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A Miniaturised Arrow Ballistic Measurement System

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Abstract—A novel miniaturised system for measurement of the in-flight characteristics of an arrow is introduced in this paper. The system allows the user to measure in-flight parameters such as the arrow's speed, kinetic energy and momentum, arrow drag and vibrations of the arrow shaft. The system consists of electronics, namely a three axis accelerometer, shock switch, microcontroller and EEPROM memory embedded in the arrow tip. The system also includes a docking station for download and processing of in-flight ballistic data from the tip to provide the measured values. With this system, a user can evaluate and optimize their archery equipment setup based on measured ballistic values. Recent test results taken at NIST show the accuracy of the launch velocities to be within $\pm 0.59\%$, when compared with NIST's most accurate ballistic chronograph.

I. INTRODUCTION

Archery is the art of propelling an arrow at a target with a bow and has been practised since ancient times traditionally for hunting and combat. Today's archers can select from equipment including longbows, recurve bows, compound bows and crossbows. There is also a wide range of arrows available on the market today. However, the selection of the proper arrow shaft for a given archer and bow must account for differences in bow draw weight, arrow shaft length, arrow weight, materials of arrow shaft construction and arrow shaft spine (or stiffness). Hence, archers are interested in understanding the overall performance of their selected equipment. Performance of a particular combination of arrow and bow can be expressed in terms of arrow velocity, kinetic energy and momentum [1, 2]. For example, while accuracy is critical to success in any type of archery, the percentage of retained speed from launch to impact is a measure of the aerodynamic efficiency provided by the overall equipment setup. In addition, bowhunters are also interested in the kinetic energy which the arrow delivers to the target.

A. Archery Equipment

1) *Bows*: There are generally 4 types of bows that are commonly used. LongBows are the oldest type of bow and usually have narrow upper and lower limbs that extend from a thicker core that includes the handle. Recurve bows are similar to long bows with the main difference being that the tip of each limb is bent forward to provide a form of stored

energy when the bow is drawn. The limbs and the base can be from made different materials including metals, wood or composites. A recurve bow is capable of delivering more energy than a long bow of similar length [3]. Compound bows are equipped with cams and pulleys at the tips of the limbs. This setup brings the major advantage that the force necessary to keep the string in full drawn position is much lower than the maximum force required to bring the bow to full-draw. Thus, an archer using a compound bow with a draw weight equal to the draw weight of a recurve or long bow can hold the bow at full draw with less force than the comparable recurve or long bow [4]. The compound bow can provide a more efficient transfer of energy from the bow to the arrow to provide increased arrow speeds and reduced shaft flexion and vibration which results in more stable arrow flight. Crossbows were historically used for combat in medieval times. Today, however, they have evolved into a modern piece of archery equipment cable of great accuracy at long distances. Some of the improvements are attributable to efforts by equipment manufacturers to provide high performance equipment for crossbow hunters in North America.

2) *Arrows*: An arrow consists of basic parts which are shown in Fig. 1; an arrowtip (also referred to as a point), insert, shaft, fletching (or vanes depending upon the material used) and a nock. The main parameters of the arrow that influence arrow behavior during flight are the overall weight, the weight of the arrowtip, the arrow spine (both the static spine and the dynamic spine) and the fletching type. [1, 2]. The weight per length unit and spine of the shaft depend on the material used to construct the arrow shaft. The most common materials used in arrow construction are carbon, aluminum, fiberglass and wood.



Figure 1. Constituent parts of an arrow

II. ARROW PARAMETER RECORDING

Archers continue to have a great interest in the performance of their equipment and the behaviour of the arrows during the flight. Modern technology has previously been applied to study arrow flight, for example, to measure the velocity of the arrow, or its behaviour during flight. This can be done through paper tuning [7], radar [8] or more usually, high speed video recording [5,6] or via ballistic chronograph [9].

A. High Speed Video Recording

High speed video recording allows users to see the movement and flexions of the arrow shaft during the arrow's launch and free flight after leaving the bow. By processing the video recording, the arrow velocity and trajectory can be estimated which is an advantage when compared to other methods. The disadvantages include the high cost of high-speed cameras having a suitable frame rate and the system setup. It is also difficult to capture arrow launch, flight and impact in one camera view with sufficient resolution. In addition, the required video processing is not trivial.

