around the same profile, of a glue curtain**
- **spraying a silicon mixture over the mould for the PVA injection.**

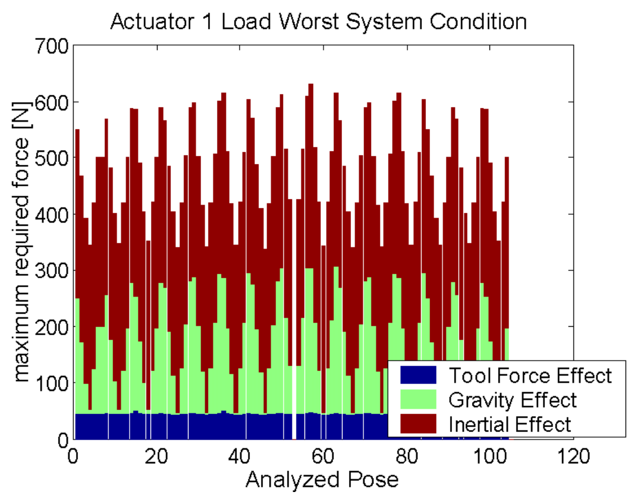
Actuators sizing

Inputs :

- max forces on E.E.
- max E.E. speeds and accelerations

Outputs **:**

- actuators max forces
- actuators max velocity
- critical loads direction



based on:

- E.E. forces ⇔ jacobian
- weight ⇔ distributed mass
- acceleration ⇔ dynamic model

Multi-body VPE-PKM: Manufacturing Errors and Internal Loads Analysis

Introducing *fictious actuators* where error sources are supposed to be and calculating the corresponding end-effector motion:

$$\delta x_{\text{end effector}} = EIJ \; \delta q_{\substack{\text{fictitious} \\ \text{actuators}}}$$

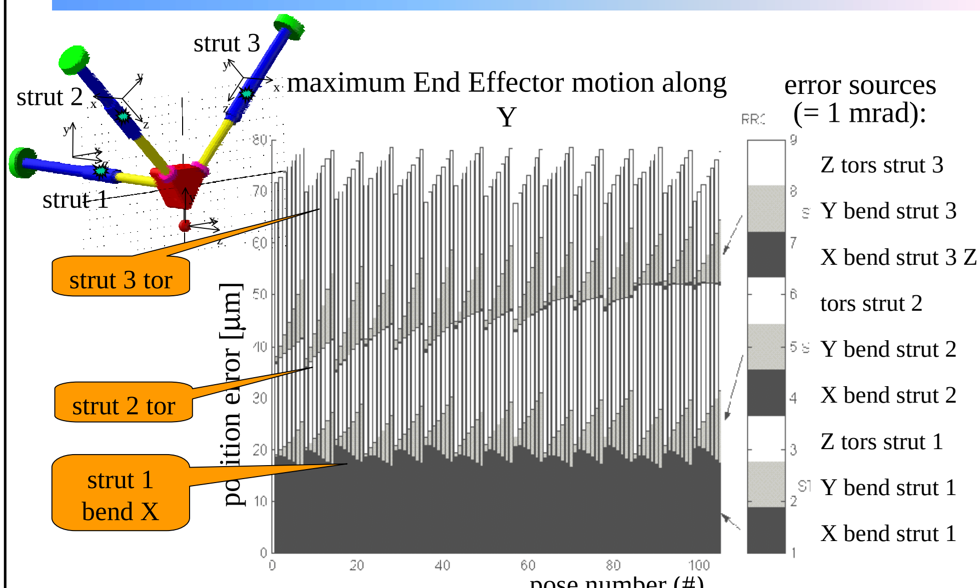
EIJ: “Extended Inverse Jacobian”

The Virtual Work principle can be used to find the dual force relationship:

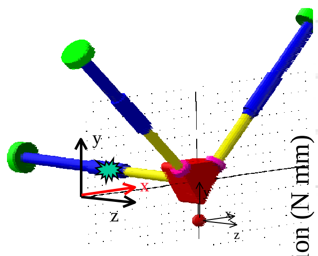
$$f_{\substack{\text{fictitious} \\ \text{actuators}}} = EIJ^{T} \; f_{\text{end effector}}$$

For the Tsai manipulator: an applied torque is not balanced by an actuator effort, but it produces loads in the mechanical structure.

