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Aerodynamics Experimental Facility Spark Shadowgraph Range Upgrade: 2021

by Kenneth Paxton

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Kenneth Paxton
Weapons and Materials Research Directorate,
DEVCOM Army Research Laboratory

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14. ABSTRACT The Aerodynamics Experimental Facility Spark Shadowgraph Range, opened in 1943, is currently still using antiquated 1980s GPIB communication, spark cans charged via remote high-voltage power supplies, and wet film photography to obtain the shadowgraphs images. Given recent technological leaps in low-cost digital cameras and low electrical noise fiber-optic communication, along with the manufacturing of wet film being quickly phased out, it was determined that now it was monetarily and technically feasible to upgrade the range to digital photography and state-of the-art communication. The details of the US Army Combat Capabilities Development Command Army Research Laboratory's Spark Shadowgraph Range Modernization Program developed and currently being implemented are fully documented for future reference.						
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Contents

List of Figures iv

Acknowledgments v

1. Introduction 1

2. First Major Upgrade: 1982 2

3. Second Major Upgrade: Current Effort Started in 2009 4

3.1 Range Controller 5

3.2 Spark Can Upgrade 8

3.3 IR Trigger Screens 12

3.4 Digital Cameras 12

4. Summary and Conclusion 15

5. References 18

List of Symbols, Abbreviations, and Acronyms 19

Distribution List 20

List of Figures

Fig. 1 AEF, circa 1943 2

Fig. 2 IR screens, spark cans, and shadowgraph stations 3

Fig. 3 Sample shadowgraph on Mylar-backed film 4

Fig. 4 ArrowTech system upgrade overview 5

Fig. 5 NI cRIO-9002 6

Fig. 6 NI-9401 digital I/O module 6

Fig. 7 NI cRIO-9074 controller 8

Fig. 8 Prism spark can, front view 9

Fig. 9 Prism spark can, side view 10

Fig. 10 Original Prism spark can air gap configuration 10

Fig. 11 New rapid-prototyped air configuration with adjustment screw, resistor, and ferrite bead upgrade 11

Fig. 12 Spark can with the air gap configuration upgrade, resistor, and ferrite beads installed 11

Fig. 13 Oehler Model 57 photoelectric screen 12

Fig. 14 FLIR/Point Grey GS3-PGE-91S6M-C camera 14

Fig. 15 Hadland/SVS-Vistek SVcam eco815MTLGEC camera 14

Fig. 16 Raspberry Pi 4 Model B minicomputer 15

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1. Introduction

The US Army Aerodynamics Experimental Facility (AEF) Spark Shadowgraph Range was opened in 1943 because of the crisis of World War II and to build on the advanced pioneering ballistic measurement techniques started at Aberdeen Proving Ground, Maryland, during the 1930s. The facility established the capability to study the aerodynamics of bodies in supersonic free flight. Since its inauguration, the facility has been the gold standard for ballistics aerodynamic testing, being named a National Historic Mechanical Engineering Landmark by the American Society of Mechanical Engineers (Schmidt 1983). Figure 1 shows the original facility setup. The facility currently consists of 39 orthogonal spark shadowgraph stations over 300 ft, broken into five groups. Each station uses a high-voltage spark can, whose sub-microsecond spark discharge produces a point light source, which allows visualization of the projectile orientation and density changes in the flow field. The spark cans use a 6-kV capacitor charged remotely by a high-voltage power supply through high-voltage cables. The spark cans are triggered by a DC-powered coil mounted before each station that senses the magnetized projectile as it flies through. The coil required to be tuned to set the spark can trigger a delay for the expected projectile velocity before each shot, which tended to shock the technician. The original film used 11- × 14-inch photographic glass plates, which were hand developed. After developing, the glass plates were then hand read on a grid-covered light table with rulers, triangles, and protractors for data reduction.

In this report, I document the history of this range and the upgrades that have happened over time. In addition, I provide recommendations on how to address current range needs.

