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Small Fixed-Wing Uav Precision Aerial Drop Capability Development

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Small fixed-wing unmanned aerial vehicles (UAVs) have proven themselves as invaluable assets for reconnaissance and surveillance missions. Their improvement and further development most often focuses on improved endurance, datalink range, camera capabilities etc. This paper presents a modular approach to "Vrabac" UAV improvement by integrating wing payload extensions, enabling precision aerial drop capabilities. This enables precise delivery of lethal or non-lethal payloads from the UAV at pre-determined coordinates or at a visually aquired target. Precision aerial drop software module is presented, focusing on the automated payload drop algorithm with continually calculated impact point prediction (CCIP) and UAV guidance to the continually calculated release point (CCRP). The chosen ballistics computation and control system implementation evaluates UAV flight parameters, wind direction and velocity, terrain profile etc. to achive a precise target strike. Simulated results with a parameter sensitivity analysis, as well as field test results are presented.

Key words: **Unmanned Aerial Vehicle, Precision Drop, Control Design, Modular Design.**

Introduction

Small fixed-wing Unmanned Aerial Vehicles (UAVs) have proven themselves as invaluable assets for both military and civilian purposes in various missions such as reconaissance, surveillance, target acquisition, search and rescue, surveys, mapping etc. Extending possible use cases consists of various performance improvements and new mission types. One of perspective mission types is payload delivery.

Payload drop use cases have been performed very successfully on an operational level for critical supply and medical deliveries in civilian use cases and are well proven [1]. The use of parachute delivery is useful for sensitive payload delivery (medical supplies etc.) but have a disadvantage of being relatively imprecise (parachute opening, wind effects etc.), with a total error, depending on dropping altitude of few tens of meters.

Precise payload delivery can be performed by utilizing either active payload guidance (GNSS or camera-guided) or precision delivery techniques and algorithms and non-guided payloads.

Non-lethal payloads such as ammunition, critical supplies (medical or technical) usually require soft-landing and parachute delivery. Depending on circumstances, precision of few tens of meters is usually sufficient. However, more precise delivery can be beneficial in time-critical, urban or combat scenarios.

Lethal payloads that can be carried on a small fixed-wing UAV have to be very lightweight. Most attempts are based on regular 40 mm grenades or similar warheads (200g - 300 g) , thus having a limited lethal radius of 5-8 m. This requires precise delivery of these non-guided munitions.

Use of hovering multi-rotor UAVs enables stable conditions and adjustment but have limitations, as they are relatively loud, vulnerable and slow to react, with much lower endurance, carrying capacity and range than fixed-wing systems.

Fixed-wing platforms present unique challenges for implementation, since these low-velocity munitions are greatly affected by wind, UAV speed and altitude above ground. The targeting software needs to account for all these factors in order to perform a successful strike. The implementation on the UAV needs to ensure safety, minimize effects on the primary reconnaissance role of the UAV and be flexible for further development and upgrades for various payload types.

This paper shows one such modular implementation on the Vrabac (Sparrow) reconnaissance UAV developed at the Military Technical Institute, Belgrade.

System integration

Sparrow UAV (shown on Fig. 1) is of conventional design with electric tractor propeller propulsion system. It is designed for hand-launch and parachute/airbag landing. It is the first UAV in service in Serbia to feature fully domestically developed avionics and software. Due to hundreds of flight tests performed and well understood UAV capabilites and limitations it was deemed easy for integration of additional payloads and modifications.

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The requirements consisted of carrying four 40 mm bomblets, based on 40 mm grenade munitions. The bomblets feature custom designed arming mechanisms and the firing charge replaced with a simple 3D printed tail fin. The system needs to be safe and easy to use. It has to avoid compromising the basic unarmed mission capability. The required precision is 10 m, to ensure destruction of an unarmored target (light vehicle, infantry etc.) with the release of four bomblets, taking into account their dispersion.

Modular design

The “Sparrow” UAV is designed for easy transportation in a backpack-type case, with easy and quick toolless field assembly and disassembly. As such, it consists of 6 components (fuselage, tail boom with the vertical stabilizer, horizontal stabilizer, central and two outer wing sections). Wing-mounted weapon stores are an obvious choice due to the parachute landing and general UAV design.