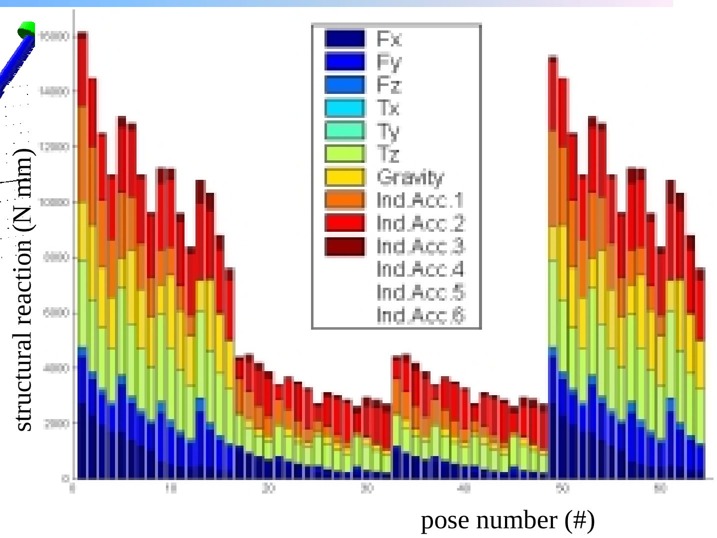
Effects of Manufacturing Errors



Internal Loads Analysis…



bending torque around X in the horizontal strut



… Effects of Lumped Compliances…

The load and geometrical error analyses can be synthetised defining, during the **post-processing phase**, a set of lumped compliances at the "fictitious actuators". The corresponding compliance at the end effector is then computed:

$$\begin{cases} \delta x^T_{\substack{\text{end}\\\text{effector}}} \cdot f_{\substack{\text{end}\\\text{effector}}} = \delta q^T_{\substack{\text{fictitious}\\\text{actuators}}} \cdot f_{\substack{\text{fictitious}\\\text{actuators}}} & \begin{pmatrix}\text{system}\\\text{equilibrium}\end{pmatrix} \\ f_{\substack{\text{fictitious}\\\text{actuators}}} = K_{FA}\, q_{\substack{\text{fictitious}\\\text{actuators}}} & \begin{pmatrix}\text{elastic reaction}\\\text{at fictitious actuators}\end{pmatrix} \\ x_{\text{end effector}} \equiv C_{EE}\, f_{\text{end effector}} & \begin{pmatrix}\text{compliance at}\\\text{the end effector}\end{pmatrix} \end{cases}$$

$$C_{EE} = EIJ^T \cdot K_{FA}^{-1} \cdot EIJ$$

Multi-body VPE-PKM: Conclusions

Results obtained

- The tool is applicable to almost any kind of PKM, with a typical required time for model set up: 4 hours, and PKM Analysis (post processing of raw data): 0.5 → 8 hours
- discretized workspace identification and jacobian analysis
- actuators sizing considering also the effect of gravity and inertial forces (1)
- internal loads (1) and effect of manufacturing errors (1) (2)
- effect of lumped structural compliances (1) (2)
- structural loads due to inertial forces

(1) : automatic worst case identification based on singular values decomposition
(2) : with sensitivity analysis

Future developments

effect of joint friction
over-constraint machines
- controllability analysis

The optimized PKM: Dragon Fly 1…

Results obtained

- optimised kinematic behavior (almost isotropic)
- acceleration analysis for control implementation
- main machine limitation: high torsional loads in the struts