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Use of Failure Modes and Effects Analysis in Design of the Tracker System for the HET Wide-field Upgrade

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ABSTRACT

In support of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), the Center for Electromechanics at The University of Texas at Austin was tasked with developing the new Tracker and control system to support the HETDEX Wide-Field Upgrade. The tracker carries the 3,100 kg Prime Focus Instrument Package and Wide Field Corrector approximately 13 m above the 10 m diameter primary mirror. Its safe and reliable operation by a sophisticated control system, over a 20 year life time is a paramount requirement for the project. To account for all potential failures and potential hazards, to both the equipment and personnel involved, an extensive Failure Modes and Effects Analysis (FMEA) was completed early in the project. This task required participation of all the stakeholders over a multi-day meeting with numerous follow up exchanges. The event drove a number of significant design decisions and requirements that might not have been identified this early in the project without this process. The result is a system that has multiple layers of active and passive safety systems to protect the tens of millions of dollars of hardware involved and the people who operate it. This paper will describe the background of the FMEA process, how it was utilized on HETDEX, the critical outcomes, how the required safety systems were implemented, and how they have worked in operation. It should be of interest to engineers, designers, and managers engaging in complex multi-disciplinary and parallel engineering projects that involve automated hardware and control systems with potentially hazardous operating scenarios.

Keywords: Hobby-Eberly Telescope, FMEA, HET, HETDEX, wide field corrector, tracker, constant force drive, hardware fault controller, Center for Electromechanics, CEM, McDonald Observatory

1. INTRODUCTION

The HET (Figure 1) is the largest telescope at The University of Texas' McDonald Observatory located on Mt. Fowlkes in the Davis Mountain Range in West Texas. A joint venture with The University of Texas, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen, the HET has been conducting science operations since October, 1999[1,2]. The HET support structure and primary mirror sits at a fixed zenith angle of 35° and can move in azimuth to access approximately 70% of the visible sky. The primary mirror, constructed of 91 identical hexagonal segments, forms an 11 m hexagonal-shaped spherical mirror with a 26,164 mm radius of curvature. The tracker is mounted above the primary mirror on the upper-most portion of the telescope, termed the upper hexagon or "upper hex" for short. The corrector optics mount to the tracker and are positioned via two linear drive systems and a six degree of freedom (DOF) hexapod maintaining the instruments' optical axis normal to and on the focal sphere of the primary mirror.

The Hobby-Eberly Telescope (HET) is currently undergoing a major redesign effort in preparation for the Dark Energy Experiment[3,4]. The upgrade, referred to as HETDEX, involves replacing the current star tracker along with its drive systems. The catalyst for the replacement of this hardware is the wide field upgrade to the corrector optics. Replacing the current spherical aberration corrector (SAC) with the wide field corrector[5] (WFC) will increase the HET field of view from 4' to 22'. In addition, the current science instruments are not in general being replaced. HRS (high resolution

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spectrograph) and MRS (medium resolution spectrograph) will be re-installed as is. LRS (low resolution spectrograph) will be replaced with a new instrument, LRS2. VIRUS (Visible Integral-field Replicable Unit Spectrograph) is being added to the current suite of instruments. These changes will allow the telescope to conduct the largest survey of distant galaxies ever attempted.

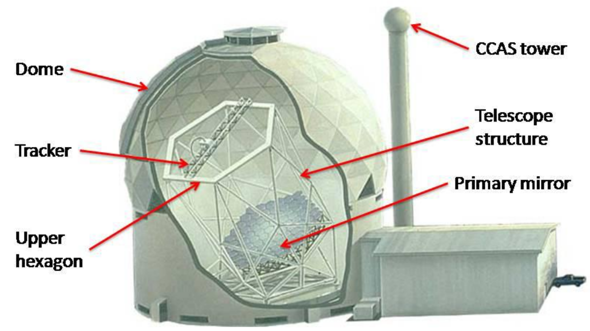

Figure 1. The figure on the left shows an aerial view of the HET with the shutter open. The computer rendering on the right reveals the major components of the telescope.

The primary impact to the HETDEX tracker caused by the replacement of the corrector optics is the approximately seven fold increase in mass of the instruments and supporting hardware. As a result, the HETDEX tracker mass increased on the order of about five times that of the HET tracker.

2. PURPOSE OF FMEA

FMEA, sometimes also referred to a as FMECA (Failure Modes and Effects Critical Analysis) is a definitive method for assessing and quantifying the potential effects of a failure in a system or process. First used by the U.S. Army, and later implemented by NASA and the aviation industry, FMEA relies on bringing together a wide range of interests to describe and assess risk in a methodical process.

