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1.0 Introduction

This product documentation and operating manual describes the *Mirror Positioning Unit* (*MP-Unit*) consisting of the HEXAPOD (*Wide Range Positioning System*), the *Tilting Mirror Unit* (TM-Unit) and the Control electronics. The MP-UNIT was designed for use at the *Infrared Telescope Facility* (IRTF) for image stabilization and correction of diffractions caused by atmospheric density fluctuations. Also mechanical deformations of the telescope structure caused by gravity can be compensated.

2.0 System Description

The MP-UNIT system consists of the HEXAPOD six-axis wide range moving platform, the PZT-driven Tilting Mirror Unit including the high resolution tip/tilt sensors and the driving electronics.

Drawing see next page

Fig. 2.1: Components of the Mirror Positing System (MP-UNIT)

The secondary mirror of the telescope is mounted on the HEXAPOD System. Slow but wide range movements in all six degrees of freedom can be accomplished with the DC-Motor driven linear actuators, representing the legs of the HEXAPOD system. These wide range movements are for compensating gravity deformations and mechanical tolerances of the telescope structure.

To correct and stabilize the optical image from atmospheric induced blurring, the PZT driven Tilting Mirror Unit (*TM-UNIT*) is mounted on top of the HEXAPOD system. The TM-UNIT allows to tilt the mirror in the range of +/- 50 arcsec at frequencies up to some 100 Hz. It consists mainly of three piezo actuators to move the secondary mirror and additional three actuators for driving a momentum compensation mass in opposite phase.

The HEXAPOD system is connected to a separate 8-axes DC- Motor Controller which is mounted about 6 m off from the mechanics inside the telescope head ring structure. Here all axis specific commands are executed. The controller also includes the tip/tilt sensor A/D converters and a fast serial data link to the MPIC controller.

The complete system is controlled by a DSP based Controller (MPIC). Most of the calculating power is needed to operate the TM-UNIT with high speed in closed loop with the built in sensors or the external image correction system. The MPIC Controller also sends all HEXAPOD motion commands to the HEXAPOD Controller. All position commands given in Cartesian coordinates have to be transformed there to HEXAPOD actuator axis specific positions and velocities and executed.

The MPIC controller contains also a 6- channel piezo power amplifiers and all power supplies to drive all components with the required dynamics.

The MPIC controller and the HEXAPOD controller are connected with three 25m long cables, one for fast serial communication, one for piezo operation and one to supply the HEXAPOD Controller and the sensors with power.

3.0 Mechanics

The mechanics of the MP-UNIT system consists of the Tilting Mirror Unit (TM- UNIT) and the HEXAPOD Wide Range Mirror Adjustment System. Both components are designed as compact and lightweighted as possible.

Fig. 3.1:

Photo of the HEXAPOD wide range positioning system with the piezoelectric fast tilting mirror unit on the top. The mirror is dummy for measurement purposes.

Drawing on next page.

Fig. 3.2 Details of Tilting Mirror UNIT (TM-Unit)

Drawing on next page.

Fig. 3.3 Details of HEXAPOD Ground Plate

Drawing on next page.

Fig. 3.4 Details of Mirror Mounting Plate

3.1 Tilting Mirror Unit

The secondary mirror (1) is made from SiC and gets three INVAR posts (2) attached at the rear side (3 x 120°) by elastic epoxy adhesive. The posts have a metric 6 mm threaded bolt to build the mechanical interface to the *mirror mounting plate (3)* of the TM-UNIT, also made from INVAR to match the thermal expansion of the mirror.

The mirror mounting plate has three mounting pads, one fixed and two radial compliant (EDM machined) for compensation of residual temperature effects. The whole construction is light-weighted for optimized dynamic behavior and is mounted on three PZT mirror actuators (4) . Depending on the electrical driving signals, the actuators can be expanded or contracted to tip/tilt the mirror mounting plate and the attached secondary mirror.

Perpendicular to the PZT-movement a steel flexure (5) supports the mirror mounting plate in radial direction to achieve the desired stiffness and to enable tilting movements around the common center of gravity of mirror and mirror mounting plate.

In case of non reliable epoxy contact the mirror could drop from the INVAR posts and be damaged. To avoid this, three small adjustable safety hooks (6) are integrated inside the chassis (7) and hold the mirror from holes in its back side. They have no contact to the mirror during standard operation.

At the circumference of the *mirror mounting plate* two pairs of inductive sensors (8) are mounted, separated by 90 degrees, This location allows to sense the tilting in two orthogonal axes. Two sensors for each axis allow differential measurement.

On the back side of the TM-UNIT, three identical PZT compensation actuators (9) are mounted to move the *momentum compensation mass (10)*. Its moment of inertia equals that of the mirror and the mirror mounting plate. Driving both masses in opposite directions, the resulting dynamic forces are almost compensated in the base structure (11) and only very small forces are transmitted into the structure of the HEXAPOD or the telescope. To minimize the residual momentum, the software allows a fine tuning of the amplifier gains.

The mirror mounting plate as well as the momentum compensation mass are connected to damping elements (12) to reduce overshoot in mechanical resonance.

3.2 Mirror Mounting/Dismounting Procedures

The design of the TM-UNIT allows to carry out all testing and calibrating procedures independent of the kind of the mirror mounted. An aluminum dummy mirror was used for testing with the same shape and about the same moment of inertia as the final mirror substrate.

To avoid any mechanical stress in the mirror substrate, the last step of the mounting procedure is to glue to mirror onto the post-flats. After that, no screw must be touched. This general rule may be broken if an mounted mirror is dismounted and later reinstalled with the same posts glued on the substrate. In that case, the mirror should be mounted in the same orientation and the three nuts should be tightened with equal torque. If even then the shape of the mirror is not good enough, the INVAR posts have to be removed from the substrate and the mounting procedure has to be carried out with a new set of INVAR posts.

Dismounting Procedure

1. The mirror is mounted via three posts on the *mirror mounting plate. Unscrew the metric M6 nuts (13) at the bottom side of the mirror mounting plate.* Reach through the free center space to the three M6 nuts at the *post mounting pads* and use the special tool to unscrew the nuts.
2. Unlock the three safety hooks (6) with an Allen key, tilt it to the center position and lock it again.
3. Carefully lift off the mirror with the glued-on INVAR posts from the *mirror mounting plate*. Avoid tilting.

Mounting Procedure

1. Mount the three INVAR posts to the post mounting pads on the *mirror mounting plate* using three metric M6 nuts.
2. Glue the mirror onto the INVAR posts. This should be carried out while all components are at room temperature. Note that centering of the mirror is necessary and also the angular orientation has to comply with the safety hooks at the base structure.
3. Lock the safety hooks again in its most radial position.

3.3 HEXAPOD Unit

The HEXAPOD unit is a W*ide Range Mirror Positioning System.* Large movements in the range of some millimeters and tilting of some degrees are required for structural compensations of gravity influenced deformations of the telescope. The compact HEXAPOD system provides wide range linear and rotational movements. Six length variable, DC-motor controlled legs (14) steer the HEXAPOD platform into the predefined position with micrometer accuracy.

The six linear actuators are mounted between a base plate (11) and the TM-UNIT. The advantages of the HEXAPOD design are low weight, compact structure, high stiffness, six-dimensional movements and high resolution.

Drawing see next page.

Fig. 3.5 HEXAPOD Actuator

Drawing see next page.

Fig. 3.6 Limit and Reference Switches

HEXAPOD Design

The HEXAPOD unit consists of six identical linear actuators (14), a HEXAPOD ground plate (11) and the TM-UNIT´s base plate (7). To reduce the weight of the whole unit, the upper joints are integrated in the TM-UNIT. No additional mounting plate is required. Due to this design, the hexapod system requires the TM-UNIT as a structural part.

