47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-1617

Rapid Sizing Methodologies for VTOL UAVs

Jonathan D. Keith*
Empirical Systems Aerospace, LLC, Pismo Beach, CA, 93448

David W. Hall†
DHC Engineering, Morro Bay, CA, 93442

This paper will present methodologies used for the rapid sizing of a vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV). This sizing approach draws heavily from historical designs (both manned and unmanned) and investigates the trends among VTOL aircraft of similar types, using powerplant installations and approaches as means to group aircraft. Once the research aircraft are categorized, pertinent weight data are researched and gathered to be used for weight trend generation within each vehicle category. Through the use of regression, trends are fitted to the historical data, creating a series of equations that help determine weights for new designs. Weight savings due to technological advancements are also explored, helping to define the weight impacts of an unmanned system. Specific constraints related to VTOL aircraft are then investigated and generated for use on a conventional aircraft design constraint plot, allowing for the user to determine the wing area and powerplant required for the vehicle. An example VTOL vehicle is then sized using the developed methodology.

Nomenclature

P	=	Power, HP
T	=	Thrust, lbs.
$TOGW$	=	Aircraft takeoff gross weight, lbs.
W	=	Aircraft weight, lbs.

I. Introduction

Vertical takeoff and landing aircraft have garnered mass appeal since their inception in the 1920's. Their ability to achieve flight without the runway space required by conventional aircraft allows them greater options for takeoff locations, maneuverability, and landing sites, the latter possibly being their largest advantage. The majority of work done by aerospace companies on the design and construction of VTOL aircraft occurred between the 1950 and 1980, during which time a variety of approaches were used for vertical takeoff. These lifting approaches incorporated a wide variety of propulsion concepts in an effort to gain greater propulsive efficiencies and higher thrust-to-weight ratios. These propulsion approaches have been broken down into four distinct categories (Table 1) in order to better classify the historical VTOL aircraft and provide commonality for comparison. In addition to the appeal of a VTOL vehicle's capabilities, the maturation of unmanned aerial vehicle (UAV) technologies allows maneuverable drones the capability to autonomously access isolated terrains, increasing capabilities within both the commercial and military sectors. While a few VTOL UAV designs have reached the flight test phase, this sector of unmanned aerial vehicles as a whole is still considered to be in its infancy, while propulsion offerings continue to arise along with more capable autonomous technologies.

The now infamous VTOL "wheel", depicting historical VTOL flight vehicles and their lifting approaches, was recently modified by ANSER Research Institute during the Joint Strike Fighter competition in order to compare historical VTOL vehicles and the similarities that exist between them. Figure 1 depicts the ANSER wheel with the wheel's two most recent additions, the two competing Joint Strike Fighters, highlighted in blue.

* Engineer and Managing Member, P.O. Box 595, Young Professional.
† Engineering Consultant, 965 Morro Avenue, Unit C, Lifetime Senior Member.

Table 1. Propulsion Integration Categories within ANSER's Wheel of VSTOL Aircraft

Propulsion Approach	Notes
Combined Powerplant Systems	The same propulsion system is used for hover *and* forward flight
Augmented Powerplant for Hover	
Combined Powerplants for Hover	Upon Transition, powerplants are separated for forward flight
Separated Powerplant for Hover	

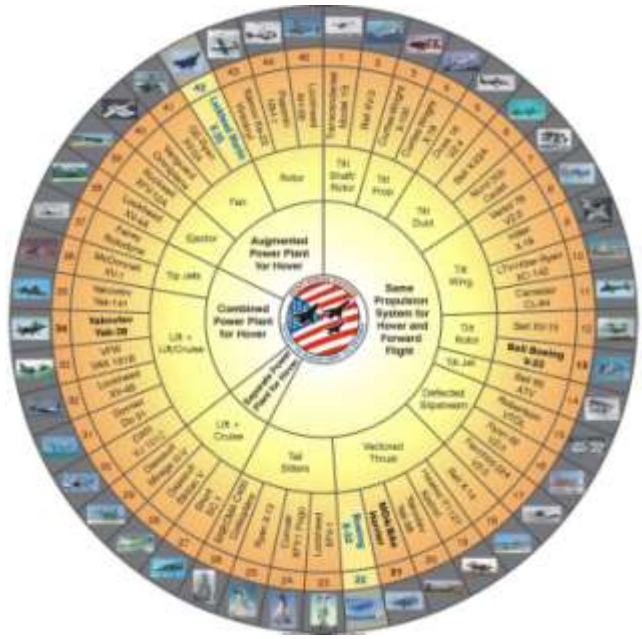

Figure 1. ANSER's Wheel of VSTOL Aircraft and Propulsion Concepts[1]

