A Conceptual Framework for the Design and Fabrication of a Segmented, Sequential-Release Propulsion System

Section 1: The Physics of a Staged-Energy Slingshot

1.1. Deconstructing the Concept: An Initial Energy Flow Analysis

The proposed device represents a novel approach to mechanical propulsion, fundamentally operating as a sophisticated energy conversion system. The core principle is to store a significant quantity of mechanical energy within a highly tensioned elastomeric element and then release this energy in a controlled, staged sequence to accelerate a payload. The energy pathway begins with the application of external work to stretch the elastomer, converting mechanical work into stored elastic potential energy. Upon activation, a sequential release mechanism, described as a "domino effect," initiates a cascade of events. Each event involves the release of a segment of the device's jacket, which in turn releases a corresponding fraction of the total stored energy. This released potential energy is then converted into kinetic energy, manifesting as the rapid ejection of the segment's mass and the simultaneous acceleration of the primary payload.

Unlike a conventional slingshot, which releases its entire store of energy in a single, powerful impulse, this segmented system divides the total energy into a series of smaller, discrete packets. The release of these packets occurs sequentially over a very short duration. This method has profound implications for the system's dynamics. The acceleration profile of the payload is not a single, instantaneous spike but rather a series of rapid, successive accelerations. This concept shares a closer analogy with a multi-stage rocket than a simple catapult. In rocketry, staging is used to shed inert mass (the empty fuel tanks of a previous stage) so that the remaining thrust accelerates a lighter vehicle, resulting in a greater final velocity.[1] Similarly, the sequential ejection of the jacket segments continuously reduces the total mass that the remaining stored energy must accelerate, suggesting a potential for higher performance and a more complex, time-dependent acceleration profile. The central engineering challenge, therefore, lies not only in maximizing the total stored energy but also in precisely controlling the rate and timing of its release to optimize the final velocity of the payload.

1.2. The Engine of the Device: Elastic Potential Energy

The energetic heart of this propulsion system is the stored elastic potential energy within the deformed rubber element. The principles governing this energy storage are rooted in fundamental mechanics, beginning with Hooke's Law. For many elastic materials, including the rubbers and elastomers under consideration, the force required to stretch or compress them is directly proportional to the distance of that deformation. This linear relationship is described by Hooke's Law.[2] Mathematically, the law is stated as:

$F=-kx$

Here, 'F' represents the restoring force exerted by the elastic material, which acts in the direction opposite to the deformation. The variable 'x' is the displacement or deformation from the material's natural, equilibrium length. The term 'k' is the force constant, often called the spring constant, which is a measure of the material's stiffness; a higher 'k' value indicates a stiffer material that requires more force to stretch by a given amount.[3] The negative sign is a crucial convention, indicating that the restoring force always seeks to return the material to its equilibrium state.[5] To stretch the material, an applied force, 'Fapp', equal in magnitude and opposite in direction to the restoring force must be exerted, such that 'Fapp=kx'.[2]

The work done to stretch this elastic material is stored within its molecular structure as elastic potential energy ('PEel'). This work can be calculated by finding the area under the curve of a force-versus-displacement graph. Since the applied force increases linearly from 0 to 'kx' over the distance 'x', the graph is a triangle.[3] The area of this triangle, and thus the stored potential energy, is given by the foundational equation:

PEel=21kx2

This equation is central to the entire design of the propulsion system.[2] It reveals that the amount of energy stored is dependent on two key parameters: the stiffness of the elastomer ('k') and, more significantly, the distance it is stretched ('x'). The quadratic dependence on the stretch distance is a powerful design lever; doubling the elongation of the elastomer quadruples the amount of stored energy. This mathematical reality dictates that the most effective strategy for maximizing the system's power is to prioritize a mechanical design that accommodates the longest possible stretch of the chosen elastomer. The proposed segmented jacket, which allows a very long, continuous piece of rubber to be constrained, is an inherently sound approach to maximizing this critical 'x' variable.

1.3. The Launch: Conversion to Kinetic Energy

The launch phase of the device is governed by one of the most fundamental principles in physics: the conservation of energy. In an idealized system, free from frictional losses or material inefficiencies, the total elastic potential energy stored within the elastomer is converted entirely into kinetic energy ('KE')—the energy of motion.[3]

The kinetic energy of a moving object is defined by the equation:

KE=21mv2
In this expression, 'm' is the mass of the object being accelerated, and 'v' is its final velocity. By equating the stored potential energy with the resulting kinetic energy, we can establish a direct relationship between the system's parameters and its performance:

PEel=KE
21kx2=21mv2
This equation can be rearranged to solve for the velocity, providing a theoretical maximum for the speed the system can impart to its payload:

v=mkx2
This relationship provides the baseline for all performance calculations and highlights the primary factors influencing the final velocity. Performance is enhanced by increasing the elastomer's stiffness ('k') and, most effectively, by increasing its total stretch ('x'). Conversely, the final velocity is inversely proportional to the square root of the mass being accelerated ('m'). This inverse relationship with mass introduces a critical design conflict. The very segments of the jacket that are essential for containing the high-tension elastomer and enabling a large 'x' also contribute to the total mass 'm' that must be accelerated. This parasitic mass is detrimental to the final velocity of the payload bucket.

