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Single Stage Light Gas Gun Control System

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Abstract

The intermediate light gas gun at the STAR facility is used for shock wave physics testing with projectile speeds between 25 m/s and 1000 m/s. In order to operate the gun, there are several remote valves, pumps, and sensors that must be operated from the control room. In an effort to improve the engineered safety and efficiency of the gun's operation, a new gas plumbing and controls system must be implemented to simplify operator interaction with high pressure and lower the chance of human error. A new plumbing system has been designed which will allow the bottle farm system, where high pressure gas is stored, to be remotely operated during gun pressurization in addition to a new control system. This new system utilizes LabVIEW, which will communicate directly with a data acquisition and control device located in the gun bay to easily operate the gun pressurization and firing.

ACKNOWLEDGMENTS

The authors would like to thank the SEERI program and especially Patricia L St. John and Kristy N. Martinez for providing partial funding, organization, and support for the project. The authors would also like to acknowledge John R. Martinez, Robert A. Polomino, and Tom F. Thornhill III for providing information about gun operational problems, desired control features, as well as taking time to help find various tools around the facility.

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FIGURES

Nomenclature

IVG	Intermediate Velocity Light Gas Gun
STAR	Shock Thermodynamic Applied Research
VISAR	Velocity Interferometer for Any Reflector
OP	Operating Procedure

1. INTRODUCTION

The Shock Thermodynamic Applied Research (STAR) facility is a major facility used for shock physics testing of dynamic material properties. One of these guns is the Intermediate Velocity Light Gas (IVG) Gun. This gun is used to accelerate projectiles to speeds between 25 m/s and 1 km/s for testing target material properties. Some major advantages of the IVG gun include the quick turnaround time of the gun, precise determination of impact conditions, large-diameter projectiles, lack of noxious propellant gases, minimal acceleration loads, and the ability to perform soft recovery of shocked samples.

Despite the many advantages of the gun, the hardware associated with the gas plumbing and electronic controls are outdated. The control room is set up to use all manual switches for each remote valve/control in the system. Additionally, the high pressure helium gas for the gun is provided from a bottle farm outside the gun bay, which is operated by setting manual valves prior to pressurizing the gun. Updating the system will improve feedback to the operator, flexibility of the system, efficiency of the operation, and add additional engineered safety to the control system.

The electronic controls for the IVG gun are all used to control the flow of gas within the gun and the gun pressurization system. The first step to improving these controls is to evaluate the status of the gas plumbing equipment and system to ensure the equipment is safe and assembled in the most efficient way. One of the main suggested improvements to the system is an increase in the number of solenoid valves, which would allow additional aspects of the system to be operated remotely.

Once the gas plumbing design was setup, a layout for the new controls system was created utilizing principals of engineered safety. Some of the most important aspects of this system were the ability to remotely control the bottle farm and gun operations, quickly operate valves and update sensor reading, and provide safe hardware and software precautions for control system operations.

2. GUN OPERATION

This section will explain the IVG gun layout, firing setup, and basic theory behind the operation. The section includes a brief discussion of the diagnostics on the gun as well as necessary pre-fire calculations to ensure the safety and accuracy of the desired impact velocity.

2.1. Layout

The IVG gun is a 4 inch diameter, 7.6m long launch barrel which accelerates projectiles to maximum velocities of 1 km/s. The gun consists of six main parts; the recoil system, wrap around breech reservoir, diaphragm reservoir, barrel, target tank, and catcher tank. A basic diagram of this setup can be seen in Figure 1 below.

Figure 1. IVG Gun Layout Diagram

In this setup, the projectile is loaded just in front of the diaphragm reservoir at the breech end of the barrel, and the target is placed on the muzzle end of the barrel inside the target chamber. High pressure lines are attached to the breech and diaphragm reservoirs for pressurizing the gun and two vacuum pumps are attached to the gun barrel on either side of the projectile. When the projectile is loaded, two O-rings on the projectile create a seal between the two vacuum chambers. The target is then hard mounted with a set of bolts to a mounting plate in the target chamber. These bolts are small enough that the heads will easily shear off during the impact between the projectile and target. Lastly, the diagnostics are setup around the target chamber to gather the desired data. This could just include the use of VISAR (Velocity Interferometer for Any Reflector) for determining target velocities after impact (Barker & Hollenbach, 1972) as well as a set of self-shorting pins on the front of the target plate for determining the projectile velocity and planarity of impact. However, it could also include high speed cameras for viewing the target/projectile after impact as well as other sensors to monitor variables such as temperature. Figure 2 on the next page shows a diagram of the diagnostic setup and a picture of a sample projectile for the gun.