Due to the effects that different propulsion systems have on the overall design of vehicles, this paper will discuss parallel approaches for the sizing of VTOL UAVs. While a universal system could be implemented, the authors believe the error introduced in the methodology would be too great, even at the conceptual design stage. By breaking historical VTOL vehicles down by vertical takeoff powerplant approaches, the system will remain less complex while ultimately allowing for better weight estimations. In order to accomplish this, the powerplant categories defined by the ANSER wheel will be used for this study, resulting in three parallel weight studies and subsequent weight trends for future use in the sizing of a VTOL UAV. While the ANSER "wheel" contains four total powerplant categories (the inner-most ring of the wheel), the fourth category, Separated Powerplant for Hover, was found to yield insufficient data to conduct a viable study; thus, this category is not included within the scope of this paper's investigation.

In order to properly establish weight trends for the three categories of powerplant configurations, a reasonable amount of historical data must be gathered so that confidence can be taken in the equations that are created. While conducting this research, all data relating to the weights of the historical vehicles is noted, with particular attention paid to the two main aircraft weight values and their ratio:

1. Takeoff Gross Weight
2. Empty Weight
3. Empty Weight Fraction

These weight values can be used along with the desired mission inputs not only help define the size of the vehicle but also to create the database that allows for regression to be performed and initial aircraft weights to be estimated. It is important to note that for the purposes of this paper, a VTOL vehicle is a flight vehicle that can take off and land vertically. In addition, the vehicles considered in this study typically transition into a more efficient flight configuration for forward flight, though the methods of transition are beyond the scope of this study. Because of this stipulation, pure helicopters will not be considered and will be omitted in historical weight investigations.

II. Weight Sizing of VTOL UAVs

The takeoff gross weight and empty weight of historical VTOL aircraft are of great importance, as their data, in conjunction with the fuel weight fraction of the aircraft's mission, produces a useable trend and helps estimate the takeoff gross weight of the VTOL aircraft. To accomplish this, the takeoff gross weight and empty weight are found for nearly all of the aircraft seen in the ANSER VTOL wheel and subsequently plotted within their respective powerplant categories. The following sections discuss this data with respect to these categories, highlighting the salient results for each of the powerplant configurations.

It should be noted that the equations generated from data for each of the following sections are to be used in conjunction with the classic weight fraction method (Ref. 3). This determines the form of the equation and while the specifics of the weight fraction method are beyond the scope of this study, the final section of this paper will cover the necessary elements of this method as it relates to developing the empty and takeoff gross weights of a VTOL UAV.

A. Combined Powerplant Systems

As the largest group of the study, VTOL aircraft with combined powerplant systems utilize the same propulsion system for both hover as well as forward flight, theoretically saving weight by making optimum use of the installed propulsion systems. Below in Table 2 are the aircraft used for the weight study in this category along with their takeoff gross weight, empty weight, and subsequent empty weight fraction.

Table 2. Weight Data for VTOL Aircraft with Combined Powerplant Systems[2]

No.	Manufacturer	Type	TOGW (lbs.)	Empty (lbs.)	Empty/TOGW
1	Transcendental	Model 1G	1,747	1,448	82.9%
2	Bell	XV-3	4,890	4,205	86.0%
3	Curtiss-Wright	X-100	5,505	4,277	77.7%
4	Curtiss-Wright	X-19	13,580	10,582	77.9%
5	Doak	16 VZ-4	3,200	2,300	71.9%
6	Bell	X-22A	18,016	11,458	63.6%
7	Nord	500 *Cadet*	2,640	2,200	83.3%
8	Vertol	76 VZ-2	3,175	2,482	78.2%
9	Hiller	X-18	33,000	26,786	81.2%
10	LTV-Hiller-Ryan	XC-142	37,258	23,765	63.8%
11	Canadair	CL-84	12,200	8,100	66.4%
12	Bell	XV-15	13,248	10,083	76.1%
13	Bell Boeing	V-22	52,870	33,140	62.7%
14	Fairchild	224 VZ-5	3,976	3,382	85.1%
15	Bell	X-14	4,269	3,168	74.2%
16	Hawker	P.1127 *Kestrel*	17,000	10,000	58.8%
17	Yakovlev	Yak-36	26,014	18,077	69.5%
18	MDA/Bae	*Harrier*	18,950	12,500	66.0%
19	Boeing	X-32	38,000	22,046	58.0%
20	Lockheed	XFV-1	16,221	11,599	71.5%
21	Convair	XFY-1 *Pogo*	16,250	11,700	72.0%
22	Ryan	X-13	7,200	5,334	74.1%

Of note in Table 2 is the absence of four of the aircraft shown in the ANSER wheel's Combined Powerplant Systems category. Sufficient data could not be found for these aircraft, but the aircraft listed provide a sufficient amount of data to properly generate a trend.

