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Engineering Note

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Miniature Launch Vehicles for Very Small Payloads

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Introduction

THE high cost of placing satellites in orbit is of serious concern for the aerospace community and the telecommunications industry. Launch services using expendable launch vehicles (ELVs) have not been able to lower specific launch costs, that is, costs per pound of payload, below those for the space shuttle. Moreover, specific launch costs for small payloads on small ELVs generally increase as the size of payload is reduced. NASA Administrator Daniel S. Goldin has recently expressed the desire to develop a small launcher for a 65-lb payload, which would have recurring launch costs under $1 million (Ref. 1). This goal is a daunting one and is unlikely to be attained using conventional ELVs with normal launch procedures. In a recent forum on the subject it was pointed out that the cost of ground operations alone during a typical launch is of the order of $1 million. Thus, it may be unrealistic to set such a seemingly unattainable, low-cost goal for recurring costs. Nevertheless, it is still vitally important to bring launch costs down for small satellites, which soon may be used extensively for the scientific space program and for U.S. military operations in space.[2]

The purpose of this Note is to show how it may be possible to design miniature launch vehicles for very small payloads (10–100 lb), which could have specific launch costs much lower than those of any ELVs currently in use. (In an order-of-magnitude classification, small payloads are 100–1000 lb, medium payloads are 1000–10,000 lb, and large payloads are 10,000–100,000 lb.) The new concept involved in the design of such small launchers is that of being able to recover and reuse the vehicle's avionics module. This expensive component is the nerve center of the ELV and performs a variety of functions in guidance, navigation, and control. Conventional avionics designed for an inertial navigation system (INS) utilize an inertial measurement unit (IMU) to measure inertial acceleration and provide a stable platform for sensing changes in vehicle attitude. Advanced INS architecture includes use of global positioning system (GPS) to enhance navigation and guidance of the final stage into a precise orbit.[3] If the avionics module were to be recovered intact after every launch for reuse, the savings in small ELV replacement cost could be substantial. This presupposes, of course, that the cost of such recovery would be a small fraction of the avionics replacement cost.

In a previous Note,[4] a novel system was proposed for recovering the avionics modules of two small ELVs (one air launched and the other ground launched). The avionics recovery system envisioned could also be used in other ways, including those of returning scientific or military payloads from orbit, servicing satellites, and providing courier service to and from the International Space Station. In the case of avionics recovery, the system requires the incorporation of a miniature winged spacecraft containing the avionics module into the final stage of each small ELV. After deployment of the payload and separation from the final stage, the autonomous avionics recovery vehicle (ARV) could begin return from orbit at a predetermined time or location along the initial orbit. For launch from Florida into a low-inclination orbit, the ARV could deorbit over the South Pacific with a Space Shuttle Orbiter-like descent into and through the atmosphere and a parachute or runway landing at Edwards Air Force Base or Vandenberg Air Force Base in California. For launch from California into a high-inclination polar orbit, the ARV could deorbit over the Arctic Ocean with an Orbiter-like descent and land on the big island of Hawaii.

General Considerations

There are several things to be considered in the design of a miniature ELV to keep recurring launch costs at a minimum. First and foremost, it is certainly desirable to save on vehicle hardware costs by recovering the expensive avionics module for refurbishment and reuse. In a typical small ELV, the avionics module contains an IMU, a flight computer, a telemetry multiplexer, a telemetry transmitter, a flight-termination receiver, a radar transponder, attitude-control system (ACS) thrusters, GPS microelectronics, and batteries in a relatively small volume. In spite of its complexity, the typical avionics module has evolved into a very durable and robust assembly of electronic equipment. It could probably be designed for even greater durability, if it were to be reused. Moreover, such avionics components will undoubtedly continue to get smaller and lighter as the trend of miniaturization in microelectronics continues. With development of a reliable and cost-effective avionics module recovery system, reuse of the avionics and attitude-control hardware could result in substantial savings in ELV replacement costs. Because the ELV then could no longer be described as entirely expendable (and would, in fact, be partly reusable), the name hybrid launch vehicle may be more appropriate.

