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A DYNAMIC MOTION SIMULATOR
FOR FUTURE EUROPEAN DOCKING SYSTEMS

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ABSTRACT

Europe's first confrontation with docking in space will require extensive testing to verify design and performance and to qualify hardware. For this purpose a Docking Dynamics Test Facility (DDTF) has been developed by MATRA under a CNES contract. It allows reproduction on the ground of the same impact loads and relative motion dynamics which would occur in space during docking. It uses a nine-degree-of-freedom, servo-motion system, controlled by a real-time computer, which simulates the docking spacecraft in a zero-g environment.

The test technique involves an active loop based on six-axis force and torque detection, a mathematical simulation of individual spacecraft dynamics, and a nine-degree-of-freedom servo-motion of which three DOF's allow extension of the kinematic range to five meters.

The configuration has been checked out by closed-loop tests involving spacecraft control models and real sensor hardware. The test facility at present has an extensive configuration that allows evaluation of both proximity control and docking systems. It provides a versatile tool to verify system design, hardware items and performance capabilities in the ongoing HERMES and COLUMBUS programs.

The paper describes the test system and summarizes its capabilities.

INTRODUCTION

The HERMES spaceplane will develop on-orbit servicing capabilities in Europe, which will open new horizons for European space system designs and operations. In this context, rendezvous and docking represents a major step in expansion of European orbital operations, and is typical of HERMES mission requirements.

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Because mission success for HERMES will be dependent on the docking function, which must be performed reliably and safely, docking must first be verified by extensive ground tests tailored to qualify the system hardware for flight. A research and technology program has been sponsored by CNES at MATRA, to develop a motion-simulation facility to evaluate the relative control of closing spacecraft, and the contact dynamics of docking systems. This test facility is proposed for design, integration/verification and operational support in the development and operation of the HERMES proximity and docking system. Currently, it is planned to utilize this facility to define the requirements, to explore the technology and to assess the dynamic performance of HERMES-baselined soft docking.

TEST FACILITY OVERVIEW

Different concepts may be considered for ground simulation of two spacecraft docking in a zero-g environment. The concept selected consists of a real-time, active loop based on a six-degree-of freedom servo-motion with six-axis force and torque detection and mathematical modeling of the docking spacecraft dynamics. The docking hardware under test is physically installed in the motion-generating device (Fig. 1).

At a high sampling frequency (125 Hz), the forces and torques exchanged during contact of the docking interfaces are sensed and transmitted to the computer as input data to the spacecraft dynamics model. Compensation for gravity effects is concurrently made in the computer. The derived relative kinematics are then transformed into real motion.

This simulation technique is adaptive enough to accommodate any change in the docking spacecraft dynamics to be evaluated with a given set of docking hardware.

The docking is provided by a relative motion in all six degrees of freedom between two structural rings representing the docking interfaces. The motion is produced by a six-axis table, driven by six electrical screw jacks. One of the rings is fixed in the laboratory coordinate reference axes.

To represent the final approach (the last five meters), three degrees of freedom have been added, consisting of large amplitude translation along the docking line, and two rotations serving to simulate the angular misalignments about the transverse axes.

At the end of the final approach simulation, the test facility must achieve a reference docking test configuration. Thus the three additional degrees of freedom must be nullified, and the test system

must have no residual structural flexibility or backlash. During the final approach there is no contact, so the rotations and lateral translations can be represented by moving the rendezvous sensor (two rotations, using a two-axis, dedicated rotation device). For arresting the translational motion, a clamping system utilizing air brakes is employed for hardlocking the mobile mount, with emphasis on eliminating flexibilities and backlash.

The algorithms which are used for handling the nine degrees of freedom are based on optimization within the constraints on the motion axes.

The facility design offers a high structural stiffness and a high motion resolution. The geometrical configuration is optimized to reach the best compromise between kinematic stroke and dynamic loads in the docking hardware.

The screw jacks used on the six-axis table use precision ball screws (3 mm per revolution) driven by stepper motors (3200 steps per revolution). They provide a motion resolution of 1 μm and a load capability of 1500 N at low speed (<2 cm/sec). The measured backlash is 50 μm, and the maximum speed is 10 cm/sec. The load sensors are mono-axis piezoelectric force transducers, selected for their stiffness (10^8 N/m), their high linearity and their low noise (0.5 N over a 1000 N range).