The trend line, shown below in Figure 2, is created using logarithmic axis for the chart, providing a visually linear trend for the historical aircraft weight data. In order to demonstrate the relative accuracy of the equation generated from the data, the generated equation is used with the empty weight values from each aircraft in Table 2 to calculate each aircraft's takeoff gross weight. This equation-generated value for takeoff gross weight is then compared against the actual takeoff gross weight value to determine that percent error caused by using the generated equation. This error data are shown below in Table 3 along with the trend line equation.

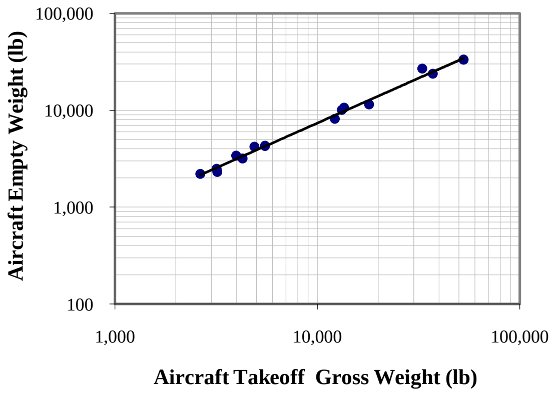

Figure 2. Takeoff Gross Weight versus Empty Weight for Combined Powerplant VTOL Aircraft

Table 3. Percent Error in the Weight Trend for Combined Powerplant VTOL Aircraft

No.	% Error	No.	% Error
1	-3.5%	12	6.3%
2	9.2%	13	-0.2%
3	14.0%	14	6.5%
4	8.7%	15	-6.5%
5	-12.9%	16	-18.4%
6	-9.0%	17	3.5%
7	0.9%	18	-4.6%
8	-3.9%	19	-11.6%
9	19.2%	20	2.1%
10	-1.7%	21	2.8%
11	-8.2%	22	-1.7%
	Maximum	19.2%	
	Minimum	-18.4%	
	Mean	-0.4%	
	Std. Deviation	9.0%	

$$W_{EMPTY} = 1.6938 W_{TOGW}^{\ 0.9088} \tag{1}$$

Of note is the error range of over 37% for the data. While such a large is range is not desirable, an average of the error for the data set of nearly zero, coupled with a standard deviation of 9.0% suggests that the trend line is a sufficiently accurate compromise between the various aircraft used in the study. For the purposes of this study, the trend line is accurate for weight estimation purposes, particularly during an aircraft's conceptual design stage.

B. Augmented Propulsion System for Hover

The second propulsion configuration category is for aircraft that augment the generated propulsion used during the hover stage of flight. This augmentation is often accomplished through careful geometric design in attempts to generate greater thrust than the engine by itself could produce. Table 4 below lists the aircraft used in this category, along with the pertinent weight data and fractions.

Table 4. Weight Data for VTOL Aircraft with an Augmented Propulsion System for Hover[2]

No.	Manufacturer	Type	TOGW (lbs.)	Empty (lbs.)	Empty/TOGW
1	Lockheed	AH-56	25,880	12,215	47.2%
2	Piasecki	16H-1	10,800	4,800	44.4%
3	Kamov	Ka-22	93,500	56,848	60.8%
4	Lockheed Martin	X-35	44,400	26,000	58.6%
5	GE-Ryan	XV-5A	12,200	7,000	57.4%
6	Rockwell	XFV-12A	19,500	13,800	70.8%

For this category, only one aircraft was omitted from the list due to insufficient data. Similarly to the previous propulsion category, a trend line (Fig. 3) was generated with the weight data found in Table 4. The original data were subsequently used to determine the accuracy of the trend line and the results of this comparison can be seen in Table 5.

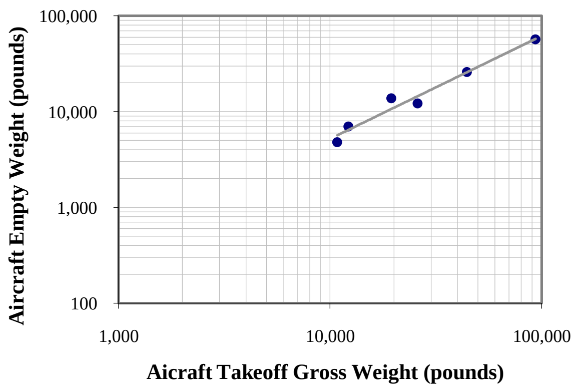

Figure 3. Takeoff Gross Weight versus Empty Weight for VTOL Aircraft with an Augmented Propulsion System for Hover