Another important consideration is the matter of air launch vs ground launch. The better choice to minimize costs is not always so obvious and requires some analysis and clarification. It is commonly thought that air launch provides a way to lower significantly ELV hardware costs by eliminating the booster stage. Whereas this may be true in one sense, the payload may be severely impacted by loss of the booster. An example of this may be found in the performances of three closely related ELVs in the U.S. inventory,[5] which are the only small launchers presently available for civil, commercial, and military payloads. Pegasus is a three-stage, solid-propellant rocket having a wing and tail that is air launched with a 700-lb (318-kg) payload for low Earth orbit (LEO). Pegasus XL is a growth version of Pegasus that is also air launched with a 1015-lb (461-kg) payload for LEO. (The first and second stages of the basic Pegasus have been stretched to hold 24% and 30% more propellant, respectively.) Taurus is a larger and heavier, four-stage, solid-propellant rocket (derived from Pegasus) that is ground launched with a 3100-lb (1407-kg) payload for LEO. Both Pegasus and Taurus have the same solid rocket motors (SRMs) in three of their stages, but the wing and tail of Pegasus were removed along with addition of a booster stage to produce Taurus. At launch, Pegasus weighs 42,000 lb (19,068 kg), Pegasus XL 52,000 lb (23,608 kg), and Taurus 160,000 lb (72,640 kg). The specific vehicle weight, that is, weight per pound of payload placed in LEO, is 60.0 for Pegasus, 51.2 for Pegasus XL, and 51.6 for

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Table 1 Nominal dimensions, weights, and thrust levels for the different stages of downsized Pegasus, Pegasus XL, and Taurus ELVs

Component	Half-size Pegasus	Half-size Pegasus XL	Half-size Taurus
Booster stage			
Length, ft (m)			14.4 (4.39)
Diameter, ft (m)			3.9 (1.17)
Weight, lb (kg)	Air launch	Air launch	13,500 (6,130)
Average thrust, lb (N)			43,475 (19,377)
I_{sp}, s			271
First stage			
Length, ft (m)	15.4 (4.70)	19.1 (5.82)	15.4 (4.70)
Diameter, ft (m)	2.1 (0.64)	2.1 (0.64)	2.1 (0.64)
Wingspan, ft (m)	11.0 (3.35)	11.0 (3.35)	——
Weight, lb (kg)	3,864 (1,754)	4,523 (2,053)	3,864 (1,754)
Average thrust, lb (N)	13,678 (60,840)	16,551 (73,620)	13,678 (60,840)
I_{sp}, s	295	295	295
Second state			
Length, ft (m)	3.8 (1.16)	5.9 (1.78)	3.8 (1.16)
Diameter, ft (m)	2.1 (0.64)	2.1 (0.64)	2.1 (0.64)
Weight, lb (kg)	938 (426)	1,219 (554)	938 (426)
Average thrust, lb (N)	3,450 (15,346)	4,314 (19,190)	3,450 (15,346)
I_{sp}, s	295	295	295
Third stage			
Length, ft (m)	2.4 (0.74)	2.4 (0.74)	2.4 (0.74)
Diameter, ft (m)	2.1 (0.64)	2.1 (0.64)	2.1 (0.64)
SRM weight, lb (kg)	271 (123)	271 (123)	271 (123)
Average thrust, lb (N)	971 (4,320)	971 (4,320)	971 (4,320)
I_{sp}, s	291	291	291
ARV (inert weight, lb (kg)	——	——	210 (95)
Avionics + ACS, lb (kg)	80 (36)	80 (36)	80 (36)
Payload weight, lb (kg)	17.5 (7.9)	56.9 (25.8)	100 (45.4)
Total length, ft (m)	25.45 (7.76)	28.75 (8.76)	45.15 (13.76)
Total weight, lb (kg)	5,250 (2,384)	6,500 (2,951)	20,000 (9,080)