The test facility involves a real-time computer architecture (Fig. 2), based on a 68020 work station for test operation and monitoring, a 12 Mflop array processor for simulated dynamics computation, and a GOULD 32/67 for data recording and output.

The software of the DDFT includes, in addition to the orbital dynamics, the simulation of structural flexibilities (first combined mode of the deployed solar panels and antenna) and liquid sloshing (one tank in each vehicle). Plume effects are computed off line, and their influence memorized to be used in real-time software.

In order to calibrate the facility and to verify validity of its performance, an extensive series of open- and closed-loop runs were made under a full range of operating conditions. The checkout culminated in testing functional docking hardware.

During these checkout operations, some limitations on the testing capabilities were identified:

1. The bandwidth is limited to 6 Hz, which is a limitation in the range of spacecraft mass and docking hardware stiffness characteristics that can be evaluated (Fig. 3).

2. The load and speed capabilities of the six-axis table make no provision for accommodating "impact docking" hardware.

3. Vibrations associated with screw-jack activation cause degradation of the contact force measurements.
4. Backlash and absolute accuracy need improvement to be more representative of real motion.

PERFORMANCE VALIDATION

A one-axis testbed evaluation has been performed to derive characteristics of the screw jacks and to validate the hardware and software configurations. The measured backlash of the screw jacks is now less than 5 μm.

The vibration level has been lowered, but it is still important because of stepper motor resonance at some drive frequencies.

Closed-loop tests have been conducted to validate the computer architecture and the management of software. The computing time has been optimized with the sampling frequency at 125 Hz, so that the simulator bandwidth attains 6 Hz.

A screw jack prototype based on a satellite roller screw has been developed. It is used for the six-axis table and is characterized by:

•Low noise level (no balls in the screw)
•Manufacturing accuracy of the screw at 10 μm
•No backlash
•Additional guidance of the screw jack (no collapse)
•Good motor-screw coupling
•Rotation lock for the linear part
•Stop pin for initial positioning

Limitations still exist. The most important one is the excessive vibration level during operation, which can be effectively reduced by substituting a DC motor/encoder assembly for the screw-jack actuation.

This solution is being studied at present and will provide further advantages (increased load and speed capabilities), so that the DDTF will allow evaluation of impact docking dynamics involving initial velocities to 10 cm/sec, forces to 5000 N and a lower noise level.

Validation

The introduction of simplified approach-control laws referenced to real test rendezvous sensor information is currently underway. This will allow validation of the closed-loop operation of the test facility through the full range of its testing capabilities.

The Imaging Rendezvous Sensor (IRS) uses a new process mode called Flash During Transfer (FDT), developed by MATRA, which allows work under marginal lighting conditions (even with the sun in the sensor field of view). The sensor uses a special target pattern, composed of five optical retro-reflectors (fig. 5), illuminated by a pulsed laser source. This equipment can measure with high accuracy the relative attitude and position of the two bodies(three rotations to 20 meters and three translations from 250 m to contact).

The Telemetry Rendezvous Sensor (TRS), which is used for distances from 1000 meters to 2 meters, measures the phase difference between the emitted and the retro-reflected wave, of an amplitude modulated laser source. This sensor can use the same target pattern as the IRS.

The characteristics of the sensors are as follows:

	IRS	TRS
Field of view	10°	10°
Attitude range	±2°	±2°
Distance range	0-250 m	2-1000 m
Attitude resolution	0.25°	0.25°
Line of sight precision	0.05°	0.05°
Distance resolution	1%	1-3%
Pulse	100W	100mW
Duration	200 nsec	-
Modulation rate	1 Hz	15 MHz
Measurement rate	1 Hz	1-10 Hz
Target	2-3 Kg	1 Kg
	0.1-1.5 m	0.1 m

Functional Synthesis:

The DDTF can perform docking tests from the last five meters of the controlled final approach (based on real sensor measurements) down to linkup of the docking interfaces (by use of simplified docking mechanisms) (Fig. 4).

Within the computer, rigid-body mass properties from 4000 kg to 60,000 kg and inertia properties from 10^4 kg.m^2 to 10^7 kg.m^2 can be simulated, providing significant margins over today's known mission needs.

