CLOSED LOOP GUIDANCE OF A NON-LINEAR SPINNING 40MM GRENADE USING MICRO-ADAPTIVE FLOW CONTROL

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ABSTRACT

The focus of this paper is to provide the technical background, summary and implementation of a Joint GTRI, ARL and DARPA effort to explore the feasibility of producing steering forces on a spinning projectile using micro-adaptive flow control (MAFC). The paper discusses the theoretical foundation for the non-linear flow control mechanism, the multidisciplinary modeling technology developed, the flight control technology required to enable the MAFC on spinning projectiles, the design of the flight test and validation hardware, and the results of the closed-loop flight test. The closed-loop tests clearly indicate that MAFC can be used as a control technology on a non-linear spinning projectile and can be extended to other subsonic munitions.

1. INTRODUCTION

The future of the U.S. Army clearly outlines a strategy for operational scenarios that feature a combined-arms combat system operating in a multi-threat, dynamic engagement environment. Precision, small- to medium-caliber munitions are integral and necessary elements of this strategy. To meet this vision, innovative technologies are needed to provide aerodynamic steering forces for small, spinning projectiles.

With support and direction from the Defense Advanced Research Projects Agency (DARPA), the Georgia Institute of Technology and the U.S. Army Research Laboratory (ARL) have teamed on a program called SCORPION (Self CORrecting Projectile for Infantry OperatioN) to develop and explore the applicability of microadaptive flow control (MAFC) technology for aerodynamic steering of a non-linear spinning projectiles. More specifically, the program is a joint venture between DARPA, the Georgia Tech Research Institute's Aerospace, Transportation, and Advanced Systems Laboratory, Georgia Tech's Departments of Mechanical Engineering, Electronic and Computer Engineering, and Aerospace Engineering, and ARL's Weapons and Materials Research Directorate.

2. MAFC CONCEPT

As part of DARPA's Micro Adaptive Flow Control program, the Georgia Tech Research Institute (GTRI) and the Army Research Lab were given the opportunity to apply flow control techniques previously developed in the laboratory to a "DARPA Hard" problem with real world application. The GTRI/ARL team hypothesized an MAFC solution for a spin stabilized non-linear 40mm grenade could be developed, packaged into the grenade and used to demonstrate flight control (McMichael, et al., 2004). The science of the MAFC and advanced micro-technology could be combined to demonstrate closed loop guidance of a munition. For the flight demonstration it was decided to use a muzzle velocity sensor that would initialize the grenade and allow the MAFC to generate in-flight corrections on the launch velocity and thus reduce the impact of the muzzle velocity variation on the grenade's trajectory. The effect of muzzle velocity on an uncontrolled 40mm grenade as it impacts a vertical target at a downrange distance of 200m is shown in Figure 1.

One of the aspects of a spin stabilized 40mm grenade which makes controlling its flight 'DARPA Hard' is the highly nonlinear nature of the projectile's flight. Range measurements of a 40mm grenade show that it exhibits the classic fast and slow mode angular precession as shown in Figure 2. Thus any type of aerodynamic control not only had to deal with a relatively fast spin rate of 60 Hz, but also had to deal with the non-linear response of the round. The rotational motion and the precession of the round greatly complicated the actual response of the round to control forces.

The team proposed to use synthetic jet technology developed at Georgia Tech which had previously been used for several other flow control applications. Several studies have shown that tiny synthetic unsteady jets can significantly alter the flow field and pressure distributions for airfoils and cylinders, Amitay et al., 1999. These synthetic jets are active control devices with zero net mass flux and are intended to produce the desired control of the flow field through momentum effects, shown in Figure 3. Many parameters such as jet location, jet

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velocity, and actuator frequency can affect the flow control phenomenon.

Smith and Glezer, 1998, have conducted an excellent study of the flow control by synthetic jets to provide increased fundamental understanding of the flow physics. Amitay et al., 1999, experimentally investigated flow separation control on a cylinder using synthetic jet actuators. Their work showed that the interaction of the synthetic jet with the free stream flow resulted in a virtual modification of the body shape and significantly increased the lift force as a result of the flow reattachment. The first phase of the research involved incorporating such a device into 40mm grenade and understanding the flow physics well enough to enable control forces to be generated.