Taurus. In this case, surprisingly, it appears that there is little reduction in specific vehicle weight from air launch. Moreover, the addition of a booster stage in place of air launch more than quadruples the payload capability of the basic three-stage launch vehicle, with the result that specific launch costs are considerably lower for Taurus than for Pegasus or Pegasus XL. However, air launch does have an advantage of simplifying ground operations and lessening the problem of ensuring launch-range safety.[6]

The basic concept involved in determining the nominal sizes and weights of miniature launchers and their components proposed in this Note is that multistage rockets can be scaled down to produce smaller versions capable of attaining orbit with lighter payloads. In this downsizing process, the fraction of mass for each stage to total vehicle mass is maintained, and the size of most components is determined by a scale factor. However, because it is unlikely that the avionics and the ACS in the final stage can be scaled down this way, the downsized payload capability may have to be further reduced to compensate. If, along with the scaling of SRMs, the reductions in nozzle size are also done properly, the thrust-to-weight levels in the various stages and rocket burn times can be maintained to ensure having adequate thrust and propellant to attain orbital speed and altitude. The mass of each stage of smaller versions of any ELV can be obtained by applying the cubic scaling law. This law infers that, for the same average density, the ratio of scaled-down mass to full-size mass of each stage is given by the cube of the scale factor. If the scale factor is 1/2, the mass ratio ideally is 1/8, and a half-size ELV has only one-eighth the mass of the full-size ELV. From a strength-of-materials standpoint, the shrinkage of SRM dimensions (including casing thickness) by a scale factor should not compromise the SRM's ability to withstand typical aerodynamic loads and combustion chamber pressures generated during rocket operation.

Miniature Launch Vehicles

Nominal sizes, weights, and thrust levels of the various stages of three miniature launch vehicles derived by downsizing Pegasus, Pegasus XL, and Taurus ELVs to half size (Fig. 1) are presented in Table 1. It has been assumed that the only components in the final stages of the full-size ELVs that do not scale according to the cubic scaling law are the avionics and the ACS. To be conservative, the mass of this equipment in the half-size ELVs is considered fixed at 80 lb (36 kg) rather than being downsized to 10 lb (4.5 kg). Thus, for half-size Pegasus, Pegasus XL, and Taurus ELVs, the downsized payloads of 87.5 lb (39.7 kg), 126.9 lb (57.6 kg), and 387.5 lb (175.9 kg), respectively, must be reduced by 70 lb (31.8 kg) to compensate for the fixed avionics-plus-ACS weight. As a result, a half-size Pegasus weighing about 5250 lb (2384 kg) would only be capable of placing a 17.5-lb (7.9-kg) payload in LEO, and a half-size Pegasus XL weighing about 6500 lb (2951 kg) would only be

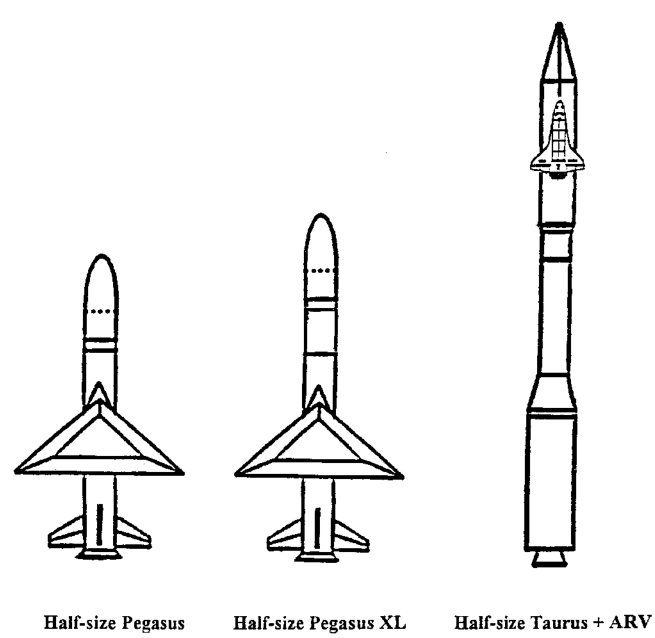

Fig. 1 Miniature launch vehicles derived from Pegasus, Pegasus XL, and Taurus ELVs.