HEXAPOD Linear Actuators

- Mechanical preloaded spindle, range 28 mm, pitch 1mm
- Backlash-free gear head, reduction rate 80:1
- DC-motor, 12 V, 3 W
- Rotary incremental encoder, 60 counts per revolution
- Axial ball bearing
- Chassis with reference edge for Limit Switches
- PCB with optical limit and reference switches
- Universal joints on both sides

HEXAPOD Details

All components are designed as short as possible and are mounted free of backlash in axial position. Due to this design, the mechanical system has an exceptional stiffness and offers an excellent positioning repeatability. The theoretical resolution of the linear actuator is 4800 counts/mm respectively 0.2083 µm/count.

Both universal joints (20) are designed as a combination of special manufactured and mechanical preloaded needle bearings with extra high stiffness in radial direction. They are designed as functional module and can be manufactured, tested and exchanged separately. The materials and lubricants used guarantee long term operation in the requested operational environment and temperature range.

The joint-modules (20) allow tilting around two orthogonal axes. The third rotational axis is accomplished by the spindle of the linear actuator itself. Due to design considerations, both tilting axes do not have a common pivot point. This causes some minor nonlinearities at larger displacements, but for normal operations these deviations can be neglected.

The operation of the limit (22) and reference switches (21) is invariant against rotations around the linear axis of the actuator and works independently of the angular position. Powering on the HEXAPOD controller, at first an initialization routine is performed and each linear actuator is directed to its absolute center position. All positioning commands are related to this center position and will be performed with a resolution determined by the incremental encoders.

The HEXAPOD ground plate (11) represents the mechanical interface of the MP-UNIT to the telescope. It contains all electrical connectors (15), cable grooves (16) and small PCBs (17) with CMOS components for buffering encoder and limit switch signals.

All of the six linear actuators have a DC-Motor driven backlash-free spindle (23) combined with a backlash-free gear head (19). Each actuator can be controlled individually in length over the range of 28 mm. For each set of lengths of the six linear actuators, there is only one defined orientation of the platform in all six degrees of freedom.

There is no mechanical stress caused by driving the legs to some random positions. All motion commands are defined in the orthogonal coordinate system, where three linear and three rotational movements are possible. For rotational movements the center of rotation can be defined individually. In the present application the pivot point is placed in the vertex of the secondary mirror as default and can be redefined by software.

In regular operation, the electronics drives the platform at orthogonal paths or around fixed pivot points. Even pivot points outside the platform can be defined to tilt the platform around them. For single axis movements or rotations defined in the orthogonal coordinate system, all six actuators have to be moved on interpolated paths to guide the platform on the defined trajectory.

4.0 Sensors

High resolution inductive sensors are used to determine the tilting of the TM- UNIT. for both orthogonal axes two pairs of sensors are used in differential mode for best resolution.

The sensors used are manufactured by *KAMAN INSTRUMENTATION CORP*., KD-5100 series, Model 15N-003 (four sensors installed).

Two matched sensors are positioned relative to the target so that as it moves away from one sensor it moves toward the other an equal amount. The transducer operates on the principle of impedance variations caused by eddy currents induced in a conductive target plate. The target material is aluminum.

See Appendix A for more details on the KAMAN sensor system.

5.0 Electronics

The Mirror Positioning Unit electronics consist of two separate controllers: About 6 m off the mechanical system, the HEXAPOD Controller (**HEXC**) is located. It contains an eight-axes DC-Motor controller, 6 axes are used for driving the HEXAPOD mechanics and two axes for customer purposes.

The other controller is the ***MIRROR PLATFORM & INTERFACE Controller*** (**MPIC**). It contains a fast digital signal processing unit (DSP), high resolution A/D converters, sensor evaluation circuits and fast data transmission links to the HEXAPOD controller.

The HEXAPOD controller is linked with the MPIC controller via three cables each 25 m long. One cable is used for power supply, another for the control signals to the piezoelectric translators and the third for communications.

Data transfer between HEXAPOD control unit and MPIC controller is based on a fast RS-422 data link. This techniques allows fast and reliable data transmission over the required distance.

After analog to digital conversion of the Kaman sensor signals, the position data words can be reliably transmitted to the main control electronics located about 25 m off site the HEXAPOD controller. This information is needed to close the loop with the piezo actuators and to provide a monitor signal for the actual mirror position with a sample time of T=100 µsec.

The HEXAPOD controller also sends some axes and power status information to the MPIC controller.

5.1 Mirror Platform & Interface Controller (*MPIC*)

The MPIC Controller consists of the following modules:

1. DSP-Module
2. 6-axis PZT Power Amplifier
3. Parallel to Analog Interface (2x)

4. Power Supplies
5. Serial Data Link

For drawings and schematics see *Document Reference Package MS43E, Appendix C*

5.1.1 DSP Module

The core of the MPIC controller is a fast digital signal processor type TMS320C31 for reading the tilting sensors and controlling the PZTs in a closed loop. The command positions are defined externally and input via a parallel or serial interface. According to the internal position control algorithm the DSP is evaluating two values out of the difference between the commanded and the actual positions. This calculations are done for both axes individually.

Then a coordinate transformation is required for converting both orthogonal tilting axes into the linear movements of the three PZT mirror actuators, each located at 120 degrees of the mounting circumference. Also the DSP generates signals used for the movement of the three PZTs moving the momentum compensation mass at the bottom side of the mirror mount. All six control signals are digital to analog converted and are fed to the input of the power amplifiers driving the PZT actuators.

The DSP has also to handle the parallel/serial interfaces, the command processing, the fast internal serial data link and watch/ service routines.

5.1.2 D/A- Converter Board (PAI)

The control voltages for the PZT amplifier are generated by two D/A converters (PAI, Parallel Analog Interface), each equipped 3 DAC AD660 (Analog Devices) with a resolution of 16 bits. Optional the control voltages can be supplied externally by commands. In this case the coordinate transformation is done analog by hardware using operational amplifiers.

Also one A/D converter is used to inspect the system status.

5.1.3 PZT- Power Amplifier

The MPIC controller contains a six-channel power amplifier to drive all PZT actuators in the TM-UNIT. The electronics breaks down into two identical 3-channel modules, one used for driving the mirror platform, the other for driving the momentum compensation mass. A common heat sink and cooling fan is used for the power transistors of all six output stages. Each 3-channel module has its own digital to analog converter and interface board (PAI).

PZT actuators are pure capacitive loads for the amplifiers. In conjunction with the 25m long cable to the operating site, a RC-circuit is formed, causing considerable phase lags between input and output signals at higher frequencies.

To minimize these cable influence, the amplifiers have additional SENSE-inputs and SENSE lines. The operating voltage can be sensed directly at the PZT actuator and can be feed back to the amplifier input. Due to these measures, the phase lag can be reduced to about 7 degrees at 300 Hz even with the 25 m cable connected.

The electrical power required is proportional to the amplitude and the operating frequency. While tilting the platform, at no time all three PZT actuators are dissipating the peak power. The total power of the power supply (around 100 Watts) is shared by all six PZTs at almost equal amounts. The major part of the dissipated heat is released in the power transistors mounted at the heat sink. Only around 5-10 % of the energy is dissipated in the PZT actuators due to dielectric losses.

The current limitation of the power stages is set to about 0.5 A. This defines the slew-rate limitation of the system and the full tilting angle of about +/- 50 arcsec can be achieved within 3 ms minimum.

.1.4 Power Supplies for MPIC Controller

The MPIC controller includes all power supplies needed for operation of the whole system. According to the required power two different linear power supplies are used with appropriate output voltages:

Operating voltages provided by the Power Supply 1:

(used for constant load)

+5.2 V, 3 A	MPIC Controller, digital part
+5.5 V, 1 A	HEXAPOD Controller, digital part
+ 15 V, 0.3 A	Kaman Sensor, A/D - D/A converter
- 15 V, 0.3 A	Kaman Sensor, A/D - D/A converter

Operating voltages provided by the Power Supply 2

(peak load, extended average power)

+15 V, 2.4 A	DC-motors
+15 V, 2.4 A	DC-motors
+120 V, 0.7 A	PZT power supply
-20 V, 0.7 A	PZT power supply

5.2. HEXAPOD Controller

5.2.1 DC-Motor-Controller

One of the major tasks of the HITACHI microprocessor is to transform the motion command input values based on the orthogonal coordinate system into the relative length changes of the six HEXAPOD leg actuators. As the result of these calculations, six target positions with the related velocities are transferred to the two DC-motor controller modules (part of the HEXAPOD controller) to be executed.