This conflict underscores the ingenuity of the sequential release concept. By ejecting the segments as part of the launch process, the system actively sheds mass. The total mass 'm' in the velocity equation is not a constant; it decreases with each successive stage of the release. The energy released from the final segments acts on a significantly lighter object (the payload plus only the few remaining segments) than the energy from the initial segments. This dynamic of a variable-mass system, which will be explored in greater detail in Section 4.4, is the key to achieving a higher terminal velocity than would be possible if the entire jacket were retained throughout the launch.

1.4. Real-World Considerations: Inefficiency and Energy Loss

The ideal conversion of potential to kinetic energy provides a theoretical maximum, but in any real-world mechanical system, energy losses are inevitable, reducing the overall efficiency. For this device, the primary source of inefficiency within the elastomer itself is a phenomenon known as hysteresis.[6]

Unlike an ideal "Hookean" spring, real elastomers like rubber do not follow the exact same force-displacement path during relaxation as they do during stretching. When plotting stress versus strain, the unloading curve falls below the loading curve, forming a closed loop. The area enclosed by this hysteresis loop represents mechanical energy that is converted into thermal energy and dissipated as heat within the material during a stretch-release cycle.[6] This means that not all of the work done to stretch the rubber is returned as mechanical energy upon release. The actual kinetic energy imparted will be a fraction of the initially stored potential energy, a fraction determined by the material's efficiency. The performance equation must therefore be modified with an efficiency factor, '

η' (eta), where '$\eta<1$':

$KE=\eta\cdot PEel$
This introduces a crucial, third-order consideration for material selection. An elastomer is not only defined by its strength and elasticity but also by its energy return efficiency. A material that can store immense energy is of limited use if it dissipates a large percentage of that energy as heat.

Other energy loss pathways will further reduce the system's efficiency. These include friction within the interlocking and release mechanisms of the segments, the energy converted into sound and vibration upon release, and the work done against air resistance by the rapidly ejecting segments and the payload itself.[2] Furthermore, a portion of the stored potential energy is converted into the kinetic energy of the retracting elastomer itself. The rubber bands have mass, and as they snap back, they acquire velocity, consuming some of the energy that would otherwise accelerate the payload. This effect is particularly significant when the projectile's mass is comparable to the mass of the elastic bands.[13] A comprehensive design must account for these losses to produce a realistic performance prediction.

Section 2: The Heart of the Machine: Selecting the

High-Strain Elastomer

2.1. Defining Performance: A Lexicon of Elastomer Properties

The selection of the core elastomeric element is paramount to the success of the propulsion system. This choice must be guided by a clear understanding of the material properties that define its performance. The following key metrics provide a lexicon for evaluating and comparing candidate materials.

Tensile Strength, also known as Ultimate Tensile Strength (UTS), is the maximum stress a material can withstand while being stretched before it breaks or ruptures.[14] It represents the fundamental limit of the force that can be applied to the elastomer and, by extension, the maximum energy that can be stored. Materials like natural rubber are known for their very high tensile strength, making them excellent candidates for high-load applications.[16]

Ultimate Elongation, or elongation at break, measures the maximum strain a material can endure before failing, expressed as a percentage of its original length.[15] This property directly corresponds to the maximum achievable stretch distance, the '

x' term in the potential energy equation. While many elastomers can stretch to several hundred percent of their original length, specialized materials such as certain high-elongation silicones can achieve extraordinary values, in some cases reaching 4,000% to 6,000%.[17]

Modulus of Elasticity is a measure of a material's stiffness. It quantifies the relationship between stress (force per unit area) and strain (proportional deformation).[11] A material with a high modulus is stiff, requiring a large force to produce a small amount of stretch, and corresponds to a high force constant '

k'. A low-modulus material is more pliable and stretches easily.