The testbed bandwidth is about 6 Hz, so that the test hardware stiffness may vary between 10^3 N/m and 3×10^6 N/m in translation, and 10^4 Nm/rad and 3×10^6 Nm/rad in rotation.

The attainable performance is subject to the testbed operating capabilities as follows:

Final Approach (emphasis on motion)

	Translation	Rotation
Position Range	5cm inside a 10° conical envelope	±5°
Velocity Range	axial 10 cm/sec	
	radial 2 cm/sec	5°/sec
Resolution	0.1 mm	0.001°
Accuracy	1 mm	0.01°
Acceleration range	5.10^{-3} m/sec^2	10^{-3} rad/sec^2

Docking (emphasis on contact loads)

	Translation	Rotation
Position Range	±7.5 cm	±2.5
Velocity Range	1.5 cm/sec axial	
	0.5 cm/sec radial	0.2°/sec
Resolution	1 µm	-
Accuracy	1 mm	-
Acceleration range	0.1 m/sec^2	10^{-2} rad/sec^2
Load range	1.500 N axial	-
	900N radial	500 Nm

The basic architecture of the testbed facility is shown in fig. 5, with hardware items separated from computer software. A computerized graphic display allows visualization in real time of the individual spacecraft response motion during a test run, in either spacecraft or orbital coordinate reference axes. In addition, provision is included in the facility to accommodate enhanced spacecraft dynamic models and pilot interfaces so that manual proximity control and docking can be evaluated.

CONCLUDING REMARKS

A dynamic testing capability for docking systems has been described. The technology, based on current off-the-shelf components, has been optimized to eliminate backlash and to minimize vibrations (which produce the most significant limitations on the testing performance). Computations and computers in the control loop incorporate complete motion generation and spacecraft dynamics simulation, so that the facility acquires a potential for implementing both spacecraft proximity control and docking systems (sequentially or independently) without limitation on the testing requirements.

This unique concept provides a versatile test tool to validate system design, to demonstrate hardware items, and to verify dynamic performance capability and reliability.

Currently, application of this facility is being planned for testing HERMES docking model hardware in a joint CNES-ESA program, and evaluating the required manual control performance for docking. Because of use in HERMES missions of the FREEDOM space station docking system, this testing is primarily intended to evaluate the design revisions of the system in order to accommodate the HERMES soft-docking requirements.