The HETDEX project is a complex system that costs tens of millions of dollars and many years to complete. The tracker system (Figure 2) with its wide field corrector cost in excess of $10M and will occupy a facility, the HET, that also costs many millions of dollars and would be difficult to replace. Safety of the hardware and the continued operation of the system are second only to the safety of the staff involved in the day-to-day operation of the system. The HETDEX tracker was designed to be safe. There are multiple layers of hardware and software safety devices to force a shutdown if an unsafe condition is imminent, along with numerous emergency stop buttons that an operator can access in the event of a pending failure. FMEA was added as an additional process to assure that the system was being designed to be as safe as practically possible. Conducting an FMEA early in the design allowed The University of Texas team to identify potential failures, assess their impact, and develop mitigation strategies before the design was finalized. This study was primarily focused on hardware since software modifications can be implemented later in the design process.

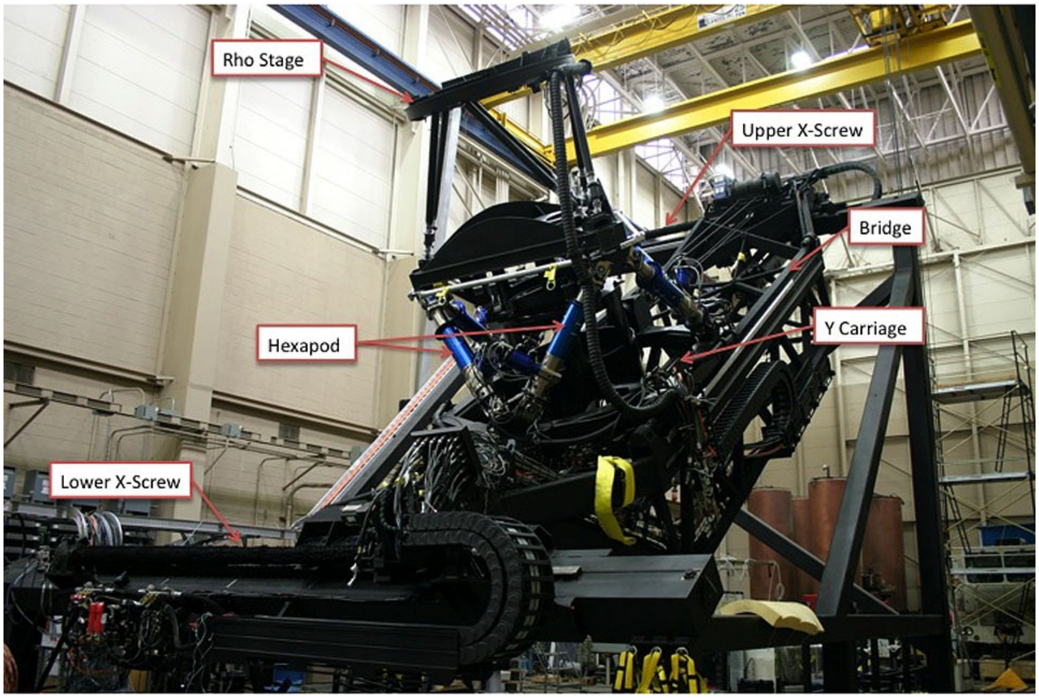

Figure 2. HETDEX tracker in CEM's lab showing the key elements of the system.

3. HOW FMEA WAS IMPLEMENTED ON HETDEX

There are a number of methods for implementing a FMEA depending on the type of project or process that is being analyzed. For the HETDEX tracker project the team utilized a hybrid approach that was tailored to addressing a complex electromechanical system. The process focused on assuring that the hardware was being developed in a manner that would assure its safe operation and the safety of the personnel over the projected twenty year life of the project. The graphic in figure 3 describes the FMEA process at the highest level. This process in more fully defined in a number of texts and technical papers[6,7,8] as a component of continuous risk management. For the HETDEX tracker project the first four steps were completed by project management. These included: selecting the tracker system; defining safety and reliability as the problems of interest; defining the type of FEMA approach to use; and dividing the tracker into logical subsystems. These tasks are much less subjective, and required less outside input, than tasks 5, 6, and 7 which are the true "heart" of the process and will be expanded on in this paper.

