KINEMATIC SIMULATION OF ACROBAT USING ADAMS

Enrico Annacondia[1], Claudio R. Boër[2], Daniele Catelani[3], Roberto Rinaldi[4]

[1]Gerardi S.p.A., Via Giovanni XXIII 101, I-21015 Lonate Pozzolo (VA) - Italy
[2] Politecnico di Milano, Fac. di Ingegneria di Como, Piazzale Gerbetto 6, I-22100 Como - Italy
[3] MDI Italia S.r.l., Via Palladio 98, I-33010 Tavagnacco (UD) - Italy
[4] Istituto di Tecnologie Industriali ed Automazione del CNR, Viale Lombardia 20/A, I-20131 Milano - Italy

Abstract

The aim of present work is the realisation of a tool that could support the researchers involved in conception and development of parallel architecture machines. These, as known, are composed by two platforms (one of them is connected to the ground), joined by six structures that can change their length. The combination of the structures' movement causes the motion of the mobile platform, inside the machine working volume, with six degrees of freedom (three translations and three rotations).
In parallel architecture machines, the simplicity is only apparent. In fact, determination of working volume and verifying of working conditions of joints that connect extensible structures and platforms present some difficulties that must be solved into the steps of development.
the Authors noted the high importance of the above kind of tool.
Basing on ADAMS, a kinematic and parametric model has been developed and used during the design of the parallel machine named "ACROBAT".
It has some interesting feature, like an user-friendly interface and others. It allowed very interesting investigations on the field of parallel machines and it will be used for further sophisticated analysis during the next steps of project.

Introduction

Usually, manipulators and machine tools (for example: milling machines, Fig. 1) work moving some joints. These joints link machine components in serial way.
This solution gives some problems. In robotics field, the main of these problems is due to the straddle (i.e. the distance between robot base and its end effector), that involves a large inertia of mechanism and limitation on payload.
Serial kinematic structures have other intrinsic limitations: for example, every segment must withstand, in addiction to payload (or, in machining the forces applied to the tools), all other connected machine parts . The derived bending gives two conflicting necessity:

- the limitation of deformation in machine's elements (slideways and beds on machine tools, segments in robots), increase their mass, because of design that gives to section an high inertia momentum (with ribs or tubular geometries), or using sophisticated materials such as composites;
- the minimisation of the machine total inertia, in order to increase its global performances (precision, repeatability and speed in movement).

Another limitation of serial architectures is connected to the growing complication of the machine when it needs a large number of degrees of freedom.
The motion characteristics are also related to the quality of the chain composed by joints and machine elements (i.e. geometrical relative positioning between axes of joints and slideways). A strong influence is given by clearances and friction, which are in every joint composing the kinematic chain of the machine.
For some applications (such as precision assembly, deburring, high speed milling, wood working, rapid prototyping, etc.) a possible solution for all of these problems is given by machines based on a completely different architecture. In our project, a subset of parallel architectures has been chosen (an example is given by Fig. 2).
The parallel architecture machines mentioned here are characterised by a structure which is light and stiff at the same time. This is due to the "closed chain" kinematic: the machine is composed of two platforms. One of these is connected to the ground, by machine's frame. The other platform (the moving one) supports the end effector (doing the specific technologic process: handling, assembling, deburring, chip removal, flow processes, etc.).
The platforms are linked by three identical chain. Each of these is composed of two elements, connected to the platforms in a convergent way. This gives to the structure the required stiffness, and every element in chains is subjected to traction or compression only: no bending exists and large inertia sections are not required.

Another advantage of considered parallel architecture machines is given by independence of error: in serial kinematics, total error is the sum of every joint error; in parallel machines, the total error has about the same magnitude of one joint error, with an evident increase in the machine's precision. Some high precision positioning devices have been studied and developed using this principle (Acaccia et al.1994, Romiti et al.1993).
In parallel machines, the moving mass is lower than in serial machines. It comprises the end effector, the mobile platform, its joins and a fraction of six extendible elements mass. This gives low inertia and very high speed and acceleration.
Under the aspect of kinematic equations, parallel structures have an opposite behaviour, if compared to serials. In these machines, direct kinematic transformation has a quite easy structure (from a computational and algebraic point of view): it is composed by sums and products between 4×4 matrixes, whose elements are, in the worst case, sums and products between sines and cosines of Euler angles. Complications are present in reverse kinematic transformation (and, in particular, in the computation of ATAN2 function). Parallel machines present the, opposite situation: the reverse kinematic transformation is very simple (it requires no matrix), while the direct is complex and requires a lot of algebraical work. In addiction, it can be represented using a polynomial expression. An additional computational advantage of considered parallel machines architectures is the following: all of them can be taken back to a basic structure, shown in Fig.3 and called "Symmetric Simplified Manipulator" (SSM), whose kinematic transformations can be found on specialised bibliography (Merlet 1990, Merlet 1996). To adapt the equations to a specific machine, the related geometric parameters must be given, simplifying the implementation of the control system.
Such structures also have very interesting advantages for their production: in fact, they are characterised by the presence of six identical extendible structures, six identical joint on the fixed platform and further six identical joint on the moving platform, with economic benefits.