REFERENCE

G. Brondino and Ph. Marchal, Centre National d'Etudes Spatiales, Toulouse, France; D. Grimbert and P. Noirault, MATRA, Velizy, France, "DDTF Improvements for More Accurate Space Docking Simulation", EIOOTS, September 1989.
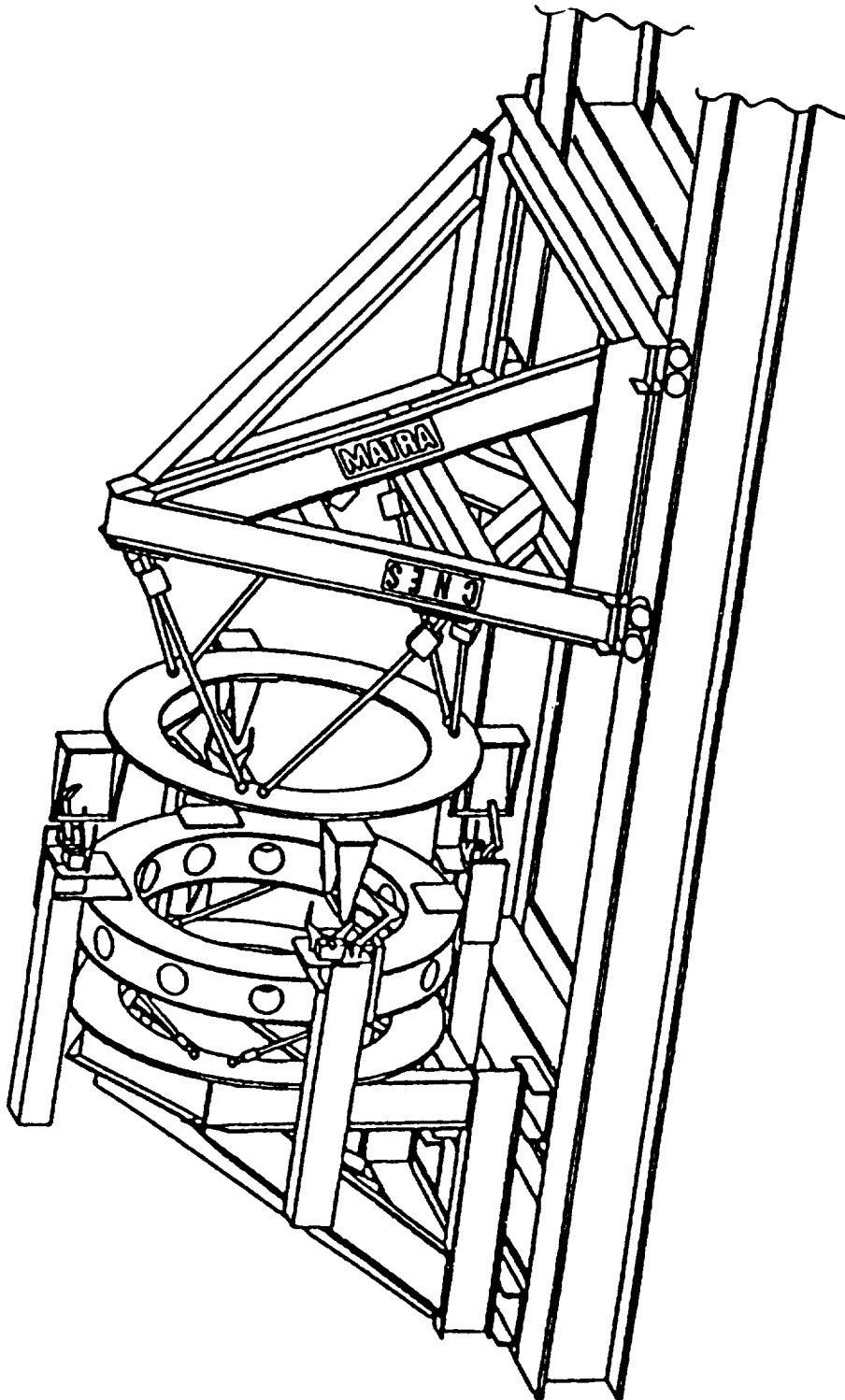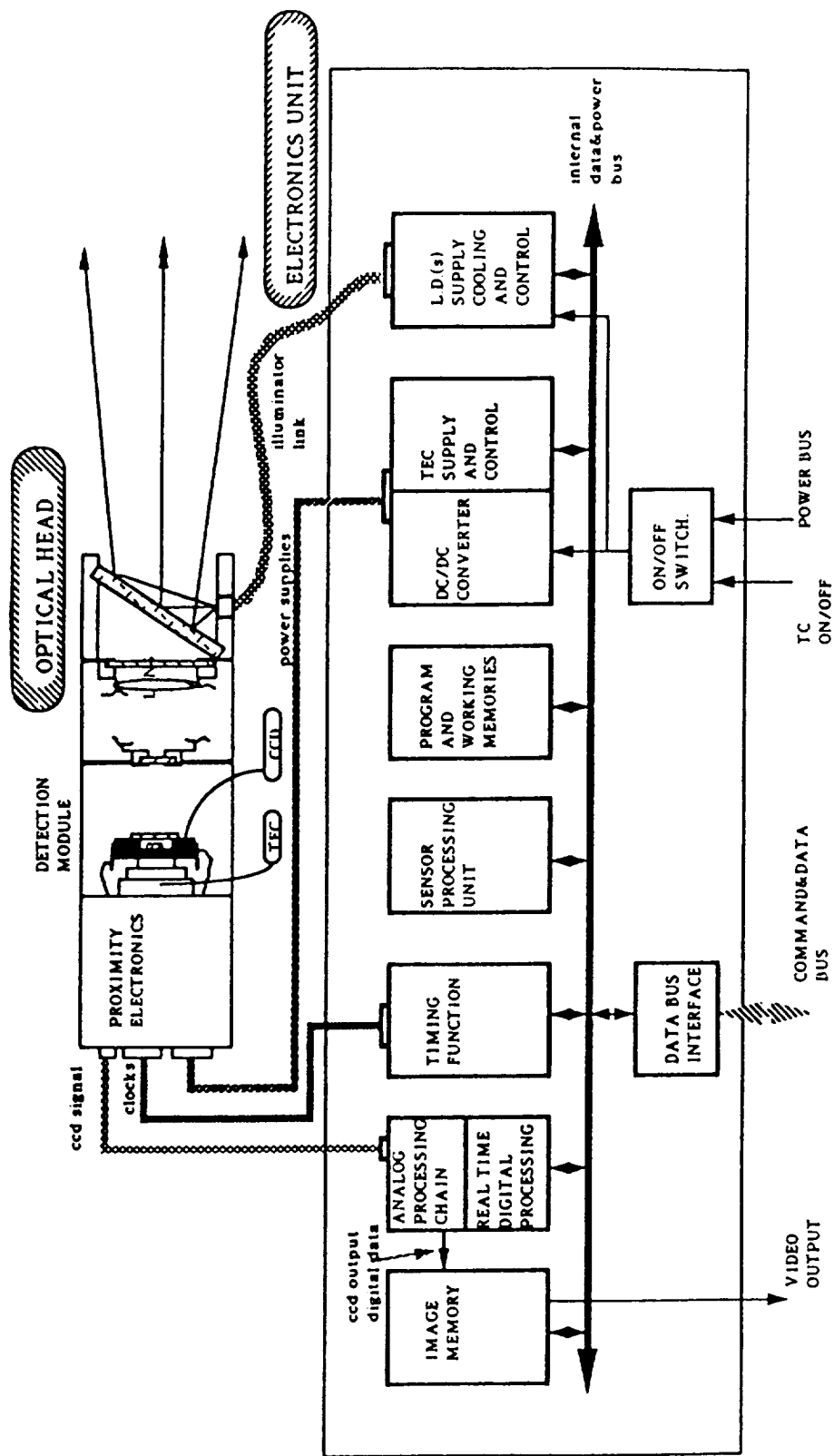
Fig. 1 : Representation of the actual DDTF

