Design of a Skydiving Glider

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Abstract: The conceptual / preliminary design of a skydiving glider, a tailless aircraft with an open cockpit and a pilot lying in a prone position, is presented. The vehicle is the first of its kind designed to land a skydiver conventionally without the use of a parachute and can be used for military covert operations or as an extreme sport vehicle. Conflicting constraints, such as a maximum stored wingspan of 9 feet and a maximum stall speed of 30 knots, led to the implementation of unique design features including telescoping wings. The tailless design required extensive twist along with a 30-degree sweep angle for the wing, an unorthodox amount for a subsonic aircraft.

Key-Words: Gliders, Skydiving, Aircraft Design

1. Introduction

Currently, skydivers land using parachutes. However, parachutes limit range and maneuverability. Any type of control comes from the skydiver manipulating his/her own body to change direction. The use of wing suits allows the skydiver to glide slightly. However, maneuverability is limited and the glide ratio is at best 1.8.

This paper presents a unique and revolutionary concept designed to bring a new dynamic to the sport of skydiving by increasing the maneuverability of skydivers and allowing them to land like a glider. The SDG-1 is small and compact, yet it provides a safe stall speed and a short landing distance.

Two distinct applications of the SDG-1 are recreational and military. The maneuvering capabilities are probably more attractive for recreational users, while the extended range will most likely be useful for military applications. The preliminary design steps and the proposed concept are presented in the following sections.

2. The Competition

The Skyboard [1] is the only other skydiving glider known to exist. It was conceived in 2001 and had its first test flight in December 2004. It was created by a New Zealand company and was co-engineered by Cambridge University mechanical engineering students. The basic design shares some common features with the SDG-1, such as the pilot laying face down and forward on the fuselage.

The largest difference between the two aircraft is their performance. The SDG-1 is designed to provide a significant improvement in maneuverability and range over the abilities of a freefalling skydiver. It is also designed with the capability to land. Because of its dramatically small wings, the Skyboard cannot provide good glide performance and is incapable of safely landing a person on the ground. Performance data on the capabilities of the Skyboard could not be found, however, a video of a flight test [1] shows the aircraft performing roughly the same as a skydiver wearing a wing suit.

3. Mission Specification

The mission requirements for the SDG-1 are as follows:

- Payload capacity: 200 lbs (1 pilot)
- Number of crew members: 1
- Deployment altitude: 12,000 ft
- Range: 12 nautical miles
- Glide speed: 50-90 knots
- Landing field length: 240 ft
- Stall Speed: 30 knots
- Stored wingspan: 9 ft

Without the restriction of Federal Aviation Regulations, the mission requirements were decided based solely on desired performance and operational constraints. A range of 12 nautical miles from a deployment altitude of 12,000 ft corresponds to a glide ratio of 6. A low stall speed is desired for safe landings. However, a low stall speed requires a large wing area and / or high-lift devices, neither of which is feasible in the SDG-1. Hence, following several iterations a realistic stall speed target of 30 knots was established.

The mission profile of the SDG-1 is shown in Figure 1. The mission begins with the SDG-1 and the pilot taken to the deployment altitude by means of a cargo plane. At a predetermined location, the pilot in the SDG-1 will slide out the back of the cargo plane facing forward. Once released, the vehicle will glide down to the surface in a controlled manner. Landing will take place on a groomed grass field.

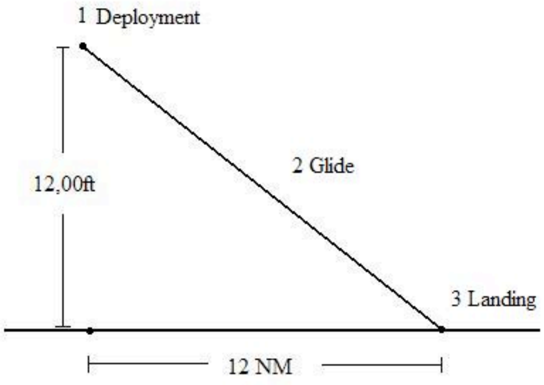

Figure 1 – SDG-1 mission profile.

4. Configuration Selection

The flying wing configuration was selected to minimize vehicle size and give it a more streamlined and attractive appearance. A horizontal stabilizer or a canard would require a lengthening of the aircraft to provide the necessary moment arm from the wing. On the other hand, it is more difficult to provide the necessary longitudinal stability with a flying wing configuration.

