Primary Mirror Actuator Test Stand Upgrade
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Introduction

The MMT primary mirror actuator test stand is an electro-mechanical test fixture for calibration and repair of mirror support actuators. A set of six arms with load cells are used to measure the 6-DOF (degrees of freedom) forces output from the actuator unit bolted to the test stand. The analog force commands and output force monitor signals to/from the actuator are wired to an on-board test computer, a VME-chassis system that likewise monitors the 6-DOF force arms to provide an independent test of the actuator's output force and stray moments generated by mechanical errors in the actuator. This system was poorly constructed and has several issues that motivate upgrading it:

A. Lack of documentation on hardware and software used in the test system.
B. Poor wiring practice throughout, particularly in the load-cell amplifier outputs.
C. Bad wiring and signal integrity in the connections to the VME chassis.
D. The power supplies are improperly mounted and have exposed AC wiring on the connections.
E. The VME computer is extremely outdated and has (nearly) irreplaceable hardware. The CPU board for just one example uses an end-of-life Motorola 68000 series processor and cannot be replaced, other than with on-hand spares (that were bought from eBay!).
F. Calibration tests take excessive amounts of time to complete due to the need to settle and filter the noisy force monitor signals in the system.
G. Calibration software uses a primitive console-based format that is not connected to the MMT MySQL database.
H. Actuator calibration results are used only for a volts/pound slope measurement correction, and could be extended to include offsets for a more complete $y = mx + b$ calculation for use in the calibrated force command set in the primary mirror support software.
I. The test stand software was written in C using VxWorks RTOS, and support is problematic due to Tom Trebisky's retirement.
J. Spare parts are not available for any of the electronics. Indeed, the Acromag 9330 VME card for analog input *is* the spare for the primary mirror cell computer. I am aware of no spare load cell amplifiers for the existing units, or any bare boards that might be populated to create them.

A set of photographs of the test stand system is available at *\\Mmto\electronics\bcardwell\Actuator Test Stand* for viewing details of the system.

Measurement Requirements

Based on John Hill's *LBT Technical Memo UA-95-02* that discusses mirror support design goals and specifications for 3.5m to 8m mirrors, we have the following systematic error allocations from Table 3 (next page):

Source of Systematic Errors	Allocation
Calibration Stand plus Actuator Fabrication	1:3000
Load Cell Reading plus Servo Error	1:3000
Actuator Installation and Alignment	1:3000
Mirror Cell Deflection plus Polishing Force Errors	1:3000
Mirror Alignment on Telescope Cell	1:3000

For the purposes of the actuator and test stand, only the first two are of interest; in line with Hill's assumption that the errors add quadratically, we have a total error allocation from this of 1:4243. Section 3.3 of *UA-95-02* lists actuator specifications that should also be incorporated –

- Measurement Accuracy: 1 part in 1200
- Measurement Resolution: 1 part in 4000
- Axial Support Errors (at zenith): 1N in 3mm, and:
  0.1% systematic error
  0.5% random error
- Lateral Support Errors (at horizon): 12N in 3mm, and:
  0.7% systematic error
  3.5% random error

The nominal actuator force output for each actuator is ±600lbf at 100psi supply pressure (6in^2 of area in the pneumatic actuators). Using the most stringent values above from the axial support actuators, we can arrive at the error budget for a given actuator (using the SI units of Newtons):

$$F_{total} := \sqrt{Fe^2 + Fr^2 + Fn^2}$$

$$F_{total} = 6.12\,N$$

where

$Ft := 2700 \cdot N$ Total force for one actuator direction

$Fe := \frac{Ft}{1000}$ $Fr := \frac{Ft}{500}$ Base and random error forces

$Fe = 2.7\,N$ $Fr = 5.4\,N$

$Fn := 1 \cdot N$ Basic force error over 1mm travel

Using the above error allocation of *1:4243*, we also calculate a force allocation error of `1.273N`, which is roughly a factor of five above the calculated F_{total} support error from the list. A safety factor should be applied above this (I suggest 4X) to supply sufficient resolution on the test stand for reliable detection of problems with actuation forces, for a final force measurement resolution of `0.32N`, at a total command accuracy of `1N` (output force resolution).