3. WIND TUNNEL EXPERIMENTS

A series of wind tunnel tests were conducted in order to characterize the flow around a 40mm grenade form factor. Initially these tests were conducted on larger diameter rounds with the flow scaled to match Reynolds number. Tests were also conducted on a spinning wind tunnel model in an attempt to capture the transient nature of the spinning round. Additional details of the wind tunnel tests have been previously reported by Rinehart, et al., 2003.

The wind tunnel tests were instrumental in optimizing the synthetic jet placement and in providing the forces developed by the control actuators. The baseline geometry of a 40mm grenade was modified such that near the base of the grenade there was a small step. In addition the boattail of the grenade was modified in order to have a more rounded geometry. This geometry was chosen in order to induce a separated flow after the step which could in turn be reattached with appropriate flow control. The synthetic jet actuator could thus be oriented to provide a controlling flow through an aft facing slot on the back side of the step. This control flow could in principal be used to reattach the flow over the curved surface using the Coanda affect as described by Amitay, et al. 1999 and Rinehart et al., 2002. When the control flow was only used over a portion of the step, only a portion of the flow would be reattached and an asymmetric force would be generated on the round.

Initially tests were conducted with aft facing slots which spanned 36° azimuthally around the longitudinal axis of the round. Slots were located on the upper and lower surface of the wind tunnel model. The wind tunnel model was mounted onto a sting which provided force and moment data as shown in Figure 4. Initial force data proved the concept that asymmetric forces could be developed and that the actuators could be packaged into the appropriate form factor. Tests on the spinning model also allowed for software development which allowed the actuators to be controlled such that force in a desired direction could be obtained. However, it was found that the forces developed were not sufficient to achieve the desired level of control.

Detailed Particle Imaging Velocimetry (PIV) measurements were made of the flow in the region downstream of the slot. First, these measurements allowed the actuators to be tuned in order to provide a stronger jet which increased the turning force. Second, the PIV measurements indicated that while the flow was turning along the centerline of the slot, the flow began to separate at angles away from the center of the slot. This is shown in the upper portion of Figure 5 where it is seen that the effect of the jet is negligible over part of its extent. This led to a redesign of the boat tail where a shallow channel was provided to contain the jet over its extent. This channel can be seen on the tail of the projectile on the lower portion of Figure 6. After implementing this channel, the PIV data indicated that the flow turning occurred over the full extent of the slot as shown on the lower portion of Figure 5. Subsequent wind tunnel data indicated an increase in the forces and moments developed by the improved actuator and boattail system.

4. NUMERICAL SIMULATIONS

Numerical simulations were being conducted in parallel in order to better understand the flow physics and in order to develop the aerodynamic coefficients of the projectile for six degree of freedom simulation. A hybrid RANS/LES solution was computed for the unsteady flows using the CFD++ code with particular emphasis paid to the wake and jet interaction region. The fully unsteady results were for a 40mm grenade which was spinning at 60 Hz and with a synthetic jet operating on one side of the round. The jet was operating once per revolution over a rotational angle of 90°. In addition the jet was pulsed at a frequency of 1000Hz to match the actual actuator. This resulted in a complex and highly unsteady flow which required thousands of hours to simulate. The computed results were found to match well with the experimental results with regards to the lift forces developed by the synthetic jet actuators. Only a brief description of the numerical work is provided in this paper. Interested readers can find much more detail in the works of Sahu 2004, Sahu 2005, and Sahu 2006.

The numerical solutions had an advantage over the experimental results as the effect of the sting on the flow was eliminated. This allowed a more accurate investigation to the wake downstream of the round. The effect of actuation can be seen in Figure 7 on the region near the jet slot and in the downstream wake. In the upper portion of the figure, it is clearly seen that the jet changes the flow structure relative to the unactuated case on the bottom of the grenade. The lower portion of the figure shows the wake a few body lengths downstream where the periodicity of the wake is evident. In Figure 8, velocity vectors are shown for the same case. In this figure, it is shown that the flow is turned in the vicinity of the jet, and this local effect changes the formation of the wake as it propagates downstream. This data is qualitatively similar to that shown in Figure 5 for the PIV experiments, however, the numerical results provide a snapshot of the flow in a larger region and without the influence of the sting.