Table 5. Percent Error in the Weight Trend for VTOL Aircraft with an Augmented Propulsion System for Hover

No.	% Error
1	-18.4%
2	-17.9%
3	-1.1%
4	0.7%
5	7.8%
6	22.6%
Maximum	22.6%
Minimum	-18.4%
Mean	-1.1%
Std. Deviation	15.7%

Initially, it is visually evident that the data for this category do not fit its trend line as does the Combined Powerplant Systems aircraft to its trend line. This becomes further evident upon examination of the test results in Table 5: a range of 41% and a standard deviation of 15.7%. What remains true, primarily due to the purpose of a best-fit trend line, is the low error for the mean of the data. Because of the equations purpose in the conceptual design stages of an aircraft, the trend line, defined by Eq. 2, is deemed sufficient for use in weight estimations within this category.

$$W_{EMPTY} = 0.5045 W_{TOGW}{}^{1.005} \tag{2}$$

C. Combined Powerplants for Hover

The last powerplant configuration category is for aircraft that, similar to the first category, use the same propulsion system for both hover and forward flight while using an additional powerplant to during hovering. Table 6 below lists the aircraft used in this category, along with the pertinent weight data and fractions.

Table 6. Weight Data for VTOL Aircraft with Combined Powerplants for Hover[2]

No.	Manufacturer	Type	TOGW (lbs.)	Empty (lbs.)	Empty/TOGW
1	Fairey	Rotodyne	33,000	22,000	66.7%
2	McDonnell	XV-1	5,493	4,268	77.7%
3	Yakovlev	Yak-141	43,000	25,680	59.7%
4	Yakovlev	Yak-38	28,700	16,281	56.7%
5	VFW	VAK 191B	19,800	12,236	61.8%
6	Lockheed	XV-4B	12,580	7,463	59.3%
7	Dornier	Do 31	60,500	49,501	81.8%

Utilizing the same approach taken with the first two categories, a trend line is generated (Fig. 4) and the original data are tested against this trend line, yielding error results (Table 7) for this last propulsion configuration category.

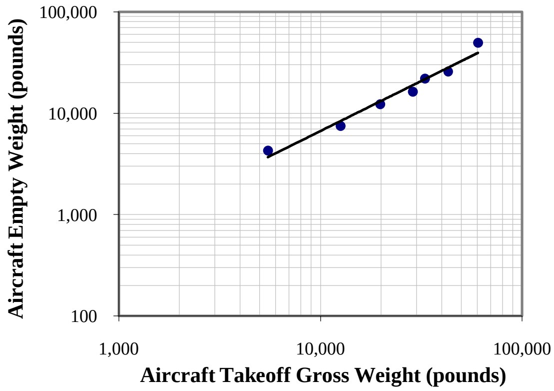

Figure 4. Takeoff Gross Weight versus Empty Weight for VTOL Aircraft with Combined Powerplants for Hover

Table 7. Percent Error in the Weight Trend for VTOL Aircraft with Combined Powerplants for Hover

No.	% Error
1	1.9%
2	14.1%
3	-9.2%
4	-15.5%
5	-6.4%
6	-11.4%
7	20.6%
Maximum	20.6%
Minimum	-15.5%
Mean	-0.8%
Std. Deviation	13.7%

The error range for these aircraft (over 36%) and the standard deviation (13.7%) fall between that of the first two categories. The mean of his category is near zero, once again suggesting that reasonable weight estimations will be given using the trend line's equation (Eq. 3) and the aircraft's empty weight that will be calculated during the conceptual design phase.

$$W_{EMPTY} = 0.7346 W_{TOGW}{}^{0.9888} \tag{3}$$

D. Weight Savings for Material Technologies and Unmanned Systems

Because each of the aircraft used in this study are from the ANSER VTOL "wheel", they consist of manned aircraft designed primarily with mid-twentieth century state-of-the-art technologies. A potential problem with using these weight data directly in the preliminary design phase is that many of the modern advancements in both materials as well as lighter support systems are not taken into account in these trends. These factors, coupled with the fact that the aircraft in this study are manned while this study focuses on unmanned vehicles, leaves room for a readjustment of the overall empty weight of the aircraft.

In order to accomplish a reduction in the calculated empty weight, two categories of data are gathered. The first category, shown in Table 8, is historical unmanned aerial vehicle weight data, similar to the data gathered for each of the powerplant categories. The criterion for aircraft chosen in this category was to find UAVs that were of a conventional configuration; i.e. fixed wing, fuselage, and tail. This was done for multiple reasons, that most important being availability of data. As mentioned earlier, VTOL UAVs are still considered to be in their infancy, thus the amount of data required to generate viable trends is not available.