Electronic Measurement Requirements

Given the above force measurement values, we can now calculate the electronic signal measurement needed. The nominal actuator command and force monitor signals are ±10V full-scale. This means that for a ±2700N force range, to achieve 0.32N resolution, the measurement resolution must be at least 1 part in 16880, or 1.18mV. For a 1N output command resolution, the force output resolution must be at least 1 part in 5400, or 3.7mV. Standard commercially-available analog-to-digital (A/D) and digital-to-analog (D/A) hardware at 16-bit resolution would have ideal resolution of 0.082N, or 305μV, assuming a ±10V full-scale signal.

Measurement Hardware

The aging VME crate with its unsupportable hardware and software should be replaced with an x86 PC running a standard MMTO copy of Fedora for the widest possible support from the software group. There is no real-time requirement for the test stand; if this turns out not the case either the standard Linux RT-preempt patch or RTAI can be installed into the kernel quite easily. Both are freely available and make it unnecessary to ever run the proprietary, expensive VxWorks RTOS – MMTO's version of PC-VxWorks is PC486, which even now is several generations behind the latest CPU cores and is easily eclipsed in performance/availability by the mentioned real-time patches.

I recommend avoidance of all proprietary buses and i/o hardware in the measurement electronics for the simplest software and hardware maintenance and longest service life. A short review of data-acquisition electronics will illustrate the issue:

> VME – a dominant force in the data-acquisition and industrial control arena during the 1980s and 1990s, most vendors no longer support or even offer VME hardware. As a long-term hardware solution for MMTO, it is ***not*** recommended for new designs. Migration away from VME is again the primary motivation for the recommendation of a PC as the computer platform above.
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> PCI – long the workhorse of the PC-bus industry, it has been supplanted in large part by PCIe (PCI express). Modern PC motherboards have fewer and fewer (in many cases, no) PCI slots built in. PCIe slots are common, but the current PCIe 2.0 specification is evolving into the PCIe 3.0 version, and it is to be expected PCI and all its various permutations will go the way of VME. Also, buying new PCI boards (and spares!) will be expensive.
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> CompactPCI – an industrial version of PCI with its own mechanical format and electrical specifications, this is very much a niche solution, and is relatively

expensive compared to PCI. With the cost of new hardware and spares, this is a prohibitively expensive choice. Software development is also an issue, since the CPCI format has its own CPU choices that are significantly different from commodity PCs.

Given the rapid evolution of the PC industry, the proper decision would be to avoid any hardware that requires installation in the PC itself. Two possible i/o hardware competitors are then available that satisfies this choice:

<u>USB</u> – Many vendors now make USB devices that provide A/D, D/A, and digital i/o. This is available at a reasonable price and makes replacement of a failed i/o unit or the PC a simple matter.

<u>EtherCat</u> – a rapidly growing standard in the industrial control market, EtherCat uses standard Ethernet hardware and frames to perform rapid i/o via ruggedized DIN-rail i/o modules. The per-channel cost is higher than for USB, but provides galvanic isolation and other features that are attractive for long-term service. MMTO already owns some EtherCat hardware for evaluation. Software development effort may be comparable to that with USB.

Signal Conditioning Hardware

The existing 6-DOF load cell amplifiers are in unknown condition, nor are spares to be found for them. MMTO has created drawings and a bill of materials (BOM) for them. A cursory examination of their design reveals several errors; for example, the output excitation voltage of ±10V exceeds the load cell datasheet maximum of 15V. At minimum, they should be repackaged into cases and their wiring connectorized in a more rugged manner. If this is not possible, MMTO should design and build new signal conditioners for this purpose. A search on the internet for pre-packaged load cell signal conditioners finds most units are DIN-rail mounted at ~$180 to $250 each, and have noise level specifications that range from barely usable to not appropriate given our stringent signal measurement requirements. Purchasing enough new commercial units and spares will probably be unaffordable for the purposes of this project. It is estimated that MMTO can construct new signal conditioners at a reasonable cost (depending on the design chosen).