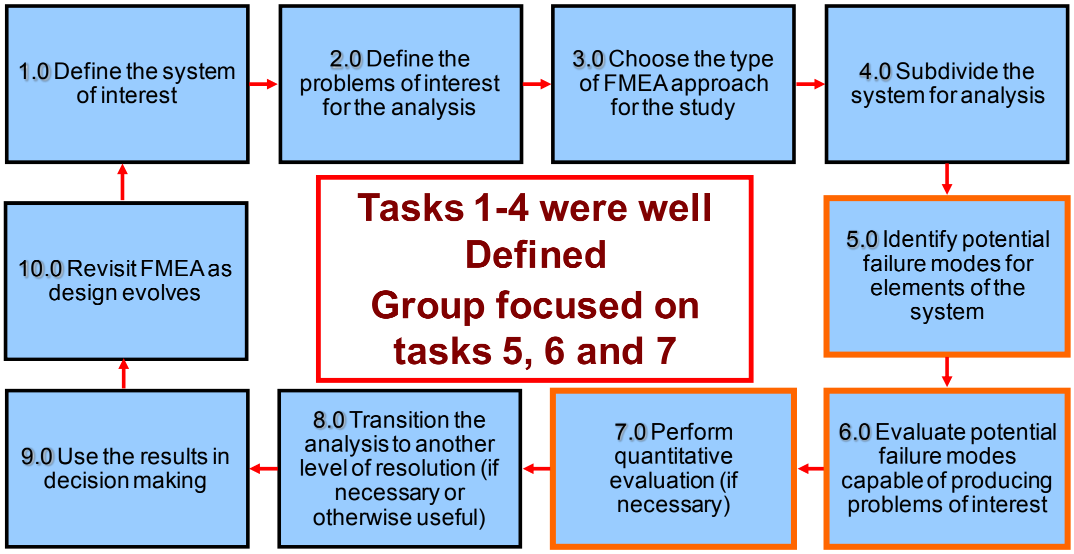

Figure 3. Critical steps in FMEA process.

To complete tasks 5, 6, and 7 representatives from every area of the HETDEX project were brought together over a two day time period. This included program managers, systems engineers, design engineers (mechanical, electrical, and controls), telescope operators, astronomers, and technicians. It was critical to have this entire team together in one place to assure all of the potential failures would be identified and evaluated with every stake holder present. This was particularly true during the evaluation process. During the Failure Identification phase, fifteen major subsystems were discussed and each team member was asked to identify every potential failure they could imagine for each subsystem. Once each team member had made their individual list, all of the potential failures were documented in a spreadsheet and redundant failures were combined. For each potential failure mode there was an associated set of potential effects that could result from the failure. Each of these distinct pairs of failures and effects typically had multiple potential causes. The failures, effects, and list of causes were then assessed and agreed to by the larger group. An example of a potential failure, its associated effects, and how it is described in the FMEA process in shown in Figure 4.

Item	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Cause/ Mechanisms of Failure	Occurrence	Current Design Controls Prevent/Detect	Detection	RPN	Recommended Actions
2.1	Tracker bridge exceeds all travel limits and decouples from upper hexagon structure.	Damage to tracker bridge, telescope structure, mirrors and possibly to staff.	5						
2.1.1				Accidental power up of drive motors	3	- Drive motors can only be powered up if both Tracker Computer (TC) and Telescope Control System (TCS) agree (presumed) - TCS detects out of bounds following error and commands shutdown (would not apply if this is not tracking event) - Software limits prevent tracker from exceeding travel limits	1	15	Implement torque limiting device in drive system. TBD as to whether this is electrical or mechanical device.

Figure 4. Example of a potential failure and how it is defined in the FMEA process.

In some risk management strategies the next step in the process would have been the development of mitigation strategies for each of the "significant" failures. What sets the FMEA process apart is a method for quantifying the impact/severity of each failure, the likelihood of occurrence, and the likelihood of detection before causing damage. Each project will have its own set of parameters for quantifying each of these items. The parameters used for the HETDEX tracker are shown in Figures 5, 6 and 7.

This part of the process generated a great deal of discussion as different stakeholders and different disciplines would at times assign different values to each risk category. However, as a group, the team agreed to take a very conservative approach and typically used the highest reasonable value in each category. Once all of the potential failures and causes had been quantified a Risk Priority Number (RPN) was calculated by multiplying the agreed to level of severity by the likelihood of occurrence by the likelihood of detection.

At the end of the process over 200 unique failures and causes had been identified and assessed, with 30 of those deemed as having a combined RPN of 27. The team deemed items with a RPN of 27 as sufficiently significant to require action and assigned an engineer to develop remediation plans for each of those items. In many cases these mitigation plans also addressed other related items with lower RPNs and, where it was cost effective, mitigation plans were developed for additional items with lower RPNs as well. A discussion of some of the more critical outcomes of this process and how it affected HETDEX is included in the following sections.

