Rocket-Assisted Takeoff Considerations and Cost Analysis of Group I-III Unmanned Aerial Vehicles

Lucas Utley*, Andrew Walsh†
Oklahoma State University, Stillwater, OK, 74078-5016

The purpose of this study was to examine the current status, usage, applications, and costs associated with rocket-assisted takeoff (RATO, also known as jet-assisted takeoff, JATO) in relation to unmanned aerial vehicles (UAVs). RATO is typically used for lifting heavy UAVs to achieve a high enough velocity or altitude for its primary propulsion system to operate nominally. Findings of this study include considerations for applying RATO to an existing UAV in terms of ground support equipment, use cases, stability and structural considerations, and cost effectiveness for Group 1-3 UAVs that weigh <1000 pounds at takeoff. Factors including UAV size and weight, number of launches, and number of operational launch pads were all considered. RATO appears most financially suited to repeatedly launching Group II and Group III UAVs that weigh 20-1000 pounds. Operating multiple pads incurs higher RATO costs, but offers an affordable solution compared to other launchers for deploying multiple UAVs in rapid succession.

I. Introduction

UAVs see many applications in military ISR (intelligence, surveillance, and reconnaissance), weather sensing, security, and research purposes. Many uses exist for such UAVs, and they perform in a wide range of operating conditions including optimization for endurance, range, altitude, flight velocity, payload capacity, stealth, recovery, and weather.

Before an UAV can execute its mission, they require a launch platform which can take many forms, depending on the UAV size, performance, and purpose. Some UAVs are tailored to a certain launcher method, including projectile tube launchers such as the Coyote UAV [1], and some launchers are designed around the UAV. Launch platforms can safely deploy the drone; however, they can be costly, complex, and require special ground support equipment (GSE).

RATO is one such launch mechanism that equips a rocket motor to accelerate a UAV for takeoff. This has seen use historically with a wide range of manned and unmanned aircraft and is still used today, especially with cruise missiles.

Concerns with RATO include storage, handling, and integration challenges as well as the high cost of consumable and expendable rocket motors. The rocket motors produce noise, hot exhaust gases, and can be expensive compared to

---

*Research Assistant, Mechanical & Aerospace Engineering, 201 General Academic Building, Student Member

†Research Assistant, Mechanical & Aerospace Engineering, 201 General Academic Building, Student Member

other launchers without consumables for each launch. These factors will be considered and examined in this study.

II. Background

A. Necessity of Vehicle Launching Devices

When considering aircraft takeoff, horizontal takeoff and landing (HTOL) is most common. Such vehicles typically use landing gear to takeoff and land at established airstrips. This is a proven method for successfully deploying and recovering aircraft, but it makes less sense to do this at the smaller UAV scale. There are a multitude of reasons for this.

The biggest advantage to using a launcher is that a traditional airfield is not required. If GSE is present, a launcher can deploy a UAV at any desirable location. This is particularly beneficial in military and active combat conditions where existing infrastructure may be damaged or insufficient. Launchers also allow for private entities to more readily deploy UAVs for use in remote locations. An example of this is oil pipeline inspection in Alaska where there can be large swaths of land between airports. Using a launcher can also increase the endurance of a UAV on a given mission. This is because it can be deployed closer to its target area, thereby reducing travel time to and from that target.

Another advantage to using a UAV launcher is that it allows propeller-based aircraft to be more efficient at their designed operating point. Due to complexity of systems, many of these aircraft use fixed pitch propellers. This means that they must be optimized to work at specific speeds and altitudes. In almost all cases these scenarios are not the same as takeoff conditions. Because of this, the propeller would have to be designed to compromise between efficiency at a given operating point and taking off in what could be an extremely limited distance on a battlefield, for instance. By using a dedicated launch system, significant off-design operation can be avoided because a given UAV can reach takeoff speed without its on-board propulsion system. Once off the ground, the UAV can quickly ascend to its optimal design condition [2].

Using a launcher for UAVs does have its downsides, however. Most notably is the fact that the launcher itself must also be transported to the location in which it is needed. In most cases this will limit their size and weight which can also reduce its effectiveness at launching UAVs. Additionally, some UAV launcher configurations require electrical power. For these cases if a preexisting power supply does not exist, a generator is also needed. Summarily, UAV launching devices serve a valuable purpose, and it is up to mission requirements to determine if they are necessary.

B. Methods for Launching UAVs

When launching UAVs, there are many available deployment methods, but only some may be best suited to the mission requirements. The most basic method, hand-launch, consists of having a human operator hold the aircraft while the engine revs up and then throwing it. From an equipment standpoint, this is the simplest configuration, requiring only a person to serve as a launcher. It does have drawbacks that can make it impractical or impossible. The successful launch of the UAV depends entirely on the individual throwing it. Two different human launchers could have different heights, strengths, or throwing techniques. This introduces large amounts of room for variation in launching performance. Additionally, the UAV to be launched is limited in size and shape by what a human can hold. Typically, the weight of UAVs using this launch method are under 10lbs and have low wing loading with adequate on-board propulsive power [3].

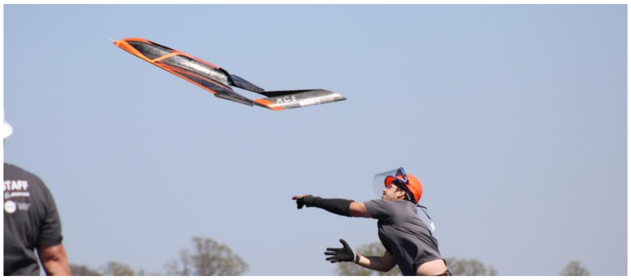

Fig. 1 A student at Oklahoma State University hand-launches a jet-powered UAV [4].

Another method for launching UAVs is by providing external power by way of a tow vehicle. An example of this would be attaching a parasail to a UAV which is then secured by tow line to a boat or other moving vehicle. The advantages are that it would allow an UAV to have both altitude and speed at time of deployment, but the ground tether restricts aerial traffic while this system is deployed [5]. Another possible configuration involves directly attaching the UAV to the top of a car or designated sled. In this instance the UAV would be released once the vehicle has reached a speed high enough to begin flying. The main advantage to this configuration is rapid deployability, but it is limited by surrounding terrain [3].

