ViLLaGEs: Opto-Mechanical Design of an on-sky visible-light MEMS-based AO system

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ABSTRACT

Visible Light Laser Guidestar Experiments (ViLLaGEs) is a new Micro-Electro Mechanical Systems (MEMS) based visible-wavelength adaptive optics (AO) testbed on the Nickel 1-meter telescope at Lick Observatory. Closed loop Natural Guide Star (NGS) experiments were successfully carried out during engineering during the fall of 2007. This is a major evolutionary step, signaling the movement of AO technologies into visible light with a MEMS mirror. With on-sky Strehls in I-band of greater than 20% during second light tests, the science possibilities have become evident.

Described here is the advanced engineering used in the design and construction of the ViLLaGEs system, comparing it to the LickAO infrared system, and a discussion of Nickel dome infrastructural improvements necessary for this system. A significant portion of the engineering discussion revolves around the sizable effort that went towards eliminating flexure. Then, we detail upgrades to ViLLaGEs to make it a facility class instrument. These upgrades will focus on Nyquist sampling the diffraction limited point spread function during open loop operations, motorization and automation for technician level alignments, adding dithering capabilities and changes for near infrared science.

Keywords: Adaptive Optics, open-loop, MEMS DM, Determinate Structures, Pyramid Wave Front Sensor

1. INTRODUCTION

A pioneering institution in the field of astronomical adaptive optics (AO), the Lick Observatory at Mount Hamilton currently operates a facility-class laser-guide-star near-infrared (IR) AO system ("LickAO") on the 3-meter Shane telescope, developed in the 1990s[1,2,3] Continuing this legacy of AO technology development, the Lick Observatory has successfully demonstrated a Boston Micromachine's Micro-Electro Mechanical Systems (MEMS) deformable mirror in visible adaptive optics system (ViLLaGEs)[4]. Successful closed loop operations were achieved during the first light run on the second night. The ViLLaGEs system is an experimental testbed that went from conception to first light in less than two years and will operate for the next two years on the Nickel 1-meter telescope. Such a short time scale was possible by leveraging knowledge gained from the LickAO[5,6], MEMs research conducted at the Laboratory for Adaptive Optics[7], and several engineering tools which will be reported on here.

ViLLaGEs was conceived as a technology testbed and was not originally intended to be a facility class science instrument. During second light closed loop operations, a Strehl of 20% in I-band was achieved on star α Ari. Performance of this magnitude was not expected this early on and triggered several science target discussions. ViLLaGEs could be converted into a facility class instrument to achieve many of the science goals now desired for this system. A possible set of changes are proposed here in §4.

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Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, edited by Eli Atad-Ettedgui, Dietrich Lemke, Proc. of SPIE Vol. 7018, 701841, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.790166

2. SYSTEM DESCRIPTION

The ViLLaGEs system uses a Hartmann wavefront sensor (WFS) with a PI S-334 tip tilt mirror and a Boston Micromachine's 140 actuator MEMs deformable mirror (DM). The bench is horizontal with the optics on the top side when the telescope is at zenith. Light from the f/17 telescope is turned onto the bench and aligned into ViLLaGEs by a pair of mirrors. Just upstream of the cassegrain focus, a negative lens creates an f/41.7 beam, which is our location for placing a fiber for testing purposes. A second lens collimates the light and creates a 3.6 mm diameter pupil, where a tip/tilt (T/T) mirror is located. A 1:1 relay creates another 3.6 mm diameter pupil for the MEMS. A relay between the T/T mirror and MEMS was necessary because placing the T/T mirror in the same optical space as the MEMS would cause unacceptably large pupil wander. It would be possible to integrate the MEMS onto a T/T stage, though this was not done because changing to a different type of DM would require an unwanted change to the T/T function. A change in beam diameter on the DM can be implemented with a change of relay optics, which is generally straightforward, and can be easily swapped via the use of rails for the optics.

ViLLaGEs Layout

In Figure 1, one can see where this layout is significantly different from other AO layouts. The light is split into two paths, one which reflects off the DM (the corrected path) and one that bypasses the DM (the uncorrected path). The corrected and non-corrected paths are imaged adjacently onto both the WFS and the science camera. This allows for a quick switch between open-loop and closed-loop configurations. More significantly for experimental verification, this makes it possible to obtain simultaneous measurements (rather than sequential measurements) between corrected and non-corrected states. This is useful for a testbed, which is a first part of ViLLaGEs' function.