One of the ways the numerical results aided the development of the integrated system was through the prediction of flight effects. In addition to the validation of measured aerodynamic coefficients, the numerical results demonstrated the forces developed on the projectile had some lag time with respect to the time when the jet was on. This later turned out to be important in trying steer the projectile in a particular direction. As shown in Figure 9, the lift force averaged over many cycles is a non zero value which varies over the course of a single cycle. It is important to note in this figure that the jet is operating for ¼ of the cycle or the first 3.75 ms. During this period the force is clearly higher and in the desired direction, however due to the presence of lingering disturbances in the wake, there is a resultant force on the projectile during the entire rotation. It was also found that a side force existed on the projectile as well which resulted in a net force and moment which did not force the projectile in exactly the direction desired. In practice, this was easily taken care of by leading or lagging the actuator, however, understanding the nature of this problem helped the team to solve this challenge in a more expeditious manner.

5. PROJECTILE INTEGRATION

One of the most challenging aspects of the program was the integration of all the components into the 40mm grenade form factor. Not only did a large number of components have to be packed into a small space, but they also had to function as an integrated system, survive the high G's of gun launch and the high spin rate of the projectile, and still be able to sense the state of the round. To accomplish this task a series of hardware development and component testing tasks had to be completed. In addition, control logic also had to be developed and tested in order to make the round controllable. Additional details on this effort are provided by Lovas and Brown, 2007.

During the wind tunnel tests, strides were made towards shrinking the size of the synthetic jet actuators, however further work was needed to both reduce the packaging size and to insure that the actuators were not destroyed during launch. A series of actuators were subjected to 8000g's of shock and their performance compared to that before the shock. From these experiments, proper actuator capturing geometries were developed.

Another challenge involved the development of integrated circuit boards which contained the desired sensors, memory, processors, and power conditioners necessary to measure the state of the round and control the actuator. The sensor package consisted of a 3-axis magnetometer, an axial accelerometer, four radial accelerometers, and a 2-axis radial accelerometer. All of these sensors were integrated onto custom circuit boards which could fit into the round as shown in Figure 10. In addition a processor and a power conditioning board were developed. Along with the batteries and the actuator all of the components were integrated into a package that was inserted into a 40mm test article. These components were potted with an epoxy resin and the nose was screwed on. The entire package was subjected to an 8000g shock and the relative position of the components was compared to that prior to the shock using x-ray images. One such comparison is shown in Figure 11 where it is seen that the internal components experienced little movement after being subjected to the shock loading.

In addition to the shock testing, spin rig testing was also conducted to insure that the components could survive the rotational loads and to test the functionality of the on board magnetometers. One of the functions of the magnetometers was to provide orientation for the round. As the round was spinning as it traversed the earth's magnetic field, it was possible to both determine the projectiles' orientation with respect to the earth's surface (angle w.r.t. magnetic field) and to measure the rotational speed and roll position (up and down) of the round about its longitudinal axis. These measurements were critical in order to fire the actuators at the desired time to produce force in the desired direction. Thus the spin rig tests were important to test and calibrate the orientation and roll position sensors and algorithms.

The changes on the boattail of the round required to accommodate the actuator and the Coanda surface also forced a change on the way the grenade could be fired. With the actuation slot open and the crimp groove removed for aerodynamic purposes, the round was not fired using the normal cartridge system. Instead, the round was fired using a sabot and pusher assembly as shown in Figure 6. High speed photography down range of the barrel indicated that the pusher system separated cleanly from the round and provided a consistent way to fire the test rounds.

6. EXPERIMENTAL VALIDATION

Flight experiments were conducted at the ARL Transonic Experimental Facility as described by Braun, 1958. Figure 12 is photograph of the test setup looking downrange towards the target which was a witness plate located 200m downrange. The onboard accelerometers were used to sense launch which in turn triggered the onboard data logger to begin recording both the sensor data and the control states. The electronic and sensor system proved to be so robust that one projectile was reprogrammed and launched ten (10) times. It was still functional at the end of the testing period. The onboard data logging capability proved invaluable as a diagnostic tool which allowed the control algorithms to be fine tuned. As an example, it was found that the some of the onboard sensors were saturated for a short duration after launch due to the high g-forces and that it took several rotations to develop a good average to determine roll orientation. Thus, it was found that the round had to travel some distance downrange before control commands could be effectively initiated.