The HEXAPOD controller (HEXC) is one functional unit of the complete system and performs the following functions:

1. Reading and transferring the analog position data for both tilting mirror axes within 100 µs intervals.
2. Parsing and execution of HEXC commands by the host interface receiving data via serial data link.
3. Data link layer with communications, traffic control and data verification on Uplink.
4. Coordinate transformation for HEXAPOD translations and rotations.
5. PID-control of all motor axes
6. System state verification within 200 ms cycles

Communication interfaces on the host (RS-232) and for the data link (RS-422) have the same priority and are not alternatively disabled. The RS-232 interface enables the text output mode when receiving the first LineFeed (ENTER, 0Ah). The text output mode is disabled when receiving the QUIT command or after reset.

Otherwise the missing handshake signal and internal buffer overflow stops the command processing. The transmission of the sensor information is not concerned.

For motion control of the six HEXAPOD axes and the two auxiliary motors two fast specialized chipsets (4 axes per chipset) is used with 500 µs servo loop update time. Each axis is interfaced by two quadrature encoder signals, two limit switch signals (right/left) and one reference TTL signal. During command processing the logical (geometrical) axes are assigned to the physical axes.

Logical Axis	Physical Axis	Controller #
1	1	1
2	2	1
3	3	1
4	1	2
5	2	2
6	3	2
7	4	2
8	4	1

The reported values for limit, reference and axis number using the STAT command refer to the physical axes. The output signal is given with a resolution of 12 bits. The limit switches for the two auxiliary axes are defined as low-active.

Limit switch hit events cause immediate stop of the referred axis and then the software moves the motor back by 1000 counts. This procedure may cause errors in the current position counter and therefore new initialization is required if any of the 6 axes hits the limit.

The amplifier for each axis has 3 Watts average output power at 12 Volts. After reaching the target position and if there is no new command to be executed, the motors are shut off (servo loops are suspended) after 10 seconds in order to save power and to avoid heating.

Inherent self blocking of the spindle avoids any undesired position changes. If the position is changed anyway, there may occur abrupt motions after a new move command is issued.

5.2.2 A/D Sensor Interface

The output voltages of the inductive position sensors are amplified with a gain of 8 by two instrumentation amplifiers. After the signals are converted periodically by an ADC (ADS7807, Burr Brown), the digital values are transferred via the internal serial data link to the MPIC. For monitor reasons later design modifications were made in order to transfer the analog sensor values down to the MPIC controller (using two lines in the serial data link cable).

Due to inherent jitter of the converting time of the ADC and software response time of the servo controller, there are minor variations (about 1..2%) of the cycle of data transfer and control response.

5.2.3 RS-422 Data Link

Serial data communication is used for digital data transfer from the sensors as well as for HEXAPOD commands and status information. Data transfer from HEXAPOD controller to the MPIC controller (downlink) occurs periodically each 100 µs with data bursts (2x16 sensor data in 2´s complement and 16 bit status data) and no validity control. A backup copy of sensor and status information is stored in the parallel interface as UOUT, VOUT and AUXOUT.

The status word has the following format:

Bit	Function
0..1	Reserved for Uplink control
2	HEXAPOD initialized and ready
3	HEXC ready for new command
4	HEXC voltage exceeds the 10% tolerance of the 5 Volts
5	Error found in sensor or HEXAPOD cables
6	Limit- or Reference-LED malfunction
7	HEXAPOD moving
8	Axis 7 moving
9	Axis 7 reference signal level
10	Axis 7 has reached PLIMIT (positive limit)
11	Axis 7 has reached NLIMIT (negative limit)
12	Axis 8 moving
13	Axis 8 reference signal level
14	Axis 8 has reached PLIMIT (positive limit)
15	Axis 8 has reached NLIMIT (negative limit)

Bits 10, 11, 14, 15 are reset with a new motion command. Handshake loss or timeouts during the downlink process cause a reset in the concerned module after 10 ms and then the data transfer is started over again. The servo control is suspended during that time and the last state of the PZT controller is maintained.

Command transmission from the HEXC to the MPIC controller (uplink) is handled by a multiple level protocol. Data packages are verified by the CRC16-polynom and are repeated up to 10 times if the transmission fails. In the case the error is still there or if the 500 ms timeout is expired, an error message is issued. Missing handshake during the uplink causes a reset of the module after 5 ms and then data transmission is resumed. During these error handling procedures the downlink transmission is not influenced and stays in operation.

5.3 User Interfaces

5.3.1 MP-UNIT Controller

Parallel Inputs: U-IN, V-IN

If the servo loop is shut off, the digital target positions (TTL level) at the parallel inputs are loaded directly into the D/A Converters (DAC) after the coordinate transformation. Changes of the position values through the parallel interface are not limited by any slew rate.

Sensor position data are processed internally with 0.002 arcsec = LSB resolution and are interpreted as 16 bit values in two´s complement notation. The value is latched at the low-high edge of the strobe signal. The strobe signal lines for U-IN and V-IN can be tied together by the jumper U048.

Connector: DB37, male

Parallel / Analog Input CTRL-INP:

Data at CTRL-INP control states of the system and are equivalent to the commands given from the serial host interface. Following states can be set:

- servo on/off
- piezo on/off
- compensation on/off
- external control on/off

Data latching occurs with the low-high edge of the strobe signal. The strobe input lines for CTRL-INP, U-IN, V-IN can be tied together internally by the jumper U0140. The latched values can be read as echo at CTRL-OUT.

All control bits are low active. With EXT-CTRL=low the PZT amplifiers are fed with the external analog position values AU-IN and AV-IN (-5 .. +5 Volts).

At external control=on two analog inputs from pin 12,13 are fed to an analog coordinate transformation network to drive the PZT power amplifier direct in open loop for minimum phase delay. This mode is not supported by the digital control capabilities!

Connector: DB25, male

Parallel Outputs U-OUT, V-OUT:

Digital position values transferred during the download process are available at the parallel outputs U-OUT and V-OUT with TTL level.

Valid new position data are indicated by the high pulse on the strobe line with a time delay of 15 µs between the U- and the V- position. The values are updated with 100 µs cycle time independent of the state of the system.

Connector: DB37, female

Parallel Outputs AUX-OUT:

The system status of the HEXAPOD controller (excluded the uplink controller) is available at the AUX-OUT line (for more information see RS-422 Data link).

Connector: DB37, female

Parallel / Analog Output CTRL-OUT:

This output is used for output TTL information regarding MPIC system status information. In addition RET-AUTO-MOVE pulse indicates the start point of internal generated tip-tilt waveforms for testing purposes (sine or chop).

The pins AU-OUT and AV-OUT output the amplified analog sensor values in the range of -10 to +10 Volts (+/- 50 arcsec is appr. +/- 6.5 Volts).

Connector: DB25, female

Serial data link (RS-422):

10 MBit/s, asynchronous according Transputer Link

Connector: LEMOSA, 16 Pin female

5.3.3 HEXAPOD Controller

HEXAPOD motor axis (Ch 1...3 and Ch 4 ... 6) outputs:

Connector: DB37, female

Auxiliary Motor (Channel 7 and 8) outputs:

Connector: DB15, female

Sensor interface:

Connector: DB15, female

Serial data link (RS-422):

10 MBit/s, asynchronous according Transputer Link

Connector: LEMOSA, 16 Pin female

Serial Host Interface (RS-232):

Connector: DB9 male, DTE type.

9600 Bd, 8 bit, 1 stopbit, no parity, RTS/CTS handshake with buffered input and output .

6.0 Programming and Software

6.1 Definition of the HEXAPOD coordinate system

Drawing see next page.

