Design, Analysis and Validation of a Tactical Surveillance Launch System

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The aim of this project was to develop a working launch test bed for an auto-rotating micro air vehicle concept, being developed at UNSW@ADFA which aims to be tactical surveillance solution for modern infantry sections. This report presents the revised design of the initiator, an improved numerical performance prediction for the launcher and validation experiment. The launcher, herein referred to as the Initiator, is a single stage gas gun with a free-piston trigger system. It was shown in the experiment that the performance prediction tool achieved less than 10% error during the test launches. The mock air vehicle that was tested, which had an average weight of 0.240 kg, attained a muzzle exit velocity of 106 ms⁻¹. This should theoretically allow the air vehicle to reach a height of 255 m, giving the air vehicle sufficient altitude to achieve its intended mission.

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Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>cross sectional area of the barrel</td>
<td>m²</td>
</tr>
<tr>
<td>A_ref</td>
<td>pressure reference area</td>
<td>m²</td>
</tr>
<tr>
<td>A_s</td>
<td>stress area</td>
<td>m²</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
<td>N</td>
</tr>
<tr>
<td>f</td>
<td>coefficient of static friction between the projectile and the barrel</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>major diameter of the internal thread</td>
<td>m</td>
</tr>
<tr>
<td>L</td>
<td>length of the barrel</td>
<td>m</td>
</tr>
<tr>
<td>L_engagement</td>
<td>thread engagement length</td>
<td>m</td>
</tr>
<tr>
<td>m</td>
<td>projectile mass</td>
<td>kg</td>
</tr>
<tr>
<td>P_atm</td>
<td>atmospheric pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>P_operating</td>
<td>operating pressure in the reservoir</td>
<td>Pa</td>
</tr>
<tr>
<td>Re</td>
<td>Reynold’s number</td>
<td></td>
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</table>

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\[ t = \text{time since valve opening (sec)} \]
\[ V_e = \text{projectile exit velocity (ms}^{-1}) \]
\[ V_0 = \text{initial volume of the reservoir (m}^3) \]
\[ v = \text{instantaneous projectile velocity (ms}^{-1}) \]
\[ x = \text{distance of projectile to barrel exit (m)} \]
\[ \gamma = \text{ratio of specific heats} \]
\[ \rho = \text{density of the driving gas (kgm}^{-3}) \]
\[ \rho_{\text{infront}} = \text{density of the air in front of the projectile (kgm}^{-3}) \]
\[ \delta^* = \text{boundary layer displacement thickness (m)} \]
\[ \tau_{\text{yield}} = \text{yield shear stress of aluminum (Pa)} \]

I. Introduction

Modern combat situations have led to the requirement for high quality, instantaneous information, surveillance and reconnaissance (ISR) capability and specifically unmanned aerial vehicles (UAVs). This project, dubbed Project Falling Spy is intended to be a lightweight, inexpensive and disposable solution to this need. The focus of the project is the simplicity of the design, construction and operation. This system is unique because of its simplicity. Other squad-level UAV systems require a large launch system [11], considerable training of personnel [22] or are much more expensive due to the complexity of having autonomous or remotely controlled closed loop systems [7]. Project Falling Spy allows a small combat section to deploy to an urban environment with no specialist crew and with minimal added weight and have on-demand live-feed ISR capability. The project has been split into two sub-systems for this year that were researched independently. The first, and the topic of this report, is the pneumatically operated launcher or Initiator and performance prediction models, the other is the passively-operated auto-rotating spy that will be fired from the Initiator. The projects are independent and do not depend upon the other to test their hypotheses. This project designed and manufactured a working test bed launcher as well as validating the computational model that was developed through an experiment.

A. Background

The idea for a gun launched surveillance system has been suggested for many years, Shook outlaid a comprehensive report on the design, assembly and testing of one such system in 1997 [23]. That system was to be launched from a US Navy five-inch cannon. Miniaturised systems, however, are only recently being developed. ST Kinetics is currently creating a surveillance munition which can be launched from the 40mm grenade launcher attachment (GLA) on most combat assault rifles. The system, dubbed Soldier Parachute Aerial Reconnaissance Camera System (SPARCS), deploys a parachute at altitude and activates a 360-degree camera to transmit images back to any device with a wireless receiver [7]. This system would provide a similar capability that Project Falling Spy aims to produce however the respective descent speeds and relative costs are unknown; hence the proof of concept study for Falling Spy must be undertaken. Another system, Firefly, developed by Rafael Armament Development Authority, also launches from a GLA however simply transmits images over its 8-second-duration ballistic trajectory [18]. This simplified system provides a considerably limited amount of data and compared to Falling Spy would not be able to provide good situational awareness of a specific area as the trajectory may cover too great of a distance. The use of a gas operated launcher instead of the pyrotechnic method used in these systems gives Falling Spy greater predictability and variability; hence an accurate performance predicting model is required.