5. Performance Sizing

An initial stall speed of 25 knots was specified, which resulted in a wing area of 72 ft^2. With the limitation on wingspan, the root chord length would have been approximately 5 ft, leaving the SDG-1 with an extremely low aspect ratio. By raising the stall speed to 30 knots, the wing area was reduced to 48 ft^2, a more reasonable value considering our constraints. The stall speed of 30 knots provides a landing distance of 240 ft. Although higher than our originally sought 150 ft landing roll, this distance it not detrimental to the overall goals of the aircraft.

6. Fuselage and Cockpit Design

Two conflicting requirements were considered in the design of the fuselage and cockpit. The first was to minimize drag and would normally require an enclosed cockpit to reduce pressure and skin friction drag created by the exposed pilot. The second is pilot safety and requires the ability of the pilot to quickly and easily release from the craft at any point, should it become uncontrollable. Safety is always paramount, so the SDG-1 was designed with an open cockpit.

7. Wing Design

7.1 Airfoil Selection

A high maximum lift coefficient over a range of Reynolds numbers is one of the most important requirements for the SDG-1. Moreover, a small pitching moment coefficient is required because of the tailless design. The selected NACA 23012 meets both these requirements.

One of the biggest hurdles in the selection of an airfoil is the low Reynolds number at landing ($\sim 10^6$). During glide the Reynolds number ranges between 2×10^6 and 3×10^6, with a "do not exceed" speed in the range of 3×10^6 to 4×10^6. These low Reynolds numbers allow laminar flow over a large percentage of the chord length, causing the boundary layer to be prone to separation. This leads to laminar separation bubbles over the top of the airfoil increasing drag and drastically decreasing the maximum producible lift.

The NACA 23012 performs fairly well at these Reynolds numbers with its only major flaw being poor stalling characteristics. More efficient modern airfoils exist, which are designed for lower Reynolds numbers but they suffer from poor performance at higher Reynolds numbers. Advanced modern airfoils also tend to have high pitching moment coefficients, something that would have an adverse effect on the performance of the SDG-1.

The SDG-1 would be best suited with a custom built airfoil, as it requires good aerodynamic characteristics for a range of Reynolds numbers between 10^6 and 4×10^6. One possible candidate for these requirements is the airfoil developed for the SWIFT sailplane [2]. However, this airfoil has a limited range of Reynolds numbers (7×10^5 to 2×10^6). Furthermore, no information is available on this airfoil.

The aerodynamic characteristics of the NACA 23012 airfoil are shown in Table 1. The maximum lift coefficient for the Reynolds number at landing conditions was obtained using linear interpolation of existing experimental data, while the zero-lift angle and the pitching moment coefficient at the glide Reynolds number were obtained from the computer program Sub 2D.

Table 1 – Aerodynamic characteristics of the NACA 23012 airfoil

Zero-lift angle $\alpha_{L=0}$	-1.10551 deg
Pitching moment coefficient C_m	-0.00882
Max lift coefficient C_{Lmax}	1.4

7.2 Wing Planform Design

The design of the wing planform was the crux of creating the SDG-1, as tailless aircraft suffer from unique problems that must be addressed during the design of the wing. Typically a wing produces a nose-down pitching moment about its aerodynamic center, which is balanced by a down force on a horizontal stabilizer or an up force on a canard. Flying wings do not have horizontal stabilizers or canards, hence they must produce a down force somewhere on their own surface. There are two schools of thought to solving this problem: use of a Plank wing with a reflexed airfoil or a combination of sweep and twist [3].

Plank wings are very sensitive to center-of-gravity movement. In addition, control surfaces end up too close to the aerodynamic center, limiting maneuverability. The pilot comprises most of the weight of the SDG-1. This could be detrimental to the longitudinal stability should he/she moves slightly forward or aft in midflight. The limited maneuverability of a reflexed wing makes it undesirable for the SDG-1.

This leaves a combination of sweep and twist as the only solution. The wing must be sufficiently twisted, so the tips produce enough down force to counteract the nose-down pitching moment. Lengthening the moment arm by adding sweep reduces the amount of twist required and reduces induced drag. Sweep and twist allow the wing to operate efficiently in a larger range of Reynolds numbers. They also allow more freedom in the movement of the center-of gravity during flight. Additionally, the control surfaces work better because of they can be placed farther from the aerodynamic center.

On the other hand, sweep and twist increase the structural weight because the wing needs to be larger to obtain the same lift coefficient compared with a straight wing. Furthermore, the chances of a tip stall at lower speeds are increased because of the spanwise flow towards the tips. Two parametric studies were conducted to determine the wing planform geometry.