Hardness is the material's resistance to localized surface indentation. It is commonly measured on a durometer scale (e.g., Shore A).[11] While hardness often correlates with a higher modulus, they are distinct properties measuring different aspects of the material's response to force.[16]

Tear Resistance describes the elastomer's ability to resist the propagation of a cut, nick, or tear when under tension.[16] This is a critical property for system reliability, as any small surface flaw in a highly tensioned band could lead to catastrophic failure if the tear resistance is low.

Standard silicone, for instance, is known for its poor tear resistance, while natural rubber and neoprene are significantly more robust.[16]

These properties are not independent and often involve design trade-offs. A material with an exceptionally high ultimate elongation might have a low modulus, limiting the amount of energy it can store per unit of stretch. Conversely, a very stiff, high-modulus material may not be able to achieve significant elongation before reaching its breaking point. The ideal elastomer for this application will not necessarily be the one that is highest on any single metric, but rather one that offers an optimal combination of high tensile strength and high ultimate elongation. This combination maximizes the area under the stress-strain curve, which is representative of the material's strain energy density—the total energy it can store per unit volume.[6]

2.2. The High-Altitude Imperative: Material Performance in Extreme Cold

The operational environment of a high-altitude weather balloon imposes a severe and non-negotiable constraint on material selection. As the balloon ascends, it will encounter temperatures that can plummet to -60°C (-76°F) or even lower.[18] This extreme cold can have a catastrophic effect on the mechanical properties of most standard elastomers.

The critical concept governing this behavior is the **Glass Transition Temperature** ('Tg'). As an elastomer is cooled, its long-chain polymer molecules lose mobility. The material becomes progressively stiffer and less elastic until it reaches its 'Tg'. At this temperature, the material undergoes a reversible phase transition from a rubbery, flexible state to a hard, brittle, glass-like solid.[19] An elastomer operating at or below its '

Tg' loses its ability to store and release energy elastically. If the release mechanism were triggered in this state, the elastomer would not contract; it would shatter, causing total system failure.

This environmental requirement immediately filters out a large number of otherwise suitable materials. Many common industrial elastomers, such as standard grades of Nitrile (NBR), Fluorocarbon (FKM), and Natural Rubber, have minimum operating temperatures that are well above the expected conditions at altitude.[20] For example, while natural rubber possesses excellent mechanical properties at room temperature, its typical minimum service temperature of around -32°C makes it unsuitable for this mission.[21]

This forces the design to focus exclusively on specialized elastomers engineered for low-temperature and cryogenic applications. The selection process is thus a search for a material that not only meets the demanding mechanical requirements for energy storage but also retains its essential rubber-like properties in the extreme cold of the upper atmosphere. This creates a significant engineering challenge, as materials optimized for low-temperature performance often compromise on properties like tensile strength and tear resistance, which are critical for maximizing the system's power.

2.3. A Comparative Evaluation of Elastomer Candidates

With the low-temperature requirement acting as a primary filter, the selection process narrows to a few classes of specialized elastomers. A comparative evaluation reveals a series of trade-offs between environmental survivability and mechanical performance.

Ethylene Propylene Diene Monomer (EPDM) is a strong contender due to its excellent resistance to environmental factors. It performs exceptionally well against ozone and ultraviolet (UV) radiation, both of which are significantly more intense at high altitudes.[16] Its low-temperature capability, with some grades rated down to -60°C, places it at the edge of viability for the mission profile.[19] While its tensile strength is generally good, it does not typically match that of high-performance natural rubber compounds.[16]

Silicone (VMQ) stands out for its superior performance in extreme cold. Standard silicone grades can remain flexible down to approximately -73°C, and specialized formulations, often marketed as "Extreme Low Temperature Silicone," can function at an astonishing -100°C (-148°F) or below.[18] This provides a significant margin of safety for high-altitude operations. However, this exceptional thermal stability comes at a cost. Standard silicones exhibit relatively low tensile strength and, most critically, very poor tear resistance.[16] This makes them vulnerable to failure if any microscopic flaws are present on the surface of the highly tensioned band.

Fluorosilicone (FVMQ) is a premium variant of silicone that incorporates fluorine into its polymer structure. This modification enhances its resistance to fuels and chemicals while retaining excellent low-temperature flexibility, typically down to around -55°C.[19] It represents a potential compromise, offering a balance of properties, though at a higher cost than standard silicone or EPDM.

Specialty Low-Temperature Compounds (HNBR, FFKM) represent the highest tier of performance and cost. Manufacturers have developed specific grades of Hydrogenated Nitrile (HNBR) and Perfluoroelastomer (FFKM), such as the Perlast® ICE range, that are explicitly engineered for sealing applications in extreme cold. These materials can operate at temperatures down to -55°C and -46°C, respectively, while offering mechanical properties (like abrasion and tear resistance) that are far superior to those of silicones.[19] These would provide the most robust solution but may be prohibitively expensive for an amateur project.