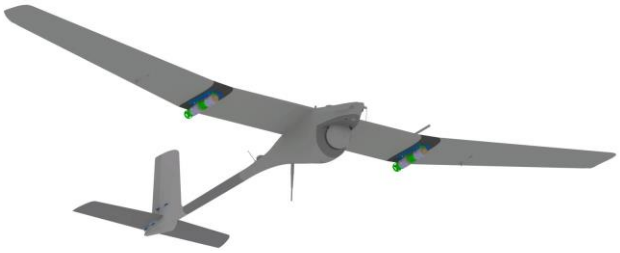

Figure 1. Sparrow UAV with wing extensions (marked in darker color) and bomblets

Wing extensions (shown with darker color on the UAV on Fig. 1 and independently on Fig. 2) were designed in order to facilitate pylon integration with minimal effect on the basic unarmed configuration. The extensions provide an increase in wing area from 0,75 m^2 to 0,87 m^2 , as such keeping most aerodynamic parameters unchanged (lift coefficient on cruise, stall speed, controls deflections etc.), which maintains good stability and efficiency with a significantly increased takeoff weight. The weight of the basic (unarmed) Sparrow UAV with the optoelectronic payload and battery is 8,3 kg. The armed configuration, with the wing extensions, weapon pylons and four 40 mm bombs weighs 9,9 kg (0,9 kg being the weapons themselves). The defined loiter, cruise and fast cruise speeds (15, 19 and 25 m/s, respectively) for the Sparrow UAV are kept the same as with the lighter reconnaissance configuration.

By mounting the wing extensions and bombs the UAV is simply converted into the armed configuration. No other modifications, setup or setting changes are required.

Safety design

Safety is ensured by the newly designed arming mechanism and its integration with the wing pylons. The bomblet is secured for transportation with dual safety pins, ensuring that the mechanism cannot get to the armed position. One of these pins is removed when the bomblet is mounted on the pylon and interfaced with the pin on the pylon itself, thus maintaining the double-safety design. The second pin is removed just before takeoff. Thus, during flight, the bomblet is still secured by the safety pin interfaced with the wing pylon.

The system is robustly designed and tested for safety in the case of UAV crash on launch or other in-flight failure. In the case of any in-flight failure and crash of the UAV the bomblet remains unarmed and secured on the pylon. The pylon release mechanism is made of a combined plastic and metal design. All bomblet interfacing components are metal and the mechanism is robust and immune to acceleration-related bomb release.

The bomblets are mounted in pairs, two under each wing, one behind the other. The mechanism ensures that the rear bomblet is always released first, thus avoiding the possibility of in-flight collision.

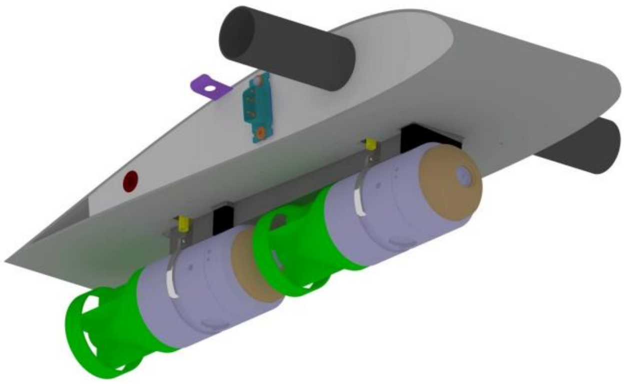

Figure 2. Wing extension with bomblets

The weapon pylon features micro-switches for payload release indication, with a secondary role of easier payload installation. It can be commanded to release bomblets sequentially, in pairs (with a defined delay) or independently, as such it can be considered as a smart weapon store solution. This way the required target area cover can be optimized.

The mechanism is servo-actuated, with known movement speed and delay, which is an important factor for achieving precision bomblet delivery, since a delay of 0.2 to 0.3 seconds leads to an additional 4 – 6 m of error. Thus, the system takes this delay into account when calculating impact point.

This way of integration is flexible and capable of supporting multiple different payload combinations, in addition to the presented ones, if their parameters are known and programmed into the system.

Targeting and software implementation

The software component of the system consists of two components: the component running on the UAV flight control computer and the component running on the GCS (Ground Control Station).

The UAV flight control computer is developed at the Military Technical Institute (VTI) and based on dual ARM Cortex M7 series microcontrollers (STM32H743) running at 480 MHz, with independently developed sensor, navigation and flight control software (written in the C programming language). It has the capability to read a Digital Elevation Map (DEM) of the area surrounding the UAV, enabling the use of enhanced safety features (terrain avoidance), target coordinate acquisition (without the use of a laser rangefinder) and ballistics computation outlined in this paper. The flight control computer runs the guidance and control loops necessary for precise payload delivery. This is tied-in with regular waypoint or camera-guided navigation

The Ground Control Station is based on a ruggedized Windows laptop (Panasonic CF-33). The VTI-developed GCS software (written in the C++ programming language) is responsible for the graphical control interface, map, video display, communication, army C2 system integration etc.

