NISTIR 7309

Automation and Upgrade of the 27.1 kN (6100 lbf) Dead Weight Machine at the National Institute of Standards and Technology

Kevin Chesnutwood, Samuel Ho, April 2006

This paper focuses on the automation and upgrades performed on the 27.1 kN (6100 lbf) dead weight machine located at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. Of the six dead weight machines maintained at NIST, this was the only machine that was not automated under the original automation program in the 1980s. The new automation approach, which incorporates the latest available technology, is detailed and compared to the original automation systems used on the other five dead weight machines.

1. Introduction

The National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland maintains six dead weight machines ranging from 2.2 kN (505 lbf) to 4.448 MN (1000 klbf) which act as primary force standards for calibrating elastic force-measuring devices such as load cells and proving rings [1]. The machines were built in the early 1960s and were designed for manual control by an operator who would oversee the movements and functions necessary to perform dead weight calibration procedures. However, in the mid 1980s, five of the six dead weight machines were automated to perform a large portion of the calibration procedure without an operator present [2]. Unfortunately at the time, the 27.1 kN machine was not automated, partly because the machine would require the most complex automation system of the six dead weight machines at NIST due to the large number of weights and configurations involved.

This paper discusses the automation process of this machine and how the new approach utilizes numerous current technologies that overcome several pitfalls encountered on the original machine automations completed nearly 20 years ago. Section 2 provides operating details and pictures of the machine and explains how the force is applied to a force measuring device. Section 3 examines the automation history and some of the technology used at the time the first machines were automated. Section 4 details the current approach used to automate the 27.1 kN dead weight machine and the subsystems that were upgraded and/or added to the machine. This section also highlights the improvements over the original automation systems. Section 5 concludes with recommendations on using the new automation system model for upgrading and improving the automation systems of the other five dead weight machines.

2. Description and Overview of the 27.1 kN Dead Weight Machine

The 27.1 kN dead weight machine consists of fifteen stainless steel weights. Their masses were adjusted to produce nominal force values for a given local acceleration of gravity and relative densities of air and stainless steel. One set of larger weights produces nominal forces in pounds-force (lbf). The other set contains smaller compensating weights which, when added in conjunction with the larger weights, produces an overall nominal force in kilogram-force (kgf). The weights can be individually loaded or unloaded from the load frame by closing switches which control 120 V solenoid-operated valves that cause the hydraulic cylinders to either raise or lower the weight onto the weight shaft. After the necessary weights are chosen, the force transducer is raised using two screw jacks, causing the calibrated weights to be applied to the force transducer under test. The load frame height (as it is raised or lowered by movement of the force transducer) is sensed using an optical sensor which will be discussed in more detail in Section 4. The force applied to the force transducer is equal to the sum of the weights selected (or loaded) plus the weight of the loading frame and weight shaft (which is 889.64 N (200 lbf) in this machine). Figures 1 and 2 illustrate the design of this type of machine.