The final selection involves a critical trade-off analysis. For a ground-based, proof-of-concept prototype where maximum performance is the goal, a high-elongation grade of Natural Rubber or NBR would be the logical choice to maximize stored energy.[22] However, for the actual flight unit, mission survival is the priority. This necessitates the use of a material like Extreme Low-Temperature Silicone or a specialty FFKM, even if it results in a lower total energy capacity. The engineering design of the jacket and its internal channel must be robust enough to accommodate this potential change in material, perhaps by allowing for a thicker band of a lower-strength, cold-resistant elastomer to be used to achieve the target energy storage.

2.4. The Stretch-to-Thickness Ratio and Hyperelasticity

The behavior of elastomers under the extreme deformation required for this application goes beyond simple linear elasticity and enters the realm of hyperelasticity.[23] A key characteristic of most rubber-like materials is that they are nearly incompressible, meaning their total volume remains almost constant even when they are stretched to many times their original length. This property is quantified by

Poisson's ratio, which for rubber is approximately 0.5.[25]

This incompressibility has a direct and significant geometric consequence. As the elastomer is stretched along its length, it must contract proportionally in its other two dimensions—width and thickness. The relationship for this contraction is dramatic. For a uniaxial stretch, the stretch ratio in the thickness direction ('λ3') is related to the stretch ratio in the length direction ('λ') by the formula 'λ3=λ−2'.[26] This means that if the rubber is stretched to five times its original length ('

λ=5'), its thickness will shrink to '1/52', or 1/25th of its original thickness.

This profound thinning under high strain has crucial implications for the mechanical design of the segmented jacket. The internal channel that houses the elastomer cannot be a simple, constant-diameter bore. It must be designed to accommodate the much thicker, relaxed cross-section of the rubber during the difficult and potentially hazardous assembly process, while also properly constraining the very thin, taut band when the system is under full tension. If the channel is too large, the tensioned band could vibrate or shift, leading to inconsistent force application.

Furthermore, this thinning effect identifies the transition points between adjacent segments as areas of high potential risk. The edge of a segment's internal channel could act as a stress concentration point, potentially cutting or abrading the highly tensioned and significantly thinned elastomer. This necessitates that the internal design of the segments, particularly at their ends, must feature smooth, generously rounded surfaces to protect the integrity of the energy storage element itself.

Section 3: Engineering the Casing: Segment and Joint Design

3.1. Anatomy of a Segment

Each six-inch segment of the jacket serves as a discrete structural unit responsible for containing a portion of the total stored energy. The design of a single segment must satisfy several competing functional requirements. First, it must be a two-part, or "clamshell," assembly. This is essential to allow the continuous elastomeric element to be laid in place before the segment is closed and secured around it. Second, this assembly must incorporate a robust interlocking and latching mechanism. This mechanism is the most critical feature, as it must reliably withstand the continuous, high tensile force exerted by the stretched elastomer without failing or deforming over time. Third, the exterior of the segment must feature a trigger surface or mechanism that allows its release to be initiated by the action of the preceding segment in the cascade. Finally, the entire segment must be designed for manufacturability using accessible rapid prototyping methods, such as 3D printing for initial models and CNC machining for high-strength functional parts.[27]

The internal geometry of the segment requires careful consideration. As established by the principles of hyperelasticity, the elastomer will be significantly thicker when relaxed than when under full tension. The internal channel must therefore be shaped to accommodate both states, providing a secure fit without causing abrasion or stress concentrations, especially at the points where the elastomer enters and exits the segment.[26] This complex set of requirements—high strength, low weight, a reliable release mechanism, and manufacturability—suggests that the optimal design will be one that cleverly uses geometry to achieve its function, rather than relying on brute-force mass. Techniques such as Finite Element Analysis (FEA) will be invaluable for optimizing the shape of the segment, ensuring material is placed only where stresses are highest to create a structure that is both strong and lightweight.[29]

3.2. A Parallel Evaluation of Interlocking Mechanisms

The choice of how the two halves of each segment are joined and held under tension is a fundamental design decision that will influence the entire system's architecture and reliability. Two primary design philosophies present themselves: a highly integrated approach using snap-fit joints, and a more traditional approach using discrete high-tension latching hardware.

