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Heat-activated Parachute Release System

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Abstract

Release of a parachute at the apex of a rocket flight is a problem for every amateur rocket enthusiast. Existing commercially available methods all require the use of gunpowder, which can have licensing and safety complications depending upon the local laws. Axiomatic design analysis has shown that there is also high information content in this method. Users must precisely calculate the amount of black gunpowder to be used based upon altitude and rocket geometry. At the highest altitudes, gunpowder combustion gases are insufficient due to the low ambient pressure, so CO_2 expansion actuation is used instead. These solutions using CO_2 have lower information content, but are still activated using gunpowder and dependent upon altitude. Our analysis has led to the technique of using heat-activated materials as a CO_2 valve release, a solution with lower information content. This design works with all sizes of amateur rockets up to Tripoli Rocketry Association Class 3 without knowledge of rocket apex altitude.

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Keywords: axiomatic design, parachute release, gunpowder

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1. Motivation

The recovery system of a rocket is the most essential part of it since all the effort put into the rocket and the gained knowledge of the mission is worthless if the rocket crashes, generally nothing can be reused or recovered. There various strategies to solve this problem, most commonly parachutes, but a perfect solution has not been found yet: the deployment of the parachute is still one of the most risky and uncertain stages in flight. In this project axiomatic design is used to develop a better parachute release system for a Tripoli Rocketry Association class three rocket[1]

2. Existing designs

So far the most common commercial parachute release mechanisms on the market for high-altitude amateur rockets are using either a spring mechanism or black powder activated mechanics that punch a pin into a CO_2 cartridge which blows the rocket into two components and pulls out a parachute. A € 1000 solution with springs is made by the company Fruity-Chutes. It consists of a pre-armed pin that is pulled back before flight and an electrical current releases the pin to puncture a CO_2 cartridge.[2] This system relies only on mechanical parts which need to withstand high acceleration forces in all directions, especially during launch. Also the low temperatures at high altitudes can cause problems for the springs. Overall these conditions lead to difficult predictions for the spring forces. To prevent this design from failure it requires a very high information content and therefore a high level of tolerance.

The same applies to the use of black powder activated CO_2. To ensure a safe and reliable release of the parachute precise calculations for the amount of powder used are needed since the force of the expanding gas is depends on altitude and climate. If too much powder is used or it explodes at a too low altitude, the parachute and rocket are likely to be damaged. If it is not enough powder or the ignition is at a too high altitude, the parachute will not deploy. This also constrains the rocket to reach a predefined altitude and affects the ability to try to reach an apex above or below the calculated altitude depending on the actual flight status. Additionally an explosive license is required in most continents to use black powder and is therefore not easily containable for the general public. A comparable black powder–CO_2system is the Peregrine IDS–4–72, also produced by Fruity Chutes [3] and is also sold for € 1000.

Reykjavík University has attempted to address this problem previously in [4]. Unfortunately, this Shape Memory Alloy (SMA) system was not able to reliably puncture the CO_2 canister due to the SMA actuator's large current draw.

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Nomenclature

CA_n	Customer Attribute *n*
FR_n	Functional Requirement *n*
DP_n	Design Parameter *n*
C_n	Constraint *n*
SMA	Shape Memory Alloy

3. Customer Direct Mapping

We first investigated the customer needs. Our potential customer Frank De Brouwer, CEO of Rebel Space[5] provided us with a detailed list of what he wanted in such a parachute release, which we annotated directly as Customer Attributes (CAs). We then created a mapping to Functional Requirements (FRs), then to Design Parameters (DPs), then a FR-DP design matrix[6]. Some CAs were clearly DPs, so they were merely propagated.

3.1. Directly mapped Customer Attributes (CAs)

CA_1 Price as cheap as possible but not that it downgrades the quality.

CA_2 Dimensions are based on a chamber with a length of 3000 mm and a diameter of 99 mm. (FR)

CA_3 Force between 1000 N and 1500 N to blow out the parachute, which is located in a middle section of the rocket, separating the rocket in the process.