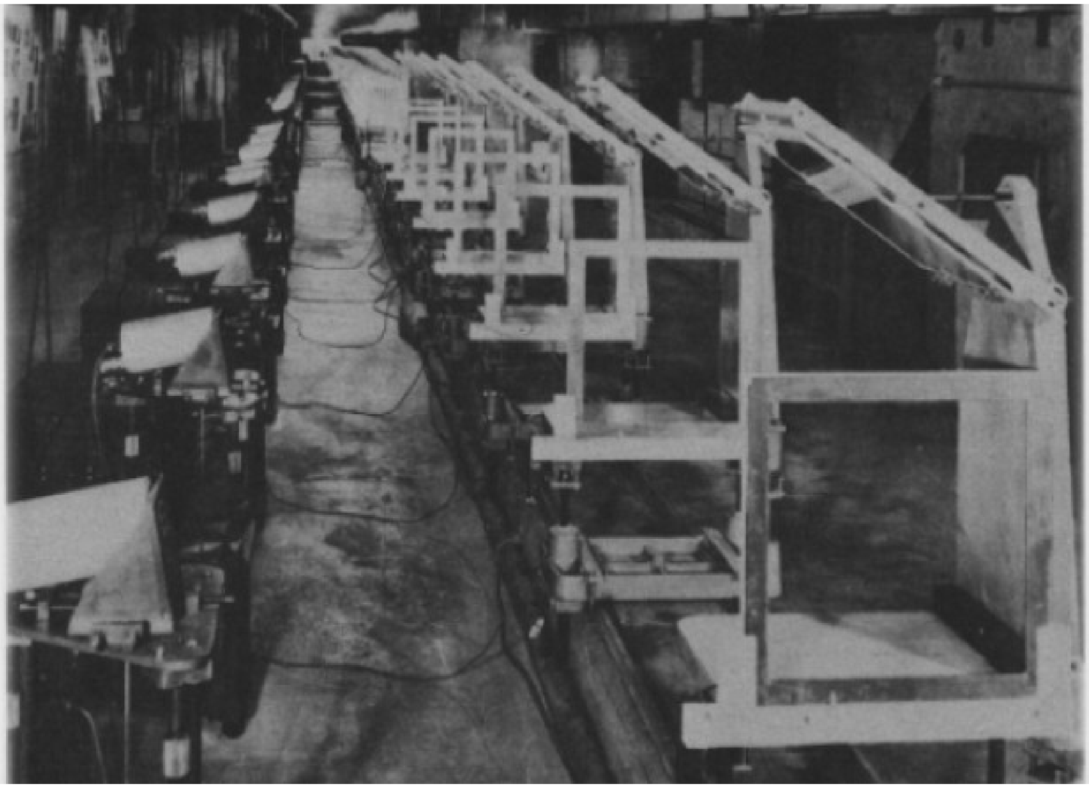

Fig. 1 AEF, circa 1943

2. First Major Upgrade: 1982

In 1982, the facility had its first major data acquisition upgrade, which was the Computer Data Systems, Inc., (CDS) system. The CDS controller system changed the facility from being 39 magnetic trigger-dependent stations to 27 timed and 12 untimed slave stations. The CDS system was controlled by an IBM 286 computer using a range control program written in BASIC. The control computer was connected to a series of daisy-chained CDS control modules using a General Purpose Interface Bus (GPIB) interface. The master module was located in the control room connected directly to the computer, with each of the other five CDS modules controlling each group in the range. The CDS units utilized a 19-inch rack-mountable circuit board rack with multiple 6- × 12-inch circuit boards, with each board having its own function, such as communication, chaining or input/output (I/O). The spark can coil triggers were replaced with IR trigger screens manufactured by the OPUS Corporation. Figure 2 shows the IR screens, spark cans, and shadowgraph stations. The IR screens transferred trigger signals via RG-58 coaxial cable to the CDS units. The glass plate film was replaced with 11- × 14-inch Mylar-backed film. Figure 3 shows a sample spark shadowgraph image using the Mylar-backed film. The original spark cans were retained and used as is.

This upgrade greatly improved range productivity from 1–2 shots per day to 4–5 shots per day. The CDS computer system allowed all of the spark stations to be set up at once for the expected velocity and trigger delay required. The projectiles did not have to be magnetized. The Mylar-backed film being much lighter allowed for faster loading/unloading of stations and was able to be developed using a film processor. And, a computer-based data reduction program was written in BASIC and instituted that allowed for point-and-click light table film reading using a cursor mouse.