Table 8. Weight Data for Historical Unmanned Aerial Vehicles[2]

No.	Manufacturer	Type	Empty (lbs.)	TOGW (lbs.)	Empty/TOGW
1	Israeli Aircraft	RQ-5 *Hunter*	1,100	1,600	68.8%
2	AeroVironment	HP01 *Helios*	1,322	2,048	64.6%
3	General Atomics	MQ-1 *Predator*	1,130	2,200	51.4%
4	Bell	*Eagle Eye*	1,300	2,250	57.8%
5	Teledyne Ryan	AQM-91 *Firefly*	3,800	5,400	70.4%
6	EADS	*Barracuda*	5,071	7,165	70.8%
7	Lockheed Martin/Boeing	RQ-3 *Darkstar*	4,360	8,500	51.3%
8	Boeing	X-45A	8,000	12,190	65.6%
9	Northrop Grumman	RQ-4 *Global Hawk*	8,490	22,900	37.1%
10	North American	X-10	25,800	42,300	61.0%

The second category of data is of historical manned flight vehicles (Table 9). The criterion used for this category was similar to that of the first; however, care is taken so as not to choose aircraft that have an abundance of composite materials used in their construction. The reason for this is to generate a better comparison and ultimately weight savings estimation against the UAV data in Table 8. Since the aircraft in all of the categories are of a conventional nature, the two major differences that exist between them are manned operation versus unmanned operation and conventional material use versus composite material construction. Thus, when the two categories are graphed and compared against one another, the resulting difference in empty weights for a given takeoff gross weight will theoretically be due to advancements in material technologies as well as the reduction in system weight for an unmanned vehicle.

Table 9. Weight Data for Historical Manned Flight Vehicles[2]

No.	Manufacturer	Type	Empty (lbs.)	TOGW (lbs.)	Empty/TOGW
1	Cessna	152	1,112	1,670	66.6%
2	BAE	*Bulldog* 121	1,430	2,238	63.9%
3	Piper	*Warrior* II	1,348	2,325	58.0%
4	Beech	*Sierra* 200	1,694	2,750	61.6%
5	PZL	104	1,880	2,866	65.6%
6	Beechcraft	*Bonanza* V35B	2,106	3,400	61.9%
7	Piper	*Saratoga*	1,935	3,600	53.8%
8	Cessna	*Centurion II*	2,153	3,800	56.7%
9	Beech	T-34C	2,960	4,300	68.8%
10	SIAI-Marchetti	S211	3,560	5,511	64.6%
11	Pilatus	PC-6	2,995	6,100	49.1%
12	Bombardier	Learjet 24	7,064	13,500	52.3%
13	Antonov	28	7,716	14,330	53.8%
14	Israeli Aircraft	*Arava* 202	8,816	15,000	58.8%
15	Beech	1900	8,500	15,245	55.8%
16	Dassault	*Falcon* 10	10,760	18,740	57.4%
17	Cessna	*Citation* III	10,951	20,000	54.8%
18	Embraer	EMB-120 *Brasilia*	11,945	21,165	56.4%
19	Fokker	F27 MK200	25,525	45,000	56.7%
20	Grumman	E-2C	37,945	51,817	73.2%
21	Gulfstream	IIB	38,750	68,200	56.8%

Once the data for each category are gathered and distilled, the two groups of aircraft are plotted against one another as seen in Fig. 5. Upon carefully examination, it can be seen that the trend line generated by the manned data is slight higher than the trend line fit against the unmanned data. For a set takeoff gross weight, this translates into a higher empty weight for a historical manned vehicle compared to an unmanned vehicle, a result that is to be expected. In order to make this data useful, however, each trend line's equation is used to generate an empty weight for various theoretical takeoff gross weights with these two groups of empty weights then plotted against one another. The resulting chart is then fitted with a trend line defining the resulting empty weight of an unmanned vehicle given the empty weight of a manned vehicle. The equation of this trend line (Eq. 4) uses the empty weight of a manned vehicle (Eq. 1 through 3) to find the empty weight of the unmanned vehicle, theoretically reducing the weight to account for materials and the removal of manned systems.