	Characterized by Either			
Severity	Safety	Operational	Repair Costs	Rating
Catastrophic	Death or major injury	Facility shutdown exceeding 60 days	In excess of $1M	5
Critical	Severe injury	Facility inoperable for 5-60 days	Between $100K and $1M	4
Moderate	Lost time injury	Significantly reduced capabablity or loss of operation for 1-5 days	Between $10K and $100K	3
Minor	Injury treated on site	Degraded or loss of operation for < a day	Less than $10K	2
Negligible	No injury	No significant affect on operations	No significant costs	1

Figure 5. Severity rating chart developed for HETDEX Tracker.

Likelihood Failure Will Occur	Over 20 Year Life	Rating
Very Likely	Greater than 1 per month	5
Likely	1 per year	4
Moderately Likely	1 per 5 years	3
Unlikely	1 per 20 years	2
Very Unlikely	Less than 1 per 20 years	1

Figure 6. Likelihood of occurrence rating chart developed for HETDEX Tracker.

Detection	Description	Rating
Very Unlikely	Very low or zero (<1%) chance that cause will be detected in time to prevent failure.	5
Unlikely	Low (1-10%) chance that cause will be detected in time to prevent failure.	4
Moderate Chance	Moderate(10-50%) chance that cause will be detected in time to prevent failure.	3
Likely	Likely (50-95%) chance that cause will be detected in time to prevent failure.	2
Very Likely	Very Likely (>95%) chance that cause will be detected in time to prevent failure.	1

Figure 7. Likelihood of failure detection rating chart developed for HETDEX Tracker.

4. CRITICAL OUTCOMES OF HETDEX FMEA

As noted in the previous section, 30 failures and causes resulted in a RPN of 27 or more. A number of these were related or could be addressed by a single design modification. The following items illustrate some of the more significant design changes resulting from the FMEA.

4.1 Torque Limiting Drive Motors

The HETDEX X-Drive system[9] utilizes two individual screw drives at the top and bottom of the upper hex to control tracker motion along the x-axis. This requires close coordination of the drives both in track and slew. From a safety aspect, this is also critical. If the two drives are not coordinated the tracker can skew. If skew becomes extreme, the tracker could potentially fall from the upper hex onto the mirror. There were a number of safety processes already in place to prevent skew including: software continuously monitoring skew using two independent measurements; redundant skew limit switches to measure skew directly and force a hardware shutdown; and structural steel brackets to prevent the tracker from exceeding its skew limits if the other safety systems failed. With all of these safety systems in place, the RPN for an extreme skew event occurring was rated at 20, below the threshold of 30. However because the consequences of this event if it does occur were so disastrous the team agreed to add one more layer of protection with the addition of torque limiting devices on the tracking drive motors. Torque limits were implemented as a part of the software in the servo drive system to limit the total current available to the motor as sufficient to complete all anticipated operations with an overhead of approximately 25%. Mechanical torque couplings (Figure 8) were also implemented between the track motors and the drive screw to provide a similar limit. These couplings disengage the drives when their torque limit is exceeded. Proximity sensors monitor the state of these couplings and in the event of an over-torque condition signal the controller to disable the high voltage contactors from the servo amplifiers and engage the brakes. The implementation of the torque limiters had the advantage of also addressing a number of other potential hazards, which while not likely or catastrophic, could damage the system and cause significant downtime.