The ACROBAT Project

Considering the advantages exposed so far, the Authors decided to start the development of a prototype, based on SSM structure and called ACROBAT (Anti Convenzionale **ROB**ot per Assemblaggio e Taglio = Not Conventional Robot for Assembly and Metal Cutting).

The underlying intention is the evaluation of this kind of machine applications in both the machine tools (as high speed milling machine) and precision parts assembly fields. In the first application, the characteristics of stiffness, low inertia, dexterity and precision can be applied, while in the latter the higher precision could make the automatic assembly of precise parts affordable.
The first step of the ACROBAT project was the development of a simulation tool, supported by a commercial software package. This software has been chosen analysing the packages present on the market and considering the specific needs of the project.
The tool is now used to test and verify a wide range of constructive solutions. By means of this interaction with simulation tool, a bi-directional "loop", between technological requirements and machine kinematic behaviour has been established.
Actually, a prototype of ACROBAT has been built (Fig. 4). It has been used to test the software and hardware control system and to experience us for the project and development of the industrial version of the machine.

The kinematic simulator

Why we have used ADAMS in ACROBAT project

All the phases of ACROBAT prototype development were characterised by a principle: everything present on markets and that can be fastly adapted to the particular needs of project is the favourite choice. In fact we had the necessity to prove the usability of this parallel machine as fast as possible.
For this reason, we discarded the idea of build a simulator fully programmed using C, FORTRAN or any other language.
After evaluating of software packages dedicated to mechanical simulation, we chose ADAMS for the following reasons:

- possibility to model any kind of mechanism, with rigid or flexible bodies, connected by joints and subjected to applied forces, motion laws, control laws
- possibility to create a fully parametrised mechanism with optimisation and design of experiments options
- possibility to extend modelisation features with user-supplied FORTRAN subroutines
- possibility to customise ADAMS/View interface, in order to create a specialistic and tailored easy-to-use design tool

- possibility to interface with Finite Element Analysis, Control Analysis, CAD software, in order to realise a fully integrated design.

Modelling

The mechanism of ACROBAT has been built using twenty rigid bodies: fixed and moving platforms, six box-shaped parts (representing the elements of the "physical" machine that contain the motors and gear transmissions), six motherscrews and six screws interconnected with thirty different joints and six motion laws.

Every "physical" screw (which is used as extendible structure) can translate along motherscrew axis through a cylindrical joint, which allows two degrees of freedom (rotational and translational). The amount of translation is related to rotation using a pitch (defined with a screw joint). Rotation is governed by a function called MOTION, which is a kinematic law function of time. This is imposed around the rotating axis of motherscrew connected to the box part through a revolute joint. Finally, the box part is connected to the fixed platform through a universal (cardanic) joint. In the same way, the driving of the moving platform is guaranteed by six cardanic joints, positioned at the lower end of each screw.

Totally, there are twelve cardanic joints, six revolute joints plus six motion laws, six cylindrical and six screw joints.

The analysis automatically stops if the upper end of a screw reaches the motherscrew location. This way, the event of bad working configuration (i.e. the outlet of a screw from its housing) for the "physical" machine has been modelled.

Parameters choice

Because of its inheritance from SSM, as mentioned above, the ACROBAT machine can be efficiently parametrised. This is the most important characteristic in an effective optimisation study.

The following parameters have been defined:

- the polar coordinates of six joints on the platform fixed to the ground. Because of symmetry, two angles and a radius are enough for this (Fig. 5)
- the six joints polar coordinates on the mobile platform, which are defined in the same way of fixed platform joints
- the relative rotation between the two platforms (simulation shows that this parameter has a big influence on machine dexterity)
- the pitch of the screws that connect the platforms
- the screws length.