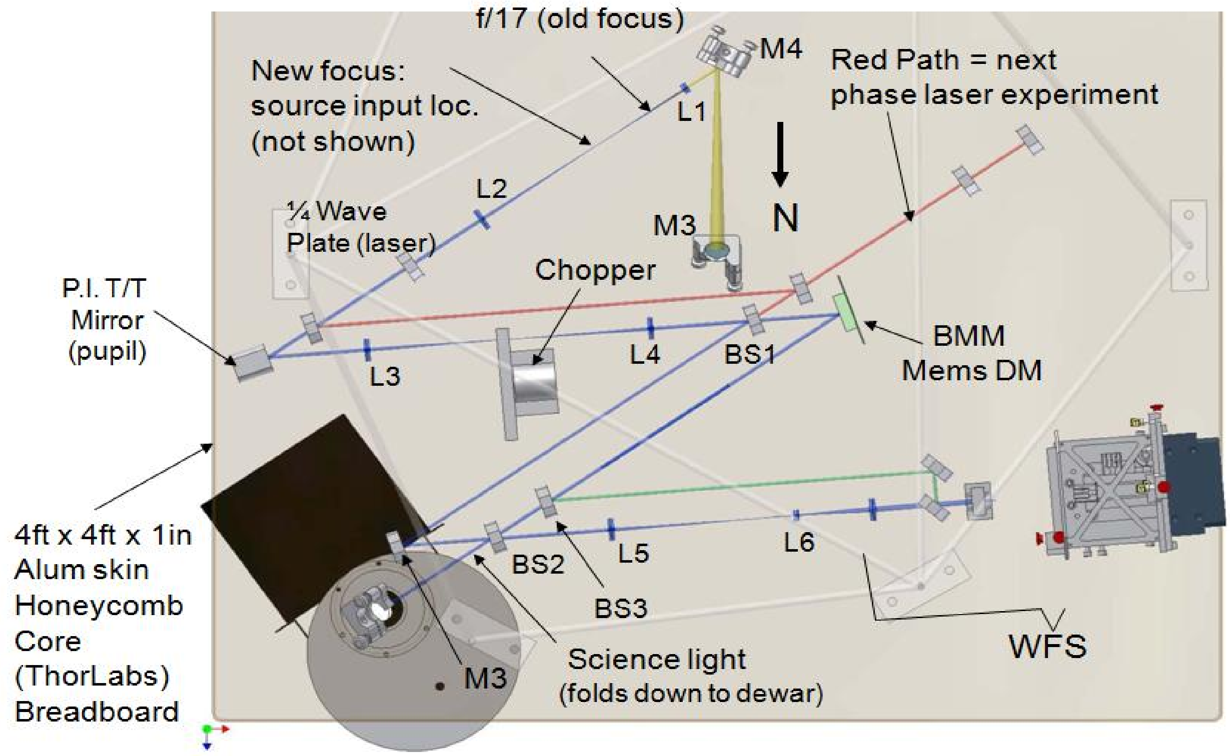


Figure 1 ViLLaGEs Layout - Top View

A 50/50 beamsplitter (BS1) splits the light between corrected and uncorrected paths. The light on the corrected path reflects off the DM, while the uncorrected light reflects off a flat mirror. Another 50/50 beamsplitter (BS2) creates paths for both uncorrected and corrected light to reach the WFS and the science paths. The two paths are offset from each other such that the pupils in the WFS do not overlap and science camera images have a minimal overlap.

The WFS CCD is a SciMeasure Lil'Joe (E2V chip, 80x80 pixels, 24μm pixels), which is divided into four portions: Shack-Heartmann (SH) WFS (corrected light), SH WFS (uncorrected light), tip/tilt sensor, and laser guide star (LGS) diagnostic. The lenslet array uses 328μm lenslets with a focal length of 24mm. A "dot relay" relays the spots created at the lenslet focal plane onto the WFS CCD. The plate scale on the CCD is 1.97 arcseconds/pixel. There are nine subapertures across the beam's diameter, and four pixels per subaperture. The WFS path has a relay telescope to convert the 3.6 mm MEMS pupil to a 2.9 mm pupil at the lenslets; the relay uses three elements to allow for easy changes of pupil size while maintaining pupil location.

The science path uses two lenses to create an f/111 beam to produce a 0.027 arcsecond/pixel plate scale (empirically measured). The first is a Newport PAC058 f/150 and the second is an Edmunds 45424 f/-35. This large f# is intentionally oversampled in the I-band, to facilitate performance measurements by resolving the Airy rings. Filters are placed in the science path to provide attenuation and wavelength selection.

For the LGS experiments a pulsed laser will be used. This is so the guide star light from the sodium layer can be time gated into the receiving system. This removes contamination from the light scattered off shared optical elements and from the lower atmosphere (Raleigh backscatter). For diagnostics, a small portion of the outgoing laser light is fed to the Hartmann sensor via a retro path. Otherwise, the outgoing light will be blocked from the receiver path with a chopper wheel timed to the laser pulses.

In LGS mode, a natural T/T star is required and there is a quadrant of the WFS CCD designated for T/T sensing. For LGS T/T, a portion of the corrected path light will be intercepted directly after the DM and folded back into the WFS path just downstream of the lenslets. The optics in the T/T light path creates an image of the T/T star at the focus of the lenslets. This image is subsequently relayed onto the CCD. The plate scale at the CCD for the T/T star is 0.33 arcseconds per pixel, and the FOV is approximately 12x12 arcseconds.

The ViLLaGEs system has much of the functionality of the LickAO system for the 3-meter telescope, but does so in a much smaller package. Much of the size reduction is due to the MEMS DM (3.6 mm versus 71mm for the 3-m system). Using a quadrant of the WFS CCD as a T/T sensor eliminates the need for a separate T/T camera. It also provides a high-speed scoring camera.