Fig. 6.1 HEXAPOD Coordinate System

All moving commands and coordinate transformations are based on the following definition:

- The HEXAPOD is mounted with the base plate at the telescope structure at 6 points B1 to B6. The set of 6 HEXAPOD legs is arranged symmetrically on the base plate on a circle with the radius of RBASE.
- The angle between the three joint pairs is 3 x 120° and the angle deviation from 120° is DELTABASE.
- The opposed three joint-pairs A1 to A6 are connected with the chassis of the TM-UNIT system. They are located on a circle with the radius of RTOP and have an angular deviations from 120 ° named DELTATOP.
- The origin of the fixed coordinate system XYZ is located in the center of the upper six joints A1...A6 and corresponds to the center of the HEXAPOD after initialization.

All translations will be performed relative to this point on an interpolated line.

For rotation it is possible to define a new pivot point with the coordinates (R,S,T) that is not identical with the origin. In this case, rotary axes are related to a new coordinate system (U,V,W) which is parallel shifted from the origin by (R,S,T). The coordinate system UVW will be parallel dragged by translations XYZ , but does not change its orientation while tilting. For this application it makes sense, to place the pivot point into the vertex of the secondary mirror. Default values therefore are defined as R=S=0, T= 55.85 mm. If R=S=T=0 the UVW coordinate system is identical to XYZ.

6.2 Command Syntax

All commands are sent as ASCII characters with line feed (LF, 0x0a) as terminator. Upper- and lower case characters are allowed. Correction of sent characters is not possible and all edit functions have to be performed by the terminal program.

Command name and parameters as well as parameters themselves are separated by spaces. All parameters are optional and are indicated by a leading parameter label. In between that and the parameter itself only an optional sign is allowed.

The HELP command gives you a list of all available commands and optional parameters.

After receiving the terminator character, the command line is parsed regarding

- Length of the line
- Implementation of the command
- Validity of the parameter(s)
- Format of the parameter(s)

The maximal length of the command line is 80 characters.

Errors within the command line are marked and the complete line is disregarded.

6.3 Command Set

Command Set of MPIC Controller

The *-marked commands contain MPIC controller specific information

Tilting Mirror Commands:

MROT {UV}	Rotate TM-UNIT platform absolute around U,V- axis [arcsec]
MPOS	Report TM-UNIT angular position [arcsec]
MSSR {S}	Set or report slew rate for TM-UNIT tip/tilt movement [arcsec/s]
MPID {PIDGFRLA}	Set or report TM-UNIT PID- ,notch filter and lead compensator parameter
MCMP {UV}	Set momentum compensation gain factors
MCHP {ABCDT}	Set or report chopping angle: Umin,Umax,Vmin,Vmax [arcsec], delay T [ms]
MSIN {UVF}	Set or report sin-wave amplitude U,V [arcsec], frequency F [Hz]
MCMP {UV}	Set momentum compensation gain factors

HEXAPOD Commands:

HMOV {XYZRSTUVW}	Move HEXAPOD absolute in X,Y,Z- axis, define the center of rotation at point R,S,T, rotate around U,V,W- axis [mm,arcsec]
HPOS*	Report HEXAPOD position [mm,arcsec]

HVEL {V}	Set or report HEXAPOD velocity parameter [mm/s]
HREF*	Initialize HEXAPOD position at reference position

Auxiliary Motor Commands:

XMOV {nP}*	Move auxiliary motor to position P [counts], axis #n
XPOS	Report auxiliary motor position
XPAR {nVA}	Set auxiliary motor motion parameter, axis #n, velocity [counts/T], acceleration [counts/T/T]
XPID {nPIDL}	Set auxiliary motor control parameter for axis #n, PID-parameters, integration limit L

System Commands:

SETF {PSCAX}	Sets or reports TM-UNIT system control flags for: piezo actuators, servo loop, momentum compensation, auto-move mode (sin, square or chopping), external analog input
STAT *	Report system status
HELP *	Reports list of available commands

Command Set for HEXAPOD Controller

The *-marked commands contain HEXAPOD- controller specific informations

Tilting Mirror Commands:

None

Hexapod Commands:

HMOV{XYZRSTUVW}	Move HEXAPOD absolute in X,Y,Z- axis, define center of rotation at point R,S,T, rotate around U,V,W- axis, [mm,arcsec]
HPOS*	Report HEXAPOD position [mm,arcsec]
HVEL {V}	Set or report HEXAPOD velocity parameter [mm/s]
HREF {M}*	Initialize HEXAPOD position at reference position according modus M

Auxiliary Motor Commands:

XMOV {n}	Move auxiliary motor to position P [counts], axis #n
XPAR {nVA}	Set auxiliary motor motion parameter, axis #n, velocity [counts/T], acceleration [counts/T/T]
XPID {nPIDL}	Set auxiliary motor control parameter, axis #n, PID-parameter, integration limit

System Commands:

STAT*	Report system status
HELP*	Reports list of available commands

6.4 Command Reference

MROT {param}[value] Rotate Mirror Absolute

This command tilts the *mirror mounting platform* of the TM-UNIT to an absolute position around the axes U,V with a resolution of 0.02 arcsec. Internal used angular increments are 0.002 arcsec (10 nrad).

Parameter:	U,V
Format:	Float
Value:	-50.0 ... +50.0 (arcsec)
Example:	**MROT U10 V-5.3**
Function:	*Rotates the TM-UNIT platform 10.0 arcsec in U and -5.3 arcsec in V direction*

MPOS Report Mirror Position

This command causes the MPIC controller to report the current Tip/Tilt position of the TM-UNIT , detected by the KAMAN sensors. Reported values are read in „arcsec“ for the tilting axes U and V.

Format:	Float
Result:	-50.0 ... +50.0 (arcsec)

MSSR {param}[value] Set or Report Slew Rate

This command defines the slew rate limit for the TM-UNIT. The maximum allowed value for the parameter S is 20000 arcsec/s because of the current limitation of the PZT power amplifiers. If no parameter S is specified, this command reports the actual slew rate setting.

Parameter:	S
Format:	Float
Value:	1.0 ... 20000.0 (arcsec/s)

MPID {param}[value] Set or Report Mirror PID- Filter Parameters

This command defines the PID filter parameter used for the TM-UNIT. Furthermore a parameter G is available, limiting the D-term at high frequencies. In order to attenuate the first mechanical resonance frequency an additional Notch filter algorithm is implemented, which realizes a rejection of R at the frequency of F. If no parameters are specified, this command reports the actual PID- filter settings.

Parameters: **P, I, D, G, F, R, L, A**

Format: Float
Value: Default values:
P= 0.012
I= 0.000016
D= 0.000002
G= 0.00002
F= 520
R= 0.59
L= 300
A= 2.0

MCHP {param}[value] Set or Report Chopping Parameter

This command defines the parameters for the Chopping mode. The parameters A and B define the Max. and Min. limits of the tilting angle in U direction, parameters C and D in V direction.

The angular units for the parameters are in arcsec.

The delay time before switching to the opposite angle position is T in ms including the settling time. Parameters become active when the command SETF A1 is issued. If no parameters are specified, this command reports the actual chopping parameter settings.

Parameter: A,B,C,D,T

Format: Float

Value: A=B=C=D -50.0 ...+50.0 (arcsec)
T (ms)

Example: **MCHP A-7.07 B7.07 C7.07 D17.07 T50**

This example defines a square wave function with a frequency of 10 Hz, an amplitude of 10.0 arcsec and an offset of 10.0 arcsec in the V-axis. The resulting tilting axis is the diagonal line in the UV plane.

MSIN {param}[value] Set or Report Sine- Wave Parameter

This command sets the sin-wave parameter amplitude U,V in arcsec, frequency F in Hz for an internal generated test signal. If no parameters are specified, this command reports the actual sine- wave parameter settings.

Parameters: U,V,F

Format: Integer

Value: U=V - 50.0 ... + 50 (arcsec)
F 1.0 ... 2500.0 (Hz)

Example: **MSIN V20.5 F25**

defines a sine wave tilt movement around the V- axis with an amplitude of 20.5 arcsec and 25 Hz.

MCMP {param}[value] Set or Read Momentum Compensation Gain

This command can be used to fine tune the momentum compensation. In case of gain=1, the momentum compensation piezos are driven with identical amplitudes as the mirror actuators. To optimize the performance with the final mirror or to compensate tolerances of piezo expansion a value different from 1 may be required for each individual axis U or V. If no parameters are specified, this command reports the actual compensation gain factor settings.