capable of placing a 56.9-lb (25.8-kg) payload in LEO. However, development of much lighter avionics using GPS solely in place of an INS could increase the payload capability of each launcher by up to 50 lb (23 kg). Then specific launch costs would be minimal, because these miniature launchers could be air launched from a much-smaller aircraft than is required for full-size Pegasus and Pegasus ELVs carrying 700-lb (318-kg) and 1015-lb (461-kg) payloads, respectively.

The half-size Taurus, weighing about 20,000 lb (9080 kg) would be capable of placing a 317.5-lb (144-kg) payload in LEO. This capability is sufficient for incorporation of a miniature ARV, patterned after a 1/20th-size Space Shuttle Orbiter, into the final stage of the miniature launcher (see Fig. 1). This size of ARV has a payload bay measuring 9×36 in. (23×91 cm) and is the same as that proposed for recovery of the avionics modules of the full-size Pegasus and Taurus ELVs. Such an ARV weighing about 300 lb (136 kg) (fully loaded with avionics and cold-gas propellant) would have a planform loading about 60% of that for the full-size Orbiter. The lower planform loading would provide a reduction in aerodynamic heating (from that experienced by Space Shuttle Orbiters) during entry into the atmosphere and yet would be high enough to give acceptable sensitivity to cross winds and gusts. All things considered, there is probably no better shape for an ARV than that of the Space Shuttle Orbiter. Moreover, this highly evolved design has been extensively tested, and its flight charateristics are very well documented. With the exception of determining some relatively minor Reynolds-number or scale effects, there is probably no need for further wind-tunnel tests. An interesting possibility is that of incorporating a Williams WJ119 integrated propulsion module (IPM) into the design of an ARV to facilitate reaching the desired landing site. This IPM only weighs 33.5 lb (15.2 kg) with fuel and contains a miniature turbojet engine that produces 100 lb (445 N) of thrust.

Conclusions

Miniature launch vehicles for very small payloads can be nominally sized by scaling down existing small ELVs. Because, in general, conventional INS avionics plus ACS in the final stage cannot be appreciably downsized, the payload capability of the scaled-down vehicle may have to be reduced to compensate. In any case, the weight of avionics is a critical factor in minimizing the size of miniature launcher for a given weight of payload. If the avionics-plus-ACS weight is considered fixed at 80 lb (36 kg), the payload capability (to first order) of half-size Pegasus and Pegasus XL ELVs is very small. For air launch to LEO, a half-size Pegasus weighing 5250 lb (2384 kg) can only deliver a 17.5-lb (7.9-kg) payload, whereas a half-size Pegasus XL weighing 6500 lb (2951 kg) can only deliver a 56.9-lb (25.8-kg) payload. However, development of lighter and less-costly avionics using GPS could increase the payload capability of each launcher by up to 50 lb (23 kg) and substantially lower specific launch costs.

For ground launch to LEO, a half-size Taurus weighing 20,000 lb (9080 kg) can ideally deliver a 100-lb (45-kg) payload plus an ARV weighing nearly 300 lb (136 kg) (fully loaded with avionics and cold-gas propellant). A suitable type of autonomous ARV would be that of a small, winged spacecraft, resembling a 1/20th-size Space Shuttle Orbiter, having an inert weight of about 210 lb (95 kg) and shared avionics with the miniature launcher. Development of lighter, dual-purpose avionics would allow such an ARV to be equipped with a miniature turbojet engine that would facilitate recovery. The resulting launch system with a returnable ARV could have broad application in providing cost-effective delivery of very small payloads to and from orbit.

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