CA_4 Withstand G's that can be as high as 10 G or more.

CA_5 Mechanism has to be reusable or reload-able.

CA_6 Flight altitudes are normally up to 50,000 feet, but can be as high as 150,000 feet.

CA_7 Only a CO_2 mechanism is accepted. No use of gunpowder nor springs.

CA_8 Use standard ♯84203*Z* CO_2 cartridges.

3.2. Directly mapped Functional Requirements (FRs)

To translate the customer needs into something the development of the product actually can be based on, the FRs are derived.

FR_1 Aiming for a price range under 100 Euro.

FR_2 System has to fit in a tube with a length of 3000 mm and a diameter of 99 mm.

FR_3 Release enough force to separate the rocket and blow out the parachute.

FR_4 Implement as few moving mechanical parts as possible to make it robust.

FR_5 Damage as few parts as possible in the activation process.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & X & X \\ 0 & 0 & X & 0 & 0 & 0 & X & X \\ 0 & 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & X & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 & X & X \\ 0 & X & X & 0 & 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \end{Bmatrix}$$

Fig. 1. Directly mapped design matrix

FR_6 System needs to work at temperatures down to −70 °C and 80 Pa pressure

FR_7 Mounting a compressed CO_2 cartridge on the system.

FR_8 Compatible with commercially available CO_2 cartridges.

3.3. Directly mapped Design Parameters (DPs)

Once FRs are in place, a proposed design emerges from the implementation details of the DPs.

DP_1 Using aluminum, plastics and simple geometries.

DP_2 Length of 400 mm and biggest diameter of 99 mm.

DP_3 Puncturing CO_2 cartridge with a needle, pressurizing chamber sealed with O-rings.

DP_4 Electrically heated coil softens thermo-plastic.

DP_5 CO_2 cartridge and plastic tablet with coil need to be replaced.

DP_6 O-rings made out of fluorosilicone (down to −100 °C).

DP_7 Mounting standard #84203*Z* CO_2 cartridges.

DP_8 Use standard #84203*Z* CO_2 cartridges.

The design is then examined for coupling between FRs and DPs in the design matrix. (Figure 1)

This mapping resulted in a coupled solution no matter how the arrangement, suggesting that the CNs needed to be revised: some were clearly duplications, constraints, or are not implementation agnostic. This initial, though flawed, process made it easier to understand how to proceed; the input information from the customer attributes was passed on to avoid loss of information. The next section details an improved set of requirements and design matrix.

4. Restructuring of Customer Attributes

We restart our design process by asking “What does the customer really want?” rather than “What did the customer ask for?” The customer in this case is an expert in the field, so this must be done very carefully. This expertise means that the needs were heavily solution-dependent; this must be sanitized to avoid that influence.

It is also clear that most of the FRs derived from the CAs were actually constraints because they do not impart functional needs, but rather boundaries for marketing the solution e.g. FR_1 (cost) must be converted to constraint C_1 to have the possibility of a decoupled or uncoupled solution. After focusing/sanitizing the needs, combining redundant requirements, and converting to constraints, these top level requirements are produced:

4.1. Top level (revised) requirements

CA_0 Release parachute from high altitude rocket using CO_2

FR_0 Release parachute from high altitude rocket using CO_2

DP_0 Temperature-actuated cap attached to pierced CO_2 cartridge

4.2. Revised Customer Attributes

CA_1 Unit is compatible with a 98 mm or larger diameter rocket.

CA_2 Separate rocket then release parachute when given electrical signal.