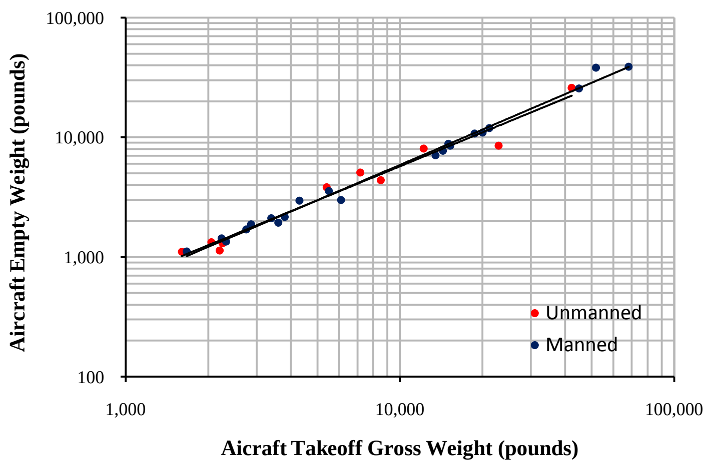

Figure 5. Weight Trend Comparison

$$W_{EMPTY_{UAV}} = 0.8872 W_{EMPTY_{MANNED}} + 558.7 \quad (4)$$

The equation should only be used for vehicles greater than 2,500 pounds as any vehicle smaller than this is outside of the scope of what the final trend line from this study can effectively account for.

III. Constraint Considerations for VTOL UAV Sizing

Once the empty weight and takeoff gross weight of the VTOL UAV are determined, the preliminary sizing of the vehicle's wing (primarily used for forward, conventional flight in this case) and the general sizing of the powerplant are required in order to fully define the preliminary size of the VTOL UAV. For conventional takeoff and landing aircraft, the following categories (along with a carpet plot depicting these categories) are typically found as constraint lines on an aircraft constraint plot, used to define a graphical area in which an aircraft can be sized to accomplish all of its requirements.

Table 10. Typical Aircraft Constraint Plot Constraints[3]

No.	Constraint
1	Takeoff
2	Landing
3	Stall Speed
4	Range
5	Cruise Speed
6	Altitude/Speed Carpet Plot

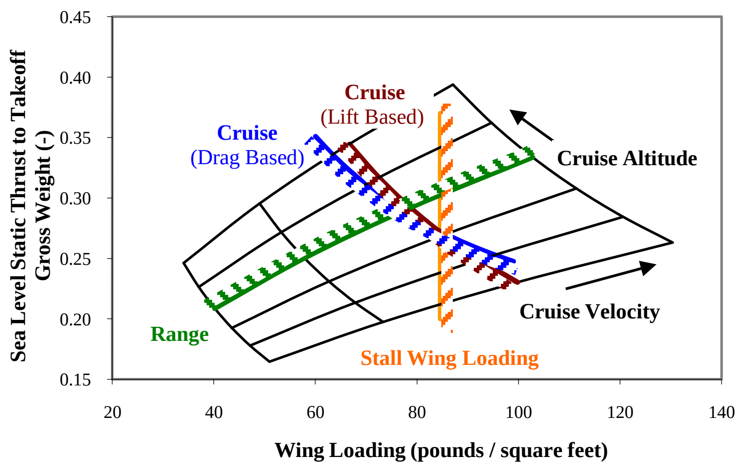

Figure 6. Typical Aircraft Constraint Plot Depicting General Constraints

While some of the above constraints are applicable to a VTOL UAV, the takeoff and landing constraints are not. The stall speed constraint, which ultimately manifests itself as a pure wing loading constraint on the constraint plot, is applicable to an extent; the method by which the VTOL UAV transitions to forward flight greatly determines what the stall speed of the aircraft is. For the purposes and scope of this study, a conventional stall speed constraint, utilizing a preliminary maximum lift coefficient, is used to yield a stall constraint for the scenario in which the VTOL vehicle is in conventional forward flight. The intricacies of transitional flight are beyond the scope of this paper, thus this forward flight stall constraint will be used for this study.

In addition to the constraints that are applicable to this study, constraints depicting the requirements of a VTOL aircraft are also necessary. In order to approach the rapid development of a constraint for VTOL UAVs, a similar approach will be taken as was taken with the weight trends; the takeoff gross weight of the historical aircraft located on ANSER's VTOL "wheel" will be used in conjunction with the aircraft's installed power and/or thrust to develop a trend for the aircraft. Installed power rather than installed thrust will be focused on for the development of this constraint, as a vehicle that relies on installed turbojet/turbofan engines for direct lift i.e. the BAe *Harrier* will need to have a thrust-to-weight ratio of greater than 1.0, defining a constraint line. One exception to this will be in the Augmented Powerplant System for Hover category, where engine thrust is used to generate power for fans on takeoff, similar to the Lockheed Martin F-35 *Lightning II*. In this case, two constraints will be developed, one for turbojet/turbofan-based aircraft and one for turboshaft/reciprocating engine-based aircraft. Tables 11 below, thus, summarizes the installed power and installed thrust data obtained for the aircraft within each of the powerplant categories.