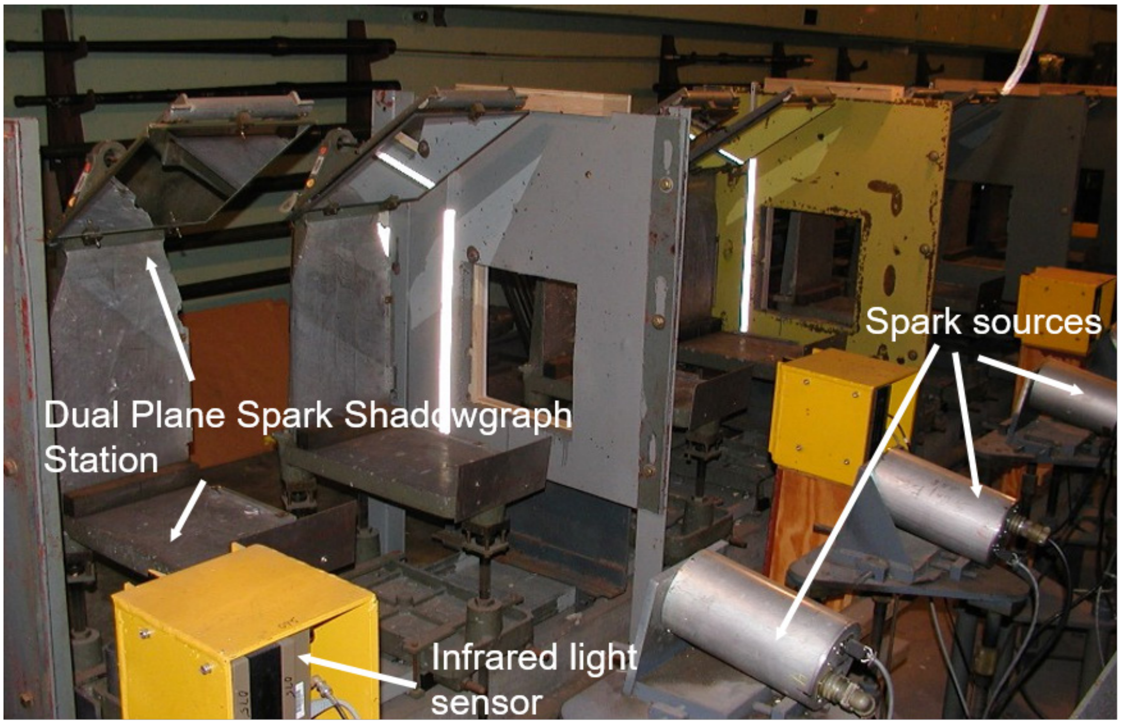

Fig. 2 IR screens, spark cans, and shadowgraph stations

Fig. 3 Sample shadowgraph on Mylar-backed film

3. Second Major Upgrade: Current Effort Started in 2009

With digital photography becoming more cost-effective, manufacturing of wet film and supplies diminishing and/or becoming obsolete, and the CDS system failing, it was decided to upgrade the entire spark shadowgraph range data acquisition system. This upgrade includes newly designed spark cans by Prism Science Works, Inc.; range controller/counters design and system integration performed by ArrowTech Associates, Inc. (www.arrowtechassociates.com); IR screens manufactured by Oehler Research, Inc.; and the implementation of digital cameras. The upgrade also included creating a short 100-ft Aerodynamic jump Spark Shadowgraph Range in R15 to be used as the test bed for the range upgrade hardware. Figure 4 shows the system overview proposed and being implemented by ArrowTech.

The key objectives for the upgrade were the following:

- Update computer control hardware, software, and communication.
- Update spark can design, reduce footprint, and increase safety.
- Replace wet film with digital photography.
- Create a data reduction software program that instantly compiles digital photographs after each experiment for reduction, and provides full data reduction and output in minutes.

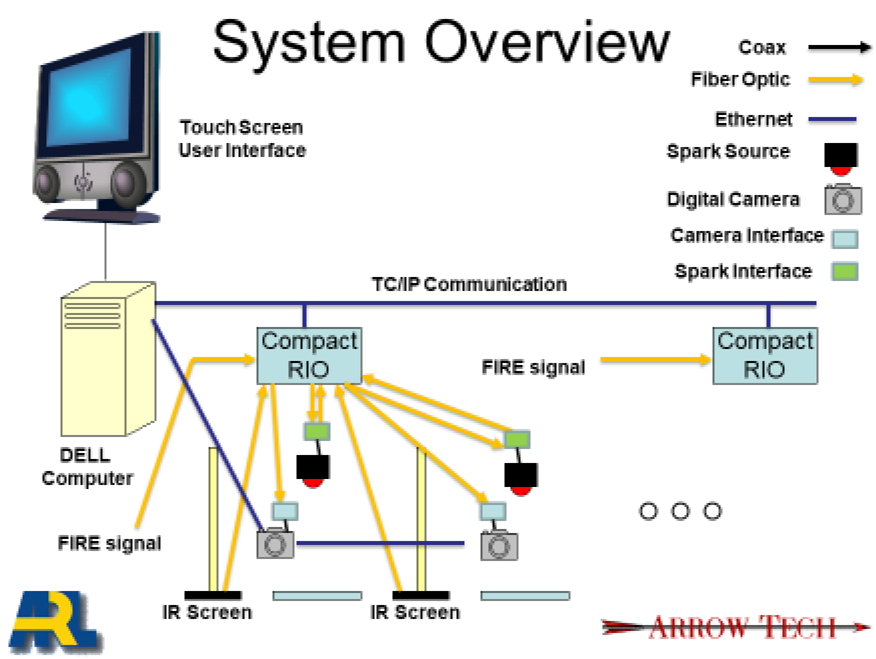

Fig. 4 ArrowTech system upgrade overview

3.1 Range Controller

The current CDS range controller circuit boards had become brittle, embedded computer chips were failing and experiencing solder joint failure, and the GPIB connections were degrading. In addition, the GPIB communication was an extremely antiquated architecture when pairing with current computer design and communication formats. These considerations led to a decision to do a complete system replacement.