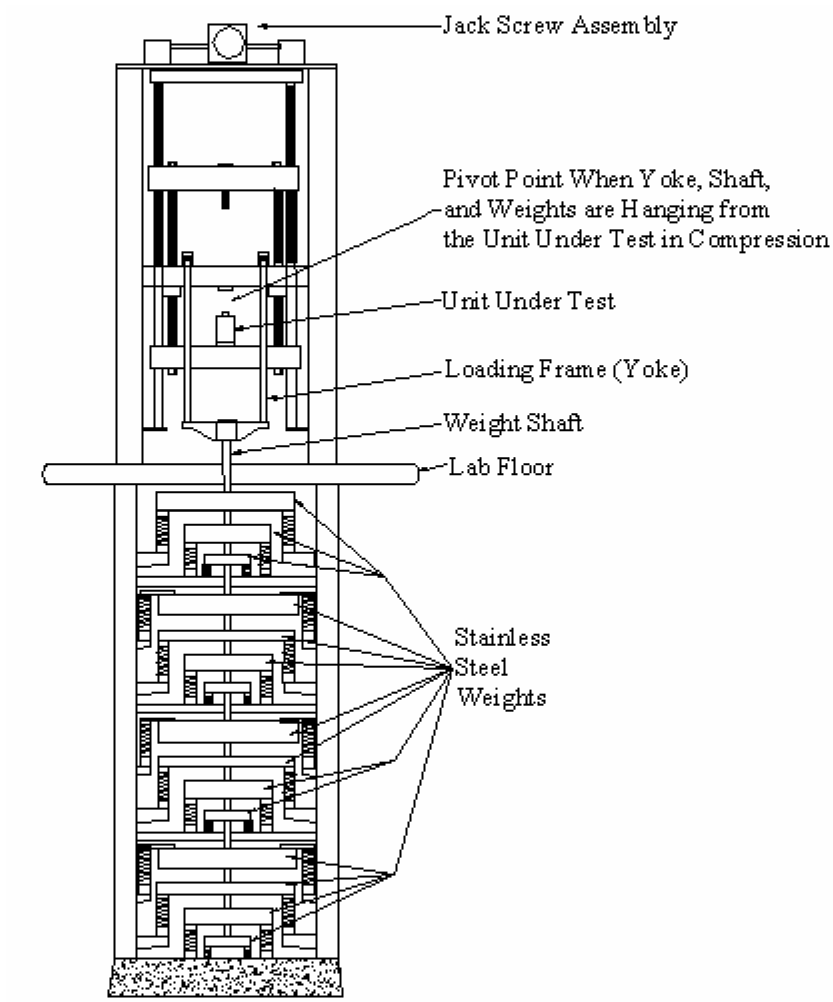


Figure 1. CAD model of the 27.1 kN (6.1 klbf) dead weight machine

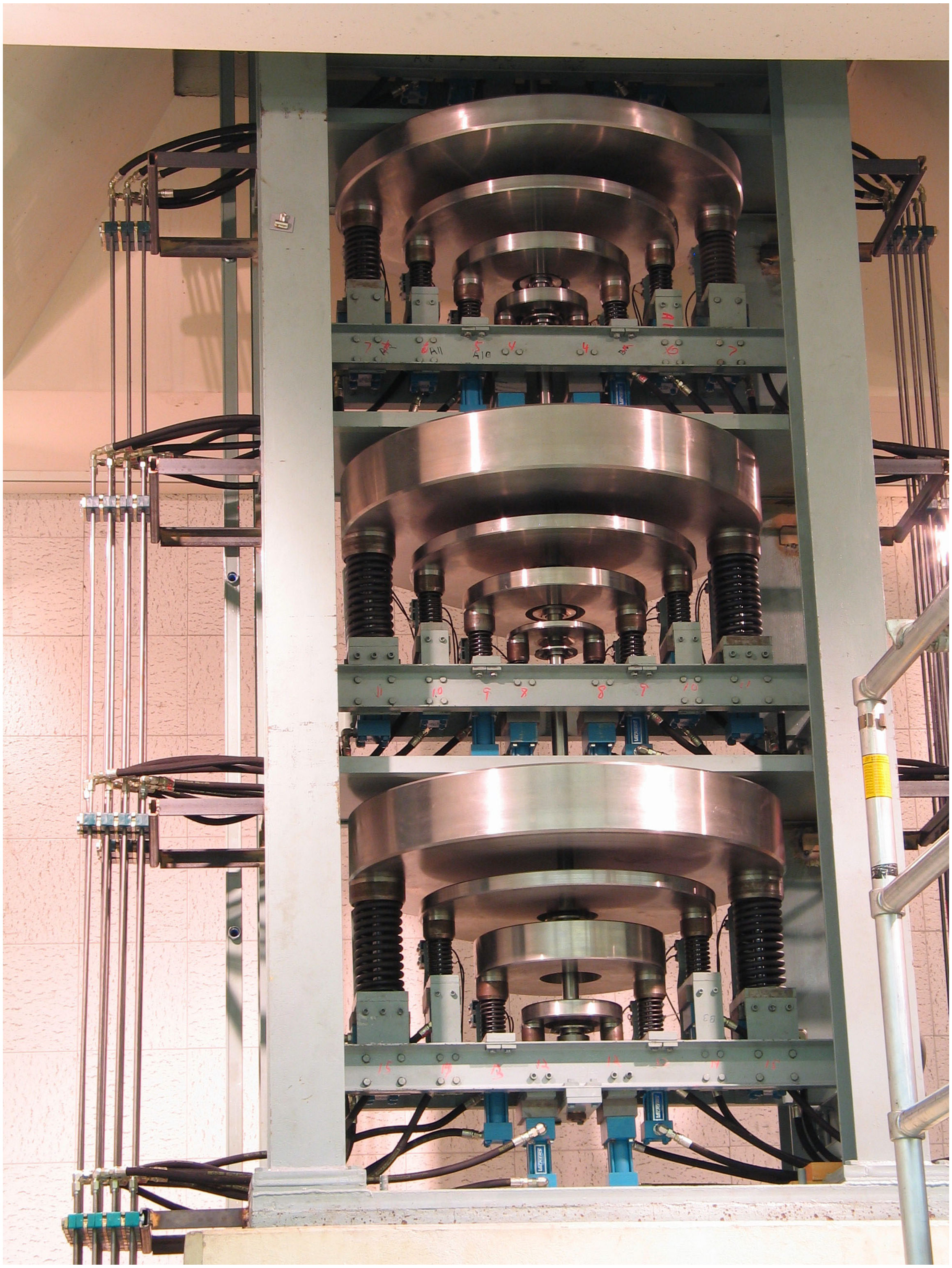


Figure 2. Photo showing most of the main weight stack of the 27.1 kN dead weight machine.

One limitation of this machine is that the weight frame was designed to be lowered to an unloaded state before a different combination of weights could be chosen and then reloaded onto the force transducer for additional measurements. Therefore, as originally designed, data normally taken to characterize the hysteresis behavior of a force transducer could not be acquired with this machine. Methods were eventually developed to allow some hysteresis data to be taken in the machine. However, it required tedious intervention from the operator and was not an ideal weight-changing environment. As part of the automation project, this limitation has been overcome and is discussed in Section 4.

3. Overview of the Technology Used in the Initial Automation Program

Of the six dead weight machines, two of the machines are of similar design to the 27.1 kN machine and were previously automated using similar approaches [2]. In summary, the machines are outfitted with a computer, data acquisition and control (DAC) unit, a custom relay board, and a high precision digital voltmeter (DVM). The DAC contains many card slots that allow for plug-in modules to control external devices, read thermocouples, and sense digital inputs. The computer and the DAC communicate to each other through the IEEE-488 bus. Turbo Pascal[1] is used for writing and compiling the control programs. The custom relay board uses optically isolated solid state relays that are connected in parallel with every switch on the console that an operator needs to use to control the deadweight machine. Figure 3 shows the operator console used to manually control the 27.1 kN dead weight machine in a manual state.