7.2.1 Panknin Parametric Study

The first of the two studies was performed using the Panknin twist equation [3]. The various parameters in this equation are defined in Table 2.

Table 2 – Parameters in the Panknin method

Constants	*Values*
Span: b	192 in
Zero-lift angle at root: $\alpha_{L=0\ root}$	1.10551 deg
Zero-lift angle at tip: $\alpha_{L=0\ tip}$	1.10551 deg
Airfoil moment coefficient at root: $C_{M\ root}$	0.00882
Airfoil moment coefficient at tip: $C_{M\ tip}$	0.00882
Cruise speed: V_{cr}	69.05 mph
Total weight: W	4800 oz
Variables	*Range*
Root chord: c_r	36 – 66 in
Tip chord: c_t	36 – 6 in
Sweep angle: Λ	10 – 40 deg
Stability Factor: SF	0.01 – 0.1

Equations (1) – (4) calculate the constants used in this method:

$$LA = \frac{b}{2}\tan\left(\frac{\pi\Lambda}{180}\right) \tag{1}$$

$$k = \frac{0.25\left(3 + 2\lambda + \lambda^2\right)}{1 + \lambda + \lambda^2} \tag{2}$$

$$k_1 = 1 - k \tag{3}$$

$$k_2 = 0.25\left(c_r - c_t\right) + LA \tag{4}$$

The lift coefficient is given by:

$$C_L = 3{,}519.8\frac{W_{oz}}{V_{cr}^2 S_{in}} \tag{5}$$

where W_{oz} is the vehicle weight in ounces, S_{in} is the wing area in inches and the numerical constant is the result of various unit conversion factors.

The location of the aerodynamic center is given by:

$$x_{ac} = \frac{c_r^2 + c_r c_t + c_t^2}{6(c_r + c_t)} + \frac{\left(2c_r + c_t\right)k_2}{3\left(c_r + c_t\right)} \tag{6}$$

The aerodynamic and geometric twist are given by:

$$\varepsilon_{aero} = \frac{kC_{M\,root} + k_1 C_{M\,tip} - C_L SF}{0.000014A^{1.43}\Lambda} \tag{7}$$

$$\varepsilon_{geo} = \varepsilon_{aero} - \left(\alpha_{L=0root} - \alpha_{L=0tip}\right) \tag{8}$$

The location of the center of gravity of the aircraft is calculated from:

$$x_{cg} = x_{ac} - c_m SF \tag{9}$$

where c_m is the mean chord of the wing.

The wingspan and aspect ratio were kept constant while varying the taper ratio, the sweep, and the SF (static margin). The result was the wing twist needed for a longitudinally stable tailless configuration.

7.2.2 Wing Analysis Parametric Study

The Panknin parametric study was consolidated by choosing set parameters for the stability factor, the taper ratio, and the sweep angle, as indicated in Table 3. It was discovered that the lower the stability factor, the better the overall performance of the craft. A stability factor of 0.05 was believed to be the minimum amount of static stability needed without a stability augmentation system.

Table 3 – Range of each variable used in Panknin parametric study

Variables	Range
Stability factor: SF	0.05
Sweep angle: Λ	20 – 30 deg
Taper ratio: λ	0.5 – 0.9

The stability factor may change later in the design process if found to be inadequate.

The reason for setting 30 degrees as the maximum amount of allowable sweep is to prevent dynamic stability problems, which could make the craft unsafe. The value of 30 degrees was an arbitrary limit chosen based on existing aircraft flying characteristics with similar angles of sweep. Any amount of sweep less than 20 degrees requires a large amount of twist, decreasing Oswald efficiencies to very low values.

The wing taper ratio must be greater than 0.5 to avoid tip stall problems. In fact the range extended to the largest structurally possible taper ratio (0.9).

The preceding range consolidation limited the Panknin parametric study to a specific number of design combinations. These combinations were then inputted into the Stanford Wing Analysis program [4] for a second parametric study to determine the best wing for a tailless aircraft. These values are plotted in Figure 2.