Both software components for precision strike capability (on the UAV and GCS) run whenever the weapons subsystem is armed by the user. The system has two usage methods, semi-automated CCIP (Continuously Calculated Impact Point) and fully automated CCRP (Continuously Calculated Release Point).

The CCIP method does not need any target data, but only computes the bomblet impact point (if released at the current UAV position) and displays it to the user. The impact point is displayed on GCS map display and overlaid on the video feed from the camera (for visual targeting). In this mode it is the users responsibility to manually control the release of the bomblets and ensure proper guidance of the UAV (preferably in camera-guided mode or by moving the current waypoint position).

The CCRP method performs the same actions as CCIP, but requires the target coordinates, thus computing the geographic position the UAV needs to get to in order for the bomblets released there to hit the target. This position is then transferred to the flight control guidance and navigation algorithm and the UAV performs the attack autonomously. The bomblets are only dropped if the UAV gets within the predefined position envelope (acceptable position error envelope, settable by the user). The user can view the current estimated impact point in the same way as in CCIP mode and has the power, at any time, to command immediate payload drop manually or disarm the system (cancel the attack).

Ballistics computation

The software implementation is based on continuous bomblet flight path computation based on multiple variables:

-UAV flight speed

-UAV climb rate

-Wind speed

-Wind direction

-UAV course (track over ground)

-UAV altitude

-Terrain elevation profile

-Payload release delay

-Payload mass

-Payload aerodynamic coefficients

The ballistics software runs whenever the software is armed for an attack on the target (arming requires user action). The simple 3-degree-of-freedom (DOF) oblique shot calculation with drag and wind effects runs iteratively, calculating the bomblet flight path from the current position (obtained from the UAV navigation data), taking into account all the above defined variables. One similar approach can be seen in [2], more detailed model in [3].

The initial projectile position and velocity vectors are the UAV position and velocity. After release, an initial short transition period takes into account various non-linear effects, such as projectile stability, lift and pitch/sideslip moments etc. in order to improve precision and, simultaneously, simplify the computation (avoid the use of computationally intensive 6 degree-of-freedom models), since after the initial short period the angles of attack and sideslip are very small, as the bomblet velocity becomes dominant over the initial velocity. The wind velocity and direction is estimated by the UAV and is critical for precise delivery.

At every iteration the altitude of the bomblet above ground is checked (using DEM – Digital Elevation Model, i.e. 3D map). When the bomblet arrives to the ground (within the defined threshold) the final path parameters are output to the autopilot flight control logic and to the user interface.

A test of the software with real input data (release point, true impact point, aerodynamic and atmospheric parameters) is shown in Fig. 3 (made using MATLAB). The UAV flown path is shown in pink, with the calculated bomblet path shown in light blue color. Actual bomblet impact photo corresponding to this is shown in Fig. 4, showing excellent agreement between the prediction and result.

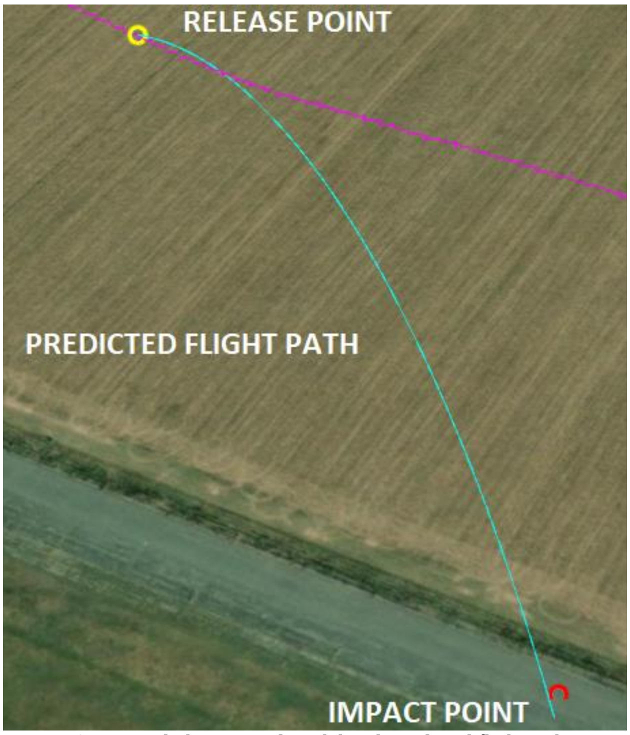

Figure 3. Flight test result with bomb predicted flight path

Figure 4. Actual impact for Fig. 5 (2-5 m error)