4.3. Constraints

- C_1 Price range under 100 Euro.
- C_2 Operate reliably at −70 °C and 80 Pa (Upper atmosphere)
    - $C_{2.1}$ No springs.
    - $C_{2.2}$ Fluorosilicone O-rings rated for −100 °C
- C_3 No pyrotechnical elements.
- C_4 Few mechanical parts
- C_5 Reusable (or re-loadable)
- C_6 Use internationally available CO_2 canisters

4.4. Revised Functional Requirements

- FR_1 Mount in 98 mm or larger rocket middle section
- FR_2 Push parachute out of rocket
    - $FR_{2.1}$ Connect to pressure storage
    - $FR_{2.2}$ Transfer pressure from storage
    - $FR_{2.3}$ Maintain pressure during flight
    - $FR_{2.4}$ Release pressure when 9 V applied
    - $FR_{2.5}$ Generate 1500 N to separate rocket and eject parachute

With completed FRs, we develop mappings to DPs for each of our proposed designs.

Table 1. Polycaprolactone material properties at room temperature[8]

Characteristic	Min	Max
	[MPa]	[MPa]
Tensile strength	10.5	16.1
Tensile modulus	343.9	364.3
Tensile yield	8.2	10.1
Compressive strength	38.7	N/A
Compressive modulus	297.8	317.1
Compressive yield	10.3	12.5

5. The design

We now present two designs that emerged from the FRs in the previous section. They share the same DPs but have different implementations and coupling that will be shown in their design matrices. A key element in both designs was the use of a thermo-plastic to change mechanical properties with resistor heating. The plastic of choice for this project was polyester polycaprolactone pellets (sold under the trade name "Friendly Plastic"[7]) due to its low melting point (90 °C) and high availability. See Table 1 for details.

5.1. Design Parameters

- DP_1 Maximum length of 400 mm and outer diameter of 98 mm.
- DP_2 70 bar CO_2 pushes piston next to parachute.
    - $DP_{2.1}$ Threaded coupler for #84203Z CO_2 tank
    - $DP_{2.2}$ Cartridge face pressed against needle to open
    - $DP_{2.3}$ Plenum sealed with O-ring shoulder seals
    - $DP_{2.4}$ Resistance heater weakens thermo-plastic valve/cap
    - $DP_{2.5}$ Minimum piston diameter of 16.5 mm

5.2. Design Revision 1.0

The concept for this design was to embed the needle that pierces the canister into the thermo-plastic to minimize part count. See Figure 2 for the associated design matrix. This configuration is decoupled due to its triangular matrix[6]. It was considered worth investigating for the advantage of concentrating the consumable and high-information element into one part.

The assembly of the first design is shown in Figure 3 and consisted of three main parts, the cover nut, the connection nut and a plastic tablet (gray box) cast with a coil of resistance wire (black line) and a needle (black) to puncture the CO_2 cartridge. The pre-flight preparation is: 1. Insert the plastic tablet/needle inside the cover nut 2. Screw the CO_2 cartridge into the connection until the needle punctures the CO_2 cartridge. Speculations whether or not the needle will puncture the cartridge in the air can be neglected since the system is armed and ready to go before the rocket takes off. At the flight apex, a flight computer's 9 V "pyro" relay heats the coil inside the plastic tablet making

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_{2.1} \\ FR_{2.2} \\ FR_{2.3} \\ FR_{2.4} \\ FR_{2.5} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & & & & & \\ 0 & & X & X & X & X & 0 \\ 0 & & 0 & X & X & X & 0 \\ 0 & & 0 & 0 & X & X & 0 \\ 0 & & 0 & 0 & 0 & X & X \\ 0 & & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_{2.1} \\ DP_{2.2} \\ DP_{2.3} \\ DP_{2.4} \\ DP_{2.5} \end{Bmatrix}$$