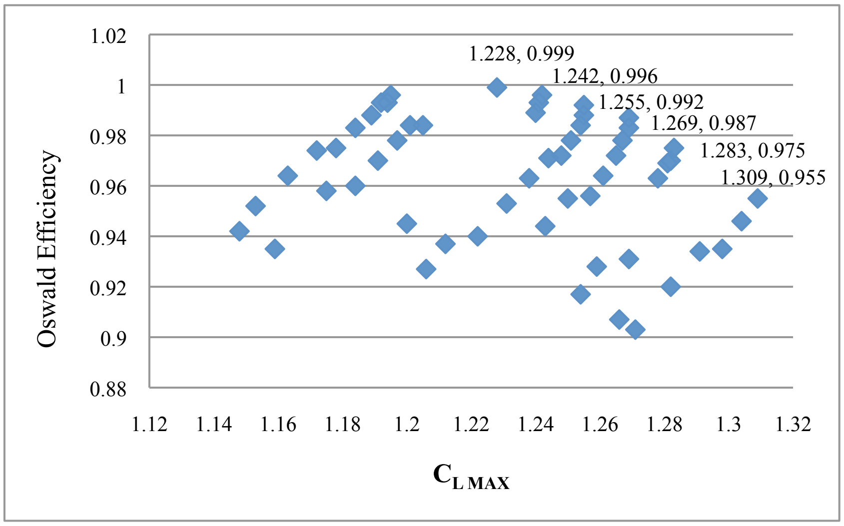

Figure 2 – Wing design parameter options, shown as combinations of maximum lift coefficient and Oswald efficiency.

The best possible designs (highest possible $C_{L\,MAX}$ and Oswald efficiency) are located in the top right corner. There are two trends which are easily visible on the graph. Taper ratio decreases towards the right and sweep increases towards the top.

There were several considerations in picking the design point: These included $C_{L\,MAX}$ values, chance of tip stall, maneuverability, lift-to-drag ratio and structural weight, all of which had varying degrees of importance. $C_{L\,MAX}$ and the chance of tip stall were the most important with a high lift-to-drag ratio being close behind.

Having a high $C_{L\,MAX}$ allows for a lower landing speed, which is important for pilot safety. Tip stall is also an important concern if the wing is swept. Sweep creates a spanwise flow increasing boundary layer thickness at the tips, making more susceptible to separation. This trend is amplified by low taper ratio, which reduces the tip chord length subsequently reducing the tip Reynolds number. A lower Reynolds number reduces $C_{L\,MAX}$ for a given airfoil causing premature tip stall. Tip stall reduces aileron effectiveness, which can be detrimental during landing and can cause unrecoverable loss of control in high g maneuvers.

Oswald efficiency is the last major parameter that must be considered in the design. Oswald efficiency is important during cruise because of its effect on lift-to-drag ratio. With a poor Oswald efficiency the SDG-1 would not be able to glide as far, thus limiting its maximum range. Figure 2 shows an increase in Oswald efficiency with an increase in taper ratio. The final values for the wing planform parameters are shown in Table 4.

Table 4 – Wing planform parameters

Gross wing area: S	48 ft^2
Aspect ratio: A	5.3
Wing span: b	16 ft
Taper ratio: λ	0.9
Sweep angle: Λ	30 deg
Twist: ε	7 deg
Wing incidence: i	9 deg
Dihedral angle: Γ	0 deg

The high sweep is necessary to achieve a sufficiently high Oswald efficiency. A sweep of 20 degrees would lessen the likelihood of tip stall but Oswald efficiency would drop off considerably while $C_{L\,MAX}$ would decrease marginally. By increasing the sweep to 30 degrees, the twist is not as pronounced, raising the Oswald efficiency while preserving the highest possible $C_{L\,MAX}$. A larger taper ratio reduces $C_{L\,MAX}$; however, a highly swept wing and a lower taper ratio would result in severe tip stall problems, too difficult to compensate by other means. The highest taper ratio possible, 0.9, was chosen. A taper ratio of 1.0 is impossible due to structural restrictions from using a telescoping wing.

The use of additional aerodynamic devices, such as wing fences, flaps, and winglets were necessary to meet the performance requirements of the wing. Finally, the constraint of limited wingspan was addressed by telescoping wings.

7.3 Telescoping Wings

The SDG-1 needs a way to get to the release altitude. The most realistic way to achieve this is with the use of a cargo plane. The C-130 with its large rear cargo door was chosen for this task. The maximum width of its hatch however, is only 9 ft. This is too small to fit the 16 ft wingspan of the SDG-1. Collapsible, foldable or retractable wings, had to be designed to accommodate the limited width of the cargo door. A telescoping wing was chosen as the best option.

Telescoping wings have several advantages with accompanying disadvantages. With the wings retracted, the SDG-1 would have a lower total lift, which would be beneficial directly after deployment from the C-130. This is because the C-130 would be traveling significantly faster than the designed cruise speed of the SDG-1. The lower lift produced by the retracted wing will help to prevent structural damage and uncontrollable pitching.