Path A: The Snap-Fit Joint

A snap-fit joint is an elegant solution where the fastening mechanism is integrated directly into the geometry of the part itself, eliminating the need for separate hardware and simplifying assembly.[30] The most suitable type for this application is the

cantilever snap-fit, which consists of a protruding beam with a hook or lip that deflects during assembly and "snaps" into a corresponding recess on the mating part.[31]

The design of a functional cantilever snap-fit is not arbitrary; it is an engineering calculation based on material properties and geometry. The **Maximum Allowable Deflection ('Y')** determines how far the cantilever arm can bend without undergoing permanent deformation or fracture. It is a function of the material's maximum permissible strain ('ϵ'), the length of the beam ('L'), and its thickness ('H').[33] The

Snap Deflection Force ('P') is the force required to achieve this deflection during assembly and is dependent on the beam's geometry and the material's modulus of elasticity ('E').[33]

For this application, the most critical parameter is the **Retention Force**, which is the force required to pull the engaged snap-fit apart. This force must be carefully engineered: it needs to be substantially greater than the tensile force exerted by the contained section of the elastomer to prevent spontaneous disassembly, yet low enough that it can be overcome by the trigger action from the preceding segment. To ensure the durability and reliability of the snap-fit, designers must adhere to best practices, such as incorporating generous **fillets** at the root of the cantilever beam to mitigate stress concentration and using a **tapered beam** (thicker at the base) to distribute stress more evenly along its length.[30]

Path B: The High-Tension Latch

An alternative path involves the use of discrete, off-the-shelf mechanical latches. While this approach adds mass, complexity, and part count, it allows for the use of components made from high-strength metals that are pre-rated for significant loads, potentially offering higher reliability than an integrated plastic feature.

One suitable category is the **Draw Latch**, also known as a toggle latch. These devices use an over-center linkage mechanism to pull two surfaces together and secure them under high tension. Their mechanical advantage allows them to be closed easily while providing a very strong and vibration-resistant connection, making them ideal for securing panels on industrial equipment.[34]

Another highly relevant category is the **Tension Shear Latch**. These are specialized fasteners developed for the aerospace industry, specifically for securing stressed panels like engine cowlings and radomes.[37] They are designed to handle a combination of both tension (pulling apart) and shear (sliding) loads within a very compact and low-profile envelope, making them an excellent candidate for this high-performance application.[37]

The choice between these two paths is a trade-off between integration and robustness. The snap-fit design is more elegant and better suited to streamlined manufacturing via injection molding, but its performance is limited by the properties of the chosen plastic. The discrete latch design is heavier and more complex to assemble but offers the high, verifiable strength of metal components. This choice also has a cascading effect on the design of the sequential release mechanism, as an impact trigger suitable for a snap-fit would be different from the mechanism needed to actuate the handle of a draw latch.

3.3. Segment Material Selection

The material chosen for the rigid segments must be compatible with the selected interlocking mechanism and the harsh operational environment.

For designs based on the integrated **snap-fit joint**, engineering-grade thermoplastics are the natural choice. The function of the snap-fit relies on the material's ability to flex elastically. Materials like **Polycarbonate (PC)** are excellent candidates due to their exceptional impact strength and toughness, even at low temperatures. **Acrylonitrile Butadiene Styrene (ABS)** is another versatile and affordable option with good impact resistance, while **Nylon** offers high strength, durability, and a naturally low coefficient of friction, which could reduce the force needed for assembly and release.[32]

For designs utilizing **high-tension discrete latches**, the segments themselves would primarily serve a structural role, requiring high stiffness and strength rather than flexibility. In this case, lightweight metals such as **aluminum alloys** are superior. Grades like 6061 or 7075 offer an outstanding strength-to-weight ratio and can be precisely fabricated using CNC machining to create strong, rigid, and lightweight segment halves.[38]

A critical consideration that applies to plastic segments, particularly those with snap-fit features, is their performance in extreme cold. Just as elastomers have a glass transition temperature, many plastics have a ductile-to-brittle transition temperature. A snap-fit arm that is flexible and robust at room temperature could become brittle and fracture upon actuation at the -50°C to -60°C temperatures expected at high altitude. Therefore, the material selection process must include a thorough evaluation of low-temperature mechanical properties to ensure the release mechanism remains functional throughout the entire mission profile.

Section 4: The "Domino Effect": Designing the Sequential Release Cascade

4.1. Principles of Sequential and Cascade Systems

The core innovation of the proposed device is its sequential, "domino effect" release. This mechanism is a form of **cascade reaction**, a term used in chemistry and engineering to describe a series of events where each step is triggered by the completion of the preceding one.[39] The entire process is a pre-programmed chain reaction initiated by a single input.

Conceptually, such systems are most famously illustrated by **Rube Goldberg machines**, which are intentionally over-complicated contraptions that use a chain of simple mechanical interactions—levers, rolling balls, falling weights—to perform a simple final task.[42] While designed for amusement, they are excellent demonstrations of the principles of propagating a mechanical action through a series of discrete stages.