3. DESIGN AND ENGINEERING

ViLLaGEs was built, tested, and put on-sky in less than two years, a very ambitious accomplishment. Without current three-dimensional parametric modeling and design, finite element analysis (FEA), and optical design tools (as well as the portability of data between these tools), the odds for success on this effort would have been slim.

1.1 System Description

ViLLaGEs is designed for the cassegrain focus of the equatorial 1-meter Nickel telescope. A MEMs deformable mirror in an adaptive optics system reduces the overall footprint of an optical design. ViLLaGEs' footprint is approximately one square meter as compared to the LickAO system which is about three square meters. Even with this smaller footprint, 200 lbs worth of electronics are required for operations. The real-time controller and power supply for the deformable mirror (DM) must be in close proximity to the device and are therefore carried with the instrument. Initial estimates of the mass and center of gravity (405 pounds and 63 inches from declination pivot) for the entire package were not outside the limits for telescope balance. However, for such an approach, mass distribution and minimization become the primary design criteria.

The Nickel has a short cylinder below the primary mirror cell called the telescope utility bin (TUB). It houses the guide camera and other utilities. A flange at the bottom of the TUB is the instrument mounting interface. The concept for the instrument based on the optical design was a bench-mounted layout on a plane normal to the optical axis approximately 10” below the TUB. A three-point attachment scheme on the TUB flange leant itself to using a hexapod determinant structure[8] to couple an optical breadboard containing the instrument to the telescope.

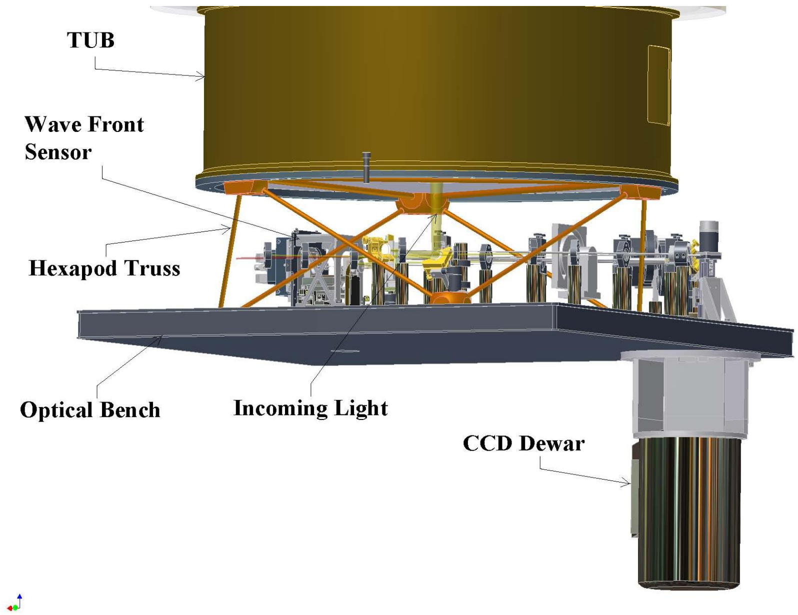


Figure 2 The Optical Bench of ViLLaGEs Mounted on the Nickel 1meter telescope (isolated for clarity).

The rack containing the support electronics is mounted below the breadboard. For balance reasons, the design required the mass of this rack to be minimized and centered as close to the optical bench as possible. It was also necessary to enclose the rack and remove the 0.5 kilowatts of heat generated within. Finally, this rack would have significant weight. It was desired to attach this load to the telescope independently from that of the optical bench. The intent being to decouple these masses for flexure concerns in the presence of a changing gravity vector. While not unprecedented, this type of decoupled support for the flexure sensitive optical portions of the instrument and the ancillary electronics is an important strategy for instruments subjected to a changing gravity vector. This becomes increasingly advantageous as portions that are not flexure-critical dominate the total mass of the instrument. This is often the case for adaptive optics instruments, such as Altair[9], the Gemini North adaptive optics system.

1.2 Truss Design

A determinant hexapod connecting two structures eliminates the coupling of bending moments from one to the other – in this case from the telescope into the bench. That is to say deflections of the truss members supporting the bench, (which vary as the telescope rotates) result only in rigid body motion of the instrument. This then becomes primarily a beam steering (first order correction) issue. For the truss to behave this way, the axes of all struts entering a single node must intersect at the same point and these strut/node connections must behave as pinned joints (zero bending momentum). Our hexapod is a welded truss so the joints obviously are not pinned. They are treated as such in the first load estimate. This was made using link elements in an ANSYS finite element analysis with mass estimates from the optical bench (and several gravity orientations). We tailor the struts’ cross-section and therefore the axial stiffness to produce the required rigidity between the telescope and instrument. Each strut is then analyzed for buckling (often the limiting factor), and the cross-section moment of inertia increased if required. Finally, link elements are replaced with solid elements and the model of the structure is analyzed to ensure bending is sufficiently low where the struts enter the nodes. (If required, struts could be necked down near nodes in order to reduce bending stiffness but maintain axial stiffness. This was not required on ViLLaGEs as it has a relatively simple truss design.) The *slenderness ratio* (length/radius of gyration) of a strut is sometimes used as a criterion for adequate flexibility in bending. In the case of ViLLaGEs the bending present was compared to that in the breadboard due to the optical components attached and was found to be trivial. The bench model used LINK8, SOLID45, SHELL63 and MPC184 elements. The later was used to connect the mass centers (the lollypops extending up from the bench) of various bench components to the breadboard.