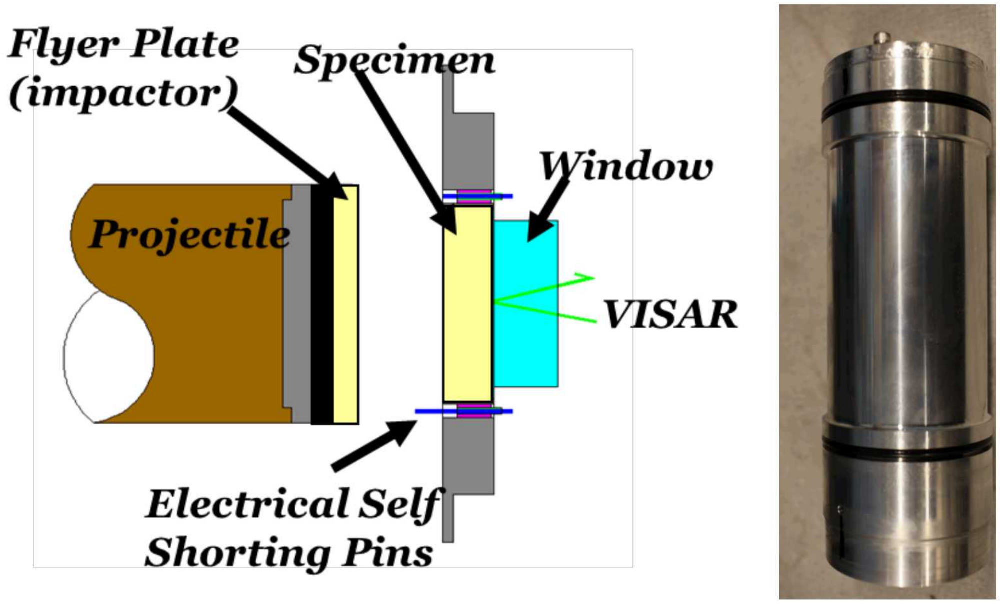

Figure 2. VISAR and Shorting Pin Diagnostics Along with Sample Projectile

When the gun is not in use, many of the components are detached from each other for cleaning purposes. In particular, the breech reservoir and catcher tank can be detached from the barrel/target chamber assembly. Before firing the gun, these components must be moved back into place and bolted down. The catcher tank is further held in place by a removable anchor system with interlocks located beneath the tank to prevent the tank from detaching from the gun assembly when firing. After each component is fastened in place, facility interlocks on the gun and all of the doors with gun bay access must be closed to fire the gun.

2.2. Operational Theory

The projectile is fired using high pressure helium gas to accelerate it down the barrel to the target. Nitrogen or compressed air can also be used as a driving gas to achieve lower velocity shots. Before firing, a vacuum is pulled in the barrel between the projectile and the target to eliminate the low pressure ramp wave that would be caused by air in the barrel compressing against the target before the projectile impact. This vacuum must be brought down to 1500 mTorr or less (typically 50-100 mTorr) to safely fire the gun. Another vacuum must be pulled behind the projectile to prevent the projectile from moving down the barrel prior to firing from the difference in pressure that would be caused by the vacuum in the barrel. The vacuum behind the projectile is pulled before the barrel vacuum and must be at 5000 mTorr or less (typically 20 mTorr) based on the OP.

Once all components are in place, the gun is ready to be pressurized and fired. The gun is fired by rupturing two burst diaphragms. For this operation, the breech chamber, volume between diaphragms called the diaphragm chamber, and volume behind the projectile are the important pressures to keep track of. The breech pressure is the pressure that accelerates the projectile, so it is important to properly choose this pressure based on the desired impact velocity. The desired breech pressure can be calculated using a log vs. log graph of impact velocity vs. pressure divided by projectile mass for past shots. A log-log graph is used since the pressure should be approximately proportional to the impact velocity squared. The latest empirical graph for a full barrel helium shot can be seen below in Figure 3. This final breech pressure must not exceed 6000 psi as this is the maximum rating for the gun.