Parameter: U,V

Format: Float

Value: 0.8 ... 1.2 default = 1

HMOV {param}[value] Move HEXAPOD Absolute

This command is used to move the HEXAPOD system in six axes at the same time. Translation axes are X, Y, Z with a resolution of 1 µm. Tilting axes are U, V, W with 1 arcsec resolution. The pivot point for the tilting axes can be defined as any point (coordinates R,S,T) within the X,Y,Z coordinate system. As default the vertex represents the pivot point for angular movements.

The velocities of the linear actuators are calculated and matched for linear path trajectories while moving from position A to position B. All movements are related to the center position defined by the **HREF** command.

Parameters: X,Y,Z,R,S,T,U,V,W

Format: Float

Value:

	X,Y	= -5.0 ... +5.0 (mm)	
	Z	= -12.0 ... +12.0	(mm)
	U,V,W	= -10800.0 ... +10800.0 (arcsec), {3 deg}	
	default: Vertex position		
	R,S	= 0	(mm)
	T	= 55.85	(mm)

Example: **HMOV X1.0 Y-.5 Z10.0 U-3600**

This Example moves the HEXAPOD platform 1 mm in X,- 0.5 mm in Y and 10 mm in Z. Also a tilting of -1° around the U-axis and the vertex is carried out

.

HPOS * Report HEXAPOD Position

This command generates a report with the current position of the HEXAPOD in the Cartesian coordinate system. The reported positions represent only the positions defined by the last **HMOV** command. The back-transformation of the length changes of the single axes in Cartesian coordinates requires a lot of calculating power and can't be accomplished by the available hardware within a reasonable amount of time.

Please note! The **HPOS** command gives only correct positions if executed from the same controller as the last **HMOV** command was executed. There is no data transfer of the last **HMOV** positions to the internal data link.

This command can also be used for reporting the coordinates of the pivot point (R,S,T) for the tilting movement.

Parameter:	X,Y,Z,R,S,T,U,V,W
Format:	Float
Result:	X,Y,Z,R,S,T (mm)
	U,V,W (arcsec)

HVEL {param}[value] Set or Report HEXAPOD Velocity

This command defines the path velocity for the HEXAPOD system. The velocity of a single axis depends on direction of motion and is evaluated from the coordinate transformation. The upper speed limit of about 1 mm/s is determined by the maximum speed of the DC-motors and the gear heads. For the rotation the velocity is determined by the angles U,V,W and the radius RTOP. If no parameter is defined the command reports the actual velocity parameter.

Parameter:	V
Format:	Float
Value:	0.001 ... 1.0 , default = 0.2 (mm/sec)
Example:	**HVEL V0.5**
	defines the path velocity of the HEXAPOD system to 0.5 mm/sec

HREF {M}[value] Initialize HEXAPOD to Reference Position

This command with no parameter or <u>M=0</u> is used to move all six HEXAPOD actuators at the same time to its absolute center position. The incremental encoder counters for the DC-motors are reset in the center reference position. All axes move with the same velocity towards the center and are shut off individually when the corresponding reference switch is encountered.

Starting far off the center position, the translation of one axis can cause small position changes of a neighbor actuators because of the coupled degree of freedom for rotation around the spindle axis. To reduce this effect and to compensate the hysteresis of the reference switches, an additional fine-positioning procedure should carried out: Again all axes are moved, but now they all move at low speed from one direction toward the reference switch and are stopped at the edge with high precision. The accuracy of the latched center position also depends on the used HEXAPOD velocity. The typical accuracy is about 1 µm at 0.1 mm/s and can reach up to 10 µm at 1mm/s.

The M=1 option is identical to the first option except the HEXAPOD returns to the last position. This is a helpful option to reference the system to its absolute center position and bring it back close to the last power off position during power on procedure. This mode is only available at **HEXC** !

NOTE:

Small movements of a few counts during power on or off procedure can not be totally avoided. This may results in small position errors for the HEXAPOD using this option. The more accurate way is to store the last power off position inside the external computer and execute it after performing the option M=1.

IMPORTANT HINT:

The **HREF** command must be executed if the system is powered up to ensure safe HEXAPOD operation. No other HEXAPOD motion commands will be accepted until **HREF** has been executed!

Parameter:	M	
Format:	Integer	
Values:	0 or none:	Go to reference center position
	1:	Find reference center position and return to last position

XMOV * {param}[value] Set Auxiliary Motor Position

This command is used to control additional DC-motors. Incremental encoder quadrature signals are required for position control.

n represents the motor axis number and P contains the target position in counts.

Parameters:	n, P
Format:	Integer
Values:	n = 7,8

P= -2^31 ... +2^31 (counts)

The **XMOV** command can be executed either from the main- or the HEXAPOD controller.

NOTE:

For some service purposes it might be useful to execute movements for each HEXAPOD actuator individually without the coordinate transformation. This results in all six degree of freedom movements. Only at the HEXAPOD controller the following command extensions are possible:

Parameter: n, P

Format: Integer

Value: n = 1 ... 6

P=-64800...+64800 (counts), (13.5 x 4800 counts/ mm)

These options should only be used from experienced engineers while observing the mechanics. It is not completely tested that there is no mechanical crash at all possible combination of parameters!

XPOS * {param}[value] Report Auxiliary Motor Positions

This command reports the current positions of the extra two DC-motors connected to the HEXAPOD controller. The reported positions represent only the positions defined by the last **XMOV** command. The axes numbers is N. See also command **XMOV**.

Parameter: N

Format: Integer

Value: * N = 7,8 for the MPIC controller

* N = 1 ... 8 for the HEXAPOD controller

XPAR {param}[value] Set Auxiliary Motor Motion Parameters

This command defines velocity and acceleration for the extra DC-motors with the axis numbers N. These settings are reported with **STAT** command at the HEXAPOD controller only!

Parameter: N,V,A

Format: Float

Value: N= 7,8

V= (counts/T)

A= (counts/T/T)

XPID {param}[value] Set Auxiliary Motor Control Parameters

This command defines the PID filter parameters and the integration limits for the extra DC-motors with axis N. These values are not reported.

Parameter:	N,P,I,D,L
Format:	Integer
Values:	N= 7, 8
	P= 1000
	I= 400
	D= 300
	L= 32767

These default settings are identical with the HEXAPOD DC-motor settings.

SETF {param}[value] Set or Report Tilting Mirror Control Flags

This command defines the control flags of the TM-UNIT system. If no parameters are defined, the command reports the actual mirror control flags. The following parameters are used:

P (Piezo)	P1 or P0 sets all PZTs ON or OFF = Freeze last PZT- Voltage
S (Servo)**	S1 = PID closed loop on, S2 = PID closed loop and lead compensator on, S0 = open loop
C (Comp)	Enable/Disable momentum compensation. This defines whether the backwards directed PZTs will be activated or not.
A (Auto)	Enable/Disable self-executing motion commands sine- wave signal or chopping. See also commands **MSIN** and **MCHP**
X (Extern)	Enable/Disable external analog inputs to PZT amplifiers

Parameters:	P,S,C,A,X
Format:	Integer
Values:	P,C,A,X: 0=off, 1=on
	S :0 = PID off, 1= PID on, 2 = PID + Lead = on

Example: SETF S1 C1 A1

Enables the closed loop position PID- control and the momentum compensation. Also the chopping or sine- wave mode is enabled with the parameters defined with the MSIN or MCHP command.

STAT * Report System Status

This command reports the current system status. There is different information available for the MPIC controller and the Hexapod controller because not all values are transferred via the internal serial link.

HELP * HELP

This command generates a list of available commands. Only the controller specific commands are displayed.

6.5 Servo Routines

6.5.1 PID Loop

The implemented control algorithm is a standard PID filter. For compensating mechanical system resonances, a notch filter algorithm is added in series to the PID. Because the settings of the PID parameters are very critical, wrong modification of the filter parameters may cause instabilities. Be very careful when using the **MPID**-command.