To run an experiment, some other parameters are necessary, in order to define the initial conditions:

- the relative position of the moving platform coordinate system in relation to the fixed platform coordinate system, given with three translation (x_0, y_0,z_0) and three Euler angles (ψ_0, θ_0, ϕ_0) for the orientation.

Each ADAMS object (PART location and orientation, MARKER location and orientation, geometries, mass and inertia values, MOTION user-function list, analysis parameters, etc.) have been built using Design Variables and ADAMS/View expressions as:

- LOC_LOCAL
- LOC_GLOBAL
- LOC_RELATIVE_TO
- LOC_ALONG_LINE
- ORI_LOCAL
- ORI_GLOBAL
- ORI_RELATIVE_TO
- ORI_ALONG_AXIS

with combination of algebraic, trigonometric and matrix expressions.

User's Panel

In order to supply an easy-to-use interactive interface, appropriate menu panels and buttons have been created. They are built for a quickly modification, kinematic analysis and postprocessing (Fig. 6).

The pre-processing phase involves the setting of the above mentioned parameters from which the model is automatically regenerated. To do this, as we have said above, location and orientation coordinates of each object (parts, joints, markers, etc.) have been related through ADAMS parametric functions.

The analysis step involves the choice of the desired trajectory for the moving platform, with the setting of translation and orientation values to be reached in a defined operational time. The user can easily switch from a trajectory experiment to another, selecting "Type of Motion" parameter. With the current release of ACROBAT simulator, he can also select between analytical law or interpolation data Spline.

The last step, called postprocessing, gives the possibility of results evaluation, through graphic animation of the multi-body system behaviour, creation of plots regarding responses of the system (displacement, velocity, acceleration of each desired point of the machine, reaction forces into each joint, screw displacement along its own axis, and others), printing of numeric results into output tables (Fig. 7 and Fig. 8).

The Driving routine

In some other works (for example: Fielding et al. 1995), simulation of motion has been implemented using the following procedure: the mobile platform is constrained to follow a trajectory and a first simulation is done to derive the motion laws for the extending structures. These laws are built through a spline function, that interpolates output results of the rotational or translational movement of each extending structure. Then the trajectory constraint on the moving platform is deactivated. While the motion laws are imposed to the motors, a second analysis is done to simulate the actual behaviour of the system and to calculate the responses.

In the presented work, an alternative strategy has been adopted.

Using an external FORTRAN motion routine, the motors move directly the screws that, consequently, drive the moving platform along a predefined and parametrised trajectory.

The routine is structured as follows:

- fourteen parameters are passed, from each MOTION statement in the ADAMS data set, to the motion subroutine. They represent current values of cardanic joints position in inertial and relative reference frame, initial global position and orientation of the moving platform, initial length of every screw, and its pitch; the necessary number of parameters are given according to the mobile platform trajectory definition
- through manipulation of the above parameters, the general law of motion is derived for every extensible structure, using Reverse Kinematic Transformation (Merlet 1990)
- the resultant value of rotational displacement, which is function of time, is passed back to ADAMS/Solver and imposed to the motors
- the complete set of kinematic equations is solved for each time step.

Examples

We present five different examples regarding some of experiments that have been done to test the tool. The first example shows the use of our tool to simulate the combination of an elicoidal motion (in Cartesian space) with two rotation of forty-five degrees around the initial X and Y moving platform axes (Fig. 9). It can be noted that this exercise could be adopted for the determination of actual working volume, giving a set of joints parameters; it can be used, alternatively, to define the optimal set of these parameters when a required working volume is given. During ACROBAT development, a mix of these two techniques is being adopted: the position of the six joints on fixed platform has initially been established (mainly for development time requirements). Then, a first simulation has been executed, to find out a first approximation volume. Finally, the positions of moving platform joints have been optimised, respecting the limits given by their internal kinematics.

The second example, Fig. 10, shows the ability of ACROBAT machine (simulated and real) in following non-monotonic path (rectangular, in this case). This is important for flow processes, such as laser, water-jet, plasma, etc.

In the third example described here, we show the ability of the machine in following an half circumference trajectory, contained in X-Y plane (referring to the fixed platform coordinate system), keeping the moving platform tangent to trajectory (Fig. 11).

Fourth example (Fig. 12) is an "evolution" of the previous. In fact it shows a complex working path composed by arcs and linear segments. This kind of motion has a great importance for application of ACROBAT in the field of high speed milling. In fact the combination of trajectories of this kind is used in complex shape milling.