Fig. 2 Example of an exdrone taking off using a parasail [5].

Fig. 3 Example of using an external vehicle to get a UAV up to launch speed [6].

The next set of launchers are based around using an energy source to fling the UAV up a guiding rail. This energy source can be either elastic, pneumatic, or hydraulic in nature. Each has its own advantages and disadvantages.

An elastic launcher is a simple design. It takes advantage of energy stored in bungee cords to fling the UAV forward when released. It is also possible to modify this configuration to be a large handheld slingshot without a rail. In either case its use is typically limited to smaller Group I UAV, and it's difficult to achieve constant acceleration [5].

Pneumatic launchers rely entirely on compressed gas to launch UAVs. They require a compressed air accumulator which is charged by an external compressor. This launcher configuration has been demonstrated to work in temperate environments, but problems have been noted in low ambient pressure, low ambient temperature, and high moisture air. Another consideration is that pneumatic launchers require good sealing between fittings to keep air from leaking. This is a major consideration for portability of the launching unit, along with a required power source and compressor to function. Pneumatic launchers can lift heavier vehicles than elastic launchers but are still limited by vehicle weight. A typical UAV launched using this configuration would be a Group III UAV weighing between 120-1000 pounds [3].

Hydraulic-pneumatic hybrid launchers (HP launchers) solve many of the problems of the other two rail launching systems. In this setup, the pneumatic air is in a closed loop, so pollutants and humidity are not as big of a concern. It also provides much more launch consistency by achieving near constant acceleration with final velocities within 1 knot of the predicted value. Published HP launchers have successfully deployed aerial vehicles weighing 1,225 lbs. with an 85-knot end velocity. While the HP launcher is more consistent than a pure pneumatic launcher, it does still suffer from portability issues and necessitates external power requirements [3].

Fig. 4 Example of an elastic launcher used to deploy the LUNA UAV[7].

Fig. 5 Example of a pneumatic launcher[8].

Fig. 6 Hydraulic launcher being used to deploy the RQ-7 Shadow 200[9].

Finally, there is the RATO system of deployment. With this method, a rocket motor is attached to an UAV which when ignited, provides a large amount of acceleration in little time and space. There are some drawbacks, including a brief moment when the rocket motors have ignited but the UAV is airborne and does not have enough speed to maintain lift and stability on its own. This is a design and integration consideration. Additionally, the rocket motors are usually jettisoned after launch, so there should be a cleared area down range. There are also concerns about the noise, heat, and sound produced during launch, especially if stealth is necessary [5]. Care must also be taken to keep the rocket propellant from excessive moisture and vibrations or stray electrical charges during storage, handling, and launch preparation [10]. An example of this launch setup can be seen below in Fig. 7.

Fig. 7 A Navy RQ-2A waiting for deployment on a ship deck [11].

Fig. 8 A Navy RQ-2A firing its rocket booster for deployment on ship [11].

RATO can also be configured to allow for the deployment of UAVs from larger aircraft. The most common occurrence of this is in hypersonic UAVs where rockets are used to fill the gap between aircraft cruising speed and required speed for ramjet operation. While turbojets can meet the requirements to accomplish the same thing, it is simpler to use rockets due to their self-contained nature. They are easy to integrate because they carry their own oxidizer and do not require an inlet or ducting with the atmosphere. This self-containment also makes the motors easier to eject during flight when their operation has ended. In this instance, the RATO system becomes comparable to missiles.

Fig. 9 A modified Pegasus rocket ignites moments after release from the B-52B, beginning the acceleration of the X-43A over the Pacific Ocean [12].

III. General RATO Considerations

A. RATO Equipment

RATO is a simple launching mechanism which does not require much GSE. A list of required items can be seen in Table 1. Smaller UAVs using RATO typically use solid propellant rocket motors as opposed to liquid rocket engines. This is because the solid motors are simple, store well, and typically cost less than a liquid engine and thus less of a waste to jettison. Solids also are simpler to operate overall, and the main advantages to liquid rocket engines, throttleability and re-ignition, is typically not necessary in RATO scenarios. The propellant is also more stable and thus less prone to explosion [3, 10].

Table 1 RATO Equipment and GSE.

Item	Notes
Rocket Motors	Primary provider of force during takeoff
Pyrogen Igniters	Inserted into rocket motor to transform electrical firing charge into flame
Rocket Motor Magazine	Used to store rocket motors and igniters before use
Ignition Command Module	Used to arm and fire rocket motor
Firing Circuit	Wiring to connect ignition control module to igniter
6TL Battery	Standard military battery used to power ignition control module and igniter
UAV Launch Cradle	Where the plane will rest until ignition

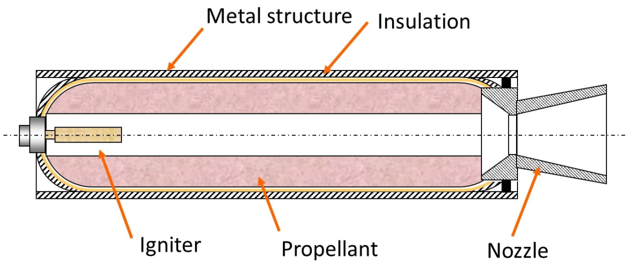

Fig. 10 A cutaway view of a solid rocket motor showing grain configuration and igniter location [13].

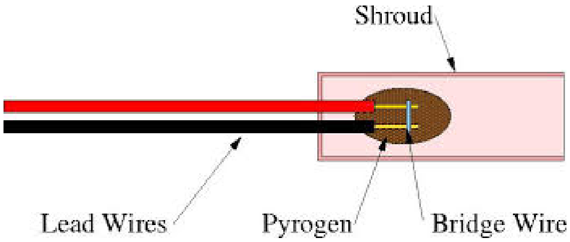

Fig. 11 A cutaway view of a typical pyrogen igniter [14].

Fig. 12 A typical flame cabinet which would be used as a rocket motor magazine for safe storage [15].