To test the control authority, the test rounds were operated in an open-loop fashion and were given a preset command to initiate a maneuver either to the left or to the right at a fixed time after launch. The impacts were measured on a downrange target. The wind tunnel data and numerical simulations were used to provide the aerodynamic coefficients as well as the predicted control force magnitudes. The open-loop test successfully demonstrated the divert authority of the system as the round could be diverted either left, right, or, in principal, in any direction. This proved that the control forces developed were as predicted and that the control algorithms worked. This success opened the door for further development as a more advanced controller could now be developed.

7. CLOSING THE LOOP

The open loop tests validated that there was sufficient control authority to correct for trajectory variations due to muzzle velocity variability. Building upon the open loop range test results, the GTRI/ARL conceptualized a closed loop system whereby MAFC enabled a steerable grenade that could reduce the muzzle velocity variability on the trajectory. Thus if the muzzle velocity was measured and communicated to the round, control logic could be developed which would allow the round to correct its flight path.

A method to measure the muzzle velocity of the round was developed and evaluated. By using onboard magnetometers already integrated into round, and by implementing software modifications, muzzle velocity could be measured. Utilizing the onboard diagnostics simplified the design by eliminated the necessity for communicating muzzle velocity corrections to the round. Using the existing onboard data logger capability of the round, an onboard measurement of muzzle velocity could be made.

Through several iterations of magnets and placement of magnets, a working system was developed which is shown on the range in Figure 13. The system relied on two sets of magnets strapped to the gun barrel and software which was able to use data from the onboard magnetometers and an internal clock to know its precise position in the gun barrel at two instances in time. By knowing the distance between these two locations, an estimate of the velocity was made by measuring the time it took the round to get from one point to the next as shown in the x-ray imagery in Figure 14. Many rounds were then fired in order to calibrate the round measured velocity against the muzzle velocity measured by an external radar. As shown in Figure 15, the muzzle velocity as measured by the onboard system was very close to that of the ground truth measurement.

With the ability to measure muzzle velocity, it was possible to use the validated simulation tools to develop a closed loop control logic for operating the actuators. This was accomplished by creating a system of lookup tables which provided an actuation start and end time as well as an actuator roll orientation based upon the measured muzzle velocity. Approximately fifteen closed loop rounds were fired and the effect of adjusting the trajectory to compensate for muzzle velocity variability was measured. Figure 16 shows the effective variation in muzzle velocity versus the actual muzzle velocity variation. By closing the loop on the muzzle velocity, the effective variation in muzzle velocity was reduced to roughly ±0.5 m/s from a variation in excess of ±1.6 m/s for the uncontrolled rounds. Statistically, the closed loop rounds demonstrated the concept that the variability in the trajectory due to variations in muzzle velocity could be reduced.

8. CONCLUSIONS

The GTRI/ARL team demonstrated that through the use of carefully tailored flow control, the flight of a spinning 40mm grenade could be controlled. Further, by implementing a closed loop controller, the dispersion of a 40mm grenade due to variations in the muzzle velocity could be reduced by adjusting the trajectory of the round midflight. To achieve this result required a multidisciplinary systems approach which involved detailed fluid dynamics, electronics development, flight simulation, control development, actuator development, and the careful integration of small parts into a grenade form factor. It also demonstrated the critical use of High Performance Computing to understand complex non-linear fluid mechanics required to develop an MAFC based control system. Additionally, a large amount of testing and experimentation was required both in the laboratory and on the test range for validation.