The last example (Fig. 13) has been introduced to show the ability in following a Spline curve instead of analytical function of time, using (it is very important to say) the same inverse kinematic law routine. This peculiarity permits to follow path derived on CAD software or experimental tests. The sinusoidal path is obtained giving to ADAMS the points lying on a curve and using the function ADAMS/SOLVER SPLINE statements and CUBSPL ADAMS utility subroutine.

Conclusions and future developments

The parametric simulation tool gave a significative help during the development of ACROBAT first prototype mechanics. It saved a large amount of time, money and materials, because it allowed the evaluation of different configuration using computer, presenting, at the same time, a feedback to the team of designers.

The role of this tool will grow in the near future, following these steps and maintaining the parametric approach:

- first of all, the analysis will be completed with a dynamic model. This allows an evaluation of the forces acting on machine's components and of the inertial effects. In addiction this model can give a correlation between performances (mainly speed and acceleration of end effector) and motor characteristics (speed-torque diagram). Moreover the dynamic model could be used in the study of transient behaviours

- as second step, the flexibility of the main structural parts and some disturbs (such as friction and clearances) will be introduced. This will enable the researchers to find out the correlation between precision of machines, motion and applied loads on end effector
- the third step is connected to the development of a control system model, in order to evaluate different control strategies, with the target of the global optimisation of the machine
- the fourth possible step is the development of an automatic optimiser. As the mentioned, aspects can be modelled using a parametric approach, the functions called "design of experiment" and "optimisation" would enable a global design of the optimised machine. This will be done in order to satisfy some predefined characteristics, such as effective working volume, dynamic performances and precision of motion.

The implementation of the above steps will be supported by the current ADAMS features, such as interface with Finite Element Packages, control interface module and optimisation functions.

It must be noted that, in the last step, probably a large amount of computational time would be required, depending on the number of parameter optimised and on the desired target.

Acknowledgements

The Authors wish to thank, for the support, the Istituto di Tecnologie Industriali e Automazione of Italian National Council of Research (ITIA-CNR).

References

J-P. Merlet. 1990. Les Robots parallèles. Hermès, Paris.

J-P. Merlet. 1996. HTML Document at Internet address: http://www.inria.fr/prisme/personnel/merlet/Etat/etat_de_lart.html

Acaccia G.M, Cagetti P., Callegari M., Michelini R.C., Molfino R.M. 1994. Dynamic Model of a Robotised Fixture for Co-operative deburring Operation. Research report GNA :37/R.1129. Istituto di Meccanica Applicata alle Macchine, Università di Genova, Italy.

Romiti A., Zhmud' N., Sorli M. 1993. Design and properties of the Turin 6 D.O.F. parallel Robot for deburring Operation. In Procedings of ISMCR 93 (Sept. 1993, Turin, Italy), Bm.III-1 - Bm.III-6.

MDI - Mechanical Dynamics Inc. 1995. ADAMS User's Reference Manual, release 8.2. Ann Arbour, Michigan, USA.

Fielding E.R., Shapiro L.S., Slogrove D.A. 1995. "The design of a three axis parallel configuration robot for gantry mounting". In Proceedings of the International Conference on Intelligent Manufacturing (Wuhan, China, 14-17 June 1995). SPIE, Bellingham, WA, USA, 645-653

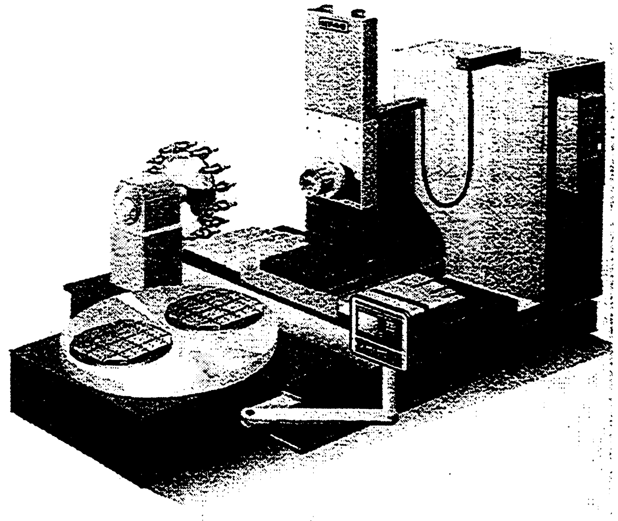

Fig. 1
(courtesy Gerardi S.p.A.)