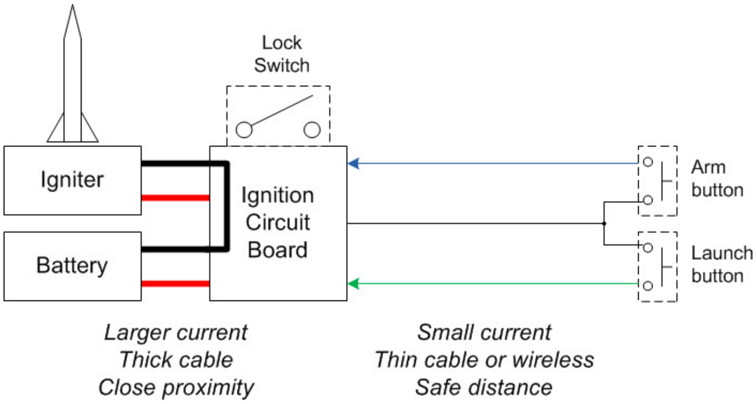

Fig. 13 A typical ignition circuit setup showing how the battery and igniter would be integrated with the ignition control module [16].

B. RATO Use Cases

RATO is particularly useful in military applications. Unlike pneumatic based launchers which require external power to run a compressor, RATO launchers can be powered by a small external battery. A standard 6TL military battery found in a Humvee is designed to provide 25 amps of power for 215 minutes before recharging [17], which is plenty as igniters are designed to light the motor in a matter of seconds. This also highlights an advantage over pneumatic based launchers which require a compressor to be charged up between launches as opposed to RATO where UAVs can be launched as fast as they can be manually loaded.

RATO launchers also offer the advantage of being compact and easily transportable. They qualify as what is known as Zero Length Launchers (ZeLL). The difference in footprint can be seen when comparing Figs. 5 and 6 with Figs. 7 and 8. This makes them particularly attractive choices for applications where space is limited such as on a naval ship deck. However, rocket motors of all types are susceptible to degradation in performance due to moisture [18]. Thus, it is important to ensure they are properly stored in a humidity-controlled environment before use.

RATO also works as a last resort launcher. If an area has been heavily bombed or gassed, it may not have enough oxygen present for an airbreathing engine to operate at peak efficiency. Rockets carry their own oxidizer with the fuel, so in this case a RATO equipped UAV could be able to boost the plane to a higher altitude where the onboard engine can get more oxygen. This is different from rail guided launchers because they must have the onboard engine producing enough thrust to climb as soon as the UAV leaves the rails.

RATO capabilities can also be applied to manned aircraft as well. A widely cited military use case of RATO is during Operation Credible Sport. This mission intended to takeoff and land a C-130 on the length of a soccer field in Tehran, Iran [19]. In initial testing the system looked promising. However, when the actual flight tests were performed, the plane took off successfully, but timing issues caused it to crash on the landing attempt. This problem combined with the political atmosphere changing shortly after the test meant that the operation was canceled, and the plane never completed its mission.

Other examples of the military using RATO on manned aircraft occurred during the Cold War. The United States wanted to ensure they could launch planes even with a shortened or destroyed runway from soviet bombings, so it began a program titled Zero Length Launch, Mat Landing (ZELMAL). The main objective was to outfit manned aircraft with rocket boosters so they could takeoff without a runway. Aircraft in this program include the F-84G Thunderjet, F-100 Super Sabre, and F-104G Starfighter. While this program was eventually canceled, many successful tests were performed [20].

F-100 ZEL (USAF*)

Fig. 14 F100 ZEL ready for launch[21].

RATO can also be useful in hot and high conditions. This could include airports either in hot areas or with high altitudes. Density is a direct function of pressure and temperature as shown by the ideal gas law in Eqn. 1. A decrease in pressure from higher altitude or increase in temperature both lead to a decreased density. Because density is directly proportional to lift as shown in Eqn. 2, hot and high conditions necessitates more velocity at takeoff. RATO was considered as a way to solve this in full sized manned aircraft. The de Havilland DH 106 Comet 1 was initially designed to have rocket boosters attached to it, but they were deemed unnecessary after a number of test flights. The Boeing 727 and Fairchild Swearingen Metroliner also had provisions for RATO but weren't often used. Presently, turbojets produce sufficient thrust that RATO is no longer necessary for manned civilian aircraft.

$$\rho = \frac{P}{RT} \tag{1}$$

$$L = \frac{1}{2}\rho V^2 S \tag{2}$$

C. RATO Stability Considerations

There are many ways to configure RATO in an aerial vehicle. Typically, a single RATO device is located on the longitudinal axis, so the force it applies passes through the center of gravity (CG) of the aircraft. It is possible to mount multiple rocket motors symmetrically around the longitudinal axis, but special care must be taken to ensure they ignite at the exact same moment. Uneven firing can easily destabilize the aircraft and cause the vehicle to crash. It is also important that the force from the rocket motor is angled slightly upwards, so the vehicle does not crash before achieving sufficient velocity to lift itself and remain airborne [3].

The specific mounting point must also take the changing mass of the rocket motor into account. It can be approximated that the mass of each RATO unit will be halved after burnout has occurred. Because of this, it is optimal to ensure the RATO unit is located as close to the CG as possible to keep the plane stable at low speeds. Most RATO configurations also involve dropping the rocket once the plane has achieved flight on its own. In this instance it is important to ensure that the rapid change in mass won't destabilize the plane [3].

D. RATO Structural Considerations

In addition to stability considerations, it is also important that a UAV can be designed to withstand a RATO launch. Electronic and structural components are particularly susceptible to the heightened acceleration and vibrations that could be caused by a RATO launch. Typically, the rocket is attached to the bottom of the aerial vehicle so it is also important to consider how the integration of the rocket will affect the placement of landing devices such as landing gears. Additionally, it is important to ensure if the rocket is planned to be dropped after launch that it is mounted in such a way that the plane will not be damaged while doing so [3].

IV. Cost Analysis

This section will cover a comprehensive cost analysis of applying RATO to a preexisting UAV. The approach for this method will be discussed, and 3 production UAV are included as examples of expected costs for a UAV in each of the Group 1-3 categories.

Several terms used in this section are necessary to define. The rocket motor contains the propellant, casing, and closures, but not the igniter, mounting provisions, or supports to the UAV or launcher. The motor is considered the primary consumable cost, i.e. equipment that is not reusable and only operates once. The launch pad contains the support guides for launching the UAV that keeps the UAV and rocket motor aligned in the intended direction until the UAV has gained sufficient speed to be stable on its own. A salvo is an array of launch pads that are available for launching multiple UAVs at once and is useful should multiple UAV be launched in rapid succession without reloading the pad with a new vehicle.