6.5.2 Optional Lead-Compensator

The lead-compensator works as an high pass filter in the command line of the control loop. It does not affect the stability of the system and can be used to reduce the phaseshift in closed loop operation. With the command **SETF S2** it can be switched on. The frequency response of only the lead-compensator is shown in the following diagrams.

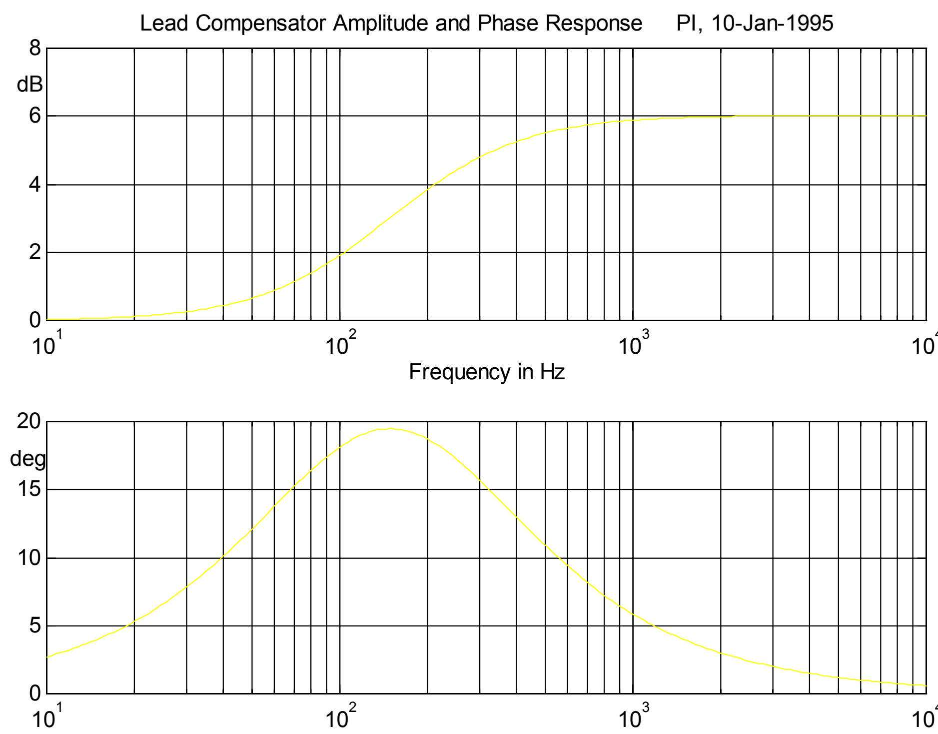

Fig 6.2: Lead compensation amplitude response

Fig. 6.3 Lead compensation phase response

Two parameters can be set with the filter:

- Frequency of maximal phase shift
- Amplification factor.

In the shown diagrams the frequency is 200 Hz and the amplification is 2 (+6 dB). These parameters can be changed by these commands :

- **MPID L** (**L**ead Frequency)
- **MPID A** (Lead **A**mplification)

The actual parameters depend on the application. There are no range checking routines for these parameters. Every correction of the mirror's frequency response does also influence the time response. Decreasing phase shift increases overshoot for step response.

Increasing the slew rate causes longer settling time.

6.6 Terminal Emulator

For sending commands and for receiving reports and error messages a serial RS-232 data terminal is required at the host interface of the MPIC and optional also at the HEXC controller.

Data are transmitted as ASCII characters. No special codes are used for protocolling the terminal. The default communication parameters are:

9600 Baud, 1 Stopbit, no parity, hardware handshake using RTS/CTS.

On the support diskette there are program examples for terminal emulation in Borland C and Pascal.

7. Calibration and Testing

7.1 HEXAPOD Static Tests

The following results from static tests were conducted with a setup according to Fig. 7.1 a,b. A laser- interferometer was used to measure the linear movements of the HEXAPOD. For testing the angular movement of the HEXAPOD and the Tip/Tilt platform an electronic autocollimator according to Fig.7.2a,b with a resolution of .1 arcsec was used. This resolution is sufficient to calibrate and test the HEXAPOD but it is not good enough to determine angular resolution of the Tip/Tilt platform. Therefore this setup was only used to calibrate the maximum tip/tilt angles to 50 arcsec and get some results about linearity.

All tests were performed by a computer test program running the unit in one full cycle with sufficient small step sizes starting from center position to minimum, then to maximum and back to center position. The measured position is first plotted versus the commanded position and in a second plot only the position error is displayed.

Figures on the following pages:

Fig. 7.1 Measurement setup, HEXAPOD XYZ check

Fig. 7.2 Measurement setup, HEXAPOD tilt, Mirror tip-tilt checks

HEXAPOD Static Tests, Results : part 1

Fig. 7.3 to 7.8 include all test results measured at linear movement in the x/y plane at nominal stroke of +/- 2 mm, in a possible extended range of +/- 5 mm and a +/- 100 µm small range with high resolution. The typical bi-directional repeatability is 1...2 µm and the absolute position accuracy is 6 µm for +/- 2 mm.

Figures on the following pages:

HEXAPOD Static Tests, Results : part 2

Fig. 7.9 to 7.12 include all test results measured at linear movement in the z- axis at nominal stroke of +/- 12 mm, +/- 4 mm, at higher resolution +/- 100 µm and +/- 10 µm. The typical bi-directional repeatability is less than 1 µm and the absolute position accuracy is -2.5 to +1 µm for +/- 12 mm. Especially in the high resolution test according Fig. 7.11 and 7.12 the typical bi-directional repeatability is typically 0.4 ... 0.6 µm and corresponds to about 2...3 counts of the used encoder.

Figures on the following pages:

HEXAPOD Static Tests, Results : part 3

The following test results were measured with the test setup according Fig. 7.2a. The used Electronic Autocollimator has a measuring range of only +/- 1500 arcsec so the measurement of the required full angular movement of +/- 1800 arcsec (+/- 0.5 degree) could not be done. It is assumed that the results are very similar even in the extended +/- 3 degree range. The typical bi-directional repeatability is less than 1 arcsec and the absolute position accuracy is in the range of 6 to 9 arcsec.

Figures on the following pages:

HEXAPOD Static Tests, Results : part 4

The following results from the wobble test were taken with the test setup according Fig 7.2a while moving the HEXAPOD linear. Linear movement in the x/y plane cause maximum tilting errors in the range of about 5...9 arcsec (Fig.7.15 to 7.16). This is like a nonlinearity and can be reduced by correcting a gain factor.

More complex test results were taken during piston movements (Fig.7.17 to 7.18). The measured wobble is in the range of about +/- 2 arcsec and has a periodicity corresponding to one revolution of the spindle/axial bearing assembly. This is caused by residual mechanical tolerances of the components used and can not be completely avoided.

For operation together with the Tip/Tilt Mirror platform and the image stabilization system these residual errors will be compensated. In other applications where these residual errors have to be reduced, a software solution using error correction tables seems to be practicable. Please note: This need to be checked more in detail because the results depend from initial x/y/u/v/w position of the HEXAPOD.

Figures on the following pages:

7.2 Tip/Tilt Mirror Static Tests

All static Tip/Tilt Mirror tests were taken with the test setup according to Fig. 7.2a. The results shown in Fig. 7.19 and 7.20 represent the calibration of Tip/Tilt Mirror within the maximum tip-tilt angle of +/- 50 arcsec. The plotted position errors of a few tenths of an arcsec are identical to the noise level of the autocollimator and the „seeing“ in the lab and is not identical with the resolution of the unit !

Fig. 7.21 and 7.22 are identical to Fig. 7.19 and 7.20 except the tilting angles were measured at the KAMAN sensor analog outputs with a KEITHLEY 197 multimeter. The full DC-resolution of the internal KAMAN sensors analog outputs can be checked with Fig. 7.23 to 7.24. The full movement is +/- 0.1 arcsec and the position error is typically 0.002 arcsec.

Figures on the following pages:

7.3 Tip/Tilt Mirror Dynamic Tests

The following dynamic TIP/TILT Mirror tests were measured with a setup according Fig. 7.2b. All tilting angles were measured at the KAMAN sensor analog outputs with a digital storage oscilloscope and the implemented sine-and square-wave generator commands (see **MSIN, MCHP**). The resolution is therefore limited at higher frequencies. For noise measurements an HP- Spectrum Analyzer was used.