For the first phase of the upgrade, ArrowTech provided a prototype range controller for R15 using a National Instruments (NI) CompactRio Controller (cRIO) (NI cRIO-9002), which is a combination of a real-time controller, reconfigurable I/O modules, a field-programmable gate array (FPGA) module, and an Ethernet expansion chassis. Figure 5 shows the NI cRIO-9002. The reconfigurable digital I/O modules were NI-9401 modules, using custom-built control boards with BNC adapters for coaxial data cables for communication. Figure 6 shows the NI-9401 digital I/O module. The range control software was written in three pieces. The first piece was written in LabVIEW FPGA programming code, which handled the communication and data dump from the modules to the range controller PC after the firing event happens. The second piece was the range control software, which handles the communication between the controller, the IR screens, the spark cans, and ultimately the digital cameras during the event, and was written using Visual Basic. The third piece was the camera control interface, which uses the manufacturer's camera control software embedded in the range control software.

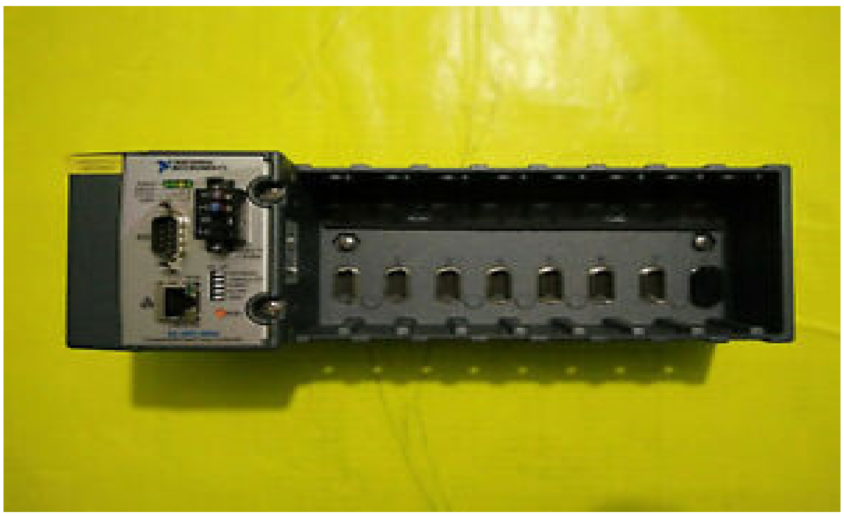

Fig. 5 NI cRIO-9002

Fig. 6 NI-9401 digital I/O module

After testing the prototype with the new screens and spark cans, it was determined that there was an interference issue, which caused simultaneous spark cans immediately downrange to fire after the range controller fired the first spark can. The interference was thought to be either electrical or visual, so numerous fixes were tried. The IR screens were wrapped with black plastic to shield them from the possibility of light from the spark can causing erroneous triggers. Coax-wrapped ferrite coils were attached in-line between the coaxial trigger cables and IR screen outputs. Various methods of grounding and floating grounds were tried on the IR screens. Mounting the range controller in a Faraday cage was also tried. Though some of these methods were somewhat successful, none of them completely fixed the problem. The solution was to reengineer the system to replace the coax with fiber-optic cables for all I/O between the range controller, IR screens, and spark cans.

Once the prototype had been tested, five modules were built to replace the five CDS units in the R16 Spark Shadowgraph Range. One change made was replacing the now outdated legacy cRIO with a newer variant, NI cRIO-9074. Figure 7 shows NI cRIO-9074 cRIO controller. The Visual Basic control software portion that was written for controlling R15 was modified to operate the five groups in R16. This was accomplished with part cut/paste and then modifying each group section with new IP address and other pertinent information for that controller. After extensive full range testing/evaluation being performed using all of the new R16 modules in R15 range, it was found that the new NI cRIO-9074 and the original NI cRIO-9002 have different protocols and use LabVIEW FPGA code and Visual Basic a little differently. This caused the cut, paste, and modification of the prototype control software for R16 modules to need a complete evaluation and rewrite, which is currently being performed by ArrowTech at their facility in Vermont.

Fig. 7 NI cRIO-9074 controller

3.2 Spark Can Upgrade

The current spark can design uses a 6-kV capacitor bank charged by a remote high-voltage power supply via high-voltage cables. This is an old, obsolete design, which has maintenance problems with spare parts becoming very limited to nonexistent and also poses severe high-voltage safety concerns.