A similar system to Project Falling Spy is being developed at the French-German Research Institute of Saint-Louis. Their system is a Gun Launched Micro Air Vehicle (GLMAV) with a rotary wing slowed and

![Figure 1. GLMAV concept mission profile. [8]](image-url)
navigated descent; however their design incorporates on-board batteries which supply power to the contra-rotating blades, electronics and GPS [8]. This design allows it to be navigated and controlled, however this added capability comes with added weight, size and cost, which consequently means that unlike Project Falling Spy the air vehicle must be launched from a larger gun, will be difficult to integrate into tactical environments and will not be disposable. Regardless, the mission profile will be very similar to Falling Spy, and can be seen in Fig. 1. The launch and ballistic flight phases are studied within this report, the transition and descent have been analysed separately.

Low-speed single stage gas guns are used quite commonly as demonstrations of projectile motion and basic thermodynamics, these are ones in which the flow is not choked and the projectile does not reach a speed at which the compressibility of air must be considered [3], [5], [15], [16], [21]. High-speed gas guns or shock tubes, which are typically two staged, have been used to produce shock speeds of over 5,000 ms⁻¹, to research impact dynamics for space debris [4] as well as to conduct hypersonic flow studies [10]. It was found that the equations governing high-speed shock tubes, specifically Hornung’s equation for the pressure in front of a piston [9], shown in Eq. 1, were not relevant to the performance prediction of the Initiator as the choked flow assumption does not produce realistic predictions for the pressures. Therefore only the low-speed formulations will be considered here in.

\[
\frac{dm}{dt} = -\rho \times \sqrt{\frac{\gamma P_{\text{in front}}}{\rho} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} A}
\]

An analytic expression for the projectile exit velocity of low speed single stage gas guns can be derived by assuming isothermal flow and simply applying Boyle’s Law and Newton’s Second Law of Motion. This was done by Denny [5], however as the reservoir pressures that are expected to be used for Project Falling Spy are not much greater than atmospheric, compared to the 7-15 MPa assumed by Denny, then a factor has to be incorporated to predict the effect of the back pressure and is done so by Rorhbach et al [21]. They provide an analytic expression to predict gas gun exit velocities, shown in Eq. 2, which will be used later to compare with other results. They found that their equation gave good comparison with experimental results.

\[
V_e = \sqrt{\frac{2}{m} \left( \frac{P_{\text{operating}} \times V_0 \times \ln \left(1 + \frac{4xL}{V_0}\right) - A \times L \times P_{\text{atm}} - L \times f}{a} \right)}
\]

This equation may be sufficient for our case, where the operating pressure is only ten times atmospheric pressure; however as accuracy is of importance, a more detailed analysis will be conducted and compared with experimental results. There are a few assumptions that the above equation makes which can greatly affect the initiator performance. The first is the assumption of zero gas leakage past the projectile; Rolph found that the out of roundness and leakage caused a 36% reduction in performance; this can be seen graphically in Fig. 2 [20]. The third assumption is that the pressure in front of the projectile is constant and atmospheric, as assumed by Denny [5].

![Figure 2. Initial trajectory predictions [20]](image-url)
B. Previous Work

Previous work on Project Falling Spy was begun by Powers who laid down the form work for the design of the Initiator and the Spy [17]. Powers developed basic computational models that demonstrated the effects that varying certain parameters would have on the design of the Initiator and the Spy as well as laying out a general conceptual design of the Spy; this design can be seen in Fig. 3. Figure 3 shows the internal componentry (a) and how the blades will sit flush with profile of the projectile until they are deployed (b). Powers’ findings suggested a set of initial design sizes for the Initiator. From Powers work a more detailed design was developed, built and tested by Rolph [20], this prototype was fabricated from PVC. Rolph concluded that the previous prototype failed due to slippage of the PVC threaded joints. This was contributed to five factors; use of tapered threads, threads were sanded to remove burrs, a reduction in thread engagement length caused by the addition of a sealing collar, the female thread expanding away from the male due to elasticity and the tightness of the thread was not measured and could have been over tightened [20]. The first three were determined to be the primary causes of the failure. As such the primary improvement the new design was the improvement of the thread strength. Rolph also concluded that the out of roundness of the barrel had a significant impact on the performance of the Initiator [20].