A high modulus of elasticity is favored when optimizing the truss for stiffness. Steel was chosen for modulus cost and workability. A mild steel (1018) could be used (for ease in machining and welding) as this is a deflection and buckling limited structure so the strength requirement is very low. A key element in this truss design is how the truss mates to the breadboard. There are no steel struts directly between the three steel nodes attached to the breadboard (Figure 3).

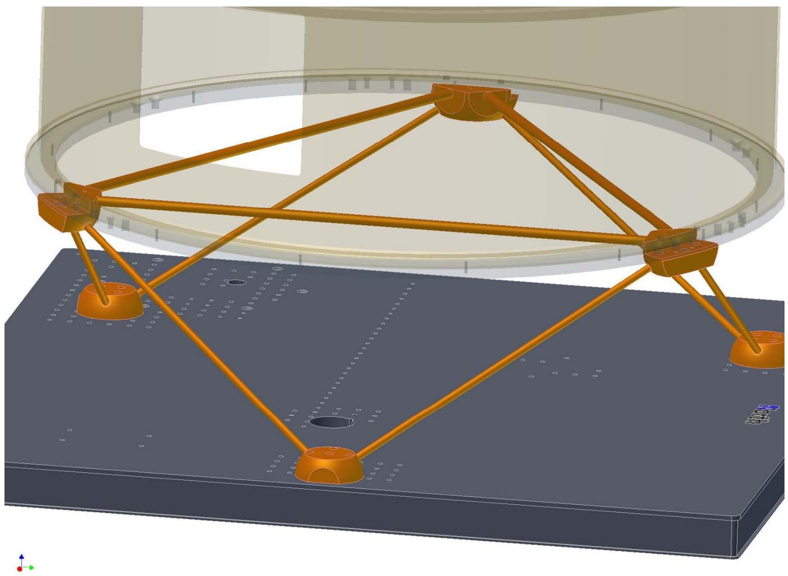
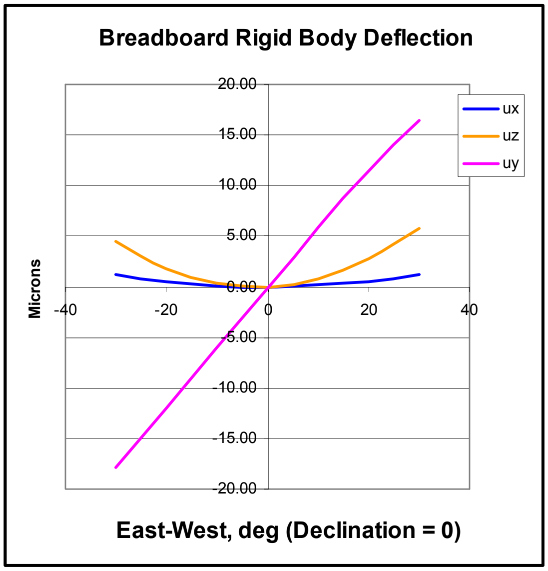
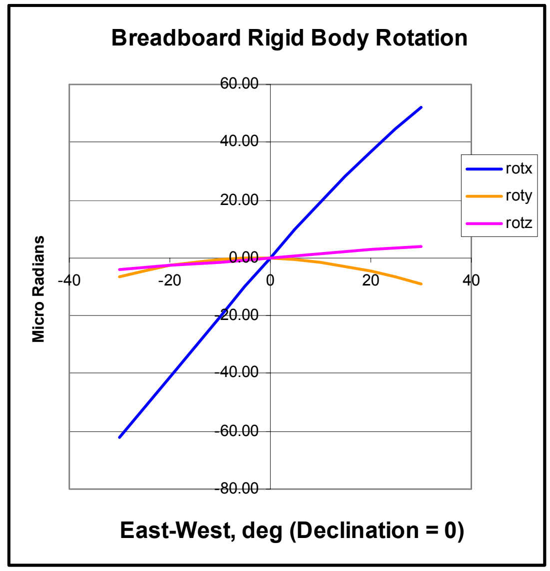


Figure 3 Hexapod Truss – This couples the instrument to the telescope. The Figure shows no struts in the plane of the breadboard - they are implicit in the breadboard skin . This keeps the bench surface clear, attachments simple and thermal concerns mute.

These breadboard “struts” are implicit in the upper skin surface of the breadboard. We wanted to use an all aluminum breadboard for weight savings. Steel struts between the breadboard nodes would have cluttered the surface and required intricate kinematics due to the dissimilar metals and thermal coefficients of expansion. The implicit struts violate the definition of a determinant structure. However, this is always true to some degree, so it then becomes an estimate of whether the nonconformity is significant. For our purposes, it wasn’t.