7.3.1 Frequency Response

Fig. 7.25 and 7.26 show the open loop amplitude and phase response if momentum compensation is switched on or off. The first mechanical resonance is close to 500 Hz with an overshoot of about 20 dB. The phase shift at 300 Hz is about 40 degree. If the momentum compensation is switched off, a lower resonance at 300 Hz from the test setup is exitated.

Fig. 7.27 and 7.28 show the influence of the two different servo routines (default settings). While the standard PID-servo1 realizes a response flat out to 160 Hz (-3dB) and a phase shift of 80 degree at 100 Hz, is the response completely different if the lead compensator servo2 is used. The amplitude response is inside a +/- 3 dB band up to 320 Hz while the phase shift at 100 Hz is reduced to 40 degree.

Figures on the following pages:

7.3.2 Step Response

Fig. 7.29 and 7.30 show the step response of the system at full scale driving of +/- 50 arcsec and compensation on / off. The response time of about 5 ms is software limited to match the slew rate limitation of the PZT- Power Amplifier. At driving from the external analog inputs only slightly faster response can be expected. While with compensation only the 500 Hz system resonance is exitated, without compensation many different modes are exitated at the same time.

Fig. 7.31 and 7.32 show the same results as Fig. 7.29 and 7.30 at smaller signals (+/- 5 arcsec) without any software slew rate limitation.

Fig. 7.33 to 7.36 show the same results as Fig. 7.29 to 7.32 in closed loop condition. The system resonance is well damped but the response time is increased. The lead compensator reduces the response time but the overshoot and ringing is increased.

Fig. 7.37 shows the small signal step response at higher frequency with different time scale.

All servo control parameters have to be optimized with the real mirror installed! The default settings are a good starting point for testing in conjunction with the attached mirror dummy.

Figures on the following pages:

Fig. 7.29 Tilt u-axis +/- 50 arcsec, open loop, 10 Hz, comp. on/off

Fig. 7.30 Tilt v-axis +/- 50 arcsec, open loop, 10 Hz, comp. on/off

Fig. 7.31 Tilt u-axis +/- 5 arcsec, open loop, 10 Hz, comp. on/off

Fig. 7.32 Tilt v-axis +/- 5 arcsec, open loop, 10 Hz, comp. on/off

Fig. 7.33 Tilt u-axis +/- 50 arcsec, closed loop (servo1/servo2), 10 Hz

Fig. 7.34 Tilt v-axis +/- 50 arcsec, closed loop (servo1/servo2), 10 Hz

Fig. 7.35 Tilt u-axis +/- 5 arcsec, closed loop (servo1/servo2), 10 Hz

Fig. 7.36 Tilt v-axis +/- 5 arcsec, closed loop (servo1/servo2), 10 Hz

Fig. 7.37 Tilt u/v-axis +/- 5 arcsec, closed loop (servo1), 30 Hz

7.3.3 Resolution and Noise

To find some precise values for angular resolution of the Tip/Tilt platform is difficult. Fig. 7.38 was measured at the same test conditions as measured the step response except the step size was reduced down to the order of noise floor. The test shows a square wave signal of 10 Hz with an amplitude of 0.01 arcsec. At this amplitude the peak to peak noise is in the same order as the signal.

Fig. 7.39 shows the test results of a FFT- analysis taken from a 1 arcsec sine-wave signal, 30 Hz. The response was stored in a storage scope and later on processed on a PC. The signal to noise ratio is about -40 dB or 0.01 arcsec which is identical to the test above.

Fig. 7.40 shows quite similar results measured with a HP- Spectrum Analyzer. The peak at 30 Hz is not as sharp because of the 3 Hz measuring bandwidth at this low frequencies.

Figures on the following pages:

Fig. 7.38 Tilt u/v-axis +/- 0.01 arcsec, closed loop (servo1), 10 Hz

Fig. 7.39 FFT analysis u/v-axis, 1 arcsec, servo1, 30 Hz

Fig. 7.40 Spectrum analysis u/v-axis, 1 arcsec, servo1, 30 Hz

7.3.4 Momentum Compensation

To measure a precise amount of momentum compensation is extremely difficult because it depends from too many parameters (mounting conditions of base plate to test bench, HEXAPOD position, final mirror moment of inertia, compensation gain factor settings, frequency, ...). We could find special frequencies with more than -40 dB damping and also some with +3 dB amplification ! Therefor the following test should only demonstrate the relative effect of compensation - an optimization is only possible on the final place with reduced sets of parameter if mounted to the telescope structure.

The momentum compensation test was measured with a setup according Fig. 7.2(b). The mirror was arranged on an piece of elastic foam to allow small movements of the base plate. On the maximum outside diameter of the base plate (opposite of cable exit) an acceleration sensor was mounted to measure residual accelerations in z-direction. Then the Tip/Tilt Mirror was exitated from the internal square-wave signal 5 arcsec, 25 Hz in v-axis.

Fig. 7.41(a) and (b) show the spectrum of the square-wave signal in open loop, comp= off (a) and open loop, comp= on (b). Some of the lower frequencies are damped but there is a lot of higher harmonics.

Fig. 7.41(c) and (d) are identical to (a) and (b) but in closed loop operation (servo1). It is obvious that the servo damps higher harmonics drastically and if comp= on (c), some frequencies are significantly reduced.

Figure on the following page:

Fig. 7.41 FFT of acceleration, 5 arcsec,square-wave, 25 Hz, v-axis

8. Troubleshooting and Error Messages

All error messages are self explaining without error code and may occur asynchronously.

Operating the MPIC requires an data terminal for receiving characters. Otherwise internal buffer overflow may block command processing. Message output of the HEXC is disabled after power-on and can be enabled by sending a line feed character.

Before disconnecting the data terminal from the HEXC, the data output has to be disabled with the QUIT command. Otherwise the command processing may be blocked. This has no influence on the transmission of the sensor data to the PZT controller.

An active data link between MPIC and HEXC (cable installed) is required for PZT control and command processing. Missing cable link disables PZT control also in open loop.

Supply voltages for the HEXAPOD motors (+15V, -15 V) are also required when the HEXAPOD is inactive. Otherwise the motors may move uncontrollable in any axis.

In case of driving the TM-Unit at high frequency and large amplitudes the power needed may exceed the limit of the power supply. To ensure safe operation an error message : ***Power dissipation exceeds limit, piezo control disabled*** will be displayed and the piezos will be disabled after a few seconds. If this happens, please remove the error condition by reducing the frequency or/and amplitude and enable piezo operation again with the **SETF P1** command. The actual RMS current from the piezo power supply is available with the **STAT** command and should not exceed 0.5 A.

Appendix A : System Specifications

HEXAPOD Specifications:

Range of Travel (independent):	X/Y Motion	+/- 2 mm
	Z Motion	+/- 12 mm
	Angular Motion	+/- 0.5 deg
Range of Travel (dependent):	X/Y Motion	+/- 5 mm
	Z Motion	+- 12 mm
	Angular Motion	+/- 3 deg
Resolution:	X/Y Motion	0.7 µm
	Z Motion	0.3 µm
	Angular Motion	0.4 arcsec
Bidirectional Repeatability:	X/Y Motion	2 µm
	Z Motion	0.7 µm
	Angular Motion	1 arcsec

Wobble during Piston Movement: +/- 12 mm range +/- 2 arcsec

Maximum Speeds: linear 1 mm/s

angular 1 mm/s (depends on the center of rotation, linear speed refers to outer diameter of the mirror)

Stiffness:	X/Y Plane	appr. 5 N/µm
	Z Axis	appr. 150 N/µm

Weight including Tip/Tilt Mirror Unit appr. 15 kg

Tip/Tilt Mirror Specifications:

(measured with dummy mirror)