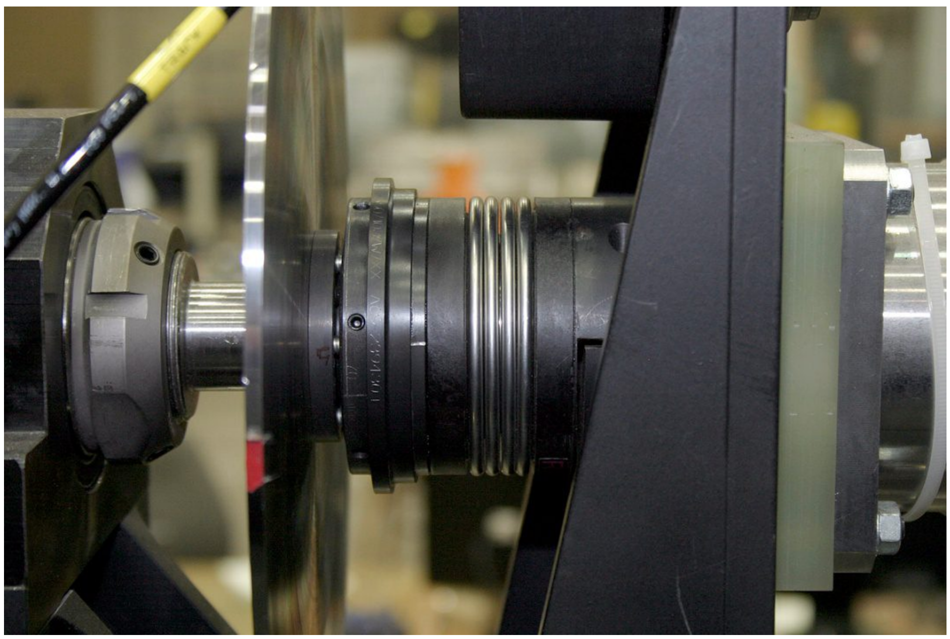

Figure 8. Torque limiter in lower X-Track Drive

4.2 Wide Field Corrector Clearance

The tracker's primary function is to carry and position the Wide Field Corrector (WFC), an approximately $4M optical system that was sometimes referred to during this study as the "crown jewels" of HETDEX. The WFC is highly sensitive to impacts and every effort was made to assure that it is not possible during normal, and even abnormal operation, for the WFC to contact any other hardware. This is complicated by the fact that the WFC is carried by a hexapod with a necessarily wide range of motion (±9° and roughly 300 mm along the Z axis)[10,11]. While the hexapod has software limits to keep its motion within a safe range there was no absolute method in place to guarantee an impact could not occur if the control system failed. While additional limit switches were investigated, no system that relied on software was deemed adequate. The final resolution for the issue was to: provide sufficient clearance in the design for the WFC from all hardware under all possible hexapod positions; verify the clearance through the use of software animation[12] (Figure 9); and test the hardware at extreme positions using a "dummy" WFC that matched the actual WFC in shape and mass.

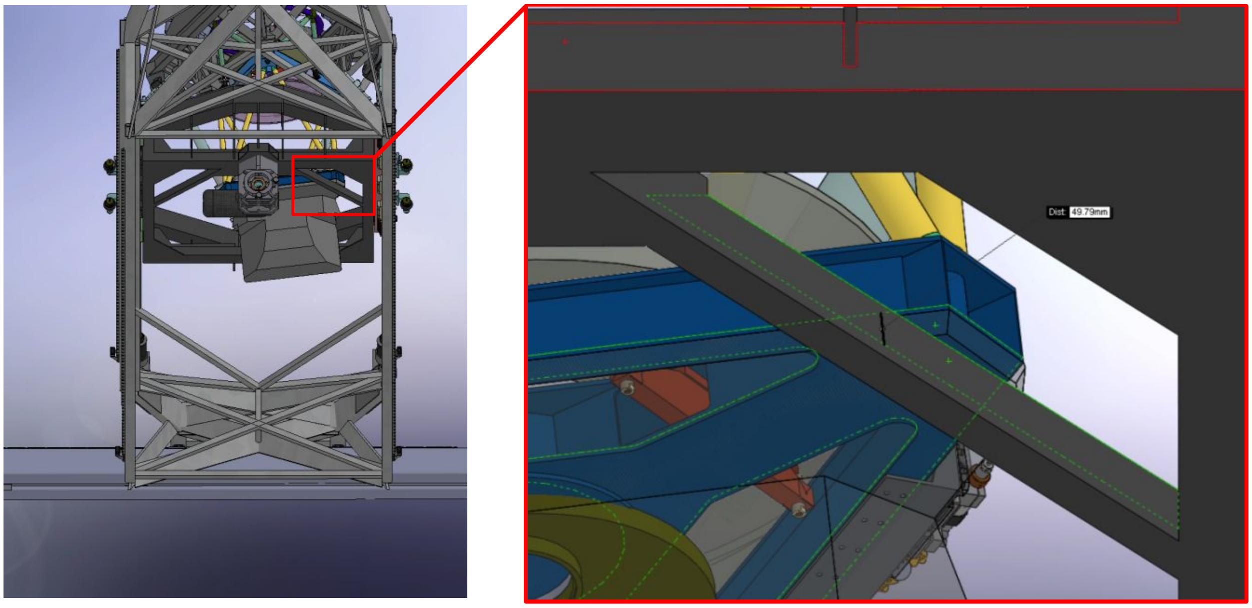

Figure 9. Example of modeling to verify WFC clearance to carriage.