Required Measurements

To run all the measurements on the test stand, we then have the following input/output signals (all analog channels at 16-bit resolution):

- 6 channels of load cell outputs (A/D)
- 2 channels of force monitor outputs from the actuator under test (A/D)
- 2 channels of force commands to the actuator under test (D/A)
- 2 TTL-compatible digital lines for control of the Integrator Lock-Out (INTLO) on the actuator card

In addition, it would be advantageous to include auto-zeroing capability on all the analog inputs and the output to confirm/test the hardware before performing calibrations, which would require at least two more output bits (one for Zero Inputs, one for Zero Outputs), for a total of 4 digital lines, if this capability is not built in to the selected hardware. Also, loopback of the analog outputs to the inputs would serve as an additional system test to ensure the measurement system is healthy.

System Design

Test Stand Computer

The test stand computer should be a commodity x86 PC. MMTO currently has on hand one Shuttle box rescued from Tim Pickering's surplus pile. It could use a newer hard drive, and if EtherCat is selected as the i/o hardware a new motherboard would be needed to provide a second Ethernet port for connection to the MMTO network.
Cost details:

Hardware	Estimated Cost
Shuttle PC, barebone (new)	200.00
Micro ATX motherboard	50.00
PCI Ethernet card	20.00
Hard drive	80.00

The total cost for the computer depending on the option selected then ranges from $150 to $300.

Load Cell Signal Conditioners

The load cells on the test stand require signal conditioning to amplify the low-level strain-gauge signals to the nominal ±10V full scale level. The existing amplifiers are not packaged into enclosures, but are attached via nylon screws to the test stand legs where they are vulnerable to hazards such as dust, dropped parts, etc. They need to be repackaged into a more robust enclosure with connectors for attachment to the system. It is noted that the as-built version of the amplifier IC (TI INA101) is end-of-life and no spares of these boards are on hand; though newer part versions are available. In addition, the voltage reference (AD588) used is an expensive part; MMTO keeps few spares on hand due to the cost.

A second option of replacing the entire amplifier with more up to date versions may be attractive.

Cost details for re-using existing boards:

Hardware Item	Estimated Cost
New enclosures for existing amplifiers	20.00 ea.
Spare INA101 units	20.00 ea.
Spare AD588 units	25.00 ea.
Connectors, wiring for boxes	10.00 ea.
Spare boards (homebrewed), incl. passives (resistors, etc.)	50.00 ea.

The total for the above option, including building 2 new complete spare amplifiers is $475.

Going to a more modern design would change the picture somewhat:

Hardware Item	Estimated Cost
New enclosures	20.00 ea.
Signal conditioning and reference ICs	20.00 ea.
Connectors, wiring for boxes	10.00 ea.
Printed circuit boards	35.00 ea.
Passive parts (resistors, etc.)	5.00 ea.
PCB tooling charge	100.00

The total for a new design (including 2 complete spares) would be $820.

Power Supplies

The existing power supplies are a 36V and a ±15V unit that supply the actuator card and test stand signal conditioners, respectively. These can be re-used and packaged into an enclosure to protect them from the environment and protect people from exposed AC wiring. The cost estimate:

Hardware Item	Estimated Cost
New enclosure	100.00
AC entrance with fuses and EMI filter	10.00
Switch/LEDs	5.00
Output connectors, wiring	20.00

The total is $135.

If EtherCat is chosen, a 24V supply will be needed for the i/o modules, which would cost about $50 more ($185 total).

Data Acquisition Hardware

Two viable choices for acquiring the test stand data and controlling the actuator under test are commercially available, a USB multifunction device from National Instruments, and a set of Beckhoff Automation EtherCat terminals. For either choice, if the option for loopback and auto-zeroing the acquisition channels is chosen, MMTO will have to develop some custom hardware and wiring to make this possible.