However, the end result of this effort is all the critical sub-systems; actuator, guidance navigation and control electronics and sensor systems for guiding MAFC non-linear spin stabilized grenades have been demonstrated, validated and vetted. These sub-system technologies will enable small diameter guided grenade systems to be developed and fielded for the warfighter. With a guided round, the soldier becomes a more effective fighter able to hit targets at further distances, firing less rounds, and becoming more lethal to the enemy. Further, the war fighter can carry fewer grenades to achieve the same effectiveness and the logistics burden is reduced

ACKNOWLEDGEMENTS

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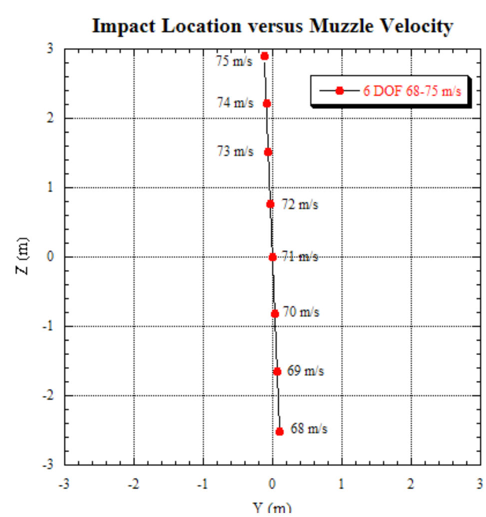

Figure 1 Vertical impact point as a function of muzzle velocity at 200m.

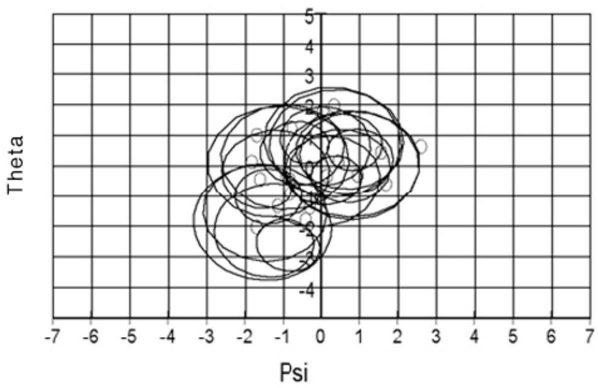

Figure 2 Measure pitch and yaw of 40mm grenade as fired in range.

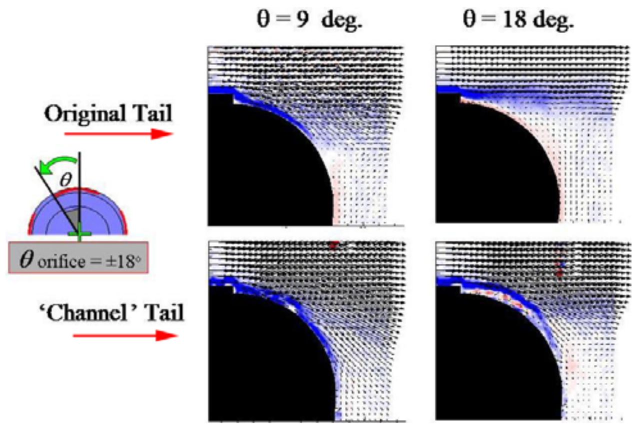

Figure 5 PIV data from wind tunnel tests.

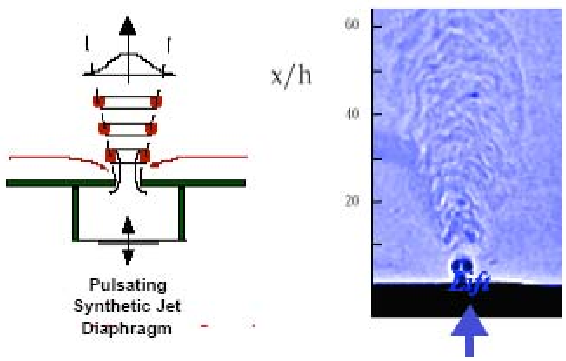

Figure 3 Synthetic jet.

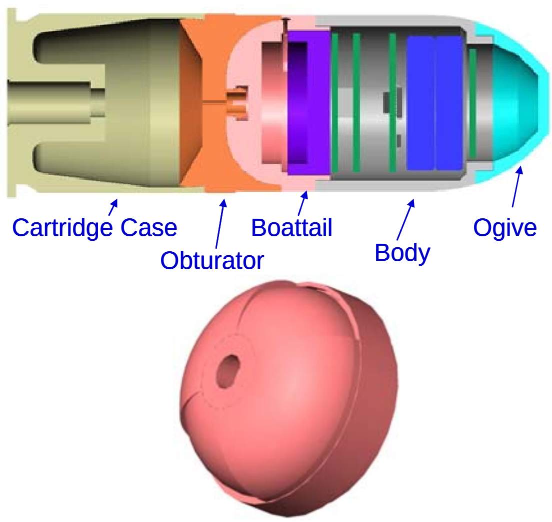

Figure 6 40mm guided grenade test article and case.