B. Ballistic Chronographs

Ballistic chronographs are the gold standard for measuring projectile speeds. Originally developed to measure the velocity of bullets, the use of chronographs to measure arrow speed has become widespread. Chronographs are usually optical gate based devices. The chronograph must be located such that the flight of the arrow passes in a relatively narrow region above the optical sensors. Because they employ optical sensing, the accuracy, repeatability and reliability of such devices is heavily dependant on ambient lighting conditions such as provided by the specific type of indoor lighting used in the vicinity of the chronograph or the variable lighting conditions typical outdoors. Where fluorescent lighting is the source of ambient lighting, a dedicated and specialized light source must be used with the chronograph. When used outdoors a diffuser must generally be employed with the chronograph. The range of measured speeds is from 6.7 up to 2438 meters per second, the cost of the unit range from \$130 to \$900 and the accuracy is generally around 0.5%. Like radar based systems, a chronograph only provides data for a single point in the arrow's flight. Other disadvantages of the ballistic chronograph include the above-mentioned problems created by ambient lighting and the challenge of precisely locating the arrow above the optical sensors at distances greater than 20 meters. Because the information provided by data collected over a longer shot-distance (even for a single point of flight) provides more complete information concerning overall ballistic performance, the preceding limitation is significant. In addition, the location of equipment downrange in the immediate vicinity of the arrow's flight can easily result in destruction of the instrument with a misplaced arrow.

III. IN-FLIGHT BALLISTIC MEASUREMENT SYSTEM

The primary requirement is that the new ballistic system will provide information of the arrow velocity at every point of the arrow trajectory because arrow velocity during the flight is not constant and depends on the distance to the target. The system requirements were the following:

- Electronic Package: must fit into an arrow tip, and be battery operated
- Communication: must be able to send information to a docking station or PC
- Power Source: battery capacity must support system operation for at least 100 shots
- Durability: Electronics and enclosure must withstand repeated hi-G acceleration/deceleration during launch and impact
- Attachment: System must be able to attach using industry-standard threaded shaft inserts for ease of attachment and removal
- Performance:
 - must automatically register consecutive shots
 - arrowtip memory capacity must allow data storage for at least 4 shots
 - provide information about in-flight vibration/shaft oscillation
 - provide information about the arrow drag
 - provide information about the time of the flight TOF
 - Form Factor: overall weight of the arrowtip including electronics and power source must be 6.479g or 8.1g.

A. Accelerations Acting On The Arrow During Launch And Impact

A FASTCAM SA1.1 Model 675K-M2 B/S high speed video camera capable of 675,000 frames per second [6] was used to evaluate accelerations during arrow launch and impact. A single-cam compound bow [Mathews Drenalin with a 29" draw length set at 64 lbs of draw weight] was used to shoot arrows during the video taping. The arrows were marked with special distance markers to easily reproduce arrow distance travelled in time. Two cameras were used where a first camera captured the launch phase of arrow flight and a second camera captured the target impact. Each camera operated at a frame rate of 5000Hz (frame rate period 0.2 ms). The arrow distance in time was approximated from the video recordings using a polynomial function and derivated twice to obtain acceleration of the arrow in time at launch and at impact. The Mathews compound bow was used to launch

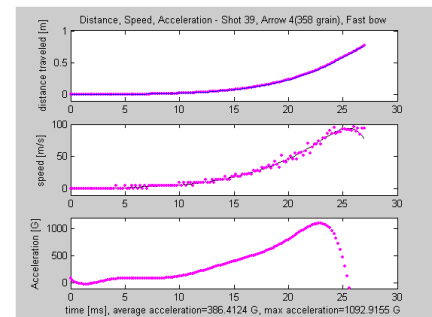


Figure 2. Arrow Distance, Speed and Acceleration in axial direction during launch with a compound bow

arrows at a Morrell standard bag target. A relatively light arrow (23.2g) was selected to provide greater acceleration at both launch and impact. Results of data processing are shown in Fig. 2 for launch. Seven different shots were processed at launch and impact to determine the highest values of impact and launch accelerations. From the results, we find that the highest acceleration at launch will be approximately 1100 G and deceleration during impact to a conventional bag target will be approximately 3700 G. From this data, we can estimate that for a wide range of compound bows the acceleration at launch will be less than 1200G and the deceleration at impact will be less than 5000G. Obviously these limit values depends on the draw weight of the bow, arrow weight, and also on the material and construction of the target.

