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Design, Simulation, and Testing of Three Unmanned Aerial Vehicles for Short Range Surveillance Applications

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This paper presents conceptual designs of three Unmanned Aerial Vehicles (UAVs) for short range, surveillance applications. The conceptual UAV designs included: a) a conventional puller-propeller aircraft, b) a sport model pusher-propeller, and c) a V-tail, pusher propeller. The objective of the study was to compare the performance characteristics of each conceptual design in order to select the most efficient design. To compare the performance characteristics of each design, theoretical performance analyses were conducted on each configuration. Computer models of each configuration were then simulated to validate the theoretical results and conduct further analysis. Results obtained from these tests were compared to results obtained from theoretical analysis. Based on these comparisons the best UAV model for the given performance required was selected for further refinement and analysis.

Introduction

Unmanned Aerial Vehicles have gained a crucial role in modern military and civil tactics. Operations in which UAVs have been deployed include reconnaissance, surveillance, target acquisition, electronic warfare and bomb damage assessment. Development of UAVs in the United States and abroad has seen great advancements in technology and application. Currently, more than three dozen nations are active in developing UAV technology, and the leader in advancements of UAV technology is the US. Over five dozen different programs including the American Predator, Global Hawk and shadow make up the United States' arsenal of UAV (Wilson) [1].

In reconnaissance and surveillance operations, UAVs have played a significant role. Many countries including Israel and the United States have implemented UAVs in high risk missions as an alternative to more expensive piloted aircraft. In the gulf and Iraqi wars, UAVs such as the Pioneer and Predator found success in military employment. Newly developed UAVs will also play a crucial role in homeland security. Short range UAVs could be deployed from boats or ground stations to protect America's vast coastlines. These inexpensive drones would be able to watch over our borders and relay information back to authorities.

The goal of this study was to develop a low cost UAV aircraft to perform short range reconnaissance and surveillance missions. Also, this craft would have a storage size of less than thirty cubic feet, storage weight of less than 200 lbs and be quickly and easily assembled. The fully assembled aircraft must have a minimum payload capacity of 200 lbs and a minimum cargo volume of ten cubic feet; fuel not included. With fuel and payload included, the craft must have a maximum flight range of ten miles, a maximum flight altitude of 10,000 feet and a maximum airspeed of 100 mph. During flight the aircraft must travel to a destination point, fly around that point for up to 8 hours and return.

Conceptual Design of Three UAV Models

Three different conceptual designs with identical lift and propulsion systems placed in different locations on the aircraft were considered. The designs also differed in fuselage configuration and tail design. The airfoil selected for the three configurations was the Eppler 423. This airfoil was chosen because of its high L/D. A plan form area of forty square feet and an aspect ratio of ten were selected for the conceptual designs based on the project parameters. This wing plan form yielded favorable L/D characteristics because the high aspect ratio decreased the induced drag acting on the airfoil. Propulsion systems were modeled after the Hirth F-36 2 cycle engine. This engine was chosen for its light weight, reliability and power. Net weight for the chosen engine was 51 lbs. The engine had a 14.78 cubic inch displacement yielding 22 hp at 6600 rpm. Approximately 90 lbs of static thrust can be produced by this engine.

X-1, Conventional Aircraft

As shown in Figure 1a, X-1 was a conventional style aircraft with a conventional pusher-propeller propulsion system located at the front of the aircraft. Directly aft of the engine was the largest section of the fuselage. Wing location was above and just behind the largest section of the fuselage. Aft of the wing the fuselage tapered off to connect with the tail. Tail configuration included conventional horizontal and vertical stabilizers with control surfaces composing fifty percent of each stabilizer.