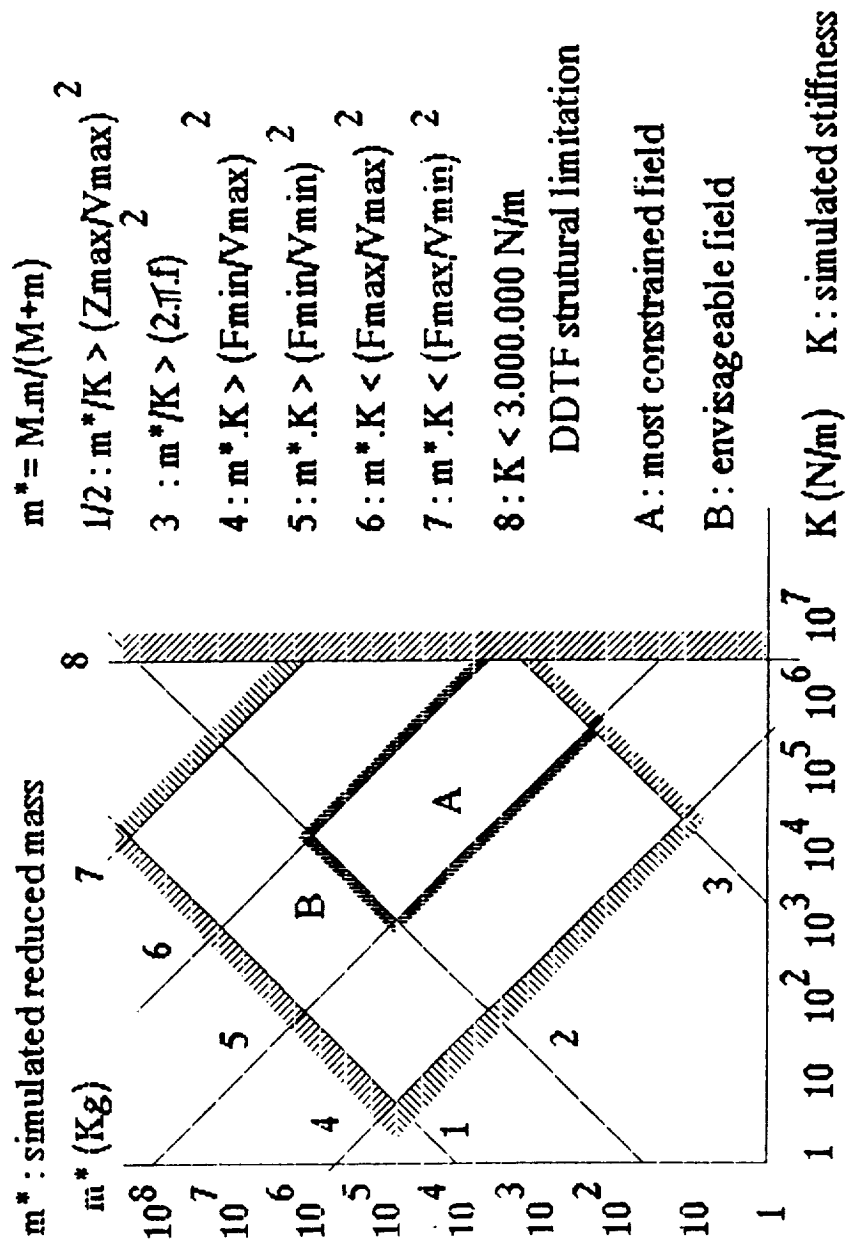Fig. 2 : Real time computer architecture

C-2

$m^* = M.m/(M+m)$

$1/2 : m^*/K > (Zmax/Vmax)^2$

$3 : m^*/K > (2.\pi.f)^2$

$4 : m^*.K > (Fmin/Vmax)^2$

$5 : m^*.K > (Fmin/Vmin)^2$

$6 : m^*.K < (Fmax/Vmax)^2$

$7 : m^*.K < (Fmax/Vmin)^2$

$8 : K < 3.000.000$ N/m

DDTF strutural limitation

A : most constrained field

B : envisageable field

K (N/m)   K : simulated stiffness

m* : simulated reduced mass

m* (Kg)