Parameter sensitivity and precision

Precision can only be achieved under correct circumstances. The best computation method will fail if incorrect data is input. Thus, sensor precision and computation parameter sensitivity need to be compared in order to assess the reliability of the computation. In accordance with this, correct computation iteration loop times have to be chosen (in order to maintain precision and minimize computational time and cost). The table below shows calculated bomblet flight path distance (X) and cross-track (Y) for changing UAV airspeed, climb rate, altitude, and wind speeds.

From this data we can estimate the required precision of input data for the calculation. UAV altitude above ground is not overly critical, with path length being around 20 times less sensitive than with regard to changes in airspeed (as shown on Fig. 5) or wind. The reason for this is the fact that, for the usable altitudes (150 m and above), the final flight path angle is already quite large, thus reducing the sensitivity to these parameters. This means that acceptable precision can be kept even when used from higher altitudes (300-500 m) above ground.

In contrast, knowing airspeed, wind direction and velocity with enough precision is essential, since even a weak wind (1-2 m/s), if unaccounted for, has a very significant contribution and can cause the bombs to miss the target completely.

Table 1. Parameter sensitivity

Parameter	Values	X[m]	Y[m]
Vx Airspeed	19 ± 1 m/s	113.8 ± 5.8 m	0 m
Vz Climb rate	0 ± 1 m/s	113.8 ± 1.7 m	0 m
Wx Headwind	0 ± 1 m/s	$113.8^{+3}_{-7.9}$ m	0 m
Wy Crosswind	0 ± 1 m/s	113.8 – 1.6 m	0 ± 3.9 m
H Altitude	200 ± 1 m	113.8 ± 0.25 m	0 m

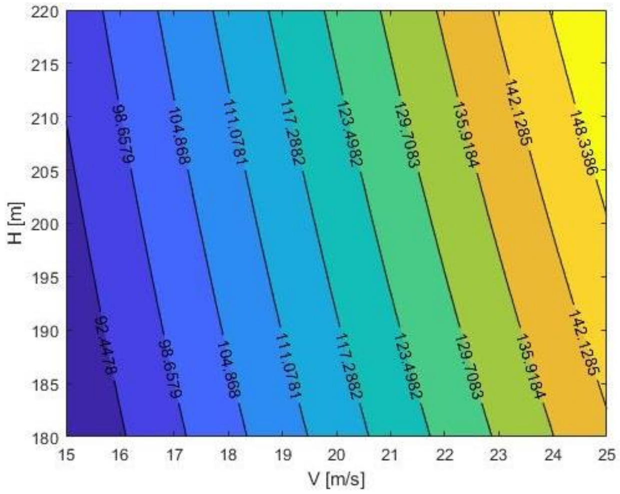

Figure 5. Flight path distance with changing airspeed and altitude

User interface implementation

The user has control of the targeting and bomb release at all times. The user control panel displays relevant data and enables the user to arm and disarm the system, release the payload on command, set the payload release threshold for the automated mode. The control panel also facilitates individual bomblet control, where they can be released independently. This feature is also used for pre-flight preparation and weapon loading.

The map displays all the regular information for the operation of the "Sparrow" UAV system. The target is defined as a special waypoint, with two possible modes (waypoint actions).

The bombing mode performs all the computations mentioned previously, while the payload drop mode simply releases the payload when reaching the waypoint.

While the weapons system is armed the impact point position on the map is continuously updated and saved in the targets list with a CCIP designation. This list can be saved for post-flight analysis.

The video feed display takes in additional data, such as camera attitude relative to the UAV (azimuth, elevation), camera fields of view (horizontal and vertical, dependent of zoom level) and performs the world-to-screen coordinate transformation (geographic position transformation into video display pixel coordinates).

At the moment of payload release, a screenshot of the map and video feed is saved automatically for post-flight analysis (Fig. 6) and comparison with actual strike locations (Fig. 7).

Figure 6. Computed impact point video display

Figure 7. Actual impact point for Fig. 6

Flight testing

The system was extensively tested in flight, as well as for safety in case of launch failure. A launch failure test with a catapult launch system with a mockup is shown in the figure below.