Fig. 15 A RATO Launchpad and Rail Guides the UAV at Launch [22].

A. Approach and Premise

This study focuses on single-use rocket motors. Other motors exist as a reload in which there is a reusable external casing and closures. Over many uses, the reloads cost less per launch than a single-use, but require retrieval, maintenance, servicing, and inspection after each use. Because UAVs can cover significant horizontal distance away from the launch pad, necessitating retrieval of motor hardware would complicate the analysis and is therefore not examined in this study.

The single-use motors are based on products manufactured by Aerotech Consumer Aerospace of RCS Rocket Motor Components, Inc. Their line of DMS (disposable motor system) motors vary in total impulse, thrust, and cost which provides flexibility in assigning a motor to be used for RATO purposes. Thrust ranges from 1.8 to 400 pounds, and costs between $22.50 and $370.00 per motor. The simplicity of the DMS products includes no additional costs, assembly, or maintenance for successful operation. Several DMS motors are listed below in Table 2.

Table 2 Aerotech DMS Motors.

Motor	Burn Time	Avg Thrust (lbf)	Peak Thrust (lbf)	Cost
F20	2.59	4.5	9.07	$22.50
G8	17.7	1.8	2.25	$33.00
G80	1.7	18	24.53	$27.99
H135	1.7	30.38	34.2	$33.00
I140	2.4	31.5	40.73	$45.00
J270	2.6	60.75	80.1	$70.00
K535	2.8	120.4	147.4	$135.00
L1000	2.7	225	283.7	$220.00
M1350	3.9	303.75	400.3	$370.00

Other costs associated with RATO include ground support equipment: the launch pad, ignition power supply and circuitry, secure rocket motor storage, and safety personal protective equipment (PPE). Each of these are variable costs for a certain number of units purchased and number of UAV launched and operated at a given time. These are shown in Table 3.

Table 3 Additional RATO Costs.

Item	Cost	Notes
TeleLCO Ignition Command	$600	Per 792 pads
TeleFireEight Firing Circuit	$650	Per 8 pads
Type II Indoor Magazine	$2800	Per 36 M Motors
Fire Extinguisher, PPE	$100	Per pad
Launch Pad	$500	Per pad

The TeleLCO and TeleFireEight are wireless control and ignition circuits that are used at high-power rocket launches. Manufactured by Altus Metrum, it allows for safe arming and ignition of rocket motors with one TeleFireEight allowing 8 separate launch pads to be controlled at once. If more than 8 UAV are needed to be launched on a single salvo, then a second TeleFireEight unit is required. The Type II Indoor Magazine by Blasters Tool and Supply Co. is used for secure storage of rocket motors prior to installation on the UAV. It has dimensions of 36"x24"x36" which is enough for housing an estimated 36 M1350 rocket motors. The remaining costs are a fire extinguisher per launch pad and safety glasses for operating personnel.

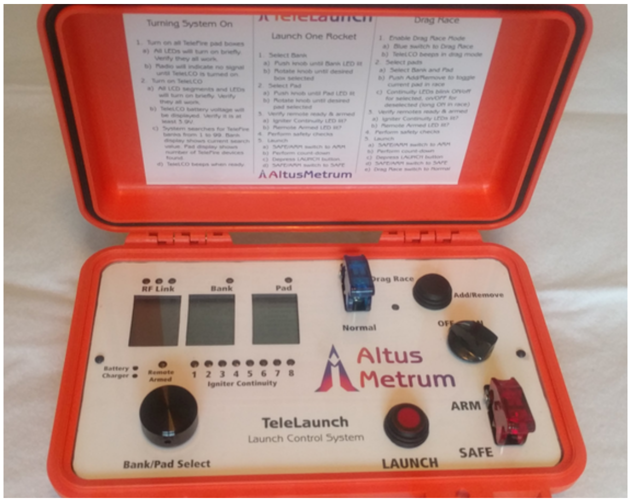

Fig. 16 The Altus Metrum TeleLCO Command Unit [23].

Fig. 17 The Altus Metrum TeleFireEight Controls 8 Launchpads [24].

The estimated $500 for a launch pad comes from comparable high-power rocketry launch pads that are collapsible, lightweight enough to be carried by individual personnel, and supports a wide range of rockets. An example launch pad used in amateur rocketry is shown below in Fig. 18. It is beyond the scope of this study to design such a launch pad; therefore, the $500 estimate is used instead.

Fig. 18 The Apogee Components Gun Turret Launchpad [25].

These parts were all chosen because of their commercial availability and accessibility of product specifications and cost. These figures do not account for tax, shipping, transportation, assembly, labor, or integration, design, and test costs. This study focuses on the financials of the parts themselves to determine material costs of applying RATO to an existing UAV.

Having established the rocket motors available for use in this RATO study, 3 different UAVs were selected to be compatible with these rocket motors that cover a range of missions, cost, and takeoff weight. Of the four groups of UAV classification, a UAV was chosen from each of the three groups and are shown in Table 3 below based upon information available online about its specifications, cost, and history. The US Air Force website archives offered valuable information about these. Group IV was omitted in this study due to the large range of possible UAV weights, upwards of tens of thousands of pounds.

Table 4 Group 1-III UAV.

UAV Group	Weight Range (lb)	Example UAV	UAV Weight (lb)
Group I	0.1-20	RQ-11 Raven	4.2
Group II	20-120	Scan Eagle	39.7
Group III	120-1000	RQ-7 Shadow	375

The RQ-11 Raven is manufactured by Aerovironment and was first deployed in 2004. The Raven is a Group I "back-packable system which features 2 air vehicles (AV), a ground control unit, remote video terminal, transit cases and support equipment [26]" at a system cost of $218,140 in 2019 dollars with each AV costing approximately $35,000 [27]. It is a hand-launched device that provides real-time situational awareness and target information in the field with 60-90 minutes of endurance and an operating altitude of up to 500 feet.

Fig. 19 Hand Launch of an RQ-11 Raven [28].