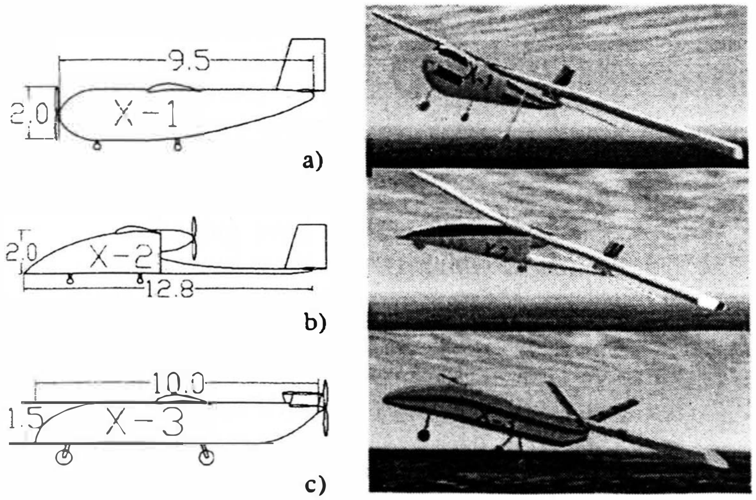

Figure 1 – Schematic side view drawings and computer screen animations of three conceptual designed UAV models

X-2, Pusher Propeller

As shown in Figure 1b, X-2 was an experimental sport-plane style with the propulsions system located behind the fuselage and in front of the tail. This craft had a large cargo volume composing the front half of the fuselage which sat very low to the ground due to short landing gears. Landing gears were shortened because of the high location of the propulsion system. In front of the propulsion system above the fuselage, was where the wings were located. Behind the fuselage and under the prolusion system was extended a small shaft which was connected to the conventional style tail. This tail was larger than X-1's to counter the moment caused by the raised propulsion system.

X-3, V-Tail

As shown in Figure 1c, X-3 was a combination pusher propeller and v-tail configuration with the propulsion system located in the rear of the aircraft. This configuration is becoming very common in the UAV market. A long and narrow fuselage configuration provided the design with the smallest cross section and the best drag characteristics. V-tail stabilizers, located just in front of the propulsion system, also reduced the total drag on the aircraft.

Theoretical Performance Calculations of the Three Designed Aircraft

Once the three UAV models were designed, performance characteristics of each configuration were analyzed using theoretical calculations. Four different performance categories were analyzed including: straight and level flight, climb and glide rate, take-off performance, and range and endurance. Due to space limitations, theory and equations used to calculate performance parameters could not be included. For more details on theoretical computations refer to Assel[2]. Based on these computations, performance parameters of the three conceptual designs were summarized and presented Table 1. As can be seen below, each conceptual design met or exceeded the required maximum velocity of 100 mph and endurance of 9 hrs.

Table 1 – Summary of most important theoretical calculations

Performance Parameters	Conceptual Design		
A) Straight and Level Flight (Gross weight of 450 lbs, altitude of 3000 ft)	**X-1**	**X-2**	**X-3**
Maximum L/D	14	23	30
Minumum Thrust (lbs)	31	19	15
Cruise Velocity at T min (mph)	75	95	102
Maximum Velocity (mph)	109	109	109
Power-off Stall Speed (mph)	51	51	51
B) Climb and Glide Rates (Gross weight of 450 lbs, altitude of 3000 ft for climb rate and 7000 ft for glide r	**X-1**	**X-2**	**X-3**
Maximum Rate of Climb (fpm)	300	470	540
Velocity at Max R/C (mph)	71	88	102
Climb Rate at Best Climb Angle (fpm)	280	408	468
Velocity at Best Climb Angle (mph)	56	68	72
Minimum Glide Rate (fpm)	390	308	276
Velocity at Minimum Glide Rate (mph)	61	68	81
C) Take-off Performance (Airport at an altitude of 1000 ft above sea level)	**X-1**	**X-2**	**X-3**
Ground Roll Distance (ft)			
Gross weight of 450 lbs	602	602	602
Gross weight of 475 lbs	671	671	671
Gross weight of 500 lbs	744	744	744
Lift-off Velocity (mph)			
Gross weight of 450 lbs	59	59	59
Gross weight of 475 lbs	61	61	61
Gross weight of 500 lbs	62	62	62
D) Range and Endurance (Flying at an altitude of 3000 ft with an empty weight of 400 lbs)	**X-1**	**X-2**	**X-3**
Range with 50 lbs of Fuel (mi)	543	930	1200
Endurance with 50 lbs of Fuel (hrs)	10	12	13