Maximum Tilting Range:		+/- 50 arcsec
Resolution:		0.01 arcsec
Residual Jitter:		0.01 arcsec
Open loop Frequency Response:	Amplitude	300 Hz (+3 dB)
	Phase	40 deg (300 Hz)
Closed loop Frequency Response:	Amplitude	330 Hz (+/- 3 dB)
	Phase	140 deg (300 Hz)
Frequency Limit by Power Supply:	U+V	35 Hz (+/- 50 arcsec)
	U or V	50 Hz (+/- 50 arcsec)
	U+V	300 Hz (+/- 5 arcsec)

MPIC Controller Specifications:

Dimensions:	19“ Rack Mount Case
Power Consumption:	110/220 VAC, 50/60 Hz max. 150 W
Weight:	appr. 12 kg
Interfaces:	RS-232, RS-422 internal, special custom specified parallel,

HEXC Controller Specifications:

Dimensions:	330 x 170 x 65 mm
Power Consumption:	< 5 W in standby mode, 20 W during HEXAPOD operation at speeds of 0.2 mm/s, < 3 W for auxiliary motors
Weight:	3 kg
Interfaces:	RS-232, RS-422 (internal) and Sensor analog,

KAMAN Sensors Specifications:

See Manufacturer Specifications

Appendix B : Pin Assignment

MPIC Controller Connectors:

Parallel Inputs U-IN,V-IN:

DB37 Pin		Signal
	1	GND
20		D0=2^0 (LSB)
	2	GND
21		D1
	3	GND
22		D2
	4	GND
23		D3
	5	GND
24		D4
	6	GND
25		D5
	7	GND
26		D6
	8	GND
27		D7
	9	GND
28		D8
	10	GND
29		D9
	11	GND
30		D10
	12	GND
31		D11
	13	GND
32		D12
	14	GND
33		D13
	15	GND
34		D14
	16	GND
35		D15=2^15 (MSB)
	17	GND
36		STROBE L
	18	GND
37		GND
	19	GND

Parallel Input AUX-IN, (not used)

Connector: DB37

Pin		Signal
	1	GND
20		D0
	2	GND
21		D1
	3	GND
22		D2
	4	GND
23		D3
	5	GND
24		D4

	6	GND
25		D5
	7	GND
26		D6
	8	GND
27		D7
	9	GND
28		D8
	10	GND
29		D9
	11	GND
30		D10
	12	GND
31		D11
	13	GND
32		D12
	14	GND
33		D13
	15	GND
34		D14
	16	GND
35		D15
	17	GND
36		STROBE L
	18	GND
37		GND
	19	GND

Parallel / Analog Input CTRL-INP

Connector: DB25

PIN		Signal / Function
	1	GND
14		SERVO ENABLE, High sets open loop.
	2	GND
15		PIEZO ENABLE, High sets PZT amplifier to 0 V
	3	GND
16		COMP ENABLE, High sets momentum compensation off
	4	GND
17		EXT CTRL, High sets internal control on
	5	GND
18		reserved
	6	GND
19		reserved
	7	GND
20		reserved
	8	GND
21		reserved
	9	GND
22		STROBE L
	10	GND
23		GND
	11	GND
24		GND
	12	AV-IN, analog input :V axis
25		AGND, analog Ground
	13	AU-IN, analog input: U axis

Parallel Outputs

U-OUT, V-OUT

Connector: DB37 Pin

PIN		Signal / Function
1		GND
	20	D0=2^0 (LSB)
2		GND
	21	D1
3		GND
	22	D2
4		GND
	23	D3
5		GND
	24	D4
6		GND
	25	D5
7		GND
	26	D6
8		GND
	27	D7
9		GND
	28	D8
10		GND
	29	D9
11		GND
	30	D10
12		GND
	31	D11
13		GND
	32	D12
14		GND
	33	D13
15		GND
	34	D14
16		GND
	35	D15=2^15 (MSB)
17		GND
	36	STROBE
18		GND
	37	GND
19		GND

Parallel Output AUX-OUT:

Connector: DB37

PIN		Signal / Function
1		GND
	20	D0, const. low
2		GND
	21	D1, const. low
3		GND
	22	D2
4		GND
	23	D3
5		GND
	24	D4
6		GND
	25	D5
7		GND
	26	D6
8		GND
	27	D7
9		GND

28	D8
10	GND
29	D9
11	GND
30	D10
12	GND
31	D11
13	GND
32	D12
14	GND
33	D13
15	GND
34	D14
16	GND
35	D15
17	GND
36	STROBE
18	GND
37	GND
19	GND

Parallel Output CTRL-OUT:

Connector: DB25

Pin		Signal / Function
1		GND
	14	REPORT: SERVO ENABLE
2		GND
	15	REPORT: PIEZO ENABLE
3		GND
	16	REPORT: COMP ENABLE
4		GND
	17	REPORT: EXT CTRL
5		GND
	18	REPORT: AUTO MOVE / Reference trigger pulse
6		GND
	19	reserved
7		GND
	20	reserved
8		GND
	21	reserved
9		GND
	22	STROBE
10		GND
	23	GND
11		GND
	24	GND
12		A V-OUT, analog sensor output: V axis
	25	AGND, analog Ground
13		A U-OUT, analog sensor output: U axis

Serial Host Interface (RS-232):

Connector DB9

PIN		Signal / Function
1		DCD, not used
	6	DSR, wired with DTR
2		RXD
	7	RTS
3		TXD
	8	CTS
4		DTR, wired with DSR
	9	RI, not used
5		GND

Serial Data Link (RS-422):

LEMOSA-Connector

PIN	Signal
1	reserved
2	AGND
3	U-OUT
4	AGND
5	-V-OUT
7	LINKIN B
8	LINKIN A
9	LINKOUT Z
10	LINKOUT Y

Connectors on HEXAPOD Controller

HEXAPOD Actuator

(Ch 1...3 and Ch 4... 6)

Pin		Signal / Function	
1		GND	Motor 1 or 4
	20	LR, Limit right (max length)	
2		LC, Reference	
	21	LL, Limit left (min. length)	
3		LED-Sense	LED check
	22	+5V	
4		M-, Motor minus side	
	23	GND, Logic ground	
5		ENC B, Encoder Ch A	
	24	ENC A, Encoder Ch B	
6		+5V	
	25	M+, Motor plus	
7		GND, Motor 2 or 5	
	26	LR	
8		LC	
	27	LL	
9		LED-SENSE	
	28	+5V	
10		M-, Motor minus	

	29	GND
11		ENC B
	30	ENC A
12		+5V
	31	M+, Motor plus
13		GND, Motor 3 or 6
	32	LR
14		LC
	33	LL
15		LED-SENSE
	34	+5V
16		M-, Motor minus
	35	GND
17		ENC B
	36	ENC A
18		+5V
	37	M+, Motor plus
19		Cable check

Auxiliary DC-Motor (Ch 7, Ch 8)

Connector: DB15, female

Pin		**Signal**
1		
	9	MOT+
2		MOT-
	10	
3		
	11	
4		+5 V
	12	LS RIGHT
5		LS LEFT
	13	REFS
6		LGND
	14	ENCA
7		
	15	ENCB
8		

Sensor Interface:

Connector: DB15

PIN		Function	KAMAN	
1		+15 V supply		1
	9	V out		6
2		- 15 V supply	2	
	10	V return	7	
3		ADCGND		
	11	n.c.		8
4		U out		4
	12	n.c.		9
5		U return	5	
	13	n.c.		
6		GND		
14		CHECKOUT, cable		
7		CHECKIN, cable		
15		VCC		
8		GND		

Serial Data Link (RS-422):

LEMOSA-Connector,

PIN	Signal / Function
2	LINKIN A
3	LINKIN B
4	LINKOUT Y
5	LINKOUT Z
7	V-OUT
8	AGND
9	U-OUT
10	AGND

Serial Host Interface (RS-232):

Connector: DB9

PIN		Signal / Function
	1	DCD, not used
6		DSR, wired with DTR
	2	RXD
7		RTS
	3	TXD
8		CTS
	4	DTR, wired with DSR
9		RI, not used
	5	GND

Appendix C: Document Reference Package

Includes schematics for MPIC and HEXC controllers

End of document MS43E.