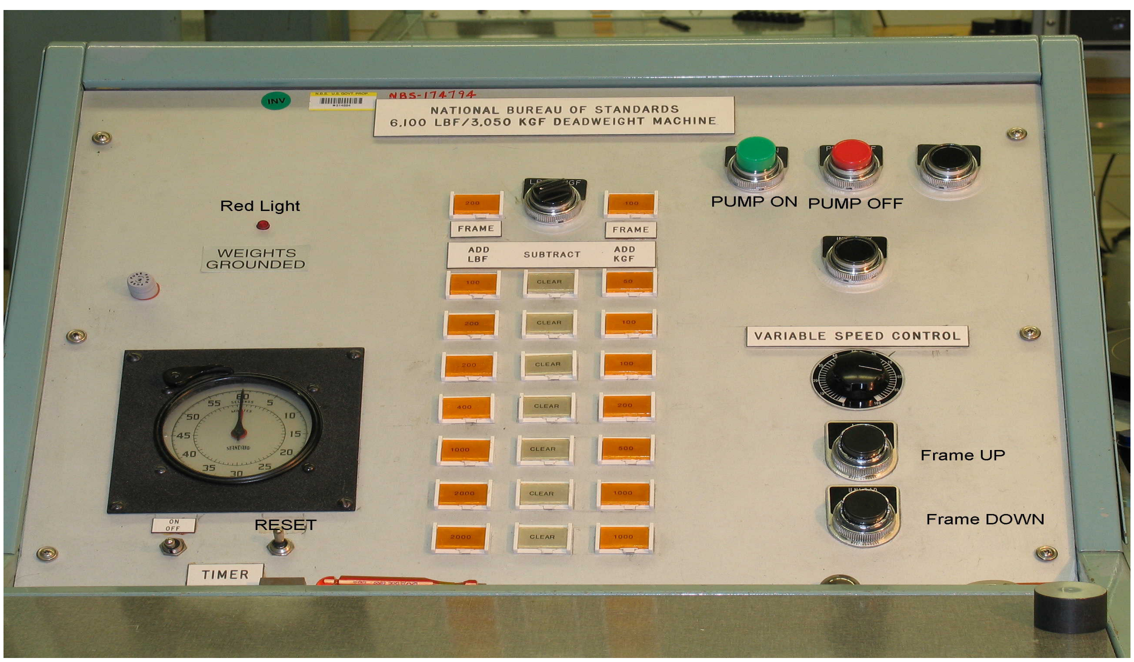


Figure 3. Manual operator controls on the console of the 27.1 kN dead weight machine.

[1] Certain commercial equipment, instruments, software, or materials are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

The push button switches on the control panel provide the momentary closing of the circuit necessary to send the AC voltage to the hydraulic solenoid and activate the proper cylinders. The manual push button switches also engage a parallel circuit that provides lighted indication of switch activity and subsequent weight status (loaded versus unloaded). The circuit for the switches operates at 24 V to power the incandescent lamps in the switches themselves. The lamp in each individual push button switch is energized or de-energized by two pairs of serial, mechanical contact switches that are located on the loading/unloading assembly. Therefore, weight positions can be monitored by the DAC using digital inputs that sense these limit switches. Thus, all actions normally done manually by an operator can now be replicated with full computer control.

The high precision digital voltmeter is interfaced to the computer through the IEEE-488 bus and is used to read the output signals from the Wheatstone bridge circuits used on many force measuring devices. The bridge excitation is commonly 10 V and the outputs are expressed as a ratio of the output voltage to the input voltage. After the force is applied to the force measuring device, a timed delay is executed and the computer takes the readings (ratios in V/V) from the DVM. Detailed information on this system and the uncertainty involved can be found in the paper "Uncertainty in NIST Force Measurements" by Thomas W. Bartel [3].

Using this system, the only time the operator has to intervene is to rotate the force measuring device in the dead weight machine as per ASTM 74-04[4] or to physically move the unit under test from compression mode to tension mode.

4. New Approach Used to Automate the 27.1 kN Dead Weight Machine

While some of the approach and operations of the newly automated 27.1 kN machine are similar to the machines automated nearly twenty years ago, there are significant changes and improvements to the newly automated machine.

First, the DAC system chosen simplifies the connection and interaction between the PC computer and the instrumentation board by using a single USB connection in place of the IEE-488 bus hardware [5]. The USB interface/controller board is significantly smaller and more compact, replacing the previous DAC package and allowing it to fit inside the existing control panel of the deadweight machine. The solid state relays and digital inputs are contained on three small boards (also located in the existing console) that allow for quick plug-in and simple customized configuration (digital input or digital output) of each channel being used. See Figure 4 for a photo of the final board assembly.