Development and Flight Testing of Simulation Models of the Three Designed Aircrafts

Flight Simulation was utilized as a tool for investigating the performance characteristics of the three designed configurations. Results obtained from these tests were compared to results obtained from theoretical analysis produced and presented in section 3. Based on these comparisons the best UAV model for the given performance parameters was selected for further refinement and analysis.

The software package used to simulate the UAV, X-Plane®, is commercially available and relatively inexpensive. The package consists of X-Plane Flight Simulator®, Plane-maker®, Foil-maker®, and World-maker®. This package was selected for its user friendly software construction and data export capabilities (Assel) [3]. Prior studies have revealed that X-Plane® accurately simulates aircraft performance characteristics. Research by Keithley[4] proved that the program accurately modeled general aviation aircraft. The capabilities of this program were further explored by Assel[1] and Cross[5] in modeling R/C aircraft. The incorporation of accurate and sophisticated physical flight dynamics models has allowed X-Plane® to be incorporated into the research and design of manufactured and homebuilt aircraft (Cross)[5].

Once the computer models were simulated, a series of simulated performance tests were performed on each model. For this, data export capabilities of X-Plane® were utilized. The utilization of these capabilities allowed easy assessment of test results. The tests performed include straight and level flight, take-off performance, climb rate and glide rate.

Straight and Level Flight

To analyze aircraft performance while in straight and level, un-accelerated flight, minimum thrust, cruise velocity, and maximum velocity were found. These parameters were determined for a gross aircraft weight of 450 lbs and a density altitude of 3,000 ft by employing flight simulation testing. To perform this test the aircraft was given an altitude of 3,000 ft using the aircraft placement screen. Next, the aircraft was piloted at different throttle settings until straight and level un-accelerated flight was achieved, as indicated by four instruments: artificial horizon, altimeter, air speed indicator and vertical airspeed indicator. Once these data points had been obtained for the entire range of aircraft velocities, data recorded by X-Plane for the entire test was exported into spreadsheets. Using these spreadsheets, data was organized to locate points where vertical velocity was less than twenty feet per minute and the difference between thrust and drag was less than two pounds.

Values for minimum thrust required, cruise velocity, and maximum velocity were obtained by plotting thrust and drag as functions of velocity. Minimum thrust required was the lowest value of drag recorded. Cruise velocity was the velocity at which the minimum thrust occurred. The maximum air speeds of each aircraft were determined by plotting thrust available and thrust required for each aircraft. The maximum air speed is the velocity at the point were thrust required is equal to the thrust available. Due to space limitation, complete sets of plotted data obtained from simulated testing could not be included in this paper. A more comprehensive compilation of results can be found in Assel[6].

A power off stall speed test was conducted to determine the lowest speed attainable by each simulated aircraft. Data recorded included aircraft velocity and stall warning. The aircraft was flown straight and level with power off until stall warning was signaled. This procedure was repeated twice more for gross weights varying from 450 to 500 lbs. The data exported was then loaded into a spreadsheet. Stall speeds were plotted as a function of gross aircraft weight for comparison.

Climb and Glide Rates

To evaluate the climb performance at full power and the descent performance for power-off glide for a gross aircraft weight of 450lbs, climb and glide rate tests were conducted. To begin the test the aircraft was placed at an altitude was 3,000 ft for climb rate tests and 7,000 ft for glide rate tests. During the test horizontal and vertical velocity were recorded while the aircraft was flown at a constant velocity and path angle relative to an artificial horizon located in the cockpit of the simulated aircraft. Multiple angles were tested in order to find vertical velocity as a function of horizontal velocity.