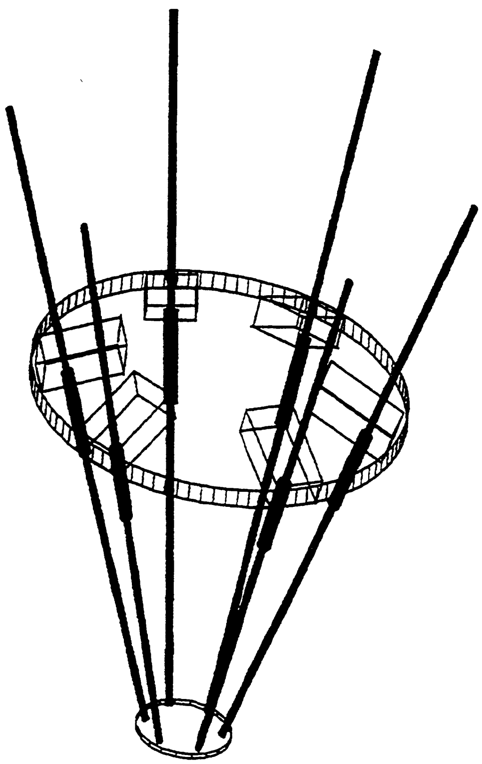

Fig. 2

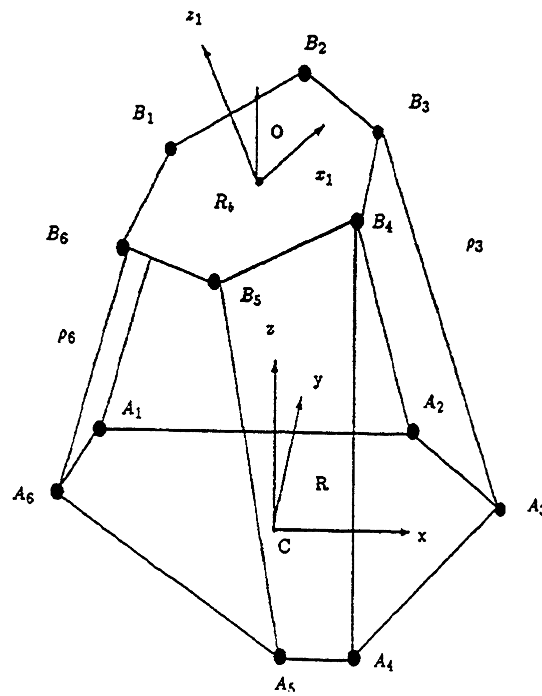

Fig. 3 [Merlet 1996]