Displacement of Optical Bench relative to the telescope TUB for Horizon to Horizon telescope rotation (Declination = 0)



Rotation of Optical Bench relative to the telescope TUB for Horizon to Horizon telescope rotation (Declination = 0)

Figure 4 Examples of ANSYS analysis data of the hexapod. Shown are gross rotations and gross displacements of the bench (i.e. rigid body motion) relative to the telescope TUB due to deflection of the trust. This flexure is due to the changing gravity vector that ViLLaGEs would see as the telescope rotates from East to West through zenith.

1.3 Optical Bench Design and Analysis

The design of the optical bench was an iterative process. Working between the optical design in ZEMAX and the CAD model in Autodesk Inventor, the light path was packaged within the breadboard envelope and around the supporting hexapod. Once the bench was populated with optics and mounting hardware, an accurate mass assessment could be made and both the breadboard and hexapod flexure reanalyzed. The later was described in section 1.2.

Flexure of the breadboard due to the component masses (and centers of gravity) relative to the 3-point support locations of the truss was required for comparison to both common and non-common path stability requirements. The all aluminum 42in x 42in x 2.2in thick breadboard with 6mm top skin, 3mm bottom skin and 6mm pitch honeycomb core would have been a computationally large finite element model. Instead, a patch of the breadboard was modeled and load vs. deflection was used to generate estimates for orthotropic mechanical properties base on the geometry described. It included uniform density.

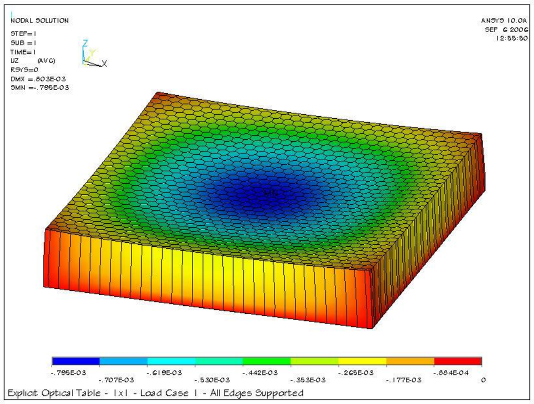


Figure 5 Explicit model of 12in x 12in breadboard (with honeycomb).

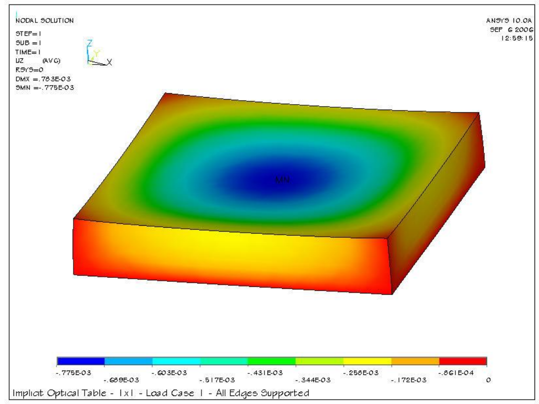


Figure 6 Implicit model of 12inch x 12inch breadboard.

The orthotropic values could then be used on the breadboard volume to estimate bending at various orientations of the gravity vector. The largest component moment present on the breadboard by far was the Nickel facility CCD science dewar #2 (approximately 25 lbs centered 8 inches below the upper surface of the bench).

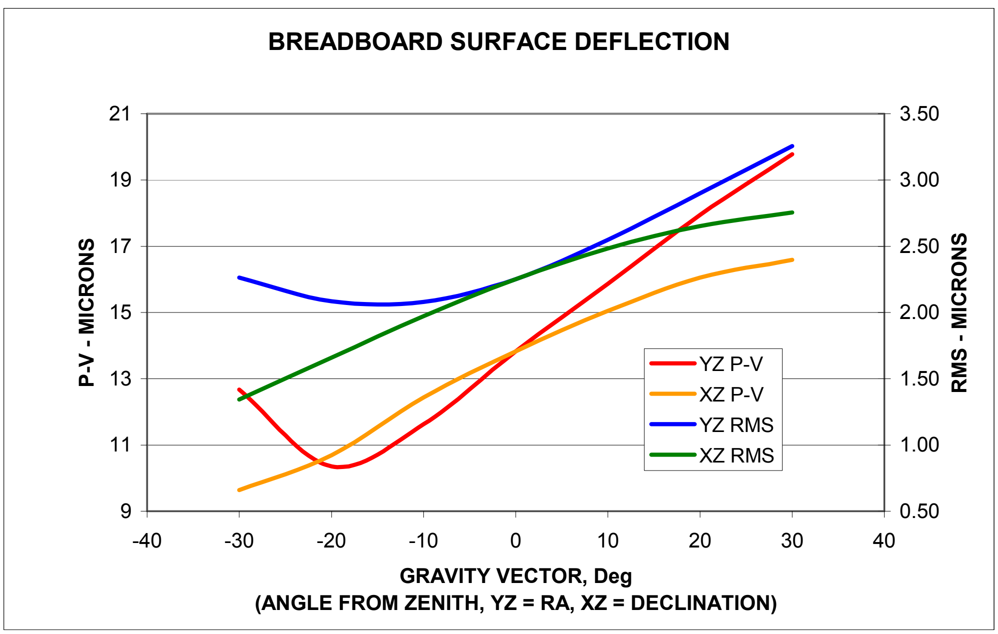


Figure 7 Example data extracted from the analysis. It shows both rms and peak-to-valley deflection estimates of the breadboard surface as it rotates both east-to-west, and north-to-south, each through zenith.