B. Mechanical Constraints And Construction

With those requirements in mind, we created an electronic field point configuration where the electronic data acquisition system is built into the arrow tip. The most common arrow tips are usually the same diameter as the shaft which means approximately 8 mm for a conventional carbon shaft. The limitation on the length is not that strict since there is no standard length of the tip. The system housing has to be equipped with industry standard 8/32 UNC thread in order to fit standard arrow shaft inserts [10]. Using mechanical system modelling software we designed a system enclosure consisting of; arrowtip cap with a cavity for the batteries and a helical spring, an arrowtip body with cavity for electronic system and a standard threaded shaft for connection to the arrow insert. The entire system was designed to fit into the cavity of the arrow tip. The overall tip body diameter is 9mm and the total length of the tip (including cap) is 40mm. The durability of the mechanical enclosure and assembled PCB was tested using drop tests at 5000G in the axial direction. The inner cavity with inserted PCB was then encapsulated for extra protection.

C. Electronic Construction

The electronic schematics consists of an ATtiny84V microprocessor, an AT24C512 512kB EEPROM memory, 3-axis digital accelerometer ADXL345 (10 bits, 16G range), SQ-ASA-150 shock switch with 150G threshold and a power management circuit. The whole system is powered by two coin cell batteries. Communication between tip and docking station is provided

by a custom 1-wire protocol. The tip body is made from an aluminium alloy and is used as a negative ground conductor. The communication line is fed through the threaded shaft at the rear of the tip body. The positive battery contact is a custom brass contact which is soldered directly to the PCB.

D. System Operation

Once the system is powered up it initializes and goes to sleep mode. Each tip is able to capture flight data (acceleration, launch and impact events) for up to 4 shots which is saved to the internal EEPROM memory. The 150G sensitive shock switch is used to trigger a shot recording. After the trigger, the microcontroller starts retrieving data from the accelerometer and stores this data to EEPROM memory. The accelerometer provides information of acceleration in all three orthogonal axes. The time stamp of any shock switch trigger is also captured and stored. The maximal duration of a shot is 800 ms and the sample rate of the accelerometer is 3200Hz. This means that for each shot, 2560 acceleration data points are stored for each of the three axes. After 800 ms, the shock switch signal is evaluated using a proprietary algorithm. Only real shots are saved and any accidental events (drop of the tip on the floor etc.) are filtered out and not stored

The arrow tip with the saved data is then removed from the arrow shaft and coupled with a docking station. Two types of docking stations were developed. The first docking station with LCD is a standalone evaluation system which can process data stored in the tip memory, calculate the flight parameters without being connected to a PC and perform basic tip maintenance. This docking station allows the user to view the arrow launch and impact ballistics in text and evaluate the data in the field. It can also be connected to a PC via USB. A smaller USB docking station used during system development, is dedicated to transfer data from the tip memory to a connected PC where spreadsheet/.csv files are created. The data is processed and the results shown in a graphical form.

IV. RESULTS

The system processes the data from the tip and calculates the following values:

- Launch and impact velocity (distance to target has to be entered)
- Launch and impact kinetic energy (distance to target and arrow weight has to be entered)
- Launch and impact momentum (distance to target and arrow weight has to be entered)
- Time of the flight between end of arrow launch and start of the impact to target (TOF)
- -Launch time and impact time
- -Arrow drag coefficient

In addition the user can see and compare shots in graphical form on the PC. Acceleration in axial direction and the corresponding shock switch signal is shown in Fig. 4. Even