Table 11. Installed Horsepower and Thrust Data for VTOL Constraints[2]

Combined Powerplant System		
Manufacturer	**Type**	**HP, Thrust**
Horsepower		
Transcendental	Model 1G	160
Bell	XV-3	450
Curtiss-Wright	X-100	1,300
Curtiss-Wright	X-19	4,400
Doak	16 VZ-4	840
Bell	X-22A	5,068
Nord	500 *Cadet*	634
Vertol	76 VZ-2	700
Hiller	X-18	11,000
LTV-Hiller-Ryan	XC-142	12,320
Canadair	CL-84	3,000
Bell	XV-15	2,500
Bell Boeing	V-22	12,300
Fairchild	224 VZ-5	1,032
Lockheed	XFV-1	5,850
Convair	XFY-1 *Pogo*	5,500
Thrust		
Bell	X-14	3,500
Hawker	P.1127 *Kestrel*	15,000
Yakovlev	Yak-36	28,000
MDA/Bae	*Harrier*	21,750
Boeing	X-32	26,000
Ryan	X-13	10,000

Augmented Powerplant System for Hover		
Manufacturer	**Type**	**HP, Thrust**
Horsepower		
Lockheed	AH-56	3,925
Piasecki	16H-1	1,500
Kamov	Ka-22	11,000
Thrust		
Lockheed Martin	X-35	28,000
GE-Ryan	XV-5A	5,900

Combined Powerplants for Hover		
Manufacturer	**Type**	**HP, Thrust**
Horsepower		
Fairey	*Rotodyne*	5,600
McDonnell	XV-1	525
Thrust		
Yakovlev	Yak-141	42,900
Yakovlev	Yak-38	30,740
VFW	VAK 191B	21,324
Lockheed	XV-4B	18,000
Dornier	Do 31	65,200

Using the horsepower and thrust data from each of the above categories, constraint lines can be created for an aircraft constraint plot, setting the minimum power required during the preliminary design stage. The following equations outline the constraint lines garnered from the data in Table 11.

Combined Powerplant System

$$W/P = 4.55 \tag{5}$$

$$T/W = 1.15 \tag{6}$$

Augmented Powerplant System for Hover

$$W/P = 7.43 \tag{7}$$

$$T/W = 0.56 \tag{8}$$

Combined Powerplants for Hover

$$W/P = 8.18 \tag{9}$$

$$T/W = 1.15 \tag{10}$$

There are two items to note about the equations presented above. First, the thrust-to-weight ratio of 1.15 is chosen as a historical aircraft design estimation[4], allowing for a buffer of thrust for the aircraft as well as a slight amount of leniency for the takeoff gross weight of the aircraft to increase over design iterations. Secondly, the weight-to-power ratio for the Combined Powerplants for Hover (Eq. 9) is a rudimentary estimate. The aircraft used to generate this number have propulsion data that is difficult to quantify in the arena in which this study is focused. Because of this, additional factors may need to be considered when designing a VTOL UAV of this type and determining where, on a constraint plot, is a viable location to begin an aircraft design.

IV. The Preliminary Sizing of a VTOL UAV

In order to properly outline the use of the rapid sizing methods previously discussed, an aircraft is sized using one of the powerplant categories along with a constraint plot and the applicable constraint lines. Ultimately, the takeoff gross weight and empty weight of the aircraft along with the wing size and required powerplant is obtained using the trends and constraints previously discussed.

A. Mission Profile and Initial Assumptions

For the purposes of sizing the VTOL UAV, Table 12 lists the assumptions that are used in conjunction with the weight fraction method and applicable weight equation to determine the empty weight and takeoff gross weight of the vehicle. In conjunction with the mission profile and the initial assumptions for some of the aircraft's characteristics, historically-based values (Ref. 3) of some of the weight fractions are used in order to define the total fuel burn fraction for the mission. Using a six percent value for fuel reserves, the calculated fuel fraction for the aircraft is 20.4%. This is a based on a profile that includes the following segments: Startup, Takeoff, Climb, Transit, Descent, Loiter, and Landing.

Table 12. Initial VTOL UAV Sizing Assumptions

Item	Value (units)
Payload	1,200 lbs.
Range	500 n.mi.
Cruise Speed	245 kts.
Cruise Altitude	15,000 ft.
B.S.F.C.	lbs./HP/hr.
Prop Efficiency	0.8
Maximum C_L	1.6
Stall Speed	60 kts.

It is with this fuel fraction and the applicable weight equation that a final takeoff gross weight can be found. For the purposes of this study, the first powerplant category, Combined Powerplant Systems, will be used to for the remainder of the sizing exercise. Designing an aircraft within this category calls for the use of Eq. 1 and through the use of computer-based iteration schemes, Table 13 outlines the resulting data generated by the use of the Eq.1 and the weight fraction method outlined in Reference 3.