Take-off Performance

In order to determine the ground roll distance and aircraft velocity required for take-off at a density altitude of 1000 ft and for gross aircraft weights of 450, 475, and 500 lbs, a take-off performance test was conducted. During this test ground velocity, vertical velocity, distance traveled, and lift were recorded at the point of lift-off. This point was defined as the point where vertical velocity exceeded 20 fpm and the lift generated by the aircraft equaled the gross weight of the aircraft.

Range and Endurance

To acquire values for maximum range and endurance, data obtained from simulated straight and level flight testing for C_L and C_D were plotted as functions of aircraft velocity to determine maximum $\frac{C_L}{C_D}$ and $\frac{C_L^{3/2}}{C_D}$. Flight testing produced comprehensive sets of performance data which was analyzed in detail by Assel[2]. Table 2 shows a summary of the most important data produced by the flight testing. As can be seen below, each design met the required maximum velocity of 100 mph.

Table 2 – Summary of test results produced by flight simulation models

Performance Parameters	Conceptual Designs		
A) Straight and Level Flight (Gross weight of 450 lbs, altitude of 3000 ft)	**X-1**	**X-2**	**X-3**
Maximum L/D	16	24	26
Minumum Thrust (lbs)	27	19	17
Cruise Velocity at T min (mph)	86	90	97
Maximum Velocity (mph)	107	113	120
Power-off Stall Speed (mph)	63	55	54
B) Climb and Glide Rates (Gross weight of 450 lbs, altitude of 3000 ft for climb rate and 7000 ft for glide rate)	**X-1**	**X-2**	**X-3**
Maximum Rate of Climb (fpm)	474	462	540
Velocity at Max R/C (mph)	86	83	79
Best Climb Angle	3.8	3.7	4.3
Velocity at Best Climb Angle (mph)	81.1	69.5	77.7
Minimum Glide Rate (fpm)	354	330	300
Velocity at Minimum Glide Rate (mph)	68.2	62.7	64.8
C) Take-off Performance (Airport at an altitude of 1000 ft above sea level)	**X-1**	**X-2**	**X-3**
Ground Roll Distance (ft)			
Gross weight of 450 lbs	675	1140	795
Gross weight of 475 lbs	760	1350	860
Gross weight of 500 lbs	910	1615	970
Lift-off Velocity (mph)			
Gross weight of 450 lbs	53	56	57
Gross weight of 475 lbs	54	58	59
Gross weight of 500 lbs	57	60	60
D) Range and Endurance (Flying at an altitude of 3000 ft with an empty weight of 400 lbs)	**X-1**	**X-2**	**X-3**
Range with 50 lbs of Fuel (hrs)	550	811	863
Endurance with 50 lbs of Fuel (mi)	8.3	10.3	11.6

Discussion of Results and Comparison of Conceptual Designs

To facilitate a comparison between results acquired from theoretical calculations and simulated flight testing, key perfromance parameters were selected from Tables 1 and 2 and assymbled in Table 3. As seen in Table 3, X-3 out performed opposing designs in maximum velocity, rate of climb, glide rate, and endurance. Simulation test results showed that X-3 had a maximum straight and level flight velocity of 120 mph, while X-2 and X-3 had top speeds of 113 and 107 mph respectively. This resultant difference is due to low drag characteristics found on the pusher-propeller and V-tail designs, as opposed to the puller-propeller and conventional tail designs. Simulation results also showed that X-1 had the shortest ground roll distance with 675 ft, while X-3 was close behind with 795 ft. Ground roll distance for X-

3 could be shortened by decreasing the amount of rotation needed to achieve maximum angle of attack, which could be achieved by increasing wing incidence angle.