![Figure 3. Conceptual design of the Spy, showing internal components (a) and with deployed rotor blades (b)](image)

The current design of the Initiator is a free piston triggered pneumatically operated gun with a concentric reservoir. The concentric reservoir minimises the amount of volume the device takes up and the free piston design reduces the number of moving parts and improves reliability compared to a more complicated design, it also provides a more immediate and uniform pressure profile compared to a valve operated system, such as the one discussed by Denny [5]. The concept of operation was outlined by Rolph [19] and can be seen in Fig. 4. Initially the pressure is raised to the operating pressure (Fig. 4 (a)); the flow leaks past the piston and into the reservoir and simultaneously seals the barrel (Fig. 4 (b)). Once the operating pressure is reached the flow is stopped and the Initiator is ready to launch (Fig. 4 (c)). To launch, a valve is opened behind the piston (Fig. 4 (d)) which evacuates the rear section which drives the piston rearwards and allows the gas from the reservoir to drive the projectile along the barrel (Fig. 4 (e)).
This report also looks at developing a computational model which can accurately predict the performance of the Initiator. This is done because one of the main benefits of using a gas operated launcher is the improved predictability and control compared with explosive operated systems. The performance of the launcher is measured by the projectile exit velocity and its subsequent maximum altitude, as this will determine how long the Spy is in the air and therefore how much data it can provide. Rolph used the polytropic relationship to model the decreasing pressure behind the projectile as it moves along the barrel. That model assumed that the process is adiabatic, which may have been reasonable for the previous design as it was made out of a thermoplastic which had a low thermal conductivity compared to aluminium. Mungan states [15] that models of this type, those being one-dimensional quasistatic expansion, should be isothermal if the material has a high thermal conductivity. The new model should thus be trialled as isothermal. Other models, such as the one utilised by Mungan assume that the leakage and friction losses are negligible [15], however Rolph’s model did take into account leakage and found that it was significant. The model developed in this report incorporated losses due to leakage, friction losses and the varying pressure in front of the projectile combined with the isothermal equations to determine the projectile exit velocity.

Figure 4. Pressure loading (a), air bleeds into reservoir and seals barrel (b), flow cut off (c), rear section evacuated (d), piston driven rearwards and projectile forced out (e). [19]
II. Design

The first step of the redesign was to prioritise the improvements needed to be made to the previous model, four performance improvements were decided, which are outlined in Table 1. As the previous model was found to fail by slippage of the threads [20], the highest priority was to improve the thread strength. The off-the-shelf PVC parts used in the previous model could be modified, however this voids the manufacturers’-pressure rating [20]. Because of this it was decided that aluminium would be used as the tubing material and brass would be used as the end cap and piston housing material. Brass was chosen as it was readily available, easily machinable and would not bind with the aluminium due to them being dissimilar metals. The required thread lengths as well as the tube wall and end cap thicknesses were then calculated, the full list of calculations can be found in appendix A. For all calculations a factor of safety of five was applied to the operating pressure, bringing the design pressure to 5 MPa. As the main priority was the improvement of the thread strength, the calculation for thread engagement length is shown in Eq. 3.

$$L_{engagement} = \frac{P_{operating} \times A_{ref}}{A_s \times \tau_{yield}}$$

Where the stress area, $A_s$, is given by section 1.7 of AS1275 to be: $A_s = \frac{\pi}{4}(D - 0.9382 \times \text{Pitch})^2$, [2]. A standard pitch for all three threads of 1.5 mm was chosen due to the fact that with increasing diameter the ability to machine the tolerance required for the thread decreases and the minimum recommended diameter for a 1 mm pitch is 80 mm [2]. Therefore the three required minimum thread lengths for the exit end of the inner tube, the exit end of the outer tube and the piston housing attachments are 6.22 mm, 3.22 mm and 4.43 mm respectively. The Australian Standard (AS1275) also states that thread must have at least four complete turns, so all thread lengths must be greater or equal to 6 mm. If the end cap or piston housing threads were to fail it would create a dangerous projectile, so as an added security a thread length of 14 mm was chosen for all attachments. This made the hoop stress to be the expected failure mode, thus making the design fail safe.

Table 1: Prioritised improvements to initiator design.