In a more engineered context, the principles of reliable sequential action can be found in systems like **sequential manual transmissions**, where a ratchet mechanism ensures that gears can only be selected in a successive order [45], or the

mechanical trip mechanisms in electrical circuit breakers, where a small trigger releases a much more powerful spring-loaded mechanism to open the circuit.[46]

The primary challenge in designing any cascade system is ensuring reliability. The failure of any single step in the chain results in the failure of the entire process. For the propulsion system, a segment failing to release would be catastrophic, leaving a significant dead weight attached to the payload and likely inducing a dangerous off-axis thrust or tumble. To ensure the cascade propagates successfully from the first segment to the last, the triggering action between segments must be robust and have a large margin of error. The energy delivered by the release of one segment must be significantly greater than the energy required to trigger the release of the next. This "energy margin" is the key to designing a reliable sequential release.

4.2. The Initiator: Trigger Design Concepts

The entire cascade begins with a single activation event from the "pin of sorts." The design of this initial trigger must be tailored to the mission's operational requirements and the high forces involved.

A **simple mechanical pin** that is manually pulled to release the first segment is a straightforward solution suitable for ground testing. However, under the high tension of the fully loaded system, the frictional forces acting on such a pin could be immense, potentially requiring a large and impractical amount of force to withdraw it.[49]

A more robust solution would be to employ an off-the-shelf **high-load quick-release mechanism**. Components such as **quick-release shackles**, commonly used in marine and rigging applications, are designed to reliably release loads of thousands of pounds with a simple pull on a lanyard or pin.[50] Similarly, high-strength

quarter-turn fasteners are available that can sustain high tensile loads while being actuated with a simple 90-degree rotation.[53] These components offer proven reliability under load.

However, the context of a weather balloon mission, which implies autonomous operation at a specific altitude, strongly favors an **electromechanical actuator**. A device such as a solenoid or a pyrotechnic pin-puller can be triggered by an electrical signal from an onboard flight controller. This allows for precise, automated activation based on sensor data (e.g., an altimeter reaching a target altitude), which is impossible with a purely mechanical trigger. This makes an electromechanical initiator the most viable option for the final flight-ready design.

4.3. Propagating the Release Wave: Parallel Concepts

The method by which the release of one segment triggers the next is the most innovative and critical mechanical system to be designed. Two distinct conceptual paths can be evaluated for propagating this release wave down the length of the jacket.

Concept A: The Mechanical Impact Cascade

In this concept, the propagation relies on direct kinetic energy transfer. As the two halves of a released segment are thrown outwards by the contracting elastomer, a feature on one or both halves is designed to physically strike the trigger point of the subsequent segment. This trigger point could be the cantilever arm of a snap-fit joint or the release lever of a discrete latch. The system operates like a linear series of mousetraps, where the bar of one triggers the next. The design of this interaction would need to be precise to ensure the impact is delivered to the correct location with sufficient force to guarantee actuation. The speed of the cascade would be limited by the time it takes for the ejected segment half to travel the distance to the next trigger point.

Concept B: The Tension-Release Cascade

This alternative concept uses the primary tensile force of the elastomer itself to propagate the release. In this design, a short, non-elastic lanyard or wire connects the body of one segment (e.g., segment 'n') to the release mechanism (e.g., a release pin) of the next segment in the series (segment 'n+1'). When segment 'n' is released, the main elastomer begins to contract, pulling segment 'n' rapidly away from segment 'n+1'. This motion pulls the connecting lanyard taut, which in turn yanks the release pin of segment 'n+1', triggering its release. This creates a self-propagating chain reaction where the release of tension in one section directly causes the release of the next. This is analogous to staged deployment systems used in aerospace, where the separation of one component initiates the deployment of another.[54]

A comparative analysis suggests that the Tension-Release Cascade is the more robust and reliable engineering solution. The Mechanical Impact Cascade relies on a secondary, less controlled event—the trajectory of a flying part—to function. It is susceptible to failure from misalignment or insufficient impact energy. In contrast, the Tension-Release Cascade uses the immense and reliable primary force of the contracting elastomer to guarantee actuation of the next stage. This direct coupling of the main energy source to the propagation mechanism makes it an inherently more positive and dependable system. Its propagation speed would also likely be much faster, limited only by the speed of the contraction wave in the elastomer.

4.4. Dynamics of a Variable Mass System

The launch event, as segments are sequentially ejected, is a classic physics problem involving a **variable mass system**.[55] The total mass being accelerated by the elastomer is not constant but decreases over time. This is directly analogous to a rocket, which becomes lighter as it expels propellant mass.