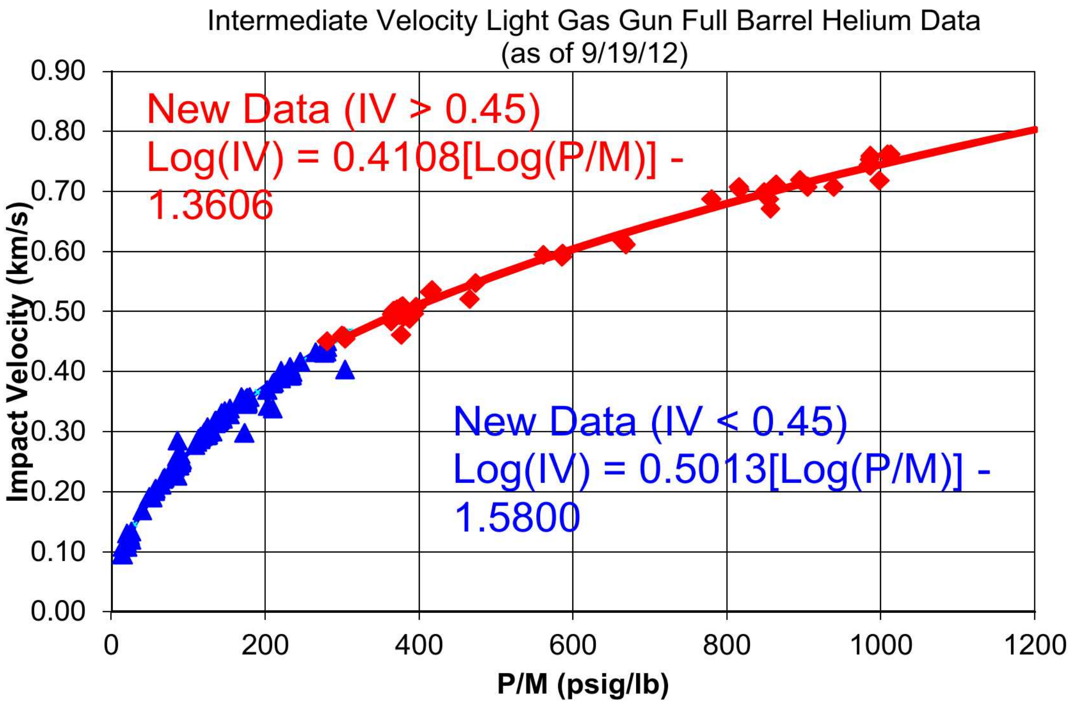

Figure 3. Impact Velocity vs. Pressure/Mass
Graph used to determine relationship between the desired impact velocity and the corresponding desired breech pressure for a given projectile mass.

After the breech pressure is chosen, two identical diaphragms are chosen with a pressure rating corresponding to the breech pressure as shown in Eqn. 1 below.

$$0.58PB < PD < 0.85PB \qquad \text{Eqn. 1}$$

Where PB is the breech pressure and PD is the diaphragm pressure. As an example of this process, suppose the desired impact velocity for a 4 lb. projectile is 0.55 km/s. Based on the best fit equation for impact velocities over 0.45 km/s found in Figure 3, we find that the breech pressure should be about 1915 psi. Therefore the burst disk rating should be between 1111 and 1623 psi. Based on this range, a 1200 or 1500 psi burst disk could be chosen.

The gun is pressurized by bringing the breech pressure up to the selected pressure while simultaneously bringing diaphragm chamber pressure up to half the breech pressure. This step must be done with caution to ensure that the difference between the breech and diaphragm pressures never reaches more than half of the desired breech pressure as this could cause the back burst disk to break early, pre-firing the gun. The pressure in the diaphragm section should never exceed the breech pressure during filling. If this occurs it is possible to reverse buckle a diaphragm, potentially damaging or weakening it, which could result in a gun pre-fire. Once, both pressures are reached; a valve attached to the diaphragm reservoir is opened, which quickly raises the pressure differential between the diaphragm and breech reservoirs, causing the first burst disk to break. This causes the full breech pressure to be applied across the second burst disk, which ruptures and applies breech pressure to the back of the projectile, accelerating it down the gun barrel into the target.

3. PLUMBING SYSTEM

The bottle farm supply and corresponding plumbing system is the system that supplies pressurized gas to the IVG gun for the firing process. One of the main problems with the current system is that it cannot be remotely operated to allow multiple pressurization options to be selected from the control room. The new design allows gas to be moved throughout the system and into the gun using manual valves as well as remotely operated valves improving the efficiency and flexibility of the operation.

3.1. Current System

The bottle farm for the IVG gun is located just outside of the gun bay and is used to do several operations. These include pressurizing the gun directly from the standard helium gas bottles, from compressors, and from accumulators which are filled from the compressors at an earlier time. These methods provide up to 2100, 6000, and 5400 psi respectively. For each of these actions there are several different valves that must be opened to achieve the desired outcome and often there are multiple pressures that must be monitored to ensure the process is operating smoothly. The current bottle farm plumbing system consists of manual valves and analog pressure transducers. This requires operators to remain near the high pressure lines at the bottle farm during accumulator filling, and it doesn't allow the gas flow to be changed from the control room. In the event of a high pressure shot where the accumulator bottles do not provide enough gas to the gun, the operators must return to the bottle farm to open up the valves connecting and leaving the compressor to allow for the compressor to charge the gun. This delays the pressurization process and forces the gun to sit with some pressure in it for a longer period of time. A photo of the current system can be seen below in Figure 4.

Figure 4. Current Gas Plumbing System

3.2. New System

The new gas system utilizes more solenoid valves to increase the number of tasks that can be performed remotely when operating the gas system. The selected solenoid valves are from Circle Seal Controls, part number SV462T32P6P43S. The valves are rated to 6000 psi, operated by 115 VAC, and have an electrical position indicator to confirm the actual position of the valve. Each of these new valves, except the direct charging lines to the gun, is placed in parallel with the old manual valves. This allows for the accumulators to be charged either manually or automatically. It also provides more flexibility in case a solenoid valve fails, or some other troubleshooting is required. Electrical pressure transducers placed in many of the analog transducer locations allow remote monitoring of pressures in addition to the analog readout used while working on the bottle farm system. A diagram of the new design can be seen below in Figure 5 where all new valves and transducers are marked by a red outline or red lettering.