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Priority</th>
</tr>
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<tbody>
<tr>
<td>Increase thread strength</td>
<td>Highest</td>
</tr>
<tr>
<td>Increase piston speed</td>
<td>Medium</td>
</tr>
<tr>
<td>Improve barrel bore roundness and surface finish</td>
<td>Low</td>
</tr>
<tr>
<td>Increase reservoir pressure</td>
<td>Low</td>
</tr>
</tbody>
</table>

There were two other sources for concern in the design. The first was that the aluminium inner tube wouldn’t be supported and would create a significant enough cantilever load on the thread to cause damage or misalignment. The moments were calculated and determined to be minor however it could cause concern when combined with the fast movements and loads associated with use in a combat environment. Because of this, a spacer was designed to support the inner tube and aid installation as well as act as a stopper for the projectile so that it does not push the piston open prior to pressure build up. The spacer can be seen in Fig. 5, it consists of four threaded metal rods screwed into the barrel so that the outer end is

Figure 5. Spacer design.
just clearing the inner radius of the outer tube, and it is then locked with a locking nut. The second concern was that the pressure in the reservoir would deform the barrel enough to restrict the travel of the projectile. It was found that the effect would be less than the tolerance expected for the inner tube radius and therefore was not of concern.

Following the design of the attachments the second priority improvement was looked at. It wasn’t known what caused the slow piston speed in the previous design, but it was observed that only once the redirecting nozzle was removed from the exhaust point did the piston move [25]. This implies that the outflow from the piston housing is likely to be the main cause of the slow firing; therefore the design of the exhaust plumbing was a priority during manufacture. Certain things can be altered even before the project gets to that stage; the first was the reduction of the clearance fit between the piston and the piston housing. This was achieved because both the piston and the housing were precision machined to a tolerance of ±0.05 mm. By reducing the clearance it causes a restriction in the flow to the rear side of the piston when the valve is operated, this subsequently causes a greater pressure differential over the piston forcing it open faster. The second improvement was made by increasing the effective area of the piston. This was possible because the design uses componentry which can be made to design. The piston used in Rolph’s design had a diameter of 95.5 mm [20] whereas the new one will be increased to the diameter of the outer tube, 101.6 mm. By altering the design it was possible to increase the piston radius, which will cause a 13% increase to the pressure force acting on the piston which will increase the piston speed even further. The final change was altering the overall design of the piston, the new design was able to reduce the weight which aids in increasing the acceleration.

The lower two priority improvements were not considered in great detail. Whilst the out of roundness and surface finish were found to have significant effects on the initiator performance these have already been improved by using extruded aluminium tubing for the barrel. The out of roundness of the tubing was improved by the tolerance of the material which was measured to be 0.075 mm. The surface finish was also improved as the coefficient of static friction for aluminium-Teflon is 0.19 [13] whereas PVC-Teflon is around 0.3-0.4 [24], where Teflon or similar is the expected material for the projectile. The bore of the barrel could be improved further if it were separately bored out; however this was not considered for the initial build so as to reduce manufacturing time.

After the improvements were made the next priority was designing the sealing and joining geometry. The issue was that the O-ring and thread need to fit within the thickness of the original tubing. It was found that there was no way that a standard thread would fit with a standard O-ring. Therefore the availability of standard sizes did not affect the design. It was decided to use O-ring cord made to fit using an adhesive and threads will machined to design. The final geometry, shown in Fig. 6, is typical for all three seals; it involves a clearance fit locating distance, a 1.5 mm pitch thread then a lead-in to the O-ring groove and seal.

It was also decided to use a separate housing for the piston as it allowed for easier maintenance and inspection, as well as allowing the stroke to be machined to a greater accuracy than is expected from the extruded tubing. The barrel length of the Initiator was originally recommended by Powers to be at least 710 mm [17]; a length of 1000 mm gives a better overall volume and subsequently greater performance [5] whilst not making it too cumbersome or weighty to be used in a tactical environment. A cutaway section of the final design is shown in Fig. 7 and the technical drawings can be found in appendix B.
III. Analysis

A numerical model was developed to predict the performance of the Initiator. This was important because the main benefit of using an air launcher was that it removed the unpredictability of explosives. The algorithm the model follows is a time-stepping process which recalculates the pressures and losses as the projectile accelerates out of the barrel. With each time step the velocity from the previous step is used to calculate the new volume and subsequently the new pressure using the ideal gas law. As mentioned earlier Hornung’s equation (Eq. 1) was also used to calculate the pressure in front of the projectile however it was found that the output pressure was less than $10^{-6}\text{ Pa}$, thus it was concluded that the high speed equations used by Hornung were not valid for this design.

