REEL.SMRT: A FEASIBILITY INVESTIGATION INTO A STRATOSPHERIC BALLOON-BORNE LOW-GRAVITY PLATFORM

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ABSTRACT

A stratospheric balloon-borne platform that can drop, reel down and up a tethered payload and perform this multiple times may have the potential to significantly expand balloon-based experimentation and the scope of low-gravity platforms. The reel.SMRT project aimed to investigate the feasibility of such a platform by developing a system consisting of a small capsule to be dropped or lowered from the main balloon gondola and then returned using a fishing reel and motor connected to the capsule by a high strength line. Complex mechanical, electrical and sensor systems were implemented to monitor the low gravity performance during operation. The reel.SMRT system was fully functionally tested and flew on-board a stratospheric balloon in October 2009 from Esrange Space Centre following an 8-month development period as part of BEXUS-9 (Balloon-borne Experiments for University Students).

1. INTRODUCTION

The primary objective of reel.SMRT was to investigate the feasibility of producing a reduced gravity environment on a balloon payload in a recoverable and repeatable manner. The secondary objective was to achieve a versatile line and reel system for increased vertical sampling range and capability for tether-based applications.

The ultimate vision is of an up-scaled platform to provide a viable and cost-effective alternative to parabolic flights and drop towers. It has the potential to drastically increase the maximum drop lengths and versatility of such systems, along with more frequent and numerous drops in a single mission.

The reel.SMRT system also has secondary applications for balloon experimentation, such as lowering a payload, making it possible to take measurements further from the gondola, increasing sampling range. Other advantages of an up-scaled system would include: capability for large payloads such as antenna deployment tests; multiple drops for more test data; and variable gravity to simulate Martian or Lunar conditions through control of the drop acceleration. Additionally, the tether has applications as a safety line for UAV experimentation, or for lowering a sensor or object closer to the surface for a low-altitude mission (such as in Martian exploration).

Our simulations have shown that, with minimal tension, milligravity performance is only limited by drag after kilometres of drop distance. Challenges to the implementation included sensor sensitivity and sampling rates as well as the line feed from the spool.

For this feasibility analysis, the system had a 30m drop length (on a 70m line) and 5g braking force, to demonstrate the quality of the low-gravity environment for a dropped payload, whilst using COTS components including standard fishing tackle and line as the reeling mechanism, on a low budget.

This investigation was developed within the framework of the REXUS / BEXUS Programme and launched on the BEXUS-9 stratospheric balloon to an altitude of 23.7km. The Programme is realised under a bilateral agency agreement between DLR and SNSB and is also supported by ESA.

The reel.SMRT project team is comprised of seven students from the Erasmus Mundus Joint European Master in Space Science and Technology, “SpaceMaster”. Throughout the project, the members were spread over multiple countries and time-zones and work was conducted in addition to university commitments. The budget of approximately 14000€ was fully raised by the students via seeking out sponsorship and support in addition to self-funding. As such, cost-effectiveness was paramount.

2. BACKGROUND

Several experiments have used high altitude balloons as platforms to drop untethered probes to create low-gravity environments. One experiment achieved up to seven seconds of reduced gravity by a drop from an altitude of 24,382m [2]. A more sophisticated approach is that of the probe of the Sawai Lab at JAXA [6]. By attaching the experiment to a free-floating sphere inside the dropped probe, it was possible to achieve a much better low gravity environment. In addition, the probe was equipped with gas thrusters to compensate for the increasing drag during the fall.

The feasibility of lowering an experimental platform off a balloon was demonstrated by a team of Japanese researchers [4], who successfully lowered a probe to 600m below their gondola.

The first published attempt to drop a probe off a balloon to achieve low-gravity and reel it back up was REEL-E, developed as a precursor to the reel.SMRT experiment [3]. However, due to a software error, the experimental data gathered during the flight was not recovered. The dropping mechanism involved unreeling the entire line before releasing the payload, but this technique was not selected by reel.SMRT due to the potential of twisting and snagging the line for longer drops and hence the inability to scale the project for commercial design. By combining drop repeatability and slow reel capability, it was believed that the reel.SMRT concept has significant potential as an alternative for low-gravity testing. Compared to other existing low-gravity facilities (such as drop towers and parabolic flights), the reel.SMRT system is more accessible, with shorter development times for low-gravity tests because of relatively straightforward preparation of a high altitude balloon payload.

Low-gravity experiments have varying requirements concerning the quality of reduced gravity [7]. If the reel.SMRT system is made available in an up-scaled version it can provide several advantages over already established low gravity facilites and can therefore be seen as a good alternative to existing and relatively expensive low-gravity platforms. For example, drops are immediately repeatable over multiple flight hours, whereas drop towers have to be evacuated in a time-consuming process before each drop (for instance, the total time of one drop sequence can be 4 hours [1]). Such a system could also allow for experimentation not currently possible with existing low gravity platforms because of size restrictions; deployment tests of large antennae and other large devices could be achieved and recovered with potential drop distances in the order of kilometres. Additionally, the stratosphere provides an alternative environment for testing experiments to vacuum or atmospheric conditions.

The reel.SMRT system does bear shortcomings such as not allowing the handling of the drop payload between drops and requiring strict safety measures to prevent damage or harm to the public in the case of a tether rupture. The system is inherently challenging to operate, considering both the operation of the balloon and the reel.SMRT system. However, such challenges are common-place in space-related experimental work, and certainly are not expected to match the operational complexity of drop towers or parabolic flights.

3. EXPERIMENTAL DESIGN

3.1. System Level

The reel.SMRT system consists of three primary segments: a ground station, the MAIN Payload containing the reeling mechanism and the dropped payload tethered to the MAIN Payload called the "FISH". There is also a camera for monitoring purposes. Each of these systems works independently, with separate power sources and communicate using xBee radio modules, which operate Zigbee in the spread spectrum to minimise interference with other experiments. The ground station is connected to the MAIN Payload via E-link [5]. These systems are illustrated by Fig. 1 with the MAIN Payload and FISH also displayed in Fig. 2. Fig. 3 shows a photograph of the MAIN Payload without insulation.

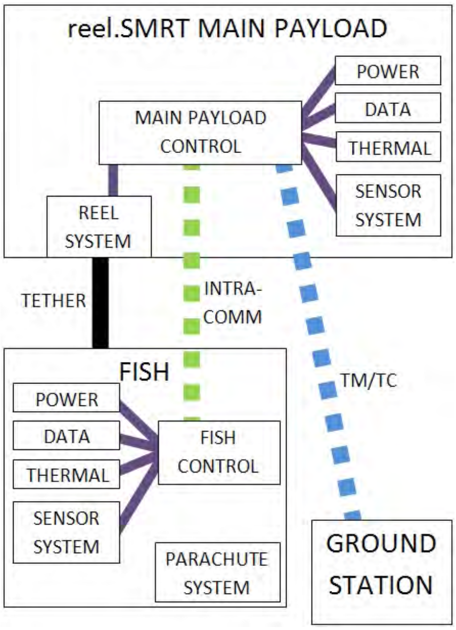

Figure 1. System Diagram