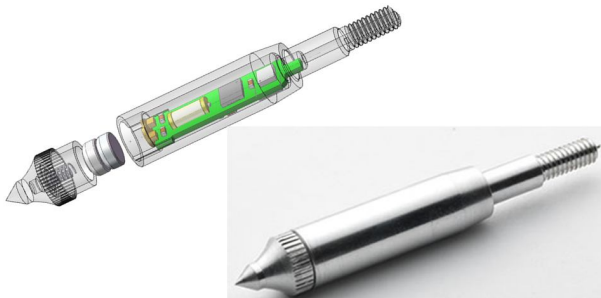


Figure 3. Electronic Arrow tip construction

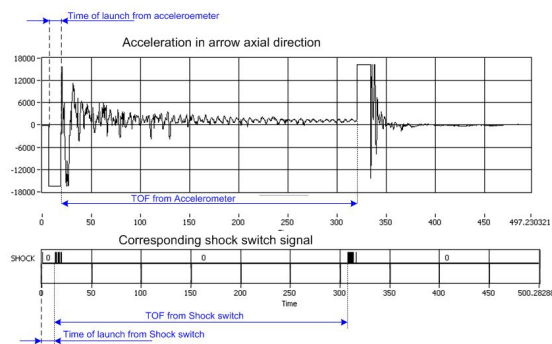


Figure 4. Accelerometer and shock switch signals during arrow flight

with an accelerometer range of $\pm 16G$ the accelerometer can be overloaded up to 10000G at launch and impact yet still provide useful information because the $\pm 16G$ range is not exceeded during free flight. The measured value in arrow axial direction drops under $-16G$ range during the arrow launch and exceeds the $+16G$ limit on target impact. These two events are also clearly visible on the shock switch signal which is recorded as well as the accelerometer signal. Up to 70 tips were manufactured and tested. The same hardware was tested for repetitive shots to test the reliability and accuracy of the system. Over 100 shots were taken with some of the tips with no degradation in performance.

A. Test Results

The U.S. National Institute of Technology and Standards (NIST) [11] has designed and built the nation's most accurate ballistic chronograph [9]. This reference chronograph is used to characterize commercially available chronographs. The reference chronograph was used to test our tips along with 3 commercially available ballistic chronographs.

Tests were conducted using the following equipment:

Bow: Elite Hunter; 29" draw length; 60.6 lb. draw weight

Arrow: Easton ST Epic; 27.5" length; feathers; weight 24.753g including 6.48g electronic arrow tip.

Shooting Machine: Spot-Hogg Hooter Shooter

Release: Spot-Hogg Friday Night Delight actuated using Kaiser pneumatic shutter release

Each shot was taken at a distance of 13.94 meters.

The results are shown in Table 1 for the arrow velocity at launch as measured by each device. The electronic tip shows a mean velocity of within 0.587% of the reference chronograph with a much lower standard deviation whereas the means of the commercial chronographs measure between 1.5-1.9% from the NIST device mean. The electronic tip is also the only device able to measure velocity at impact and calculate Time of Flight with means of 78.193 meters per second and 173.926 milli-seconds respectively.

V. CONCLUSIONS

The presented arrow tip electronic system allows archers to determine in-flight kinematic values. The whole electronic system was accommodated into the arrow tip with a maximum diameter of 9mm and length 40mm.

TABLE I. ARROW VELOCITY AT LAUNCH (METERS PER SEC)

	NIST Ref Chrono	Electronic Tip	Chrono1	Chrono2	Chrono3
Shot 1	82.67	82.08	81	81	n/a
Shot 2	83.05	82.15	81	81	81
Shot 3	81.97	82	81	81	81
Shot 4	82.61	82.13	81	81	82
Mean	82.575	82.09	81	81	81.33333
Std Dev	0.447921	0.066833	0	0	0.57735

The tip can be easily mounted to a wide range of shafts using standard threaded inserts. The system allows capture of up to 800ms of recording which corresponds to a distance of 61.96 meters (200 feet) or more when modern compound bows are used. The system is also able to measure the launch and impact velocity and the arrow drag coefficient. The accuracy of the launch and impact velocities is within $\pm 0.59\%$. The PC based system is also able to show the instantaneous values of arrow velocity in time. Constant velocity for a given combination of compound bow and arrow also raises the possibility of using this system for distance measurement when a calibration shot was taken over a known distance

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