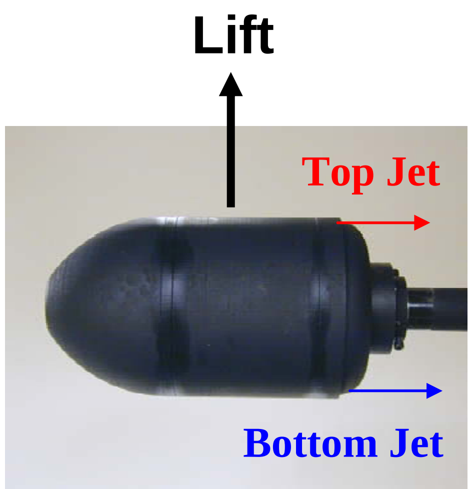

Figure 4 Wind tunnel model with synthetic jets.

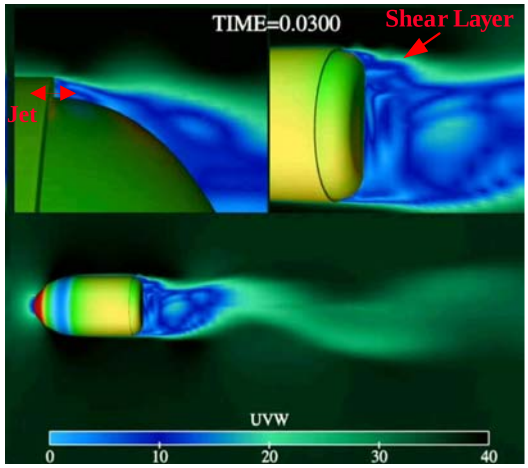

Figure 7 Velocity magnitudes, M = 0.11, $\alpha = 0°$

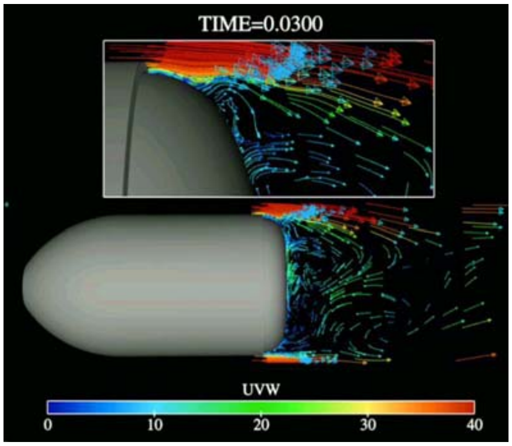

Figure 8 Velocity vectors, M = 0.11, $\alpha = 0°$.

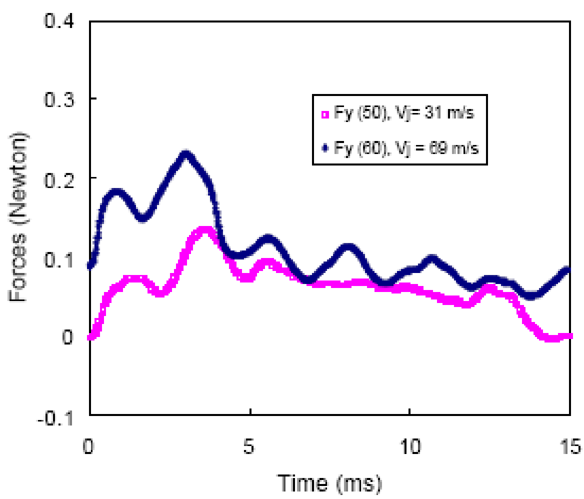

Figure 9 Computed lift force over many spin cycles for different jet velocities, M = 0.24, $\alpha = 0°$, Spin = 67 Hz.