1.4 Electronics Rack Design

The electronics rack is suspended below the optical bench. This was achieved using four legs that straddle the corners of the bench and attach to a box frame that houses the electronics. This is a frame within a frame that has standard 19inch rack-mount rails - 2 x 13U (side by side). There is approximately 2in of clearance between inner and outer frames. In operation, the rack is enclosed with insulated panels. Filtered, cross-flow dome air is ducted across the internal electronics and exhausted outside of the dome via a flexible insulated duct hose. Heat dissipation required is approximately 500W.

The support legs attach to the same flange on the telescope TUB to which the hexapod truss is anchored. In contrast to the truss, the frame is a redundant structure where mass minimization is a priority. It was therefore driven by strength and/or natural frequency. The legs are welded assemblies of 1.5 in diameter 4130 alloy steel tube with 1/8 wall. The rectangular frame is constructed from 4130 (1 x 1 ¾ x .06 wall rectangular tubing). Bolted joints attach the legs to the upper ring and to the rectangular frame. The upper nodes of the hexapod truss also bolt to the ring. Through holes secure these nodes directly to the flange when mounted on the telescope.

The rack hangs from the telescope when mounted. When dismounted, loading reverses. When dismounted, the frame becomes the support for the truss and breadboard, which hang from the ring at the top. This ring, which is mostly redundant when mounted, now carries considerable load. Also, the cassegrain mount for this instrument means that the rack may go from hanging vertically below the telescope to cantilevered fully horizontal in all rotations.

A versatile FEA tool was necessary for the analysis of the breadboard previously described. This was due to the need for multiple types of structural elements, customized material properties and a rather complex model/boundary conditions. From within Autodesk Inventor however, a simplified version of ANSYS is available. The evolution of ViLLaGEs was quite rapid. As such, configurations, component choices, and system requirements were very fluid. The Inventor FEA tool provided a quick and easy way to (re-)analyze the simple structures of the rack and frame for gravity loads. Below are some examples of the use of this tool.

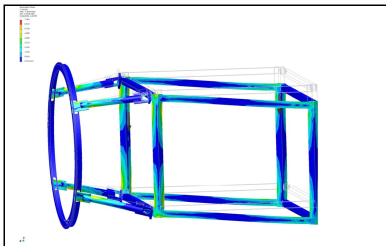


Figure 8 Cantilevered Rack (telescope pointed at horizon)

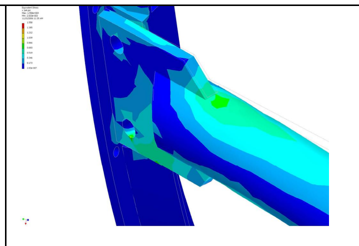


Figure 9 Bending Detail of Support Leg

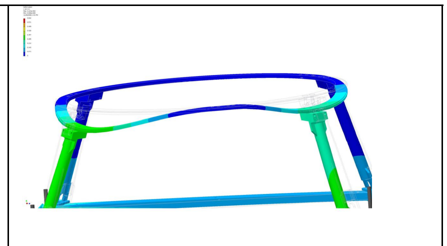


Figure 10 Stress in Ring for Incorrect Installation (survival evaluation)

Once the structural design was complete the detail work could begin: insulating, enclosing and ventilating the electronics rack, installing custom optical mounts, cowling (light sealing) the bench, and cabling. These where non-trivial tasks, however they did not require the iterative effort necessary in optimizing the structural design with a complex set of drivers.

Dome Seeing

Poor dome seeing is detrimental to the success of on-sky experiments. Thus, steps had to be taken to mitigate any dome seeing effects. Infrastructure improvements to the Nickel Telescope Dome were necessary.
The primary cause of poor seeing at this site is warm air moving from the building's visitor center upwards into the dome and out the slit. The first step was to isolate the dome as much as possible from the rest of the building. Airlocks accomplished the majority of the isolation. The lower level of the dome had adequate airflow restrictions but the upper level (dome floor and control room) did not. A wall was constructed at the upper landing to create the airlock and block this flow.

The second step was to seal the gaps where the telescope support structure penetrated dome floor. This insulation was installed on the floor side and was aloud to float on the telescope side to prevent building vibration from being transferred unnecessarily. Insulation was also added around the dome floor to several areas of low R value such as access hatches and a wiring pass through.