Fig. 3 : Field of DDTF limitations
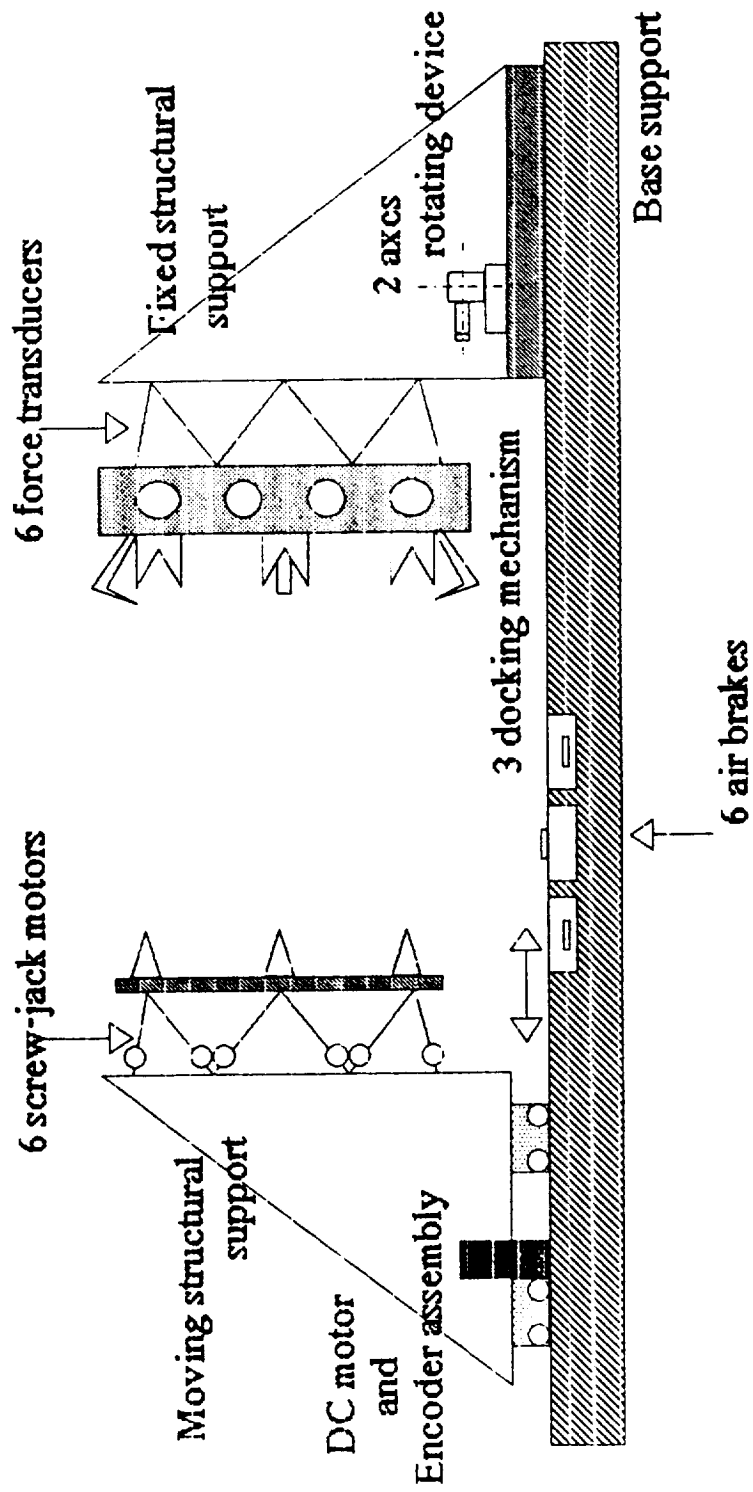
Fig.4 : Testbed hardware configuration
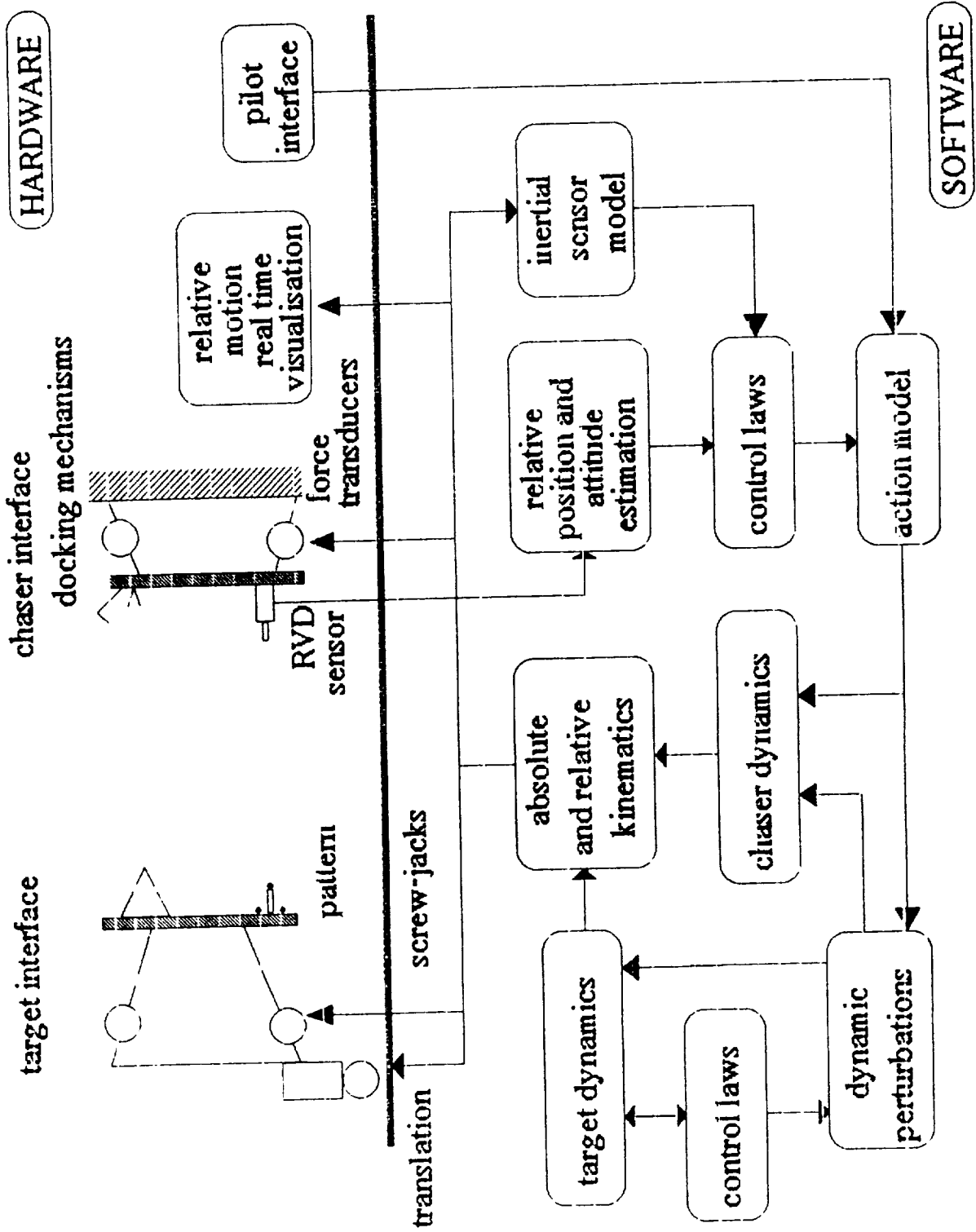
Fig. 5 : Global architecture