Now that a preliminary takeoff gross weight and empty weight have been found for the vehicle, the empty weight of the aircraft can be lowered through the use of Eq. 4. By applying Eq. 4 directly with an empty weight of 9,732 lbs., the new empty weight for the UAV is found to be 9,192 lbs. Depending on how aggressive one chooses to be with the use of composite materials, this new empty weight may appear conservative; for the purposes of this study, a conservative value is deemed to be beneficial so as to allow for errors later in the design process and/or vehicle growth.

Table 13. Preliminary Weight Data for VTOL UAV

Category	Value (lbs.)
Takeoff Gross Weight	13,695
Reserve Fuel	685
Trapped Fuel	137
Fuel Weight	2,791
Empty Weight	9,732
Payload Weight	1,172

Lastly, in order to determine the initial sizing for the aircraft's wing planform and powerplant, a constraint plot is generated using the methods and equations outlined in Reference 3. Figure 7 depicts the major constraints used for this study: aircraft stall wing loading, cruise speed, and minimum power loading found in the previous section. These three constraints generate a bound area inside of which a point can be chosen to define the wing area of the aircraft as along with the required horsepower.

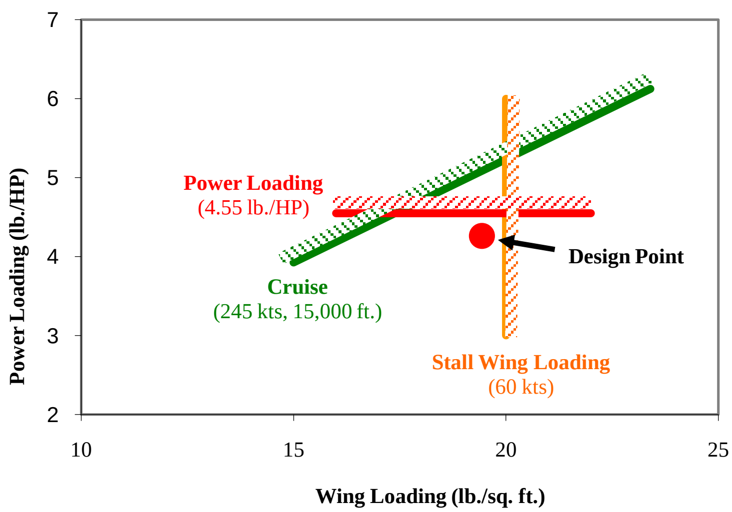

Figure 7. Constraint Plot for VTOL UAV

Once the constraint lines have been laid out and a design space presents itself, a conservative point within the design space chosen, again to account for future errors and/or growth of the vehicle. For this sizing effort, a power loading of 4.25 lbs./HP. is chosen along with a wing loading of 19 lbs./ft.^{2}. These values, used with the initially estimated 13,695 lbs. takeoff grow weight, yield a required horsepower value of 3,222 HP and wing area of 720 ft.^{2}. With these four pieces of data (takeoff gross weigh, empty weight, engine size, and wing area), the aircraft can begin to be physically laid out and research into a specific engine can now begin.

V. Conclusion

Using historical aircraft with information about their weight and powerplants, a methodology has been developed to provide the aircraft design engineer with a set of tools to quickly size vertical takeoff and landing unmanned aerial vehicles. A natural extension of this study is to look at the difference within each of the powerplant categories as it relates to weight trends. For example, within the first powerplant category, there exists both propeller-based aircraft as well as jet-based aircraft. While these two differences were noted in the formation of constraint lines, there may exist slightly different weight trends amongst these two categories. Additionally, future studies may include methodologies beyond weight, engine, and wing sizing, potentially including preliminary stability calculations and drag estimations as they relate to a vertical takeoff and landing unmanned aerial vehicle.

References

[1]Hirschberg, M. J., "V/STOL: The First Half-Century," *American Helicopter Society*, URL: http://www.aiaa.org/tc/vstol/VSTOL.html [cited 22 December 2008].

[2]Lambert, M. (ed.), Munson, K. (ed.), and Taylor, M.J.H. (ed.), *Jane's All the World's Aircraft*, [1950-2007], Jane's Information Group Limited, Coulsdon, UK.

[3]Roskam, J.R., *Airplane Design Part I: Preliminary Sizing of Airplanes*, Roskam Aviation and Engineering Corporation, Ottawa, 1985.

[4]Kohlman, D.L., *Introduction to V/STOL Airplanes*, Iowa State University Press, Iowa, 1981.