The standard form of Newton's second law, 'F=ma', is insufficient for this scenario. The more general form, which states that force is equal to the rate of change of momentum ('p=mv'), must be used:

F=dtdp=dtd(mv)
The consequence of this is that the acceleration of the payload is not constant, even if the force from the elastomer were constant. As each segment is ejected, the total mass ('Mtotal') of the remaining assembly (payload + unreleased segments) decreases. Therefore, the force from the remaining stored energy produces a progressively greater acceleration on the now-lighter system. The contribution to the payload's final velocity (its "delta-v") from the release of the last segment will be greater than the contribution from the first segment, because the last segment's energy is accelerating the least amount of mass—only the payload itself. This principle is precisely why multi-stage rockets are used to achieve high orbital velocities; they shed unnecessary structural mass at each stage to maximize the efficiency of the subsequent stages.[1]

This dynamic suggests a potential avenue for design optimization. If the later stages of the release are more effective at accelerating the payload, the system could be designed non-uniformly to capitalize on this effect. For example, the segments closer to the payload could be designed to be significantly lighter than the segments at the start of the chain. This would further reduce the mass being accelerated during the most critical final phase of the launch, potentially yielding a higher terminal velocity for the same total initial system mass.

Section 5: A Practical Path to Fabrication

5.1. A Phased Prototyping Strategy

Bringing a complex mechanical concept from idea to reality requires a structured and iterative development process. A phased prototyping strategy is essential for managing complexity, identifying design flaws early, and minimizing cost and risk.

The first phase should focus on creating **"looks-like" prototypes**. These are non-functional, geometrically accurate models of the segments. Their purpose is to validate the basic form, ensure the two halves fit together correctly, and test the ergonomics of assembly. These models are invaluable for identifying gross geometric errors before any functional testing is attempted. Given their focus on shape over strength, they are ideally suited for rapid fabrication using low-cost 3D printing methods.[28]

The second phase involves building **"works-like" prototypes**. These are functional models designed to test the core mechanisms of the device. Initial works-like prototypes might consist of just a single segment to validate the strength and reliability of the interlocking latch under a representative tensile load. Once the single-segment design is proven, a small, multi-segment prototype (e.g., three segments) should be built to test and validate the cascade propagation mechanism. These prototypes must be fabricated from materials that can withstand the operational forces, which may necessitate moving from basic 3D printing to more robust materials and methods.[28]

The final phase is the development of a full-scale, **integrated system prototype**. This is the flight-ready version of the device, built from the final selected materials and incorporating all necessary components. This prototype would be used for comprehensive performance testing to measure the actual payload velocity, as well as for environmental qualification, such as testing the release mechanism's reliability in a cold chamber that simulates high-altitude temperatures.

A critical and often overlooked aspect of the fabrication process will be the development of a safe and repeatable method for assembling the device. The high-strain elastomer must be stretched and held under immense tension while the segments are closed and latched around it. Attempting this manually would be both extremely difficult and highly dangerous. Therefore, a parallel engineering task is the design and construction of a dedicated **stretching and assembly jig**. This piece of ground support equipment would use a mechanical advantage, such as a winch or screw drive, to safely stretch the elastomer to the required length and hold it securely in place, allowing for the controlled and safe assembly of the segments.

5.2. A Guide to Prototyping Methods

Modern rapid prototyping offers several powerful tools for fabricating the components of this system. The optimal approach will likely involve a combination of different methods at different stages of development.

Additive Manufacturing, more commonly known as 3D printing, is the ideal technology for the early prototyping phases. Processes like Fused Deposition Modeling (FDM), which extrudes thermoplastic filament, or Selective Laser Sintering (SLS), which fuses powdered material, excel at producing parts with high geometric complexity at a relatively low cost and with a very short turnaround time.[28] This allows for rapid design iteration. If a snap-fit design doesn't work, it can be modified in the CAD model and a new version can be printed and tested within hours or days. 3D printing can be used with a variety of engineering-grade plastics, including ABS, Nylon, and Polycarbonate, making it suitable for initial functional prototypes as well as looks-like models.

Subtractive Manufacturing, primarily **Computer Numerical Control (CNC) machining**, is the essential technology for producing the final, high-strength, high-precision components for the functional and flight-ready prototypes.[27] CNC machining works by starting with a solid block of material (such as an engineering plastic or an aluminum alloy) and using computer-controlled cutting tools to remove material until the final part shape is achieved.[38] This process produces parts with superior strength, dimensional accuracy, and surface finish compared to 3D printing. The resulting components have isotropic (uniform in all directions) material properties, making their performance under load highly predictable and reliable. While more expensive and time-consuming than 3D printing, CNC machining is necessary to create components that can safely and repeatedly withstand the high tensile forces of the final design.