The upgraded spark can being implemented was manufactured by Prism Science Works. With the advancement of electronics since the original spark cans were designed, the new power supply is integrated within the spark can while still retaining close to the original can size. Figures 8 and 9 shows the new spark cans. After extensive testing, even after converting all communication cables to fiber optics, there was still a RF electrical noise problem when the spark cans fired, causing erroneous light screen triggering. Therefore, a 47-kΩ resistor and six ferrite beads were installed in the spark can air gap discharge circuitry. The air gap standoff and adjustment designed by Prism was too cumbersome, fragile, and problematic, so Ilmars Celmins of the DEVCOM Army Research Laboratory designed a more robust rapid-prototyped air gap module with a finer adjustment mechanism. This adjustment mechanism is important since the air gap distance is what allows the charged capacitor bank to hold its charge without pre-firing, so there needs to be a way to easily change this gap depending on the humidity conditions during testing. Figure 10 shows the original Prism spark can air gap configuration and Fig. 11 shows the rapid-prototyped air gap configuration with fine adjustment screw, 47-kΩ resistor, and ferrite bead upgrade components. Figure

12 shows the new air gap configuration, resistor, and ferrite beads installed. The upgrade components have been retrofitted on every new spark can.

Fig. 8 Prism spark can, front view

Fig. 9 Prism spark can, side view

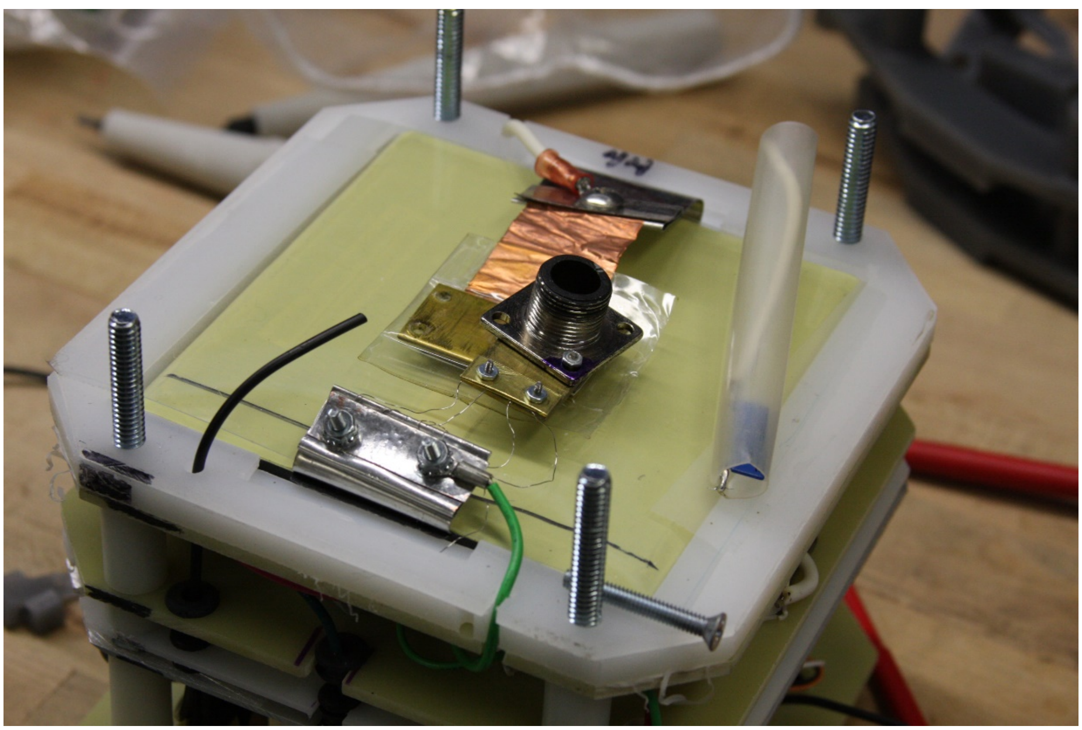

Fig. 10 Original Prism spark can air gap configuration

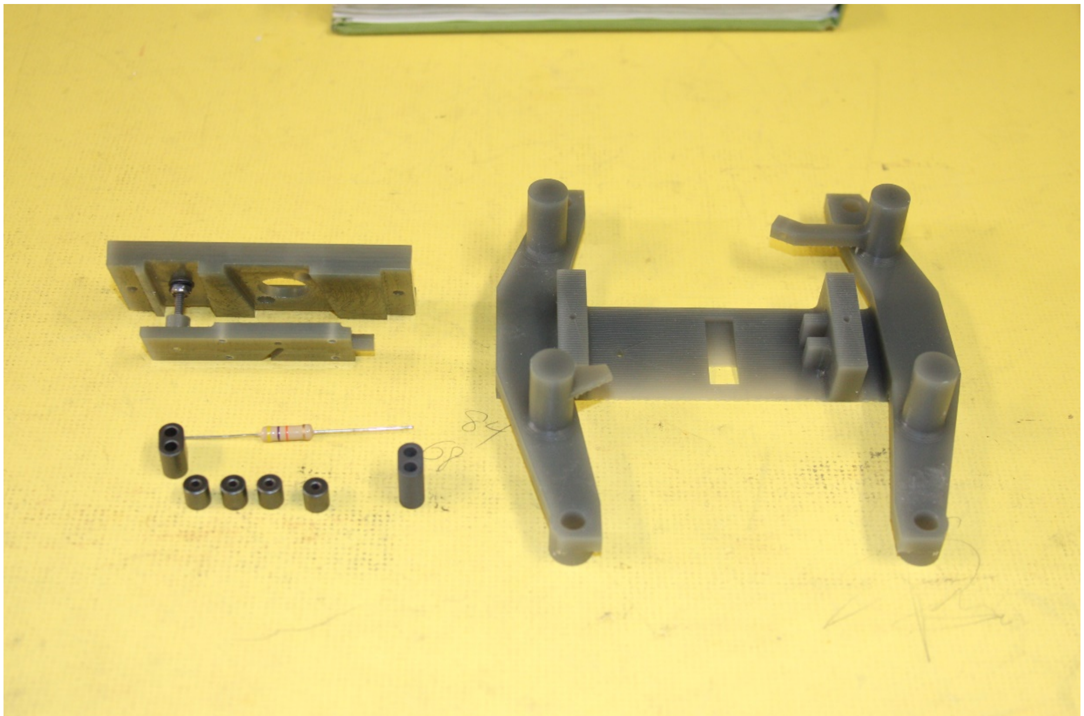

Fig. 11 New rapid-prototyped air configuration with adjustment screw, resistor, and ferrite bead upgrade

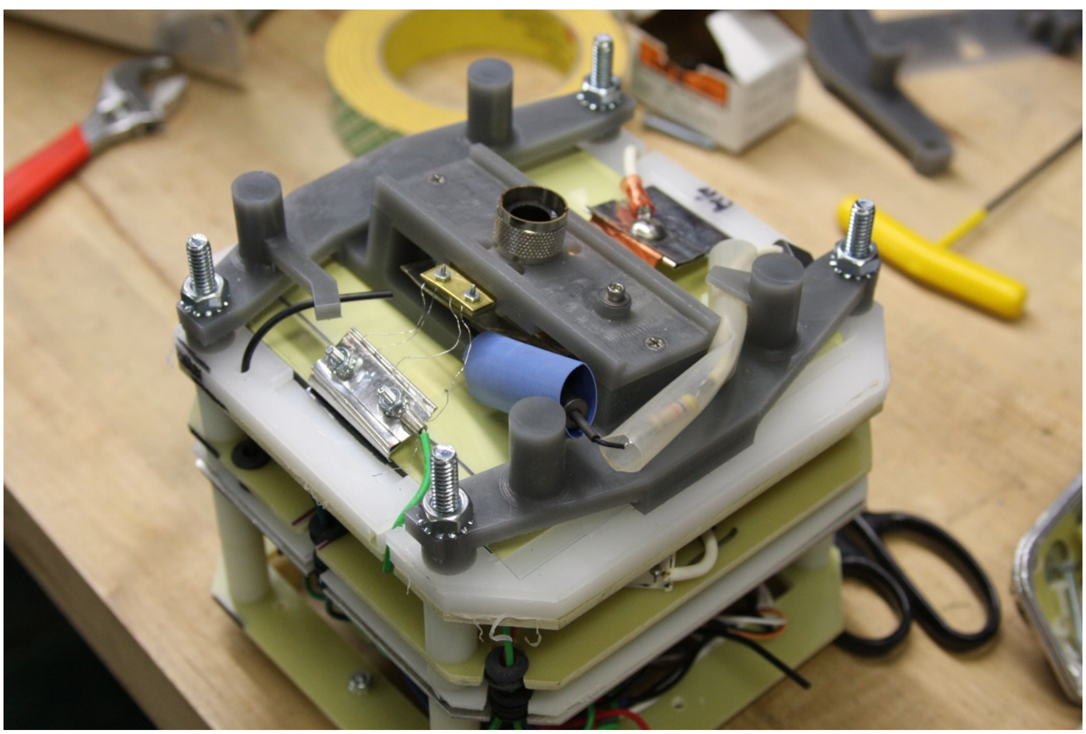

Fig. 12 Spark can with the air gap configuration upgrade, resistor, and ferrite beads installed

3.3 IR Trigger Screens

The currently used IR trigger screens from the 1982 upgrade are a complementary metal–oxide–semiconductor design that uses IR transmitter/receivers that look through a convex lens to shine an IR beam on a reflective strip mounted on the shadowgraph station. The screen manufacturer has been out of business for approximately 20 years, and on-hand spare screens and parts are nearly exhausted.

A rather exhaustive search was performed, showing that this is a very niche market, with Oehler Research, Inc., being the best choice for supplier and the only manufacturer of IR screens in the United States. They offer the Model 57 Photoelectric Screen containing an IR light source mounted at the top of the screen and multiple photodetectors mounted at the base. Figure 13 shows the Oehler Model 57 photoelectric screens. The screens can detect projectiles from 0.17 cal. and larger, and velocities of 250+ fps. ArrowTech designed analog-to-fiber-optic signal convertor boxes for communication between the analog Model 57 IR screens and the fiber-optic range controllers.