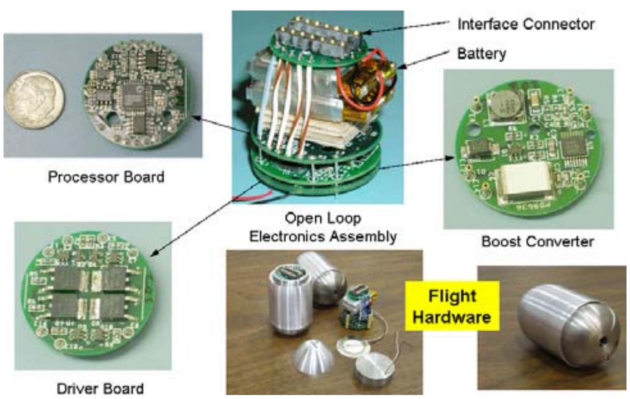

Figure 10 Components of the Scorpion guided grenade.

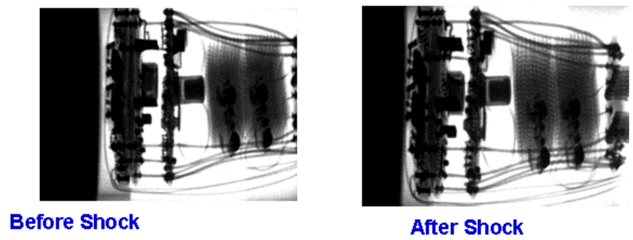

Figure 11 X-ray photographs of components before and after shock testing.

Figure 12 Range test setup of guided grenade at ARL.

Figure 13 Muzzle velocity measurement hardware on range.

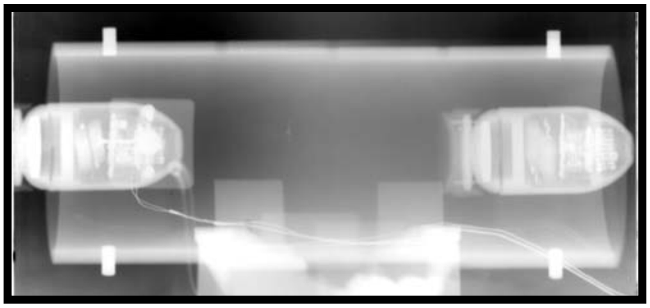

Figure 14 X-ray imagery of instrumented round passing through barrel instrumented with magnets.

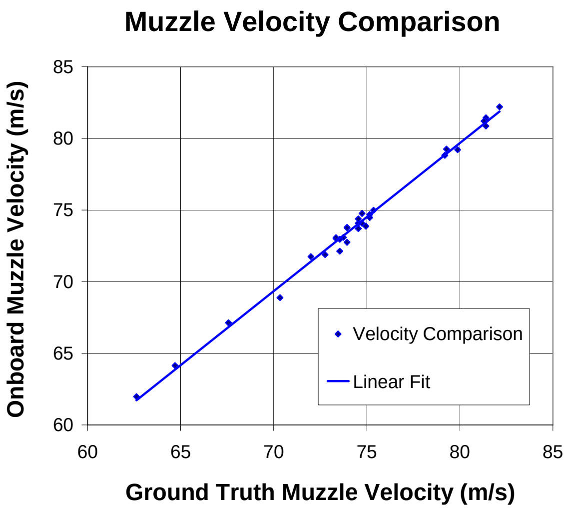

Figure 15 Comparison of velocity measured by the 40mm grenade versus that measured by ground truth.

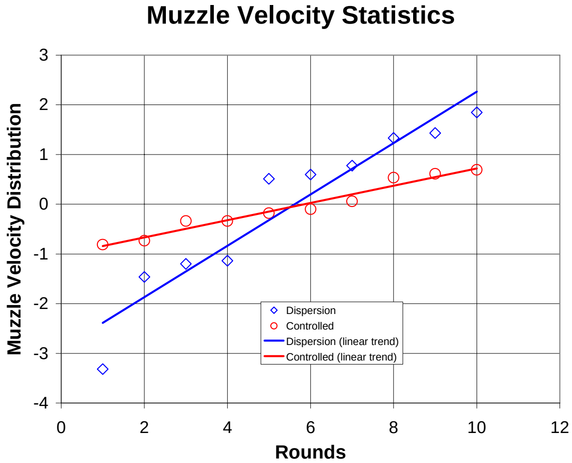

Figure 16 Effective variation of muzzle velocity variation for uncontrolled and closed loop controlled rounds.