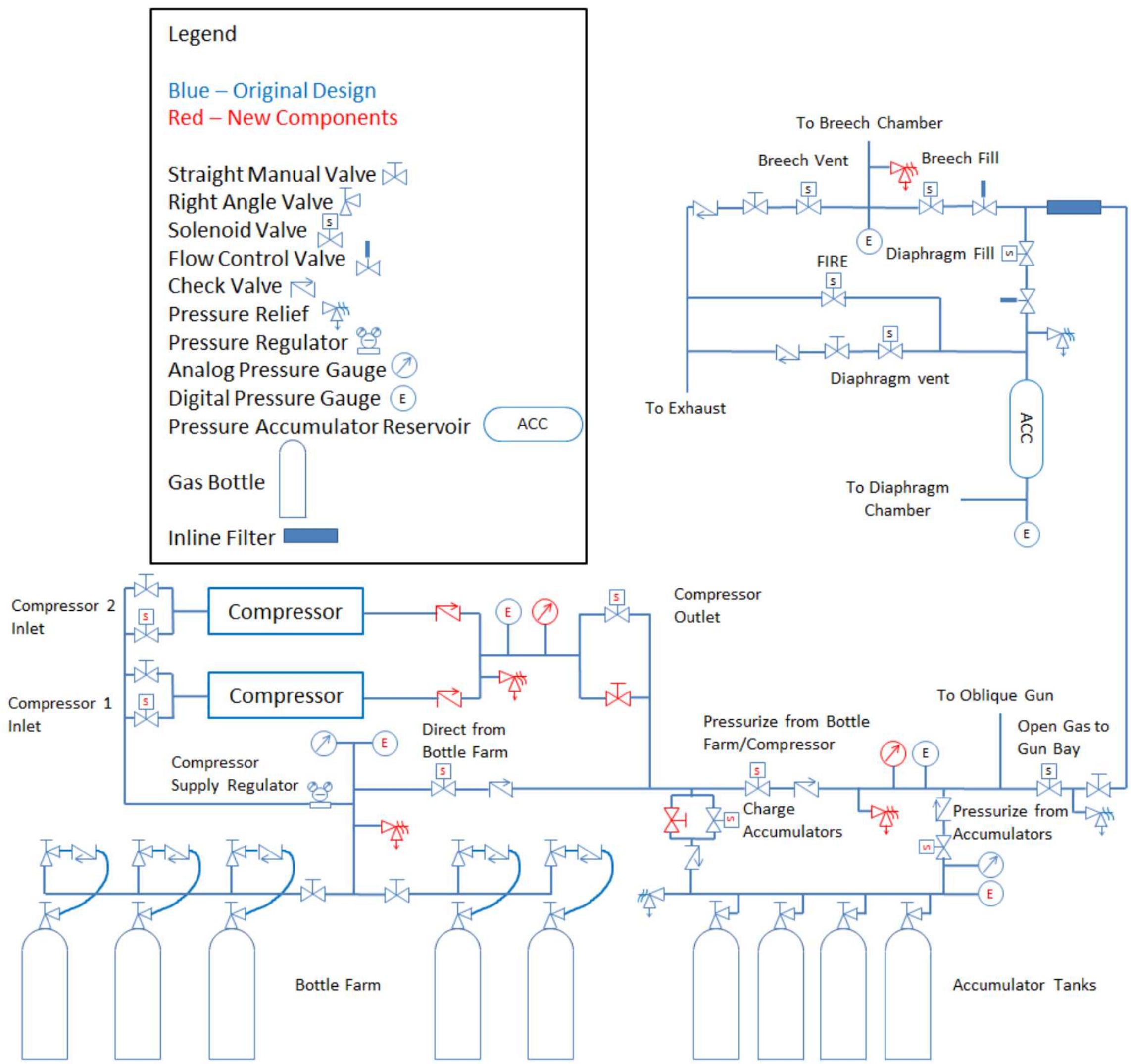

Figure 5. New Plumbing Design Diagram
All new components marked by red outline or red lettering

4. CONTROLS SYSTEM DESIGN

The new controls system design for the IVG gun utilizes the LabVIEW software program along with various pieces of hardware to control the gas plumbing and gun controls remotely. This system will replace the original system which was built around 1980 and is based on the system that was installed on the oblique gun in 2009. The IVG gun system design has several advantages on the oblique system that are discussed throughout this section. These improvements include enhanced efficiency, flexibility, and equipment safety.

4.1. Previous Controls Systems and Improvement Areas

The original controls system for both the IVG gun and the oblique gun was built around 1980 and uses push buttons on a console in the control room to operate the valves in the gun bay. In addition to the push button control, there is a separate display for several different pressures as well as cameras looking at several analog vacuum gauges in the gun bay. A picture of the control console used for both guns is shown below in Figure 6.