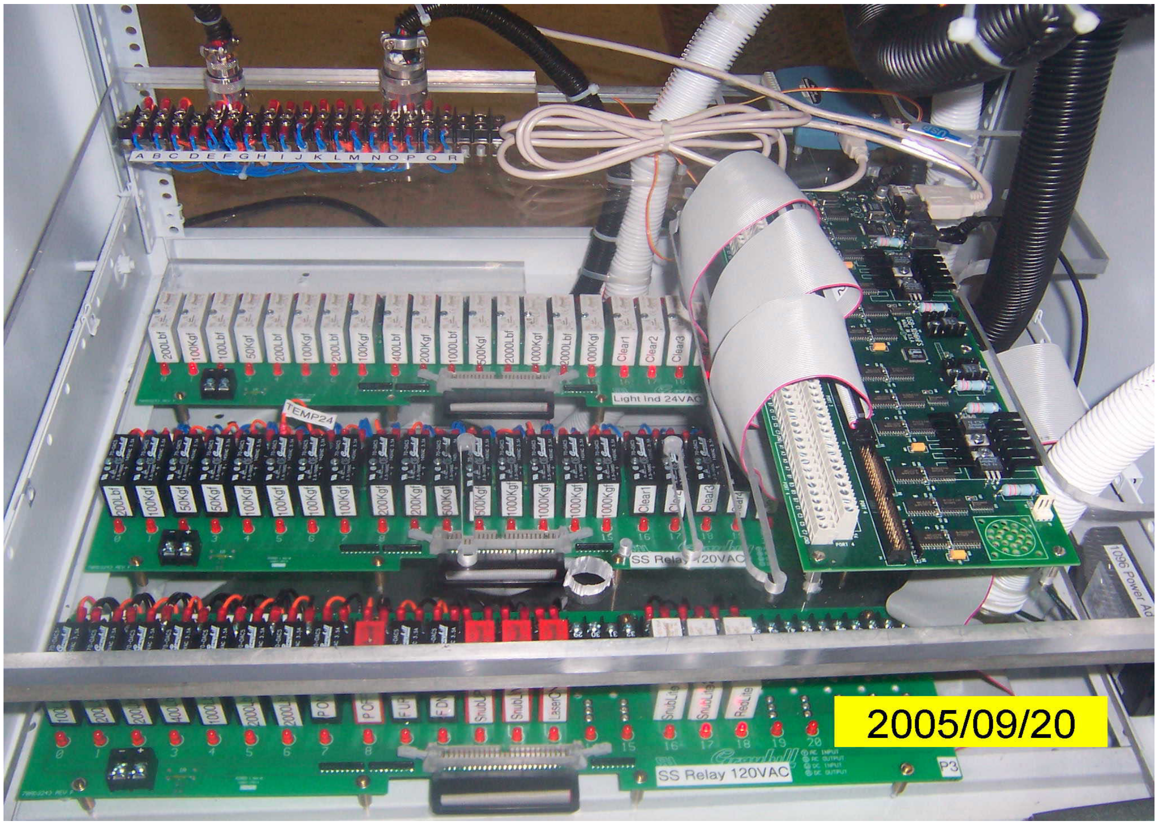
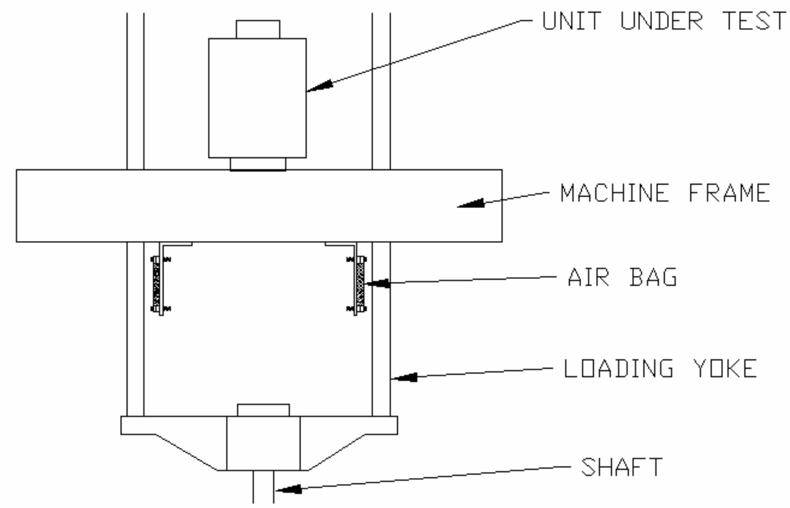
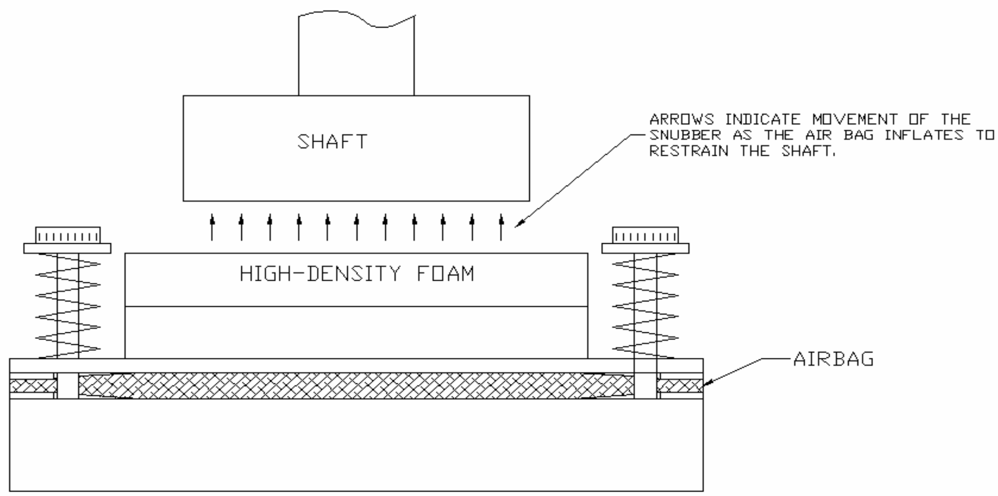