These two methods should be viewed not as competing alternatives but as complementary tools in a phased development workflow. 3D printing should be used to "fail fast and cheap," allowing for extensive iteration to perfect the complex geometry of the segments and their release mechanisms. Once the design's geometry is validated, CNC machining should be used to fabricate that same design from a high-performance material to validate its structural integrity and performance under full operational loads.

Section 6: Mission Context: Integration with an

Amateur Weather Balloon

6.1. The Governing Rules: FAA Part 101 for Unmanned Free Balloons

The intended application of this propulsion system—as a payload for an amateur weather balloon—places it under the jurisdiction of the U.S. Federal Aviation Administration (FAA). The operation of such balloons is governed by Title 14, Part 101 of the Code of Federal Regulations.[57] These regulations are not suggestions; they are legal requirements that establish hard, non-negotiable constraints on the design.

The most critical of these constraints are the **payload weight limits**. According to Part 101, an unmanned free balloon is exempt from many of the more stringent regulations if its payload meets specific criteria. The key rule for this project is that if the balloon carries a single payload package, that package must not weigh more than six pounds (approximately 2.7 kg). If it carries two or more packages, their combined total weight must not exceed 12 pounds.[58] For the purposes of regulation, the entire propulsion system—including the payload bucket, the elastomer, and all of the jacket segments—would almost certainly be considered a single "payload package." Therefore, the

6-pound weight limit is the absolute maximum allowable mass for the entire device.

Another important rule is the **weight-to-area ratio**. If a payload package weighs more than four pounds, the ratio of its weight in ounces to the area of its smallest face in square inches must not exceed three. This rule is designed to ensure that the object has sufficient drag to slow its descent after the balloon bursts, minimizing its impact energy on the ground.[59]

In addition to these physical constraints, there are operational rules that must be followed. The launch cannot take place over a congested area, and the nearest Air Traffic Control (ATC) facility must be notified between 6 and 24 hours prior to the planned launch.[57] There are also weather-related restrictions, such as a requirement for less than 50% cloud cover and a minimum horizontal visibility of five miles for flights below 60,000 feet.[57]

6.2. Design for Compliance: A Concluding Analysis

The 6-pound payload weight limit imposed by FAA Part 101 is the single most dominant design driver for this project. It overrides nearly every other consideration and forces a rigorous and unforgiving optimization of every component for minimum mass. This regulatory constraint creates a direct and unbreakable link back to the fundamental physics equations that govern the system's performance.

The goal is to maximize the final velocity, 'v=η·kx2/m', under the absolute constraint that the initial mass of the system, 'minitial', must be less than or equal to 6 pounds. The initial mass is the sum of the payload mass, the elastomer mass, and the total jacket mass ('mjacket=n·msegment', where 'n' is the number of segments and 'msegment' is the mass of a single segment). This creates a complex optimization problem. To increase the stored energy, one must increase the total stretch 'x', which generally requires increasing the number of segments 'n'. However, increasing 'n' directly increases the total system mass. At some point, adding another segment will push the total mass over the 6-pound limit, making the design non-compliant. Furthermore, even before hitting the limit, every gram added to the jacket mass increases the 'm' term in the velocity equation, which actively works to reduce the final velocity.

Therefore, the entire design process must be an iterative loop of trade-offs. For a given material choice for the elastomer and the segments, one must calculate the mass of a single segment, determine the maximum number of segments that can be included while staying under the 6-pound budget (including the payload), calculate the total potential energy for that configuration, and then model the resulting launch velocity. This entire process must be repeated for different material and design combinations to find the single configuration that yields the absolute maximum velocity while remaining legally compliant.

Ultimately, the success of this project hinges on a holistic system optimization. A heavy, high-strength elastomer is useless if it consumes the entire mass budget, leaving no allowance for the jacket needed to contain it. A feather-light jacket is equally useless if it lacks the strength to withstand the required tension. The final, optimal design will be the one that finds the perfect balance point between maximizing energy storage capacity and minimizing system mass, all within the strict confines of the 6-pound regulatory ceiling. This implies that a crucial, and perhaps counter-intuitive, aspect of the launcher's design is the aggressive minimization of the mass of the *payload* it is intended to launch. Every gram saved in the scientific payload is a gram that can be reinvested into the propulsion system—allowing for a longer elastomer, an additional segment, or a stronger latch—directly translating into higher performance.

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