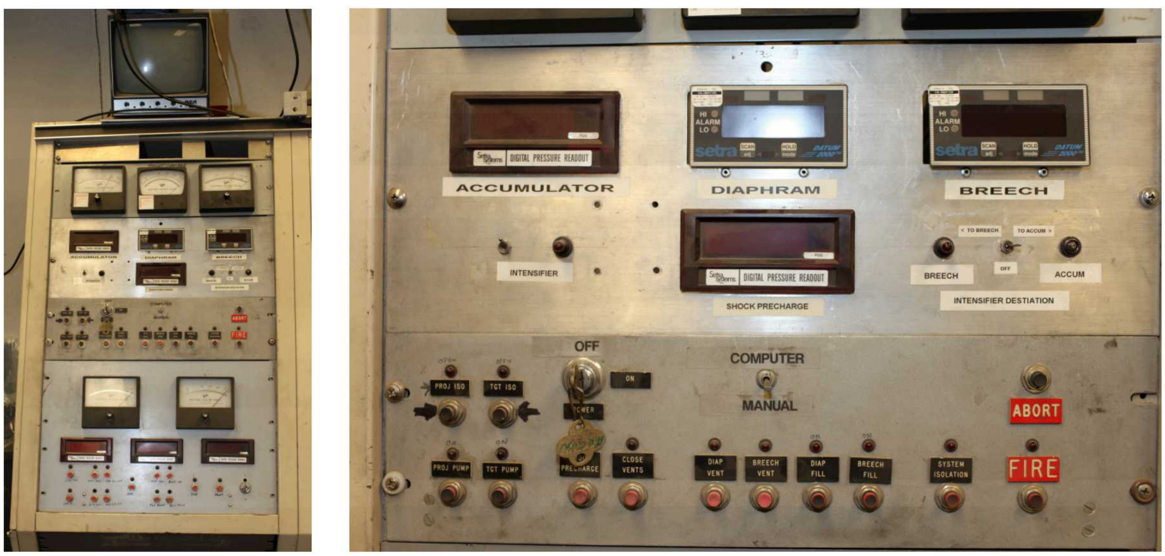

Figure 6. IVG Gun Control Console

There are several aspects of this system which could be improved with a modernized system. Additional logic within the control system reduces the chance for operator error. The physical size, wiring complexity of the current system, and the lack of flexibility in the design contribute to a high level of intricacy in firing operations. Recently, the oblique gun has been updated to operate the gun through a computerized control system which alleviates many of these issues, but the IVG gun was never updated.

The oblique gun's system has worked well enough to operate the gun successfully, but installation firing officers at the facility have suggested an improvement involving faster response/read-out of the systems gauges during pressurization. Slow read-out of the gauges makes it harder to stop the pressurization process at the desired pressure. This is problematic for low pressure shots where small errors in pressure could cause a pre-fire or deviations from desired projectile velocity. Other improvements on the system include the use of a dual screen to control the bottle farm system when the new plumbing system is implemented as well as the inclusion of additional software controls to improve the efficiency of firing operations. Specifically, software could be utilized to ensure equipment safety, and automated processes could be developed for the pressurization and vacuum processes. The IVG gun control system was designed using the oblique gun system as a starting design, but incorporating these additional improvements to provide a more robust system as a whole.

4.2. LabVIEW Program

The main change in the overall architecture of the system was a transformation from a manual switch user interface to a computer based interface. LabVIEW is a visual programming language developed by National Instruments which allows the user to interact with the program as if they were interacting with similar controls on a manual console. Another key feature of LabVIEW is the built in abstraction layers it offers for communicating with a variety of instrumentation hardware. For these two reasons, LabVIEW is the perfect program for this type of control system involving basic communication between the user and the bottle farm/gas gun system.

4.2.1. LabVIEW Interface

The LabVIEW interface allows users to view different LabVIEW interfaces for each desired operation/gun system on one computer, but still provides user friendly graphical displays which simulate the look of a manual switch control board. This significantly reduces the size and expense of control equipment, while still providing operators an easy environment to work with. The IVG gun front panel has two main sections associated with it. These are displayed on a dual monitor with one section per screen. The main section contains the controls for operating and firing the gun, while the other section provides the controls for remotely operating the bottle farm system. The section for the main gun operation is shown in Figure 7 on the next page.