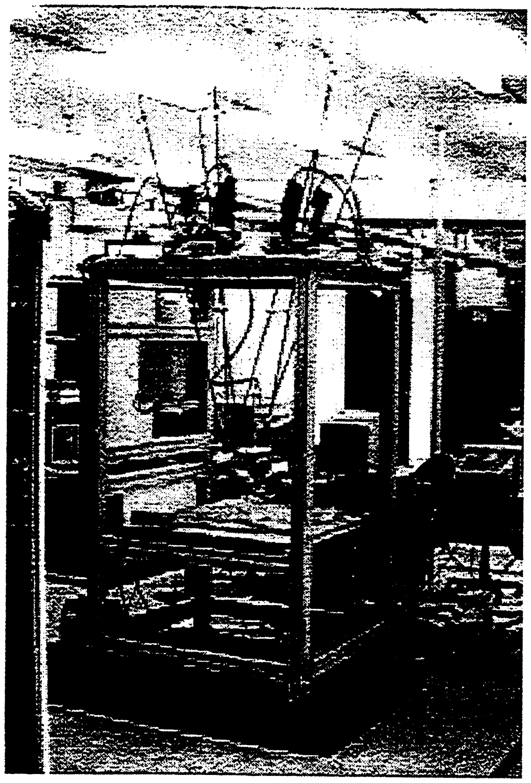

Fig. 4

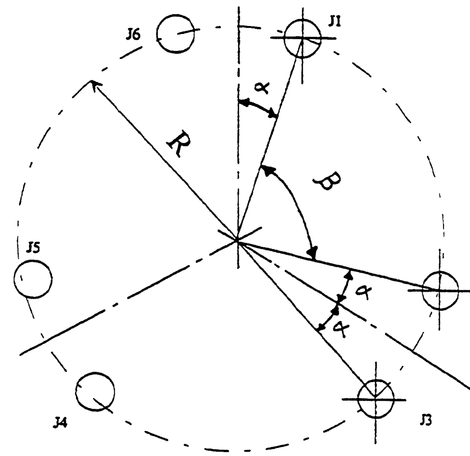

Fig. 5

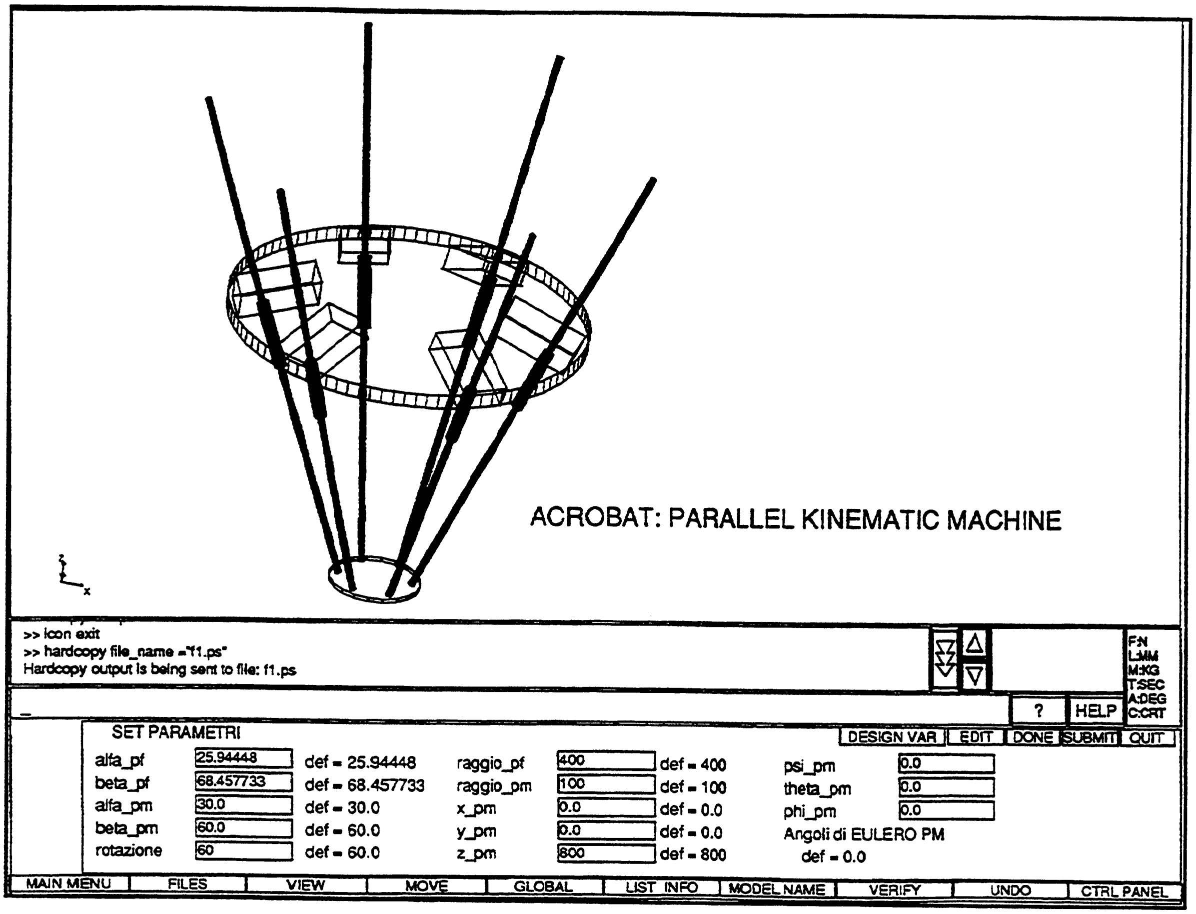

Fig. 6