First, the loopback and auto-zero hardware:

Hardware Item	Estimated Cost
Enclosure	30.00
Electronics board	50.00
Analog switch ICs, interface ICs	20.00
Connectors, wiring, sockets	50.00
Passives (resistors, etc.)	15.00

The total here is $165.

USB Multifunction I/O
National Instruments makes a multifunction USB unit that contains 8 differential-input 16-bit A/D channels, 2 16-bit D/A outputs, and 24 digital i/o lines. The product requires an external power supply and uses screw-terminal wiring.

Hardware Item	Estimated Cost
NI M-series USB multifunction unit (USB-6221)	1049.00
Power supply	5.00
DIN rail mounting kit	49.00

The total cost for this hardware is $1103.

It is not certain what NI charges for their Linux C driver library, which could add a substantial amount to the above total. MMTO has some older licensed Labview software, and the UA also has a site license for Labview, so this cost could be potentially be zero. A University discount may also apply to their quoted website price.

EtherCat Terminal I/O
Beckhoff Automation makes a series of industrial-rated EtherCat terminals that use a DIN rail mounting format. To construct the complete data acquisition system, we will need the following:

Hardware Item	Estimated Cost
EK1100 EtherCat bus coupler	137.00
EL3102 2-channel differential input 16-bit A/D	189.00 ea. (4 req'd)
EL4132 2-channel 16-bit D/A	189.00
EL1004 4-bit digital output	32.00
EL2004 4-bit digital input	36.00
DIN rail, Cat-5 cable	10.00
PCI Ethernet card	20.00

The total cost for this hardware is: $1180

Miscellaneous Items
The test stand as constructed could use some mechanical overhaul in addition to the above upgrades:

- Clean and paint the entire unit to prevent rusting and make working on the test stand cleanlier.
- Remove the existing wiring, computer equipment, and shelves and replace with a 19" rack screw rail to mount all new and upgraded hardware.
- Enlarge cutouts where possible to make easier tool access for attaching actuators to the test stand.

- Collect all spare actuator parts and adapter hardware for use on the test stand and store in a nearby cabinet kept locked to prevent unauthorized access.
- A complete set of tools (wrenches, sockets, etc.) should likewise be stored in a dedicated toolbox at the test stand.
- Any operational actuator cards should be stored in the cabinet; cards that need repair should be the only ones around at the MMT Electronic Shop (other than a few spares for repair of units in the primary mirror cell).
- Provide a work table or other convenient surface for performing work on actuators near the test stand.

No additional cost is expected from this miscellaneous list, other than the labor to complete the items.

Software Requirements

The new test stand software should be designed to meet the following:

- Standard Fedora Linux on a commodity x86 PC platform, such as a Shuttle box.
- Real-time, if needed, from RT-Linux or RTAI patch.
- Linux driver support from the i/o hardware vendor.
- Support all measurements on the test stand, including:
  - Auto-zero analog inputs.
  - Zero analog outputs (e.g. connect to ground).
  - Signal loopback – connect D/A output to A/D input for “sanity check”.
- A GUI for interaction with the test stand user.
- Measurement results should be written to the MMTO MySQL database.
- Measurements should support not only the standard “vpp” (volts per pound), but should include offset values to supply the complete $y = mx + b$ linear fit data.
- Many measurement samples for selected measurement points should be taken for “live” standard-deviation calculations and stored as part of the calibration data to keep a record of the measurement uncertainties for each calibration.
- Calibrations should be complete within 60s of starting.