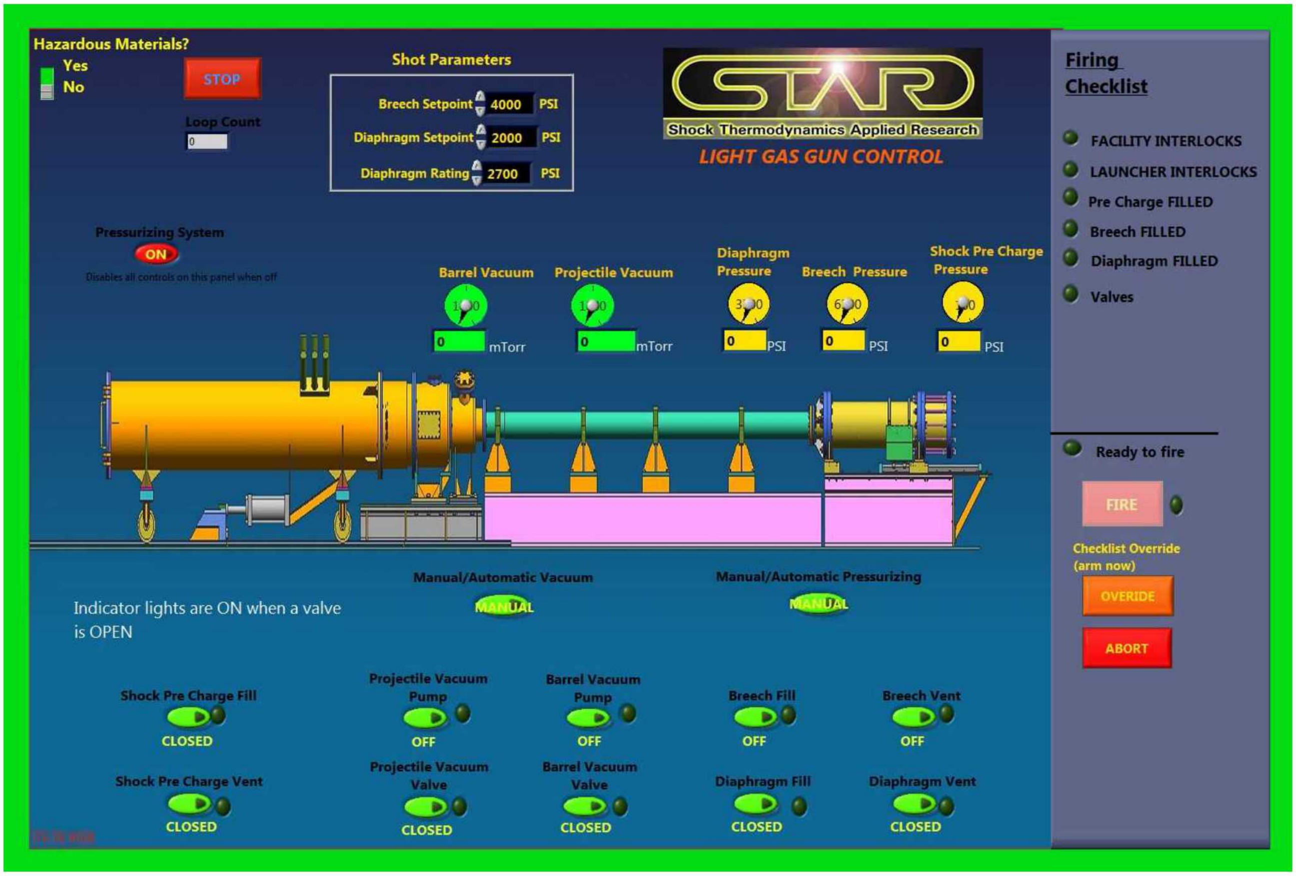

Figure 7. Front Panel User Interface for IVG Gun Operations

In the panel above, there are five main display areas. The first is the shot parameters in the upper left corner starting with indicating whether hazardous materials are present. Currently, the IVG gun is not setup to shoot with hazardous materials, however the option has been included in the program since it is anticipated that the catcher tank will be updated to accommodate hazardous material testing. If hazardous materials are shot, a procedure will be developed for the OP to handle the post shot venting process which will be programmed to reduce the risks associated with that process. The section also includes information on the desired breech and diaphragm pressures for the shot. Next, at the bottom of the panel, there are controls for each remotely operated valve/pump. These also have a button to control whether the user would like to conduct the operation manually or automatically. Next, there are five pressure displays which show the breech, diaphragm, and shock pre charge pressures as well as the projectile and barrel vacuum levels. Finally, there is a checklist that lets the user know which of the required pre-fire tasks have been completed as well as an area just below it which contains the fire and shot abort buttons. This screen is displayed on the right screen of the dual monitor, while the bottle farm controls display is shown on the left. The bottle farm screen can be seen on the next page in Figure 8.

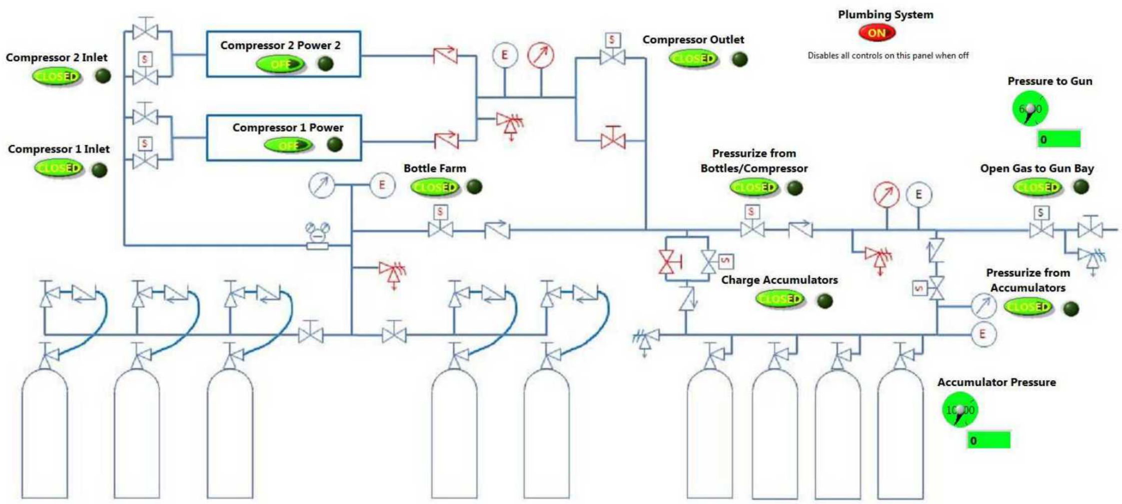

Figure 8. Front Panel for Operating Bottle Farm System
Includes diagram of the updated system with button controls for each remote valve on the new system as well as pressure displays for the accumulators and output pressure.