The pressure in front of the projectile is instead calculated by taking the mass flux out of the barrel, calculated from the known projectile speed. This is done by using a variation of Newtons Second Law of Motion, Eq. 4, to find the force in terms of the mass flux. The boundary layer effect is also taken into account with a displacement thickness incorporated which effectively reduces the exit area; this thickness is calculated using Blasius’ solution for laminar boundary layers, shown in Eq. 5 [1]. The build-up of the pressure in front with velocity can be seen in Fig. 8. Whilst this increased the final pressure in front by 12% it changed the final exit velocity by less than 0.5%. This is because the pressure behind is significantly greater than the pressure in front of the projectile. Therefore we have shown that the assumption made by Denny that the pressure in front can be assumed constant and atmospheric [5] is reasonable for this design.

\[ F = \frac{d(mv)}{dt} = v \times \frac{dm}{dt} \]  
\[ \delta^* = \frac{1.72 \times x}{\sqrt{Re}} \]

Once the pressure in front is known it is then factored with the friction force and the pressure behind the projectile to give a resultant force on the projectile. These are then applied to the first-order kinematic equations to find the displacement of the projectile for that time step. Two methods were used to find the final velocity; the first was to simply take the final velocity reached from the kinematic equations of motion, and the second was to integrate the work done of the driver gas in the reservoir using the isothermal equation for work, shown in Eq. 6.

\[ F \times \delta^* = W \]

\[ W = \int P \, dv \]

\[ W = \int \frac{1}{2} C_d \, P \, A \, v^2 \, dl \]

\[ W = \int \frac{1}{2} C_d \, P \, A \, v^2 \, dl \]

\[ W = \int \frac{1}{2} C_d \, P \, A \, v^2 \, dl \]
The losses are calculated by assuming choked flow around the clearance of the piston in the housing and the barrel and projectile. This assumption is proven to be valid as even at the exit point the reservoir pressure is seven times that of atmospheric and all that is required is $\frac{P}{P_o} > 0.528$ [1]. The full code can be found in appendix C.

$$W_{A-B} = -n \times R \times T \times \ln \left( \frac{V_B}{V_A} \right)$$

(6)

This model assumes that the flow within the Initiator is quasistatic and isothermal, i.e. the temperature is constant. The two exit velocities were compared to determine how valid the program was, the code outputs a value of 104.8 ms$^{-1}$ for the direct method and 112.2 ms$^{-1}$ for the isothermal work done method. The difference was proven to be independent of the time step at or below 0.000001 seconds so the there is no convergence error. Both equations take into account the same loses so the error cannot be contributes to that. The error may be from the approximated value of the ideal gas constant, 287 J/kg/K, however it is unknown precisely why they are different from the expected as the two methods have the same assumptions. Both methods assume the driver gas is expanding quasi-statically and isentropically, the both account for the loss in mass of the driver air, the sliding friction of the projectile and build-up of the pressure in front of the projectile.

The results were then compared with the analytic expression shown in Eq. 2. Figure 9 shows the predicted exit velocities for various reservoir pressures, the expected exit velocity for a reservoir pressure of 1 MPa is 113.9 ms$^{-1}$. The work done calculation provided a result that was much closer but still lower than the value from Eq. 2; however a lower value is expected as the model estimates the losses around the projectile and piston. Following this, the two exit velocities were averaged and inputted to a trajectory calculation which accounted for the drag and outputs the predicted maximum altitude. As shown in Fig. 10 it is predicted that with an exit velocity of 109 ms$^{-1}$, the Spy will reach an altitude of 277 m.

![Figure 9. Initial pressure versus exit velocity calculation using Eq. 2](image)

![Figure 10. Trajectory calculation for an exit velocity of 109 ms$^{-1}$](image)

IV. Validation

In order to validate both the computational model and the new design an experiment was necessary. This experiment aimed to measure the two key performance indicators of the launch device, the muzzle exit velocity and the maximum altitude reached by the projectile. To do this the device was taken to an experimental firing range which had restricted air space that would allow the test to be undertaken without interfering with low-level air space. Several launches were conducted with a high-speed camera and radar to measure the exit velocity and an on-board micro altimeter to measure the altitude of the device.
V. Future work

The work conducted presents a few issues that need to be overcome in future iterations of the launch system. The first is stabilising the projectile during the ballistic phase of the flight. This could be done by very careful measurement of the centre of mass of the payload, rifling the barrel which would also create pressure losses, or using some form of fins or sabot. The second is to improve the design of the launch device for operational use. This would involve reducing the devices mass, reducing noise generation, improving the recoil suppression and imbalance as well as improving the mobility and inbuilt variability control.

VI. Conclusion

The work conducted throughout the year made several contributions to the overall project. If future work continues on the project concept it will mean that there is a working test bed for live tests to be conducted and it has a proven performance. The predictions tool also means that changes to the design could be made with no additional work needing to be done to the prediction tool. The performance of the launch device was shown to be more than satisfactory to achieve the aims of the project. The exit velocity is sufficient to achieve the altitude desired, assuming the aerodynamic issues in the ballistic trajectory are resolved.
Acknowledgments

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References