Table 3- Comparison of performance parameters from theoretical calculations and simulated flight

Performance Parameters	X-1		X-2		X-3	
Gross weight of 450 lbs	Theoretical	Simulated	Theoretical	Simulated	Theoretical	Simulated
Maximum Velocity (mph)	109	107	109	113	109	120
Maximum Rate of Climb (fpm)	300	474	470	462	540	540
Minimum Glide Rate (fpm)	390	354	308	330	276	300
Ground Roll Distance (ft)	602	675	602	1140	602	795
Endurance with 50 lbs of Fuel (hrs)	10	8.3	12	10.3	13	11.6

As can be seen in Table 3, Differences in results obtained from theoretical calculations and simulated flight testing for maximum velocity, rate of climb, glide rate, and endurance varied slightly. However, much dissimilarity was observed for ground roll distance. These discrepancies might have been caused by the variance of propulsion system placement. This variance caused different moments about the center of gravity for respective designs which acted against the moment of the horizontal stabilizer and inhibited rotation. More velocity was needed for the aircraft to reach rotational speed, so lift-off velocities and ground roll distance were significantly higher. This moment was not accounted for in theoretical calculations. This observation was most notable in X-2, because of its high propulsion system placement. Also, ground roll testing of X-3 observed inhibited rotation because the aircraft could not reach the maximum angle of attack without the propeller striking the ground.

Possible sources of error could cause inaccuracies in test results. One source of error is the limitations of using flight simulation software. Primarily, simulated models are based on rough conceptual designs with limited aircraft specifications. Also, model simulation is limited to certain parameters defined in the software that do not include all factors involved in determining aircraft performance. Flight Simulation software is also limited by hardware. The personal computers used to conduct testing can not compute all the instantaneous calculations required for absolute accuracy. Another factor is pilot error, it is impossible to fly the exact maneuvers necessary for complete precision. However, test results will give a relative idea of how the aircraft will operate.

Despite the discrepancies and errors described above, theoretical calculations and flight simulation testing provide valuable sources of information for comparing the different design configurations. From the comparisons, advantages and disadvantages of each design were more accurately determined. Design configurations that cause these advantages will be further analyzed in this paper to develop an even better short range, surveillance UAV model. In this analysis, small scale models will be implemented in order to conduct actual flight testing.

Conclusions, Recommendations, and Comments on Future Work

Three conceptual UAV designs were presented, evaluated, and compared employing theoretical calculations and flight simulation models. Comparisons found in this paper show that an aircraft with a V-tail, pusher propeller configuration like X-3, would produce the best performance. Distinctive design aspects of X-3 are the V-tail stabilizers, pusher-propeller propulsion system, and long, narrow fuselage shape. This configuration provides the best drag characteristics. The V-tail has less surface area than a conventional tail. A pusher-propeller located in the rear of the aircraft keeps turbulent propeller wash from flowing over the aircraft. Also, the fuselage shaping has less frontal area and a swept back nose.

Having a similar pusher propeller configuration, X-2 also had favorable performance in most tests. However, X-2's take off performance test yielded unsatisfactory results. The pusher-propeller on X-2 is located in the middle of the aircraft and above the center of gravity. This causes a large moment that limits the rotation of the aircraft during ground roll. A drastic increase in take-off distance is produced by this occurrence. In most comparisons X-1 had unfavorable performance. However, it had the best take-off performance. The X-1 configuration allowed more aircraft rotation at lower velocities, but produced more drag during ground roll. Features from each design could be incorporated into the final design to yield the best configuration.

Since X-3 had the best overall performance, many of its traits should be incorporated into the final design. A V-tail configuration is helpful in reducing the gross aircraft weight, tail area and tail drag. Having a sloped, narrow fuselage and a rear pusher-propeller on the final design would provide better performance in-flight and during ground roll. X-2 had favorable in-flight performance but performed poorly in take-off testing. Take-off performance might be improved if X-2's propulsion system was set closer to the vertical center of gravity and the tail was raised above the propeller. This would decrease the moment caused by the thrust line location.

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