Figure 4. Photo of inside console showing the USB interface/control board (right) and the 3 relay boards (left).

Another major improvement is the capability to obtain hysteresis data in an automated fashion. As part of the earlier effort to automate the 112.5 kN dead weight machine, a method was devised to allow for hysteresis data to be taken using air pistons to stabilize the shaft during weight changes while the weight frame remained in a loaded condition. Unfortunately, as explored in the "Redesign of the 112.5 kN Dead Weight Machine Snubber System [6]," the system was not optimal and needed to be improved. As a fix to the problem in the 112.5 kN machine and a precursor to the automation of the 27.1 kN machine, a new system was designed that used air bags to hold the shaft in proper position while weights are being changed. The air bag concept was built, tested, and implemented as part of the existing automation system on the 112.5 kN machine. The paper listed above [6] goes into extensive detail regarding hysteresis measurements, the original piston snubber system, and the subsequent improvements made using the air bag snubber system. The success of the design led to the recommendation to apply a similar design to the 27.1 kN machine automation. The design was modified slightly (mostly due to space restrictions) and installed as part of this automation project. The airbags (3 total) operate using compressed air at a pressure between 68.9 kPa (10 psi) and 137.9 kPa (20 psi) and are inflated or deflated using two 12 V solenoid-operated air valves. Figures 5a and 5b show CAD models of the airbag snubbers and where they are located.



(a)



(b)

Figure 5. CAD model of the air bag snubber used (a) on the loading frame and (b) at the base of the machine.

Another improvement to the system is mostly attributed to advances in software and programming over the past few decades. LabVIEW [7] graphical programming software was chosen for user interface and automation control because of its intuitive processes in programming, ease of use in interfacing with various devices of different types, and the longevity and support of the software. The NIST 1.33 MN dead weight machine was the test bed for evaluating the software and learning techniques needed to ensure that custom programs could be written to interface and run the older automation hardware as well as any new equipment or interfaces. LabVIEW allows for a gradual changeover of our older systems to the newer ones, because it can be used efficiently with both systems, allowing them to co-exist if necessary during transition/verification. The new automation system for the 27.1 kN machine runs solely under LabVIEW.

The next improvement that this current automation project has over its predecessors is how the height of the loading frame is determined as it is loaded or unloaded. As mentioned earlier, the old system uses an optical sensor to indicate one of four frame positions; zero load, below target position, target position (loaded), above target position. A modified pointer assembly that visually indicates frame position to the operator was retrofitted with a metal bracket that strategically blocks the sensor's infrared light to correlate one of the four frame positions. Since the pointer assembly is part of the calibrated mass of the loading frame, one drawback of modifying the pointer assembly is having to perform a new mass calibration on the modified pieces. The mass of the new pointer assembly had to be unchanged from that of the original pointer assembly. In order to avoid this scenario, a different method was chosen.