Fig. 2. Design matrix for Revision 1.0

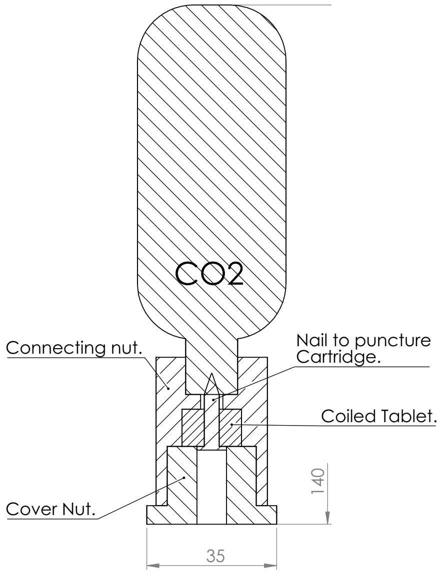

Fig. 3. Cross-section of design 1.0. All dimensions in mm.

it soft enough for the pressure from the cartridge to rupture the tablet to generate sufficient ejection force on the piston.

Upon implementation, it was discovered that the manufacturing tolerances were to challenging for reliable operation; there was high information content in both manufacture and use. If the needle is not in the right position during placement it could happen that the cartridge did not get punctured at all. If the needle punctured too early before the seal was engaged gas leaked. Manufacturing the needle and tablet to the needed tolerances in the university facilities also proved challenging. These components are coupled because multiple design parameters, to puncture the cartridge and seal, are implemented in one part.

In response, a second design (2.0) was drawn up to use a spring loaded release similar to the Fruity-chutes product, but was abandoned due to the "No Springs" constraint. This constraint was not clear at that time, and so this design is not relevant.

5.3. Design 3.0

To come up with a solution for the problems from Section 5.2 the independence axiom was used to uncouple puncturing the tank from sealing the plenum. Each separate part is designed for only one purpose: the needle punctures the cartridge in a already sealed plenum and the tablet heats up to release the pressure. The only consumable part in this design is the tablet. The modified design is shown in Figure 5 and its associated design matrix in Figure 4. This design is still only decoupled, but exhibits much less coupling.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_{2.1} \\ FR_{2.2} \\ FR_{2.3} \\ FR_{2.4} \\ FR_{2.5} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & & & & & \\ 0 & & X & 0 & 0 & X & 0 \\ 0 & & 0 & X & 0 & 0 & 0 \\ 0 & & 0 & 0 & X & 0 & 0 \\ 0 & & 0 & 0 & 0 & X & X \\ 0 & & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_{2.1} \\ DP_{2.2} \\ DP_{2.3} \\ DP_{2.4} \\ DP_{2.5} \end{Bmatrix}$$

Fig. 4. Design matrix for 3.0

In contrast to the first design (Figure 3) the ending of the cover nut has been widened to 99 mm to fit the parachute chamber. A separation disk *i.e.* piston $DP_{2.5}$ (not pictured) will be located next to the cover nut aperture. Its function is to prevent damage to the parachute from blown out parts from the plastic tablet. It also ensures that generated pressure is converted to sufficient and consistent force to eject the parachute $FR_{2.5}$. If the expanding gases are not presented a continuous interface, then any holes *i.e.* "blow-through" in the parachute-tube interface can bleed pressure, decreasing the force to insufficient levels. Figure 5 also shows a test adapter for the parachute chamber.

5.4. Results

Test where made to check for leakage of gas and overall functionality of the system. The 3.0 prototype (Figure 6) had three general failure modes: leakage, premature opening, and failure to open.

Leakage issues were initially linked to thread manufacture. During preparation, gas was observed leaking out through the threaded part between connection nut and the cartridge. Teflon plumbing tape was applied as a temporary fix. With the addition of an O-ring on a shoulder seal, leakage was eliminated.

A series of nine tests were performed. The first three tests all failed due to an overly thick tablet that failed to rupture completely, indicating that our structural calculations were incorrect.