Telescoping wings also allow the use of high strength composite materials such as carbon fiber to be used for the skin of the craft. This increases the structural rigidity and decreases the weight dramatically as opposed to a skeleton and fabric skin design otherwise needed on a folding or collapsible wing. The structure inside the wing will be simple adding to the manufacturability of this design.

The negative aspects of telescoping wings arise as a result of the limited research of their use on aircraft. Known complications are mostly concerned with the control surfaces on the wing. The control surfaces are not in a fixed location making it difficult to achieve the no-play condition required in the linkage. Analog controls would be very difficult to use on a telescoping wing so electronic controls would probably have to be used instead. In addition, telescoping wings limit the different types of flaps and their placement. Moreover, the aspect ratio could never be exactly 1.0 due to the structural restrictions.

7.4 Wing Fence Design

Wing fences will be used to address the tip stall problem of the wing with its 30-degree sweep. Wing fences used on swept wings break up the spanwise flow, reducing boundary layer thickness past the wing fence.

The wing fence will be placed at the end of the first section of the wing. This is the ideal placement because it will get the fence as close to the inner edge of the elevon as possible, where it works best at preventing tip stall. It will be approximately 3 inches in height and extend $^2/_3$ of the chord length from the leading edge over the top of the wing and another $^1/_3$ of the chord length from the leading edge on the bottom of the wing.

7.5 Winglet Design

Winglets are absolutely essential for the SDG-1. They serve several purposes, including induced drag reduction, increased directional stability, prevention of tip stall, and the creation of induced thrust [3]. Winglet design can be complicated, especially when tailoring them for a particular task. Reference [3] provides equations for calculating winglet height, effective dihedral due to the winglets, and effective dihedral due to sweep:

$$h_{win} = 0.1b \tag{10}$$

$$\Gamma_{eff\ win} = \frac{40\,h_{win}}{b} \tag{11}$$

$$\Gamma_{eff\ sweep} = \frac{\Lambda}{16.6} \tag{12}$$

Apart from their positive aerodynamic properties, the winglets can also extend the wings from their retracted position without using heavy actuators or mechanisms. By placing winglets on the tips of the wings, which can pivot out to a predetermined angle, the forces generated by the forward velocity pull the wings out from their retracted position. Once fully extended, the winglets could be set back to a zero degree angle of attack, flush with the straight edge of the wing and parallel with the forward velocity of the aircraft.

7.6 High Lift Devices

The landing velocity of the SDG-1 is 40 knots with a corresponding C_L of 1.8. The wing design chosen from the parametric study gives a wing with a $C_{L\ MAX}$ of only 1.23. This lift is insufficient for the landing velocity and wing loading requirements. Therefore some type of high-lift device is needed to safely land the aircraft. A split flap was chosen to provide the additional lift and still allow for the telescoping wing design. To produce an additional C_L of 0.572, the flap will have a chord 20% of the wing chord, a deployment angle of 18 degrees, and a length spanning the inner 47% of the wing.

8. Weight and Balance

To estimate the various component weights were, a structural analysis was needed. This analysis assumed a maximum load factor of 5 and a safety factor of 1.4. The material used for the fuselage and the wing is epoxy carbon fiber AS-4. For the main spar of the wing, aluminum 6061-T6, T651 will be used. The thickness of carbon fiber and aluminum spar were found to be 1/16 inch and 1/8 inch respectively. Table 5 lists the weights of the various aircraft components.

Table 5 – Aircraft component weights

Fuselage	14.3 lbs
Wing spar	31.2 lbs
Wing skin	56.3 lbs
Winglets	3.25 lbs each
Total Weight	*108.3 lbs*

The total weight is 8% higher than the 100 lb goal, however, it is still within reasonable limits. The total weight of craft and pilot needs to be less than 300 lbs and with the average weight of a person being approximately 150 lbs, there is still 42 lbs of leeway.

9. Stability and Control

9.1 Longitudinal Stability

Longitudinal stability is inherently built into the wing through the incorporation of sweep and twist. The static margin is set at 5%. This translates into the center-of-gravity being approximately 2 inches in front of the trailing edge of the wing root.