The Scan Eagle is a Group II UAV manufactured by Boeing and Insitu Group introduced in 2006. The Scan Eagle system "features four air vehicles, a ground control station, remote video terminal, and a launch and recovery system known as the Skyhook system" costing $4.03 million in in 2019 dollars [29]. It is catapult launched that requires no runway for takeoff or landing. It has over 20 hours of endurance with an operating altitude of 16,000 feet.

Fig. 20 Catapult Launch of a Scan Eagle [30].

Lastly, the RQ-7 Shadow 200 is a Group III UAV contracted by AAI Corporation (Textron) that launched in 2001 to provide tactical intelligence, surveillance, and reconnaissance (ISR). The system includes 4 AVs with payload, launcher and ground control and support equipment including: power generation, communications equipment, automated recovery equipment, one system remote video terminals vehicle mounted shelter, and High Mobility Multipurpose Wheeled Vehicle (HMMWV) with trailer [31]" at an estimated system cost of $17.5 million [32]. It has an endurance of 6-9 hours by means of a hydraulic launcher.

Fig. 21 Hydraulic Launch of an RQ-7 Shadow [33].

With these UAV selected, an applicable DMS rocket motor was assigned for RATO cost estimation purposes. Due to varying UAV structure, launch requirements, and proprietary design information for each UAV, a precise analysis of RATO kinematics, aerodynamics, stability and control, and structures is beyond the scope of this study; therefore, a rocket motor maximum thrust of 1-2 times the UAV gross take-off weight (GTOW) was assumed to be suitable as a DMS rocket motor. As there are few DMS rocket motors to begin with, there was only one motor that fit each UAV based on the criterion above. In Table 5, the UAV are matched to a DMS motor.

Table 5 Motors for UAV RATO.

UAV	UAV Weight (lb)	DMS Motor	Motor Peak Thrust (lb)	Motor Avg Thrust (lb)
RQ-11 Raven	4.2	F20	9.07	4.5
Scan Eagle	39.7	I140	40.73	31.5
RQ-7 Shadow	375	M1350	400.3	303.75

B. Cost Study

The cost analysis for applying RATO to each of these UAV began with one launch pad and one rocket launch on the appropriate rocket motor: an F20 for the Raven, an I140 for the Scan Eagle, and an M1350 for the Shadow. The associated ground support and safety equipment shown in Table 3 were added to the cost. Next, multiple flights were factored into the cost for a single launch pad. In this situation, the ground support and safety equipment costs were held fixed, and the only recurring cost was that of the given rocket motor. The cost is shown in Fig. 22. As expected, the overall cost of RATO increases with the larger number of consumable rocket motors. However, much of that cost is due to the comparatively expensive ground support equipment that becomes more affordable with a large number of launches for that fixed cost.

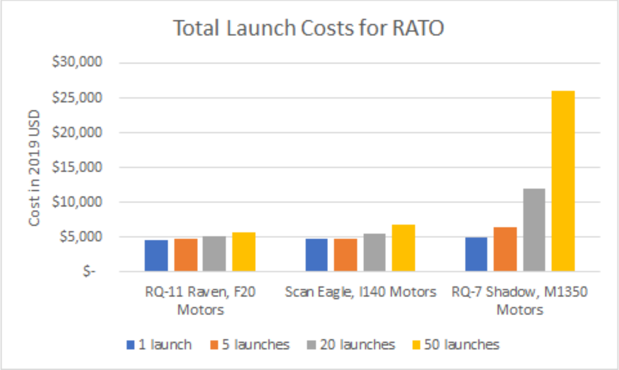

Fig. 22 Graph of Total Costs Associated with RATO for a Given Number of Launches.

After determining these costs for up to 50 RATO launches, the costs were divided by the number of launches that took place to calculate the average cost per launch when accounting for the ground support and safety equipment. This parameter indicates that the costs associated with RATO become drastically more affordable with increasing numbers of launches. For example, launching the Scan Eagle on an I140 motor would cost $4,695 for a single flight but $130 per flight when averaged across 50 launches. This data is shown in Fig. 23.

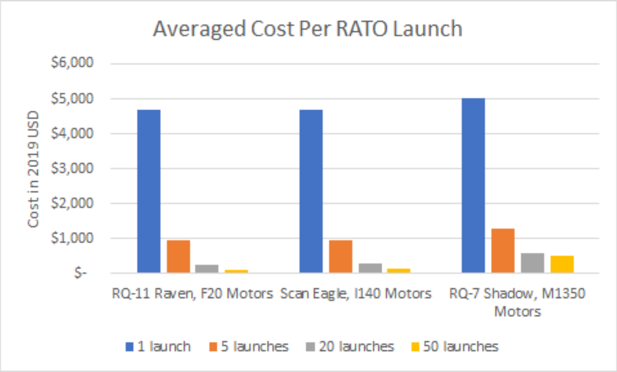

Fig. 23 Graph of RATO Costs Averaged Across the Number of Launches.

Another statistic of interest is how that averaged cost relates to the individual rocket motor cost used during each launch. Fig. 24 shows the percentage difference of the averaged launch cost compared to the rocket motor's standalone cost, i.e. the averaged cost and motor cost become more similar.

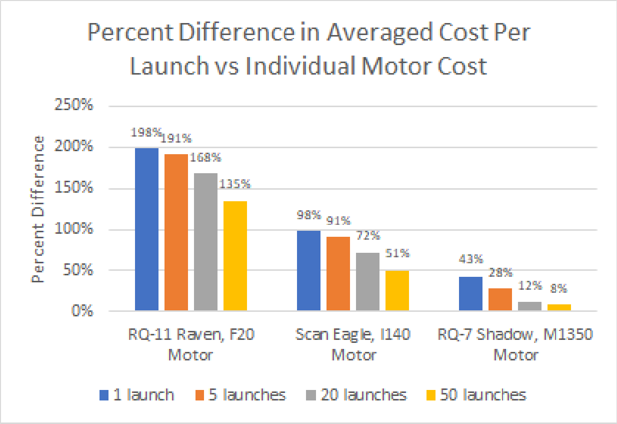

Fig. 24 Plot Indicating Percent Differences in Averaged Launch Costs Compared to Motor Cost.