Fig. 13 Oehler Model 57 photoelectric screen

3.4 Digital Cameras

Since 1943, the AEF Spark Shadowgraph Range has used some form of wet film, from the original glass plates to the currently used Mylar-backed X-ray film as direct image film. Wet film requires chemicals and film processors to develop into usable pictures. All three of these items, film, chemicals, and processors, fall into the commercial category of medical field. Most of the medical field in the United States and other parts of the world has converted to digital photography, making wet film products obsolete. This has forced most manufacturers to cease production of these products, making the AEF's transition from wet film to digital spark shadowgraph photography more pressing.

It was determined that the minimum resolution needed is 7 MP and preferably a gigabit Ethernet (GigE) interface. While evaluating cameras, there is also the issue of lens choice, and while there is a huge selection of lens prices and quality, the main determination is best price versus performance. When looking at camera and lens selections, one specification that must be considered is sensor format (i.e., 1 inch or 1-1/2 inch, as most lens are designed to be matched to this format but are not required to do so). Once a camera and lens combination is chosen, the next challenge is designing a method to mount the cameras in the AEF Spark Shadowgraph Range. A couple of options are mounting a single camera in such a fashion as to use the existing station mirrors to take orthogonal images; mounting two cameras orthogonally, which might possibly need a second spark can mounted at each station with it; or mounting two cameras in such a fashion as one camera looks at the mirror from an angle that uses the light provided by the single spark can but still takes the orthogonal image.

Two GigE camera models are being evaluated: the FLIR/Point Grey GS3-PGE-91S6M-C and the Hadland/SVS Vistek SVcam eco815MTLGEC. The FLIR/Point Grey is 9.1 MP and has a frame rate of 9 fps, a maximum trigger input of 40 V, and dimensions of 44 mm × 22 mm × 58 mm. Figure 14 shows the FLIR/Point Grey camera. The Hadland/SVS Vistek is 9 MP and has a frame rate of 7 fps, a maximum trigger input of 24 V, and dimensions of 38 mm × 38 mm × 45 mm. Figure 15 shows the Hadland/SVS Vistek camera. Both are capable of being triggered with a 5-V time-to-live (TTL) rising edge trigger. While evaluating the cameras with a few lenses, it was decided that a full lens characterization was needed to determine the best lens for format, price, and quality. The lens characterization is being performed at the ARL Transonic Experimental Facility (TEF) Spark Range by the personnel there.

Fig. 14 FLIR/Point Grey GS3-PGE-91S6M-C camera

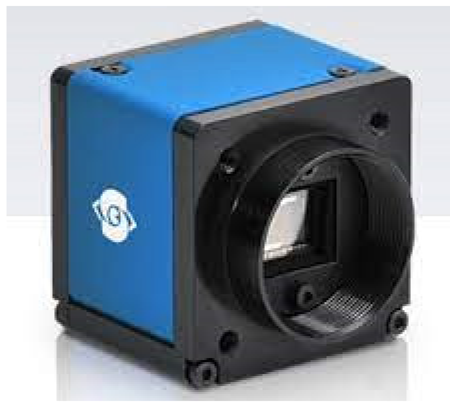

Fig. 15 Hadland/SVS-Vistek SVcam eco815MTLGEC camera

While performing equipment testing/evaluation of the NI cRIOs and a few of the digital cameras, a communication issue was found with connecting multiple cameras directly to the cRIOs. The cameras tried to override each other during communication with the cRIOs. It was determined that some form of minicomputer, such as a Raspberry Pi minicomputer, would need to be added between the cameras and the cRIOs to sequence communication and solve this problem. Figure 16 shows the Raspberry Pi 4 Model B. This is just one version of minicomputer that could be utilized.