detection module TII 7863

optical fiber

laser source
+ electronics

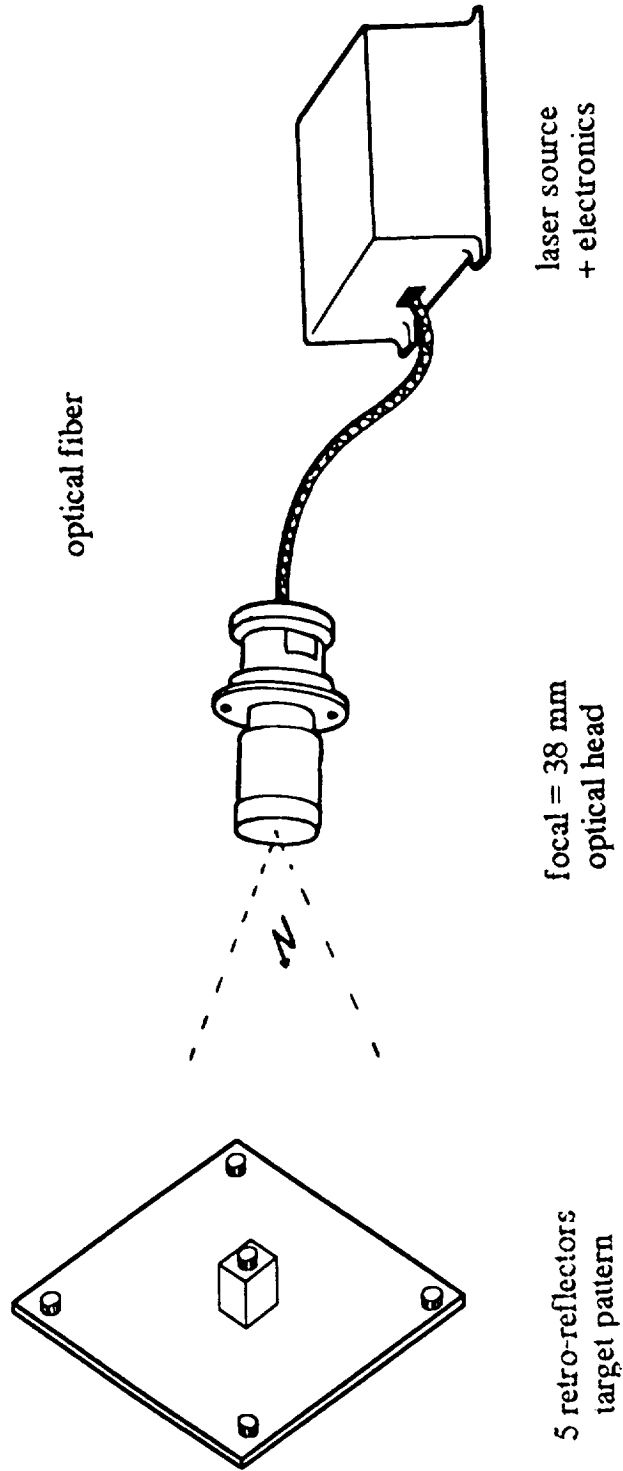focal = 38 mm
optical head

5 retro-reflectors
target pattern

Fig.6 : Imaging Rendez-vous Sensor and target pattern