Fig. 24 shows that launching even as many as 50 Ravens on F20 motors would cost 135% more per launch than the motor itself. By contrast, launching 50 Shadows on M1350 motors would only cost 8% more per launch than the M1350 individual cost.

Upon initial inspection, RATO appears to be more cost-effective for larger-scale rocket motors and UAVs where the motor cost is greater and more similar to the high initial cost of ground support and safety equipment. Additionally, numerous launches help lower the averaged cost as well.

RATO is not limited to one operational launchpad for a single UAV at once. There may be 8 or more launchpads used at once where a salvo of rocket-launched UAVs may be on standby to be released all at one time or in rapid succession. In this case, the above figures must be recalculated for different combinations of ground support equipment and storage.

Fig. 25 shows the total costs associated with RATO when operating 1, 4, and 8 launch pads. Due to the increased number of launch pads, it is expected that the total cost increases.

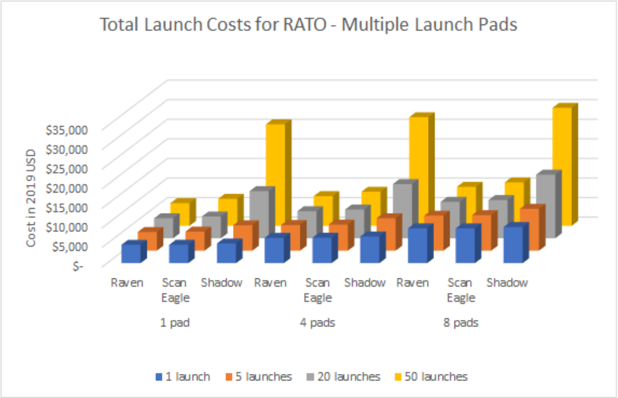

Fig. 25 Plot Indicating Total Costs Associated with RATO for Multiple Launch Pads.

By once again averaging the total RATO costs across 1, 5, 20 and 50 launches, the ground support equipment and additional launch pad costs per launch greatly decrease. Fig. 26 indicates that like operating a single pad, using 4 or 8 pads is most economical when repeatedly reused, even for just 5 launches.

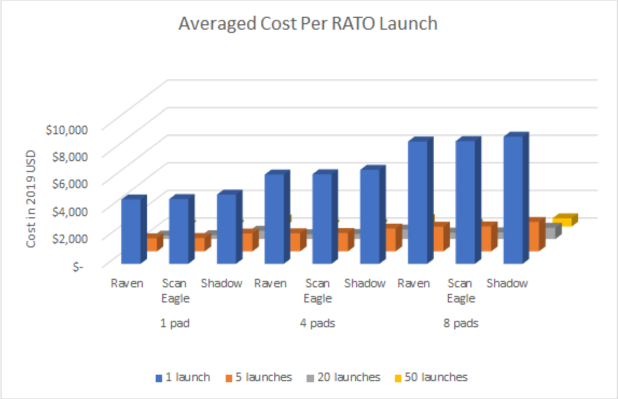

Fig. 26 Plot Showing the Averaged Costs of RATO for Multiple Launch Pads.

As previously discussed, the averaged cost across many launches is a useful parameter, but the difference between those figures and the consumable rocket motor cost is also significant. While launching many times may lower the average cost per launch, that figure can still be many times higher than the standalone rocket motor cost. It is desirable that the averaged cost per launch be as close to the motor's cost itself. Fig. 27 shows that by operating multiple launch pads, the percent difference per launch and the motor cost increases. When operating one launch pad, multiple launches become a fraction of the single launch cost, but when using 4 or 8 pads, there is less of a decrease in the percent difference. That is to say, the averaged cost remains significantly greater than the motor cost even with 20 to 50 launches. For larger rocket motors to lift heavier UAVs, this effect isn't as pronounced, and the averaged cost is closer to the motor cost.

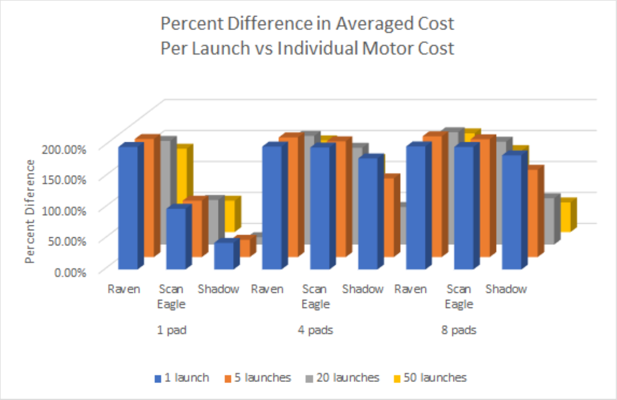

Fig. 27 Plot of Percent Differences in Averaged Launch Costs Compared to Motor Cost for Multiple Launch Pads.

The final parameter to be discussed in this cost analysis is the total RATO cost as a percentage of the total UAV system cost. Each of the 3 UAVs discussed has a price that includes multiple aerial vehicles, ground support equipment, communications, video, recovery mechanisms, and mechanical launchers of their own. This information is shown below in Table 6.

Table 6 UAV System Costs.

UAV	System Cost (2019 USD)	Number of AVs	Ground Station, System Components
RQ-11 Raven	$218,140	2	Power, Recovery, Transit Cases
Scan Eagle	$4,030,000	4	Pneumatic Launcher, Video Terminal
RQ-7 Shadow	$17,500,000	4	Hydraulic Launcher, Power, Recovery

The RATO costs for a given number of launches are plotted as a percentage the UAV system costs in Fig. 28. This figure indicates how much of the system cost it would require to outfit that UAV with the RATO equipment described previously.

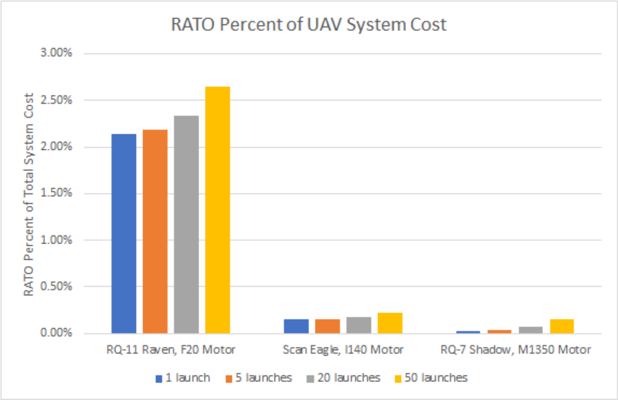

Fig. 28 Plot of RATO as a Percent of the UAV System Cost.