In the new bottle farm system design, there are a total of 8 circle seal solenoid valves (marked by a red s and a valve symbol in Figure 8) which will each have a corresponding push button control in LabVIEW. There are also controls for the compressor power, as well as displays for the pressure in the accumulators, and output pressure, which allow the user to easily monitor the pressures while charging the accumulators or while pressurizing the gun. This system is contained in the same LabVIEW program as the gun control program, which allows simultaneous operation from the same computer.

4.2.2. LabVIEW Logic

The use of LabVIEW also allows for improved ease of use and additional safety features that the previous system lacked. The LabVIEW program will provide the user with options to "automatically" operate the vacuum pumps/valves as well as automatically pressurize the gun. For this process, the user would just have to enable the automation process, press an initiation button, and then monitor the pressure readings to ensure the process is working as anticipated. As part of the automation process, the program will open and close valves to ensure that the projectile stays fixed in place by the vacuums and none of the diaphragms are prematurely fired. This will help to eliminate any human error associated with this process since the computer would monitor whether any of the pressure differentials throughout the gun were approaching a dangerous value. Given the complexity of the operation, the program allows the user to take over manual control at any point in the process. However, even in manual operation mode, the program notifies the user based on sensor readings if they attempt to open a valve or leave a valve open for too long that may result in a premature firing or over pressurization. While there are a few warnings like this on the oblique gun control system, the new program is much more complete, which will help ensure the safety of the equipment and reduce the chance of an abnormal event. An example of this type of feature is a warning that notifies the user if they try to pull vacuums in the wrong order. If this happened, the projectile would be pushed down the tank by the atmospheric pressure behind it, which would ruin the target sample and require the whole shot to be set up again from the beginning.

Similar to the original control system, the LabVIEW logic prevents the user from proceeding with the firing process by disabling, "graying out", the firing button until all necessary firing checklist steps have been completed. The firing checklist consists of facility interlocks, launcher interlocks, shock pre charge, breech final pressure, diaphragm final pressure, as well as ensuring that each valve that is connected to the gun is shut. This list allows the user to keep track of what still needs to be done before firing, and provides them with confirmation that the system is in a state ready to be fired.

In complex control systems involving a broad range of components, failure of a component may result in an unexpected state of behavior of the system. In these situations, troubleshooting is typically required to diagnose and resolve any issues. For this reason, in almost all cases, the user has the ability to override any warning the system provides or grayed out button the system prevents them from pressing. For each of these cases, the user must confirm that they understand the warning message from LabVIEW and press a button saying they would like to proceed with the action. The user does not have the ability to fire the gun if launcher or facility interlocks are not in place.

4.3. Hardware

There are several hardware components which must be used with the LabVIEW program to interface between the output/input from the computer and the output/input to the gun controls in the bottle farm and gun bay. The steps of this process include converting the Ethernet output to a fiber optic signal to shield the signal and move it quickly out to the gun bay. Next the signal is converted back to Ethernet and ported into a data acquisition and control device, the ADAM 5000L/TCP. The ADAM device outputs and receives all the digital and analog signals. Relays and fuses are used on all digital outputs to increase the voltage to 115 VAC to operate the gun hardware, while pressure/vacuum displays and controllers are used to receive and display outputs from their respective sensors before sending the signals to the data acquisition hardware. A display of this layout can be seen below in Figure 9.

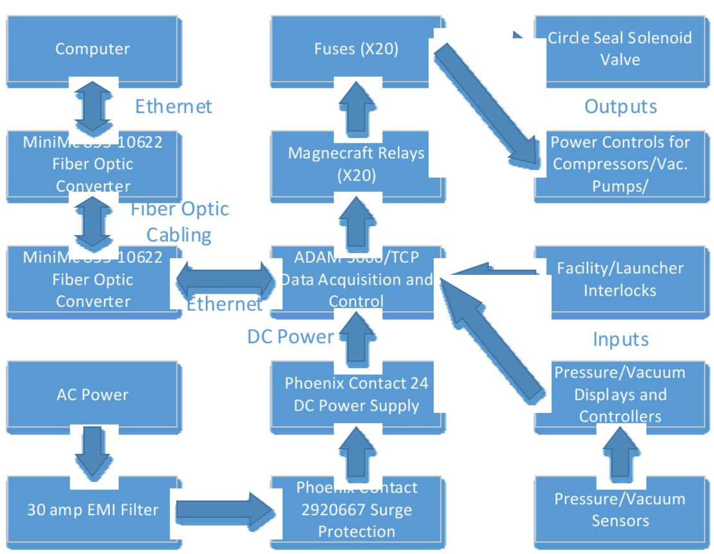

Figure 9. Hardware Data Flow Chart Layout

Of the components seen in Figure 9 on the previous page; the computer and first fiber optic converter are located in the control room; the power controls, solenoid valves, and pressure/vacuum sensors are in their operating position spaced throughout the gun bay and bottle farm area; and all other hardware will be placed inside a control box. The control box is a 10.5”X22.0”X19.0” aluminum enclosure purchased from Bud Box Industries. It is designed to be rack mounted into a cabinet so that it can be pulled in and out of the cabinet for troubleshooting or relocation, if necessary. A SolidWorks model of the control box which shows the location and spacing of the different hardware is shown below in Figure 10. For this model, an exact CAD model could not be obtained for all hardware pieces, but the overall dimensions and spacing of each component is correct.