4.3 Constant Force Drive

The failure that probably generated the most concern among the team was the potential for the carriage, which carries the hexapod, WFC, and PFIP to experience an uncontrolled descent down the trackers 35^{o} incline. This was deemed a highly likely and potentially catastrophic failure because similar events had occurred both on the HET and at SALT (Southern African Large Telescope) previously. The reason for the high likelihood is that the Y-drive actually consists of two drive motors, the track and the slew, and two sets of brakes to control which system is active. The control system must switch between these two motor and brake combinations multiple times each night, and if both brakes are off at any time an uncontrolled descent can occur. There is no reasonable option for stopping the 3,100 kg payload once it has slid even a meter, uncontrolled, without damaging the WFC. The best option is to not let it ever exceed the peak operating velocity of 80 mm/s. While software limits were in place to accomplish that already using two independent speed sensors, this was not deemed adequate. Initially the team decided to use an "elevator brake" type system that would incorporate a mechanical brake on the Y-bearing rails with an independent speed sensing system. However after significant review of this design it was decided that a system that was "always on" would be preferred due to concerns about testing the "elevator brake" on a regular basis. The system selected was a constant force drive (Figure 10) and based on a similar system at SALT. The SALT system was actually developed to reduce the loading on the Y-drive but experience has shown it to be a reliable safety device as well. As noted, one advantage of the constant force drive (CFD)[13] is that it is always on, applying a constant "uphill" force to the carriage, and reducing the load required from the Y-drive motors. If a brake or motor, or screw fails, the CFD is already taking a significant portion of the load and when that load increases it will trigger one or both of the CFD's integral braking systems. It is worth noting that the addition of the CFD, while one of the most significant outcomes of the FMEA, was also one of the most cumbersome to implement. However, it has now been thoroughly tested in the lab and has worked safely and reliably to date.

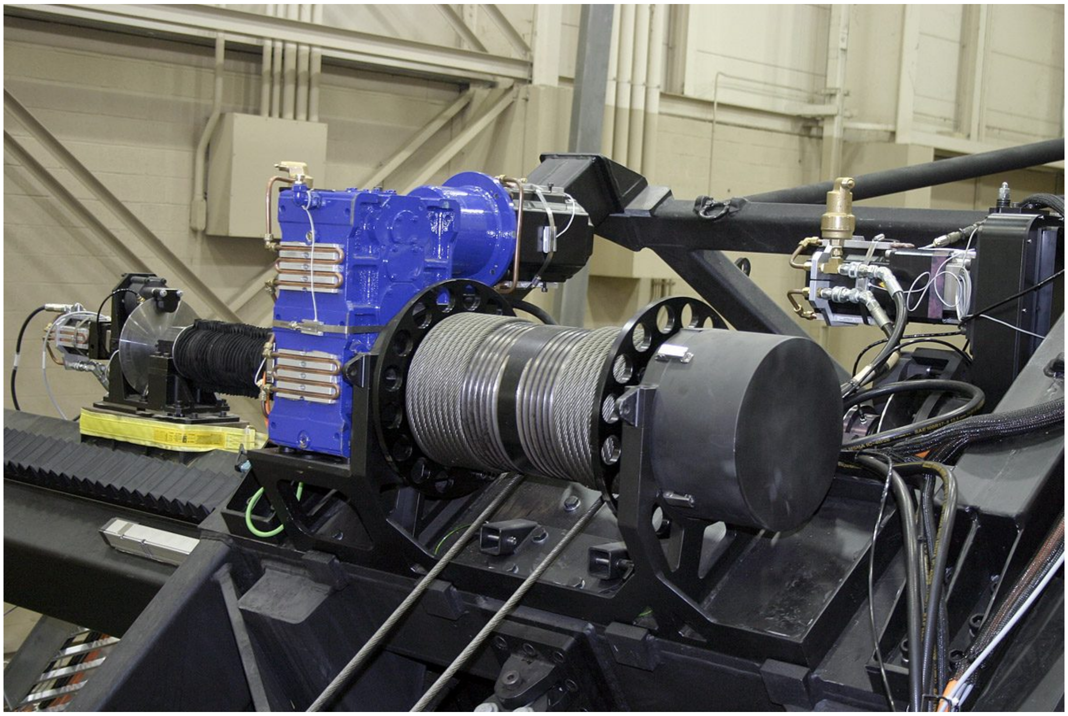

Figure 10. Constant force drive system and gear box.