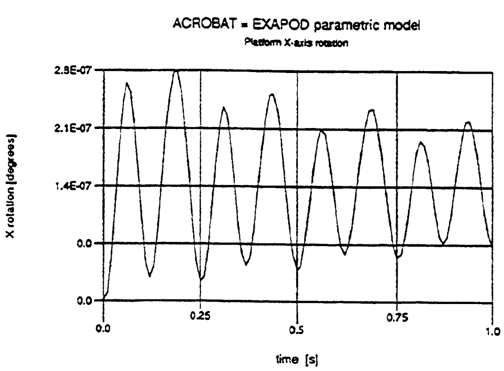

Fig. 7

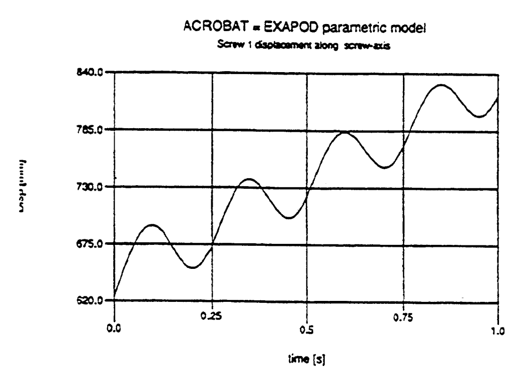

Fig. 8

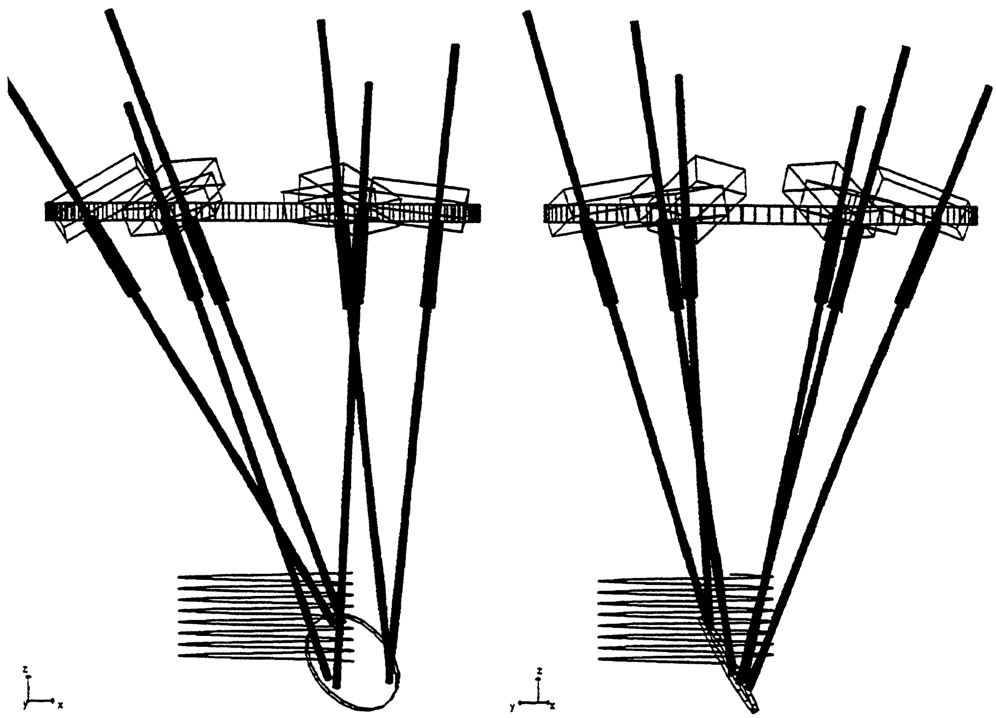

Fig. 9

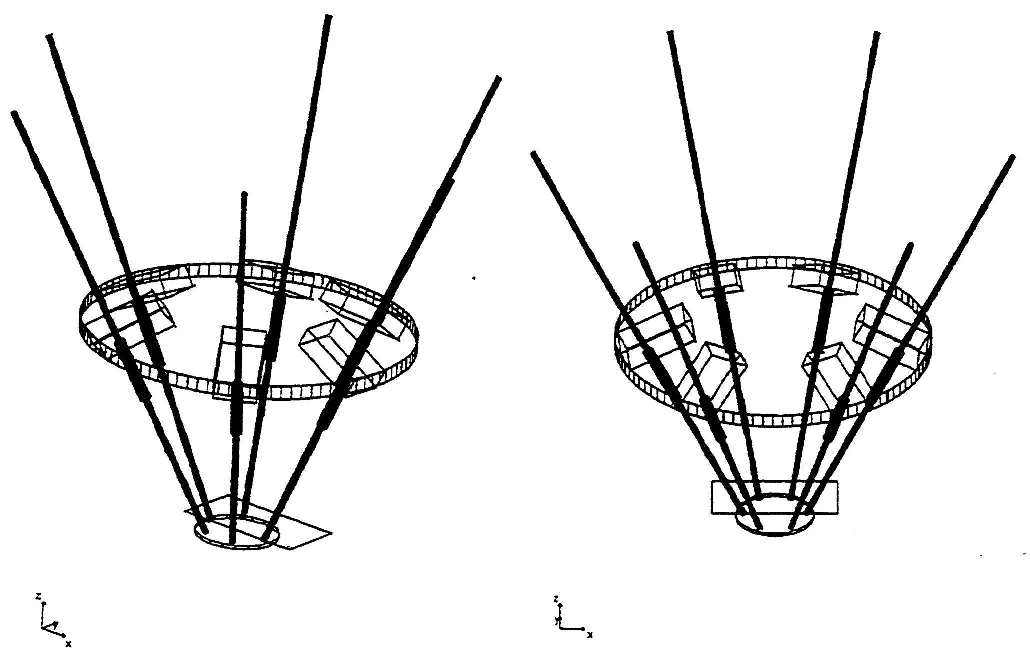