RATO is most costly for the Group I Raven due to the low overall system cost. The Raven does not need or include a special launcher, and therefore, adding RATO represents a higher cost percentage than for the Scan Eagle or Shadow. However, for more expensive systems, the comparatively low RATO costs make this method of launching Group II or III UAVs more feasible.

Lastly, Fig. 29 graphs the percentage cost for multiple launch pads. RATO consistently costs much more of the Raven's system than the Scan Eagle or Shadow, regardless of the number of launch pads.

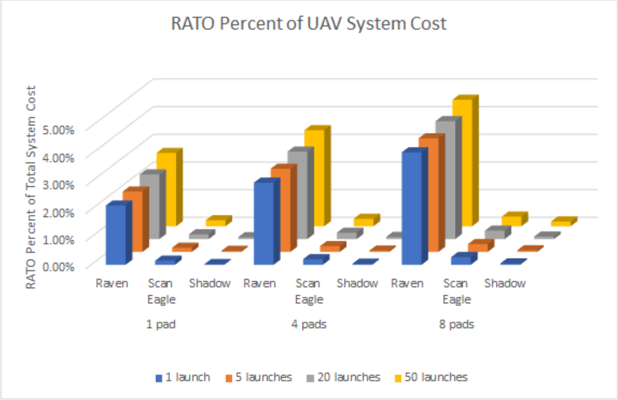

Fig. 29 Plot of RATO as a Percent of the UAV System Cost for Multiple Launch Pads.

C. Analysis and Findings

Some of the trends gathered from these plots and throughout this study stem from three variables: number of total launches, larger rocket motors for lifting heavier UAVs, and multiple launch pads.

By launching UAVs often and frequently, the relatively high cost of GSE to motor cost is diminished and RATO becomes more financially feasible. From Fig. 23, even launching just 5 times versus 1 time corresponds to a 79% reduction in average cost per launch for the Scan Eagle, for example.

When comparing the averaged cost per launch to the motor consumable cost, there are still benefits to numerous launches. Launching the Raven on F20 motors results in a 63% reduction in percent difference for 50 launches versus 1. The Shadow has a 35% reduction between 50 launches and 1.

This general trend indicates that by launching more frequently, the average cost per launch is decreased, which offsets the cost of relatively high GSE. This trend makes sense as the ground equipment sees more repeated use.

Next, the trends associated with launching larger UAVs on more costly rocket motors is the most significant aspect of this study. Fig. 24 shows this data best. By launching the Shadow just once, the percent difference in averaged launch cost with that of the M1350 rocket motor is already less than the percent difference in launching the Scan Eagle 50 times. Fig. 22 shows that the overall cost is also lower, but RATO costs for the Shadow are more representative of the consumable rocket motor, the cost per launch is closer to the motor's cost. Because of the M1350's relatively high cost, it quickly makes the associated GSE investment more worthwhile than for launching Group I UAVs like the Raven.

This finding is further supported by Fig. 29 that shows the significantly lower percent cost of the UAV system cost for the Scan Eagle and Shadow. Because of those costly UAV systems, RATO as presented in this study would only cost between 0.03% and 0.22% of the overall system cost. Even launching the Shadow 50 times only represents 0.15% of the Shadow's overall cost, which makes RATO very financially feasible, especially for these Group II and Group III UAVs.

The third trend studied was the influence of operating multiple launch pads at once. Appropriately, there were increased costs associated with multiple launchpads. The higher cost becomes apparent in Fig. 27 where even launching 50 times doesn't offset the percent difference significantly. This is a special consideration that the cost of multiple pads can make RATO less financially appealing. However, the Scan Eagle and Shadow systems only include a single launcher for its 4 AVs, so RATO with affordable ground support and launch equipment would be useful for launching those multiple UAVs in rapid succession.

Based on these trends, variables studied, and resulting findings, RATO appears to be most effective when launching a single AV repeatedly and when the AV is in the Group II or Group III weight category. By launching many times with the same ground support and launch equipment, the average cost per launch is reduced and makes RATO more of a financial possibility.

By operating more than one launch pad, higher RATO costs are incurred, but this offers affordable flexibility versus purchasing additional multi-million-dollar UAV systems for a second launcher, or even additional launchers individually.

For Group II and III UAVs, RATO as studied here is only a fraction of a percent of the total UAV system cost and offers the ability to launch 8 or more UAVs in rapid succession which cannot be said for the included launchers associated with the Scan Eagle and Shadow.

This cost analysis study did not account for labor, shipping and transportation, or costs associated with design and testing of RATO integration. Those were expected to vary greatly from manufacturer, contractor, mission, and UAV. Commercial, off-the-shelf parts were used for availability and accessibility of products and information. Integration considerations are necessary for applying RATO to a UAV, but this analysis was intended to provide guidance and estimates for RATO costs and in which situations RATO would be most appropriate from a financial perspective.

V. Conclusion

Rocket-assisted takeoff does not presently see significant use for launching many UAVs but is nonetheless a feasible launch option for Group 1-III UAVs. There are integration and logistical considerations including safety, design, kinematic, and financial. RATO appears best suited for rapidly deploying multiple UAVs from several launchpads. RATO is most effective for heavy Group II and Group III UAVs, where the high rocket motor and system cost validates the expendable rocket motor cost and ground support equipment. Multiple launches lower the averaged cost, and RATO is best suited when used repeatedly. This study did not include specifics of integration design, test or labor costs. It was intended to study the considerations and cost of a RATO system for deploying Group I-III UAVs, using the Raven, Scan Eagle, and Shadow as example UAVs.

References

[1] "Coyote UAS, One System, Multiple Missions," , 2017 (accessed April 28, 2019). URL `https://www.raytheon.com/capabilities/products/coyote`.

[2] Austin, R., *UNMANNED AIRCRAFT SYSTEMS: UAVS DESIGN, DEVELOPMENT AND DEPLOYMENT*, 1st ed., Wiley, 2010.