9.2 Lateral Stability

Lateral stability is obtained through wing sweep and the winglets. Winglets create an effective dihedral of 4 degrees and when coupled with effective dihedral due to sweep, the wing acts as if it had ~6 degrees of dihedral in level flight. The effective dihedral will reduce sideslip and spiral divergence but increase Dutch roll. Effective dihedral due to sweep depends on angle of attack. Hence, the effective dihedral during glide will be low, minimizing Dutch roll. At the higher angles of attack during landing, the effective dihedral will be increased, providing more lateral stability than an unswept wing [3].

9.3 Directional Stability

Directional stability is achieved by the winglets. The following parameter is defined as the measure of directional stability [3]:

$$\sigma_w = \frac{S_w x_w}{S\frac{b}{2}} \qquad (13)$$

where S_w is the winglet wetted area and x_w is the distance between the neutral points of the wing and the winglet. For flying wings σ_w must be in the range 0.03 – 0.06, the exact value depending on sweep. For the SDG-1, σ_w = 0.037. Considering the significant amount of sweep of the SDG-1, this value is sufficient.

10. Drag Breakdown

The drag breakdown was calculated as follows [7]:

$$\begin{aligned} C_D &= C_{D_F} + C_{D_W} + C_{D_{winglets}} = \\ &= 0.0097 + 0.0268 + 0.0007 = 0.0372 \end{aligned} \qquad (14)$$

The original design goal for the SDG-1 was a lift-to-drag ratio L/D = 6 but our estimated value is L/D = 14, which is significantly higher. However, the drag of the pilot has not been accounted for in our analysis (the fuselage was assumed enclosed). The decrease in induced drag and the addition of induced thrust from the winglets was also not taken into consideration. The increase in drag from the pilot will most likely outweigh the reduction of drag from the winglets. Having a calculated L/D of 14 makes an actual L/D of 6 quite plausible, with a value higher than 6 very likely.

11. Conclusion

The final 3 – view drawings of the SDG-1 are shown in Figure 3. Designing for an adequate lift-to-drag ratio while satisfying the structural constraints of the aircraft, so that it could be deployed from a cargo plane, was the primary design challenge. This challenge was met with a tailless configuration. This paper focused on the feasibility of the design, however, the SDG-1 has an elegant appearance greatly adding to its overall appeal. Further work will focus on designing an airfoil specific for the mission, building and testing a scaled model, and constructing a full sized aircraft.

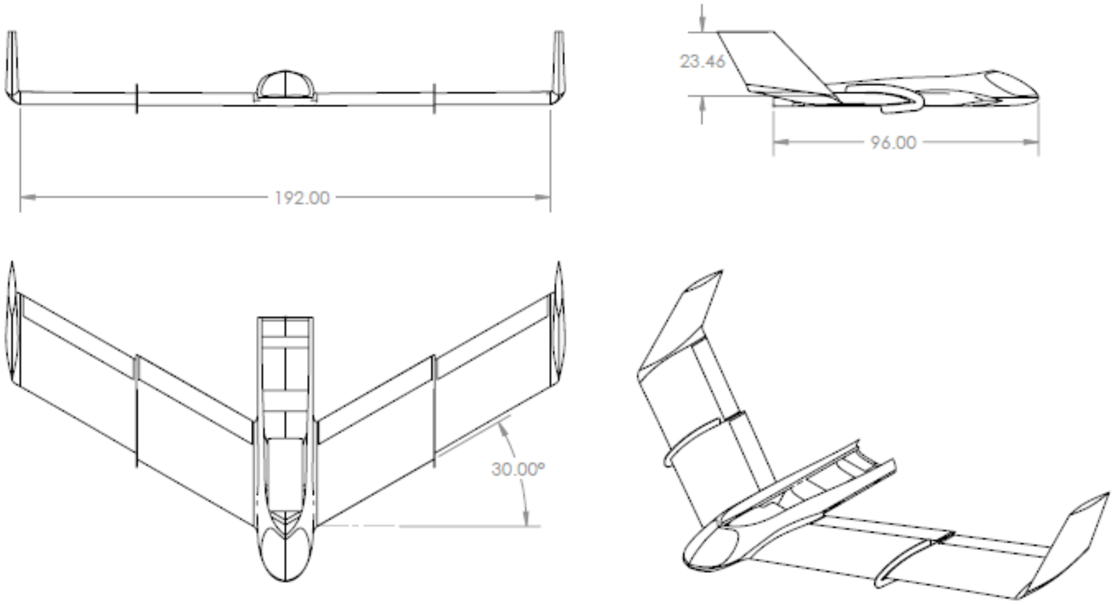

Figure 3 – Three-view drawings of the SDG-1 (dimensions in inches)

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