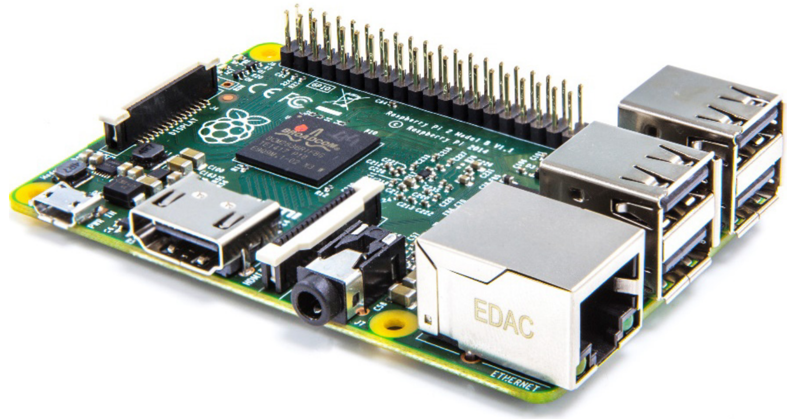

Fig. 16 Raspberry Pi 4 Model B minicomputer

4. Summary and Conclusion

The current AEF Spark Shadowgraph Range upgrade effort has been ongoing for 12 years. There has been a large learning curve concerning RF noise with current electronics and hardware versus antiquated AEF hardware, posing a number of hurdles requiring numerous design changes. Other challenges slowing the project have been contracting and procurement issues with the multiple ArrowTech service contracts, the Prism spark can prototype design, and subsequent product purchase contracts. The lengthy effort has had the positive parallel occurrence that digital camera technology has been rapidly advancing while cost is rapidly decreasing. This effort can also be applied as we begin the AEF TEF Large-Caliber Spark Shadowgraph Range upgrade, looking at using some of the same hardware such as controller design, software, and digital cameras/lens.

At this time, ArrowTech was working on debugging and finalizing the range control software to include a digital camera interface, including the addition of minicomputers, even though the final camera decision has not been made, but their contract has expired. A new contract is in the process of being drafted. Digital camera evaluations are still being performed periodically at the AEF and TEF as new cameras become available. The lens characterization is still in process at the TEF. A procurement contract was placed and fulfilled to acquire enough replacement spark cans for the facility, including spares. All of the replacement spark cans have also been modified with the new air gap configuration, 47-kΩ resistor, and ferrite beads. There have been small batch purchases over the 12 years giving the AEF the ability to replace over three-quarters of the IR screens. The last quarter of IR screens required will be purchased as funding allows.

Depending on current efforts of hardware/software debugging and camera/lens determination, the AEF is planning on two paths forward: removing all of the existing CDS equipment and original spark cans, and then replacing with the ArrowTech cRIO equipment and Prism spark cans. If, at that time, a choice has been made determining which digital camera and lens will be used, a purchase will be made and then we will continue with their implementation. If those decisions and purchases have not been accomplished, the AEF will work toward continuing operation using wet film until such a time as the digital cameras are available to be implemented.

My recommendations are the following:

- TEF personnel complete lens characterizations by performing static image tests and vignette tests for the proposed lens with both current camera options.
- The Flight Science Branch (FSB) Upgrade Team reviews the characterization data and makes a decision on camera/lens choices for the AEF and TEF. Ideally, utilize the same camera for both facilities, which will provide a greater stockpile of spares in case of any future catastrophic test failures.
- The AEF Upgrade Team and ArrowTech evaluate the minicomputer options and make a final product decision.
- The FSB Upgrade Team finalizes the ArrowTech AEF contract to include supplying ARL-chosen digital cameras with spares, minicomputers, and spare cRIOs. If possible, incorporate a preliminary design for hardware and range operation software for the TEF upgrade effort.
- AEF personnel remove all CDS hardware, power supplies, original spark cans, and current communication cables.
- The AEF Upgrade Team purchase a last batch of Oehler IR screens needed to provide the AEF with spares and swap out with current CMOS screens. The current estimate is 10 screens are needed. Save any working CMOS screens as backups in case of any future catastrophic test failures.
- AEF personnel install and align the new spark cans.
- The AEF Upgrade Team contacts the ARL Communications Team to install the new Ethernet communication lines required in the upgrade plan.
- The AEF Upgrade Team finalizes the location placement of the new cRIO hardware in the AEF and starts fabricating any stands and/or protection covers required. AEF personnel create CAD drawings of any materials needed for the ARL Fabrication Shops to fabricate.

- The AEF Upgrade Team finalizes the digital camera mounting design and purchases or has fabricated any required hardware.
- AEF personnel start fabricating the fiber-optic communication lines and install them so as to be ready to connect when the cRio and camera equipment arrives.
- The FSB Upgrade Team researches a vehicle or path to update/upgrade the Spark Range Data Reduction software. The end goal is to have a reduction software that compiles images, runs complete reduction, and outputs data package in minutes after each test event.
- The AEF Upgrade Team works with Mr Celmins and Mr Cler to design a range survey system. Ideally, combine high-resolution pinpoint laser system, which is in the process of being purchased, along with a lower-resolution, higher-power laser system to create a complete range survey mapping system.

5. References

Schmidt EM. The Aerodynamics Range: A National Historic Mechanical Engineering Landmark. Ballistic Research Laboratory (US); 1983 May. Report No.: ARBRL-SP-00028. https://apps.dtic.mil/sti/pdfs/ADA128042.pdf .

List of Symbols, Abbreviations, and Acronyms

AEF	Aerodynamics Experimental Facility
CAD	computer-aided design
CDS	Computer Data Systems, Inc.
cRIO	CompactRio controller
FPGA	field-programmable gate array
FSB	Flight Science Branch
GPIB	general purpose interface bus
I/O	input/output
IR	infrared
NI	National Instruments
PC	personal computer
RF	radio frequency
TEF	Transonic Experimental Facility
TTL	time-to-live

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