The third seeing improvement step was to create a negative pressure through the dome slit by improving the ventilation system. The dome had one existing exhaust fan but it did not provide adequate airflow to create the desired slight negative pressure through the dome slit. Two 20 inch fans where added bringing the total airflow capacity from 3000 cfm to 9000 cfm. The volume of the dome is approximately 8000 cubic feet. When all three fans are on, the air is changed over nominally 65 times per hour. This rate creates a negative airflow through the slit, insuring warmer inside air does not ventilate to the outside. Creating this negative pressure has had the added benefit of accelerating the time to equilibrium.

On-sky Performance

In the ideal setting, first light would have been at the zenith, but due to dome limitation and the realities of bright star positions, we were forced to operate at zenith angles as large as 45 degrees. Because of this design, the first ViLLaGEs opto-mechanical challenges were principally pointing and centering (P/C). Additionally, ViLLaGEs was designed as a testbed with certain limitations. Those limitations were almost immediately exceeded. For example, it was not intended to go beyond 30 degrees from zenith, but routinely exceeds this condition. With the design steps taken ViLLaGEs has been able to successfully adapt to each change.

4. IMPROVEMENTS FOR SCEINCE GOALS

In the current testbed configuration, the ViLLaGEs system is very limited for astronomical research “science”. As an engineering test system, ViLLaGEs is designed to evaluate open loop and closed loop performance simultaneously. The science camera displays both open and closed loop images at a separation of 31 arcseconds at 45 degrees. This split causes a greater than 50% reduction in total flux on target for a given integration time. Additionally, the science camera over samples the redder bands in order to enable performance assessment of the system (Airy rings are clearly visible with an eight pixel peak to peak separation at a plate scale of 27 milliarcseconds per pixel at 900nm).

One way to convert ViLLaGEs to a facility class instrument would be to remove the closed loop imaging leg. The first step would be to remove beam splitter two (see Figure 1) and use pointing and centering (P/C) mirrors on the open-loop leg to recenter the beam into the WFS. The “closed-loop” beam (i.e. the one bouncing off the DM) would go straight into the Science Camera. The “open-loop” beam would go into the WFS. This would increase throughput to both the science and waverfront sensor cameras and remove the possibility of an accidental overlay of a science target on top of the open loop path.

The second change would adjust the final f ratio in the science leg. The f-ratio in engineering mode is f/111. This is oversampled by about a factor of two from Nyquist in V-band. To set it to Nyquist sampled in V, we would remove the negative lens (see Figure 11) and change the focus lens to bring the f-ratio to f/50. A more significant change would be to change the negative lens holder to a motorized lens turret synchronized to the filter wheel so that Nyquist or near Nyquist sampling can be achieved in bands B to z.

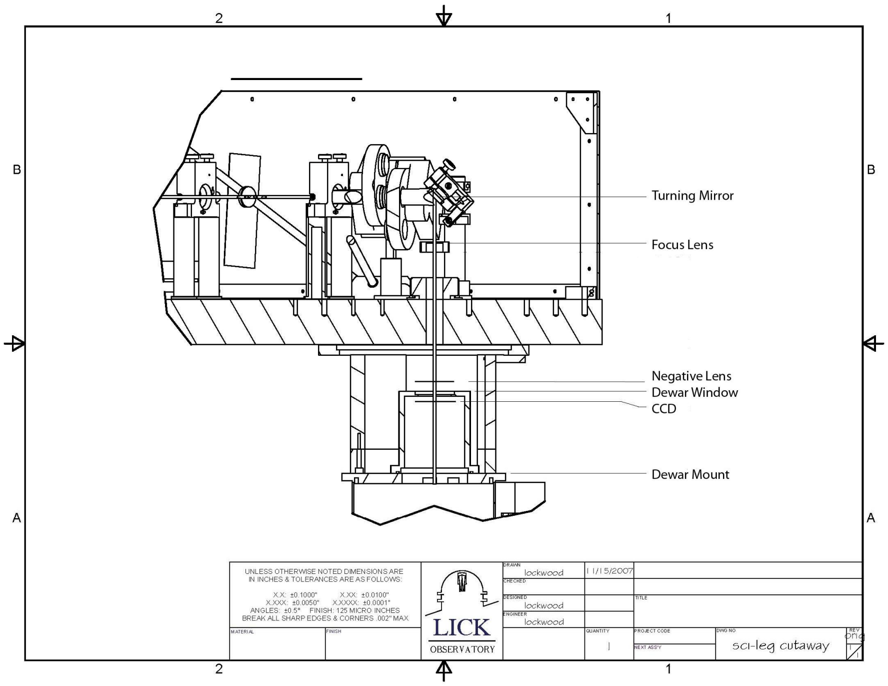


Figure 11 Science camera leg cutaway

The current science camera has 20% quantum efficiency in Gunn z and less than 2% J. At this wavelength cutoff, the highest performance wavelengths of the ViLLaGEs system cannot be imaged. A camera using a shortwave HgCdTe (SNAP) detector [10] would be ideal for a science instrument as it covers the visible to the near infrared.