Flight testing was performed on the Kovin airfield (with dummy and shock bomblets), Nikinci and Pasuljanske Livade test and training ranges (dummy, shock-flash and live rounds).

The initial tests with dummy munitions were performed using the hand-launch method, proving the capability to successfully hand-launch the aerial vehicle even with a weight of 10 kg.

For safety reasons, for tests with shock-flash and live munitions, the Sparrow test UAV was equipped with catapult interface pins and a bungee catapult launcher was used (Fig. 8). The catapult used was from a significantly larger and faster UAV and thus much bigger than needed for the Sparrow. However, based on launching process analysis (similar to that in [4]) bungee cords were replaced and a Sparrow UAV adapter constructed. On two of such tests the UAV survived (with minor damage) two unsuccessful launch attempts, both due to the flaws in the catapult itself. On both occasions, the bomblets remained on their pylons and were secured and removed properly, thus further proving the correct approach with regards to the safety of the system.

Figure 8. Sparrow UAV catapult launch

The UAV was also flown with the release of only two bomblets (one wing remaining) and it successfully compensated for the asymmetric loading [5].

UAV landings were performed with the two or all four bomblets remaining on the wing, with good results. However, this should be avoided, since a higher probability of damage is to be expected, especially in more difficult terrain conditions.

Dummy bomblet tests were performed with a colored pigment marker infill. After initial tests, modification of the system were made in order to improve precision, reliability and practical usage, after which, the system was mostly tested with shock-flash munitions, with some live munition tests performed (Fig. 9).

Figure 9. Live munitions test

In total more than 30 test flights were performed, dropping bombs from altitudes of 150 – 250 m, with bombs falling within the required 10 m area. The dispersion was in the range of 2 - 4 m. The path calculation was proven as accurate, with most deviations from target being correctly predicted by the algorithm and caused by wind gusts and UAV movement in the lateral direction (as seen in Fig. 3 and 4).

The system was tested with wind speeds ranging from 0 m/s to 7 m/s at altitude, with the system compensating correctly, but the dispersion increasing with increased wind speeds. With further improvement in the wind estimation algorithm (improved crosswind estimation) and lateral flight control compensation (gusts), it is possible to improve these results further.

Conclusion

The results of the tests have proven the viability of the concept. The UAV with the added weight and wing extensions performed excellently and the catapult integration, after some initial problems were corrected, was successful and reliable.

The targeting software and path estimation have proven reliable and practical. The results of the tests have demonstrated the required precision and accuracy

Safety of the system was proven both for the bomblets independently and as part of the system, with intentionally mis-launching a dummy structure and during two mishaps in early development.

Future work will aim to further improve the algorithm and lateral control to better correct for cross-wind and to prepare the system for series production as an add-on kit for equipping already produced and future Sparrow UAV systems.

Further development of additional payload types and integration on larger UAVs, capable of carrying heavier payloads, is also possible.

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Razvoj sistema preciznog odbacivanja tereta sa male bespilotne letelice avionskog tipa

Male bespilotne letelice avionskog tipa su se dokazale kao izuzetno korisna sredstva za misije izviđanja i nadzora. Njihova poboljšanja i dalji razvoj najčešće se fokusiraju na poboljšanje istrajnosti leta, dometa komunikacije, kvaliteta kamera itd. Ovaj rad prestavlja modularni pristup poboljšanju bespilotne letelice „Vrabac" interacijom dodatnih segmenata krila za nošenje tereta, čime se omogućava precizno odbacivanje tereta iz vazduha. Ovo omogućava upotrebu ubojnih ili drugih sredstava sa bespilotne letelica na ranije definisanim koordinatama ili vizuelno uočenom cilju. Prikazan je softverski modul za precizno gađanje sa fokusom na algoritam automatskog odbacivanja tereta sa kontinualnim proračunom padne tačke (CCIP) i sistemom vođenja bespilotne letelice prema kontinualno proračunatoj tački odbacivanja (CCRP). Prikazan je odabrani princip proračuna balistike odbačenog tereta i implementacija sistema upravljanja koji uzimaju u obzir parametre leta bespilotnog vazduhoplova, brzinu i pravac vetra, profil terena itd. kako bi se postigla zahtevana preciznost pogađanja cilja. Prikazani su simulirani rezultati sa analizom osetljivosti parametara, kao i rezultati poligonskih ispitivanja.

Ključne reči: **bespilotna letelica, precizno gađanje, sistemi upravljanja, modularni dizajni.**