The tablet was reduced in thickness and more tests performed. Even though both tablets were the same thickness of 2 ± 0.1 mm the result were not. Test 4 seemed promising: the canister was screwed in, and punctured. Then after several minutes with no noticeable leakage, the leads were energized and gas was released through a small hole. Test 5 fired prematurely: the tablet blew out with a loud bang before the coil was hot. From these test we concluded that the production of the coiled tablet was a precision operation. A difference in canister pressure due to manufacturing or temperature must also be considered. A deeper study of the thermal and structural properties of polycaprolactone needs to be performed to optimize the inter-

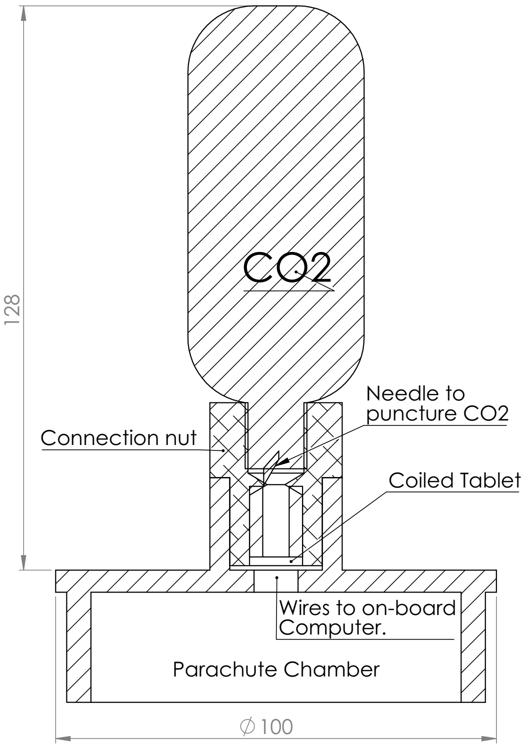

Fig. 5. Cross-section of design 3.0 module. All dimensions in mm.

Fig. 6. Physical implementation of Design 3.0.

action.

Tests 6 and 7 failed in a new way: when expanding CO_2 came into direct contact with the heated polycaprolactone, it produced a foam, much like styro-foam. This foam weakly sealed the aperture which greatly reduced the rate gas could escape. This failure mode forced us to more carefully consider the gas-plastic interaction.

In our final tests (8 & 9) the holes in the base and needle were drilled out to expand the surface for the gas to push on. The base unit was expanded from 6 mm to 9 mm. These tests were successful even though the thickness of the tablet varied from 2–4 mm. Such a large tolerance indicates that low-cost manufacture might be worth considering; more experiments are needed to characterize the tolerances.

To continue testing, a new prototype is needed with a lot more testing before releasing it to the market. Unfortunately, our supply of available canisters was exhausted. For the final tests and future tests, a 220 bar extinguisher was adapted.

More practical testing has to be done before the system is ready for a rocket launch. Tests will be performed at subzero temperatures to mimic real conditions in flight. Shake and drop tests must be underdone to simulate the high-G rocket environment. Final material selection is left to be done on the plastic tablet itself. Throughout our tests the question arose if polycaprolactone is the best material for this product; other thermally active materials need to be evaluated for suitability.

6. Conclusion

Each second level functional requirement is checked for the final design to ensure that the release system met its goals.

FR_1: Mount in 98 mm *or large rocket middle section.*

The unit including mounting hardware has a length of 400 mm and a maximal diameter of 99 mm, which is within the allowed dimensions.

FR_2: Push parachute out of rocket.

The successful tests show electrically-actuated release of 7 bar compressed CO_2 gas against a piston to generated sufficient force.

6.1. Summary

All functional requirements are met in the final design. The new thermo-plastic activated parachute release system lacks the limitations of the existing designs. There are no moving mechanical parts seen in the heat-actuated designs that may become frozen in flight conditions. Release configuration does require prior knowledge of the flight altitude nor access to gunpowder. Further experimentation on the tablet tolerances is the only additional research needed. Once this research is complete, the parachute release system is ready to be further developed into a commercial product.

Acknowledgments

Many thanks to Frank De Brouwer of Rebel Space for inspiring this project and providing the team with specifications and contacts in the field. Thanks also to the Mjölnir [9] and T-865-MADE 2014 team [4] who made previous investigations into the parachute release systems.

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