Fig. 10

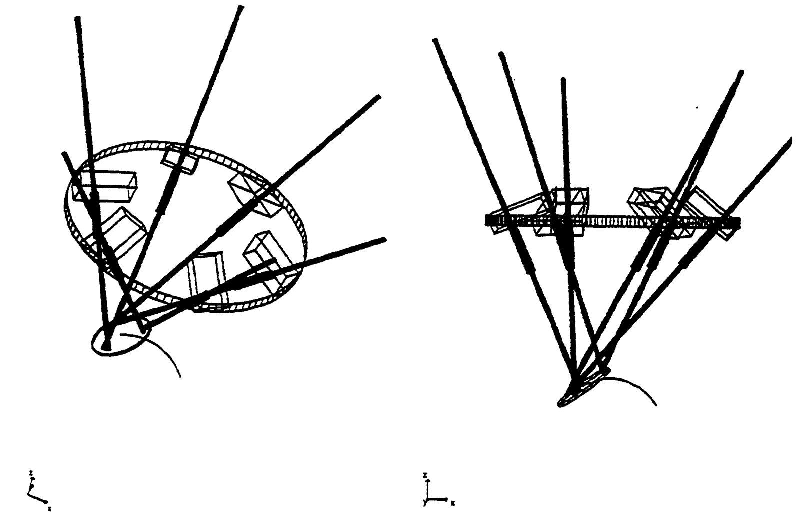

Fig. 11

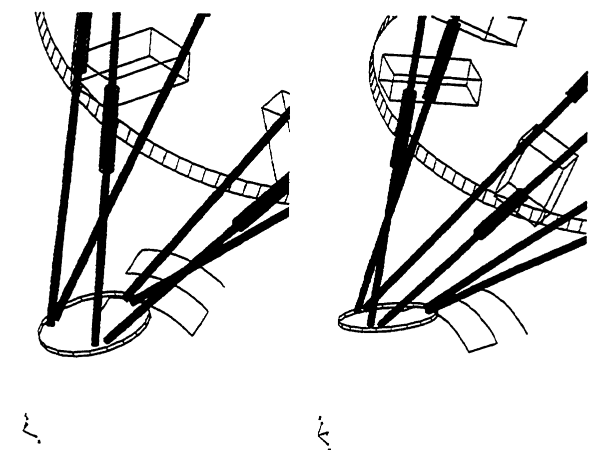

Fig. 12

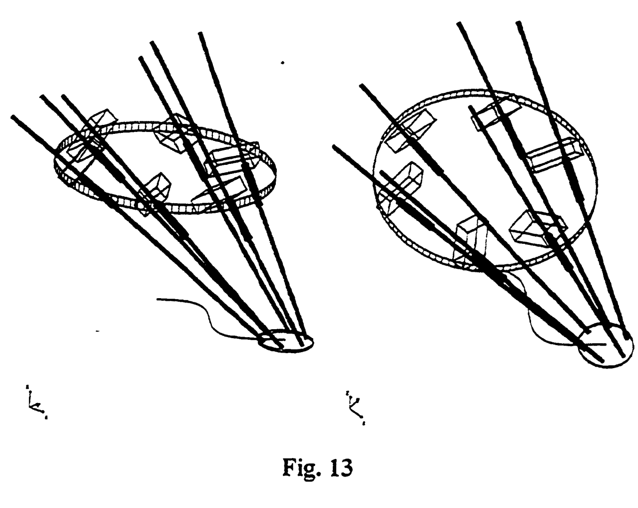

Fig. 13