A machine vision laser measurement sensor capable of projecting a laser beam onto the weight frame and using the principle of triangulation on the reflected beam is capable of differentiating frame movement to within 1.0 mm. The laser sensor was selected as the best solution since it is no contact and therefore requires no modification or reweighing of the pointer assembly. The sensor has an analog output that can be read by any DVM, which in this case is a USB-interfaced module piggybacked to the USB interface/controller board. The output from the DVM is correlated to the frame position and is used as input to the control programs that raise or lower the weight frame. Another advantage also comes from the fact that the weight frame on this machine can be "split" and serves as two loads. If the frame is loaded in whole with no other weights added, the applied force is 889.6 N (200lbf). However, if the two removable spacers on which the weight frame normally rests are taken out (one of which can be seen in Figure 6), the top half of the loading frame (the yolk) then can be loaded separately resulting in an applied force of 444.82 N (100 lbf). From this point, the frame can then continue to be raised and subsequently pick up the lower half of the shaft for normal operation using the full frame. The laser sensor has a range sufficient to automate this entire range of motion. See Figure 6 for more detail on the split frame and laser sensor installation. Although the 112.5 kN dead weight machine frame also has the same split frame capability, it is limited in the fact that the optical sensor is not flexible enough to work over that entire range of motion. Therefore, splitting the frame in the 112.5 kN machine to take advantage of the lower applied force needed in many calibrations is a process that is not currently automated.

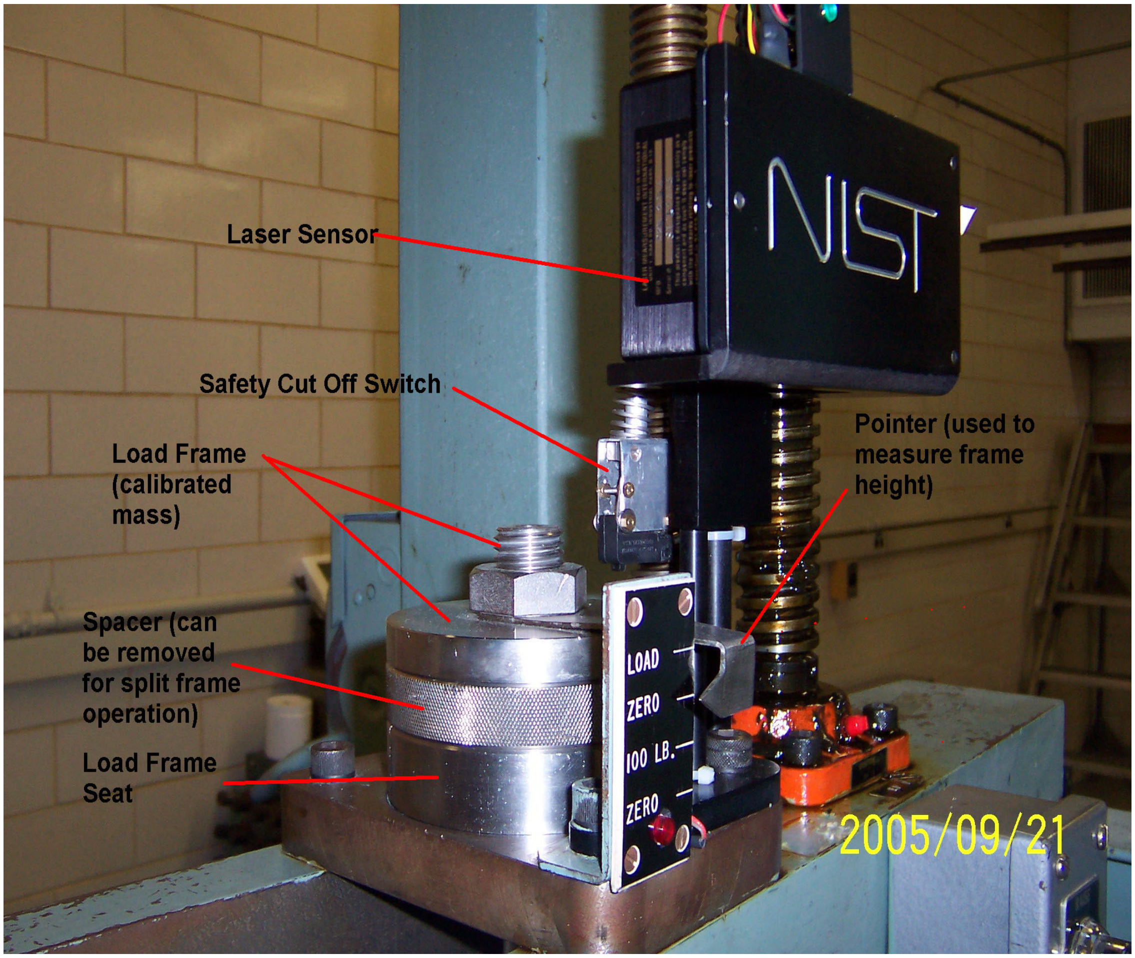


Figure 6. Photo of the laser sensor, pointer, spacer, and the top portion of the load frame.