4.4 Hardware Fault Controller

The FMEA, as previously stated, was focused on hardware but a number of top level software concerns were raised and ultimately addressed during the FMEA process. These were addressed as a group with the implementation of a single component, the Hardware Fault Controller (HFC)[14,15]. The HFC (Figure 11) is an independent safety/control system that operates in parallel with the tracker control system. It can manage up to 96 digital signals, four analogue inputs, and incorporates two analogue outputs. Its sole purpose is to react to inputs from the critical sensors and load cells on the tracker and to shut the system down if preset limits are exceeded. It serves as a critical safety system for all of the primary drive systems and subsystems. One significant feature that sets the HFC apart from software based safety systems on the tracker is that it cannot be overridden or bypassed inadvertently. To modify a parameter, such as a limit set point, requires completing a series of specific steps through an additional layer of software, whereas similar modifications in the normal control system can be made from the operator's console. This assures that the HFC is not accidently modified and not recognized until a failure occurs. When the normal tracker controls are set and working properly the HFC does nothing. It is only when those controls have failed to catch an error that the HFC forces a shutdown.

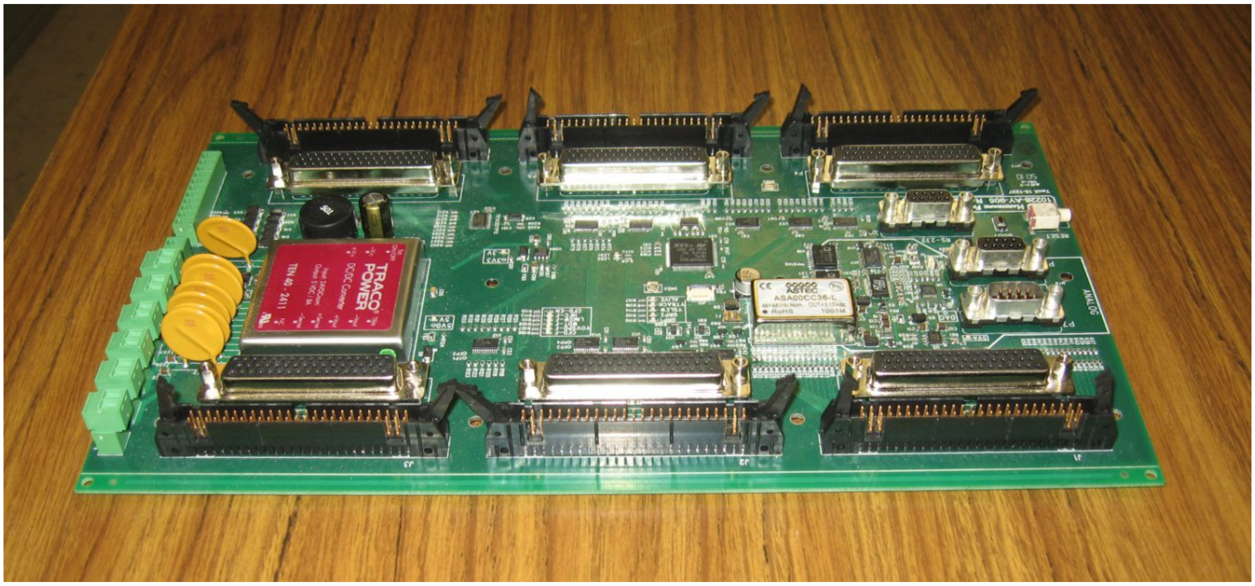

Figure 11. Hardware fault controller board.

4.5 Extensive Laboratory Testing

While it does not address a single defined failure, it perhaps addresses the biggest concern of all by the team, the failure no one identified during the FMEA. The tracker is a entirely new, complex mechatronic system with an entire new software and control system. Much of the hardware cannot be tested until it is fully assembled in the lab. The unexpected should be expected. Testing in a controlled laboratory environment at UT's Center for Electromechanics had already been planned prior to conducting the FMEA, but the FMEA process highlighted how important this was to the success of the project in order to allow the team to "work the bugs out" without all the high value optics in place and with more sets of trained eyes watching the operation. To reflect as much realism as possible in the lab the system has been installed on the identical set of bearing rails with all the actual sensors that will be used at the HET on a test stand sitting at the required 35^{o}. This is a significant effort, and incurred a significant cost, considering that the tracker system weighs in excess of 19,000 kg[16]. Again to reflect realism, the system includes test masses to replicate the Wide Field Corrector size and weight. While this is a costly effort it will ultimately save the program many weeks of downtime after installation and allow the current HET to continue current science operations for a longer period of time.