[3] Austin, R., *Introduction to UAV Systems*, 4th ed., Wiley, 2012.

[4] "Picture of Hand Launching," , 2018 (accessed April 16, 2019). URL `https://mae.okstate.edu/content/mechanical-and-aerospace-engineering-professor-james-manimala-awarded-darpa-young-faculty`.

[5] Eriksson, M., and Ringman, P., "Launch and recovery systems for unmanned vehicles onboard ships. A study and initial concepts." Master's thesis, KTH Centre for Naval Architecture, 2015.

[6] Cassano, J., Seefeldt, M., Palo, S., L. Knuth, S., Bradley, A., D. Herrman, P., A. Kernebone, P., and J. Logan, N., "Observations of the atmosphere and surface state over Terra Nova Bay, Antarctica, using unmanned aerial systems," *Earth System Science Data*, Vol. 8, 2016, pp. 115–126. doi:10.5194/essd-8-115-2016.

[7] "Picture of Luna elastic launcher," , 2012 (accessed April 16, 2019). URL `https://defence.pk/pdf/threads/pn-contracts-to-buy-luna-uav-for-its-maritime-shore-surveillance.191348/`.

[8] "Picture of pneumatic launcher," , 2016 (accessed April 16, 2019). URL `https://i-hls.com/archives/79565`.

[9] "Picture of hydraulic launcher," , 2015 (accessed April 16, 2019). URL `http://phasezero.gawker.com/tag/60-days-of-drones`.

[10] Sutton, G., *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets*, A Wiley-Interscience publication, Wiley, 1992.

[11] "Picture of RQ-2A RATO," , 2007 (accessed April 16, 2019). URL `http://www.designation-systems.net/dusrm/app2/q-2.html`.

[12] "Picture of RATO air launch," , 2004 (accessed April 16, 2019). URL `https://www.dfrc.nasa.gov/Gallery/Photo/X-43A/HTML/EC04-0092-32.html`.

[13] "Picture of Rocket Motor," , 2019 (accessed April 25, 2019). URL `https://www.narom.no/undervisningsressurser/sarepta/rocket-theory/rocket-engines/the-engine-types-solid-liquid-and-hybrid-and-a-fourth/`.

[14] "Picture of Pyrogen Ignitor," , 2019 (accessed April 25, 2019). URL `http://www.vk2zay.net/article/14`.

[15] "Picture of Flame Cabinet," , 2019 (accessed April 25, 2019). URL `https://scimatco.com/products/sc7132`.

[16] "Picture of Ignition Control Circuit," , 2019 (accessed April 25, 2019). URL `https://www.robotroom.com/Rocket-Ignition-System-1.html`.

[17] "US 6TL Battery Specs," , 2018 (accessed April 16, 2019). URL `https://www.usbattery.com/products/12-volt-batteries/us-battery-6tl-deep-cycle-12-volt/`.

[18] McDonald, B. A., Rice, J. R., and Kirkham, M. W., "Humidity induced burning rate degradation of an iron oxide catalyzed ammonium perchlorate/HTPB composite propellant," *Combustion and Flame*, Vol. 161, No. 1, 2014, pp. 363 – 369. doi: https://doi.org/10.1016/j.combustflame.2013.08.014, URL `http://www.sciencedirect.com/science/article/pii/S0010218013003180`.

[19] Brendan, M., "Credible Sport: The Super-STOL Hercules," , 2012 (accessed April 27, 2019). URL `https://www.defensemedianetwork.com/stories/credible-sport-the-super-stol-hercules/`.

[20] van Pelt, M., *Rocketing Into The Future: The History and Technology of Rocket Planes*, Springer, 2012.

[21] "Picture of F100 ZEL," , 2001 (accessed April 16, 2019). URL `https://www.airvectors.net/avf100.html`.

[22] "Mirach 100/5," , 2008 (accessed April 25, 2019). URL `http://ukarmedforcescommentary.blogspot.com/p/combined-aerial-target-service-cats.html`.

[23] "TeleLCO," , 2019 (accessed April 25, 2019). URL `https://altusmetrum.org/TeleLaunch/`.

[24] "TeleFireEight," , 2019 (accessed April 25, 2019). URL `https://altusmetrum.org/TeleLaunch/`.

[25] "Gun Turret Pad," , 2014 (accessed April 25, 2019). URL `https://www.apogeerockets.com/Launch-Accessories/Launch-Pads/Gun-Turret-Pad?zenid=p6lftnng706bndeqs85j0bp5m4`.

[26] "Factsheets: RQ-11B Raven," , 2011 (accessed April 17, 2019). URL `https://web.archive.org/web/20130605185332/http://www.af.mil/information/factsheets/factsheet.asp?fsID=10446`.

[27] “RQ-11 Raven Unmanned Aerial Vehicle,” , 2015 (accessed April 17, 2019). URL `https://www.army-technology.com/projects/rq11-raven/`.

[28] “Picture of Raven - Most Widely Used Small UAV,” , 2018 (accessed April 16, 2019). URL `https://i-hls.com/archives/85885`.

[29] “Factsheets: Scan Eagle,” , 2011 (accessed April 17, 2019). URL `https://web.archive.org/web/20130710112005/http://www.af.mil/information/factsheets/factsheet.asp?id=10468`.

[30] “Picture of U.S. Marine Corps Sgt. Michael Kropiewnicki launches a Boeing ScanEagle drone during the training exercise Desert Talon 2-06 at the Marine Corps Air Station.” , 2018 (accessed April 16, 2019). URL `https://dronecenter.bard.edu/scaneagle-drone/`.

[31] “AAI RQ-7 Shadow 200 Info, RQ-7, M2, Budget/Costs,” , 2017 (accessed April 17, 2019). URL `http://www.fi-aeroweb.com/Defense/RQ-7-Shadow.html`.

[32] “RQ-7A Shadow 200,” , 2009 (accessed April 17, 2019). URL `http://www.deagel.com/Support-Aircraft/RQ-7A-Shadow-200_a000513001.aspx`.

[33] “Picture of Shadow 200 RQ-7 Tactical Unmanned Aircraft System,” , 2018 (accessed April 16, 2019). URL `https://www.army-technology.com/projects/shadow200uav/`.