Additional improvements to the machine include safety features that have been implemented to protect the dead weight machine and/or customer devices. One involves the electrical lockout of the frame up/down buttons on the console when the snubbers are activated. This lockout protects the airbags and the machine frame from damage that could occur during manual control of the machine if the frame were set in motion while the snubbers are in contact with the loading frame. A double-pole, double-throw (DPDT) mechanical relay is used to provide a mechanical break in the electrical circuit of the frame up/down buttons while the snubbers are activated. Also, a frame limit switch was installed to add protection to a customer device in the case of a “frame up” runaway. This miniature limit switch is installed directly above the upper frame collar to cut off power to the screw jack motor and ensure that the frame stops before it picks up additional weights and potentially overloads a customer device. This switch is supplemental to existing limit switches that protect the dead weight machine, but could ultimately allow the entire weight stack to be loaded onto the device under test before it stops frame movement. Therefore, it provides an additional layer of protection to the dead weight machine and is supplemented even further with software timeouts that limit the amount of frame travel.

Another improvement achieved in this automation project is the incorporation of the "red light" circuit. The "red light" circuit currently exists in the other deadweight machines within the NIST Force Laboratory and is used to ensure that the weights or weight frame is not touching anything while they are suspended from a unit under test. If the weights are touching, or grounded, the "red light" circuit is completed and allows a red LED to light on the console (as can be seen in Figure 3) indicating a potential problem to the operator. In the automated setup, the "red light" circuit is monitored using a digital input on the relay board that updates a Graphical User Interface (GUI) summarizing if any "red light" conditions existed during the calibration run.

One final improvement undertaken as part of this project is somewhat independent of the automation. The motor/starter control for the electric motor that turns the screw jack assembly for raising and lowering the weight frame was replaced. The motor/starter control was 40 years old and far exceeded the expected lifetime of the components. The upgraded motor/starter uses newer "soft switching" technology which results in noticeably quieter and efficient operation and improved control characteristics. The motor speed is still controlled from the console via a potentiometer dial which ultimately varies the frequency of the voltage input to the motor. The new motor/starter assembly also has the advantage of increased feedback/troubleshooting information in case of a problem with the screw jack assembly.

5. Conclusions and Recommendations

Improvements to data acquisition and control hardware and software have dramatically improved in capability and smaller packaging since the 27.1 kN dead weight machine was built. The new system used to automate this machine takes advantage of these features and improvements. Considering the age and availability of the current control hardware used on the older automation systems, the same technology advancement procedures and system will be used to eventually update all of the NIST dead weight machine automation systems.

6. References

1. T.W. Bartel, S.L. Yaniv, and R.L. Seifarth, Force Measurement Services at NIST: Equipment, Procedures, and Uncertainty, 1997 National Conference of Standards Laboratories Workshop and Symposium, 421-431 (1997).

2. Kenneth W. Yee, Automation of Strain-Gauge Load-Cell Force Calibration, National Institute of Standards and Technology, Gaithersburg, Maryland, NISTIR 4823, April 1992.

3. Thomas W. Bartel, Uncertainty in NIST Force Measurements, Journal of Research of the National Institute of Standards and Technology, Volume 110, Number 6, 589-603 (2005).

4. ASTM E74-04, Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines, available from the American Society for Testing and Materials, West Conshohocken, PA (2004).

5. Richard Norcross and Roger Bostelman of the NIST Intelligent Systems Division consulted on technology advancement systems and made recommendations based on their experiences using similar systems in other automation projects.

6. Kevin L. Chesnutwood, Redesign of the 112.5 kN Dead Weight Machine Snubber System, National Institute of Standards and Technology, Gaithersburg, Maryland, NISTIR 7164, March 2005.

7. LabVIEW, National Instruments Corporation, Website: www.ni.com, Austin, Texas.