These optical changes would be sufficient for diffraction limited visible light science, but with poor sky coverage and ease of use. The engineering system has a measured guide star limiting magnitude of about 9th magnitude. Extrapolating to visible wavelengths using the known near-IR limits used for LickAO, the anisoplanatic angle is about three to five arcseconds. These two factors greatly limit the science that can be done. Therefore, the next obvious step in increasing the utility is to add LGS with AO uplink correction. LGS is planned as part of phase two experiments designed to demonstrate on-sky AO laser uplink correction. The LGS T/T star's limiting magnitude should go from ninth to 13th/14th for R-band and the isokinetic angle (as extrapolated from the LickAO parameters) would go to around 10 arcseconds, increasing the sky coverage of ViLLaGEs by a few orders of magnitude[11].

A separate way to increase the sky coverage by increasing the limiting NGS or T/T star magnitude is to use a pyramid wavefront sensor. This technology is being researched at the Laboratory for Adaptive Optics and will be tested on-sky at ViLLaGEs when prepared. Due to its larger diffraction-limit providing for more signal, a pyramid wavefront sensor is more sensitive in flux than a Shack-Hartmann wavefront sensor. Therefore, the limiting magnitude would also increase and hence the sky coverage through use of a pyramid wavefront sensor.

The final step to converting the testbed into a facility class instrument is to create motor control systems for P/C control and dithering. Currently, open loop control has an implementation of P/C using pico motors and simple Tcl/Tk GUI controls. These motors could be combined with the existing POCO telescope control software in conjunction with the dither algorithms already in use with the Shane 3-meter LickAO system. This quick change would enable full dithering and P/C control[12]

The final and most fruitful step for science conversion would be to leverage all that was learned from the Nickel 1-meter telescope to create a new system or redesigned the ViLLaGEs system for the Shane 3-meter telescope. Several opto-mechanical changes and software changes would be required but are low risk changes over the total scope of the ViLLaGEs project.

The principal elements in a 3-meter redesign would be changing the lenslet array, DM and realtime code. The current lenslet assumes 10 cm sub apertures and the Shane system would most likely retain the 10 cm size requiring a different lenslet array. For the DM to retain its high order correction the 140 actuator Boston MEMs would be exchanged for the 1000 actuator Boston MEMs. Three VME boards would be added and additional memory would also be required. The real time control code would also have to change in order to handle the new lenslet array, DM and VME boards. The real time code change would require the largest portion of time, but since the design is very scalable, it would require about three man-weeks. A new scale factor for tip tilt offloading to the telescope would be necessary, and debugging could add several more weeks.

The required T/T guide star magnitude for a 3-m AO system operating at bluer wavelengths can be scaled from the current IR AO system on the Shane telescope. The current LGS T/T limiting magnitude is about R = 16 for minimum correction in K-band. Fixing the required residual T/T correction error (wavefront equivalent in nm) to be the same fraction of a radian as in K-band implies that the number of photons from the T/T star go as the science wavelength squared. Thus a 3-m conversion requires a T/T magnitude of R = 14.0 for science in the visible bands (R-band) and R = 15.0 for science in the near-IR bands (J-K bands).

A 3-meter conversion would put the system at a LGS T/T limiting magnitude of about 16^{th} magnitude (with slightly reduced correction). This is three magnitudes better than the 1-meter. A similar conversion could take place using the closed loop correction in place of the open loop but it would not have the additional advantage of having better correction in poorer seeing conditions[13,14].

5. CONCLUSIONS

The ViLLaGEs multi-arm optical design is a revolutionary attempt to multiplex several functions onto a single lenslet array and Hartmann CCD. With this design, it is possible to compare closed- and open- loop performance in real time, while setting aside camera pixels for rapid centroiding of a tip/tilt star for LGS mode. These multiple arms are coupled by few optics, so simultaneous alignment is simplified in this inexpensive design.

After a rapid Integration and Testing phase in the Lab for Adaptive Optics at UCSC, ViLLaGEs was assembled and delivered to the Nickel Telescope at Lick Observatory on Mt. Hamilton. It saw first light in October of 2007. As is common with testbeds, almost immediately it was expected to perform beyond its original requirements and did so exceptionally. It will continue to perform as a testbed through fall 2009. During this period, it will test LGS modes, open loop control, pyramid wavefront sensing, and explore the limits of closed loop NGS performance acquiring science data when possible. As these tests are carried out, the future of Lick Observatory's next generation AO system will become more certain with many new technologies and techniques developed with ViLLaGEs.

6. ACKNOWLEDGEMENTS

This work is supported by the Gordon and Betty Moore Foundation through their generous grant forming the Laboratory for Adaptive Optics at U.C. Santa Cruz. The work of graduate student Katie Morzinski was supported under the Michelson Graduate Fellowship for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the United States Government under a Prime Contract between the California Institute of Technology and NASA. Additional support was provided by a minigrant from the Institute of Geophysics and Planetary Physics through Lawrence Livermore National Laboratory. This research was supported in part by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST-9876783, and directed by Claire E. Max. Ammons acknowledges the support of the Allen family through UCO/Lick. This work was also performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

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