5. RESULTS IN THE LAB

While many of the changes resulting from the FEMA may never be fully tested due to the primary safety systems that will catch failures before they progress any further, some of the FEMA related changes have already been tested in the lab, typically intentionally. In most cases these have pointed out the benefit of the modification but in some cases, where the modification or existing safety system, did not work quite as expected they pointed out the benefit of more lab testing. It is also worth noting that many of the potential failures the FMEA was designed to address were only anticipated to occur once or twice in the system's 20 year life so it is unlikely that they will ever be seen in laboratory testing.

5.1 Torque Settings

One of the first issues identified during HETDEX tracker testing was an inability to slew in X at full design speed under cold weather conditions. This was observed initially on a very cold day when the laboratory heating system failed. Tracker operation was sluggish along the X-axis and this was traced back to several factors including the increased grease viscosity as temperature decreased and a higher than anticipated preload on the drive nut. This required several changes to the drive system including a resetting of the torque limiters on the X-drive. These changes have all been tested now, under cold weather conditions and are all working properly.

5.2 Wide Field Corrector Clearance

Wide Field Corrector (WFC) clearance has been verified in CEM's lab with all of the actual hardware and the WFC test mass which replicates the mass and shape of the actual WFC. The clearance testing closely matches the modeling done in SolidWorks with adequate clearance in all areas while moving the hexapod to its most extreme positions. Clearance will be re-verified in the future if additional hardware is added to this area.

5.3 Constant Force Drive

A unique aspect of the constant force drive (CFD) is that it is always on if the tracker is powered up. It is critical to good performance on the Y-Drive and safe operation of the system. For these reasons, it was tested very early in the project and has been tested intentionally many times since. This is something that the operators rely on to prevent runaway conditions as the brakes and Y drive systems are tested and it has worked very well to date. It has also been noted during testing, that due to friction in the drive system and the gear ratios, an actual free fall is less likely than originally anticipated. The CFD has performed flawlessly as a safety device although it does add complications to the control system due to now having two passive forces acting in opposite directions (gravity and the CFD), and one active force controlling the Y drive motion.

5.4 Hardware Fault Controller

Like the CFD, the hardware fault controller (HFC) is always on. While certain sensors that were not in place initially (motor temperatures being one example) could be bypassed, once a sensor was installed and connected to the HFC it was continuously monitored. Monitoring approximately 100 sensors continuously has taken considerable effort to get all parameters set and all sensors properly configured to assure a shutdown is always triggered when required, but never prematurely. This process has been made more cumbersome because the HFC was designed to be hard to modify. Once everything is set correctly and all systems are functioning properly very few events trigger the HFC.

5.5 Laboratory Testing

Without a doubt, the lab testing has been invaluable and has taught the team a great deal about how to safely operate the system. While there have been no significant failures that resulted in harm to the hardware or personnel, there have been hundreds of lessons learned related to making the system safer, and more reliable. Several of those have been related to the CFD, HFC, and the drive motors as noted previously. The motion control system has probably benefited the most from lab testing, as this has enabled all the many interfaces and software development steps to be checked out in a safe environment with no impact on day to day telescope operations. Another huge benefit of building the complete system in CEM's lab is that it allowed the team to test and modify all the assembly processes as the system went together. Many key processes including: the bridge installation; hexapod assembly; Y-drive installation; and the WFC installation, were much lower risk to install in the lab the first time and the team benefitted greatly from this experience.

6. CONCLUSIONS

The FMEA process has worked very well for the HETDEX project. Over 200 separate failure-cause relationships were identified in 15 distinct component groups. Based on the quantitative FMEA process, 30 of these received a sufficient priority rating to require development of mitigation strategies. The process is important when attempting to understand and quantify the risks associated with a large, technically complex project where engineers and scientists from multiple disciplines must work together. Completing the FMEA process, early in the design of the HETDEX tracker, was very beneficial and resulted in a number of changes to the design which has enhanced the safety and reliability of the system. While several of these did add significant cost to the project, they have resulted in a system that will be safer and lower cost over its entire operational life. Several important lessons were learned as a result of conducting this analysis. It is critical to have all the stakeholders in the project involved. Every team member involved in the process, from the program manager, to the technicians in charge of maintaining the system, made very valuable contributions based on their singular experience and insight. Conducting the analysis early in the design process and updating it, as changes are made, results in the safest design and the highest value from the process. Conducting the process early, also allowed changes to be made to the design before hardware was in process and prevented expensive modifications. It also made the team aware, at a very early stage, of all the safety issues and reinforced the requirements for each of those systems. Future major telescope efforts and upgrades should consider conducting a FMEA during their design phase. It is a cost effective method to enhance any project.

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