The user GUI should incorporate the following elements:

- An input field for the actuator serial number.
- An input field for the actuator electronic card number.
- A limited number of characters (255?) for any notes.
- The current timestamp automatically appended to the test record.
- Selection of the actuator type (single, dual).
- Selection of the actuator axis to test (valid only for dual actuators).
- A “direct force” mode where a given force can be commanded by the user.
- An automatic test mode that performs the calibration.
- A “special” test mode that performs calibration over a limited force range, which should be selected for force-limited mirror edge actuators.
- A “bump test” mode that mimics the mirror cell “bump test” for quick testing of suspect actuators.

- Automatic/manual control of the integrator lock-out (INTLO) bits.
- Step outputs/step response should be able to be output and plotted for evaluation of time/frequency response.

The GUI should be written in a supportable, accessible language for easiest maintenance over the long term. It is suggested that PyQt/Python or Java with Swing/AWT might both be good candidates, as would our current PHP/Ajax/Firefox browser-based approach.

Decision Matrix

Design Choice	Technical Risk	Cost	Time to Complete
Repair "rescued" Shuttle PC	medium	low	1-2 weeks
Purchase new Shuttle PC	low	medium	2-3 weeks
Repackage existing amplifiers	low	low	4 weeks
Construct new amplifiers	low	medium	4-8 weeks
Repackage existing power supplies	low	low	1-2 weeks
Add 24V supply	low	low	1 day
Purchase NI USB-6221	medium to high	high	4 weeks
Purchase EtherCat terminals	medium	high	4 weeks
Construct loopback hardware	medium	low	3 weeks

For each of the major sections of the test stand upgrade, I find the following technical reasons compelling:

I. **Computer –** it is appropriate to choose new hardware for a systems upgrade, especially as the "rescued" PC becomes essentially a free spare. Using a PC allows cheap commodity hardware and with Linux we have the cost advantages of open-source software and will be able to run Matlab for data acquisition and analysis if needed.

II. **Load Cell Amplifiers –** the existing amplifiers are not easily packaged into an enclosure given the connectors used. In addition, they use expensive parts that may not be available over the long term, and have relatively high power dissipation and design errors. No spares are available, and if we wanted to make new ones, the cost would be comparable to a re-spin of the printed circuit boards anyway. With new boards we have better control over chosen parts, number of spares, packaging, and electrical performance.

III. **EtherCat** – the NI offering uses proprietary hardware and software that is not necessarily easy to implement and use. The EtherCat choice is more expensive but uses readily-available industrial strength hardware with electrical isolation to protect the computer, and has free open-source master code. In addition, Ethernet as a communications medium may well have more lifetime than USB. The hardware takes up less space than the NI-6221 and will be much easier to install in the same chassis as the loopback hardware. The modularity of the i/o terminals means that should one fail, only that part need be replaced, instead of the whole thing as is the case with the NI unit.

IV. **Loopback Hardware –** a feature never before available on the test stand, it will allow the gravity loading on the bare test stand and any offsets to be measured in a routine, repeatable way, as well as diagnostic tests in case a problem is encountered. Since the cost of implementation is fairly trivial compared to the rest of the project, this is a simple way to increase the test stands' capabilities.

Recommended Upgrade Path

For the best long-term life of the test stand, MMTO should undertake the following:

1. Remove the existing electronics and clean, paint, and prepare all hardware for mounting new equipment.
2. Begin design and construction of new load cell amplifiers with a modern, packaged solution that provides sufficient spares for future use.
3. Purchase a new Shuttle PC and install a network card for use on the test stand. Since most micro-ATX motherboards now come with integrated Ethernet, the second port can be dedicated to EtherCat communications, while the mainboard connection can be connected to the MMTO network. The "rescued" Shuttle box can be used as a development and test machine, as well as the spare for this new computer.
4. Replace the power supply and load cell wiring in favor of a new power supply chassis and the new data acquisition hardware.
5. Purchase EtherCat data acquisition hardware and install into an enclosure along with the loopback and auto-zero hardware for mounting on the test stand.
6. Prepare new software on the PC with Fedora and EtherCat Master software.

Many of the tasks listed here can be done in parallel, so the work could be completed within 2-4 months, at an estimated cost of <u>$2650</u>.