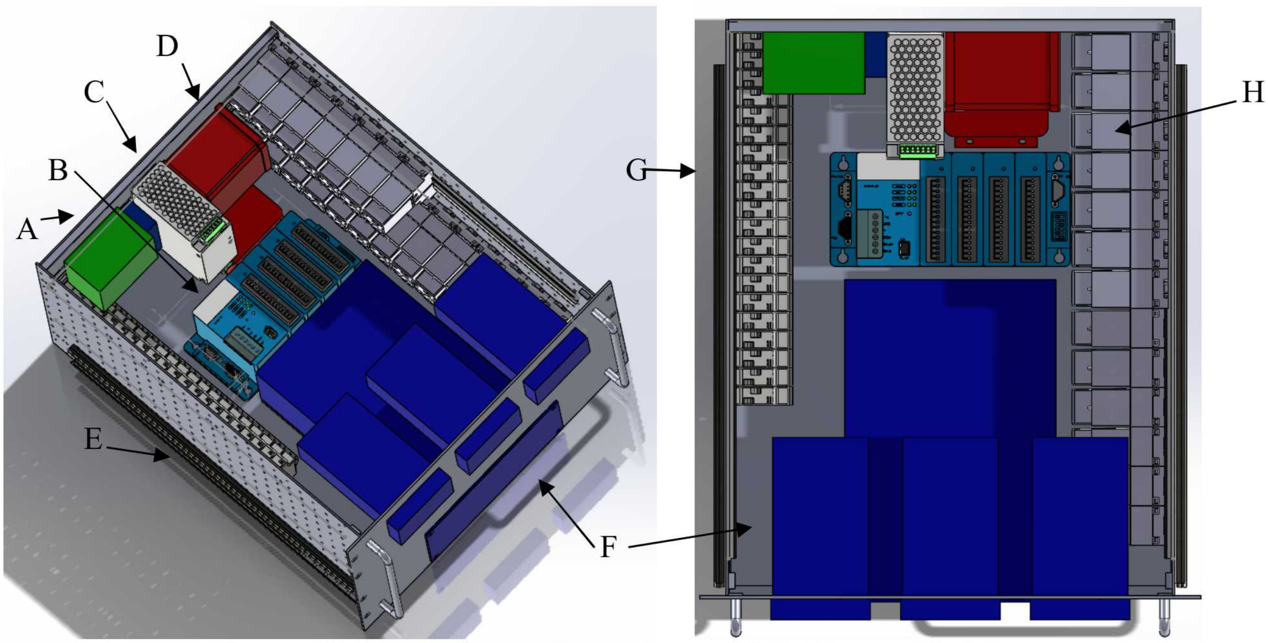

Figure 10. Isometric and Top Views of SolidWorks Model
A. MiniMc Ethernet-fiber optic converter as well as the D-sub interface device; B. ADAM data acquisition device; C. Phoenix Contact DC Power Supply, D. EMI Filter and Surge Protection devices; E. slide for the chassis mount; F. represents the vacuum and pressure displays, G. Cooper Bussmann fuse holders H. Magnecraft relays.

Within the box, most items will be mounted using DIN rail mounting including items A, C, D, G and H from the figure above. The ADAM data acquisition and EMI Filter will be attached to the floor of the control box, while the displays for pressure readings will be attached using a rectangular punch out to open up space to fit them through. Wiring will be connected within the box to match the flow of data represented by the data flow chart layout in Figure 9. The box is designed such that all connections to the box can be disconnected easily allowing for mobility and flexibility during operation.

5. CONCLUSIONS

The IVG gun is an integral component of the STAR facility because it provides a quick turnaround time as well as the ability to perform experiments with large-diameter projectiles, inexpensive temperature testing, and soft recovery of shocked samples. The gun operates by pulling a vacuum to reduce interference with the target from the air in the barrel chamber, and then firing a projectile using a double burst diaphragm system. The desired velocity of the projectile can be reached very accurately by choosing a breech pressure based on empirical calibration from past experiments. Currently the bottle farm system used to hold compressed helium for pressurizing the gun and the controls system used on the gun are outdated. A redesign of the bottle farm system to include remotely operated solenoid valves was completed to allow increased efficiency and safety of operation.

Another major improvement to the system is a redesign of the controls system used to operate the gun. By implementing a LabVIEW operated control system, the system is more adaptable to changes since it requires less hardware in the form of switches and wiring running to and from the control room. The system improves on the previous LabVIEW operated system by utilizing an Ethernet connection with the computer and direct analog communication with the pressure sensors for improved response time of the pressure sensors. The IVG gun system also allows all programs to be run from one device and the additional logic programmed into the system enhances the safety and efficiency of operations. The control system warns the user if they attempt to do something that may be dangerous based on the current sensor readings of the system. The LabVIEW program also provides a user friendly setup with easy to use buttons and displays that make the process simple to follow. The hardware associated with the control software will be placed in a compact aluminum enclosure which rack mounts into a cabinet for easy storage, troubleshooting, and transportation throughout the gun bay. With the new improvements to the IVG gun gas plumbing and control system, the system as a whole will be much more organized, user friendly, and efficient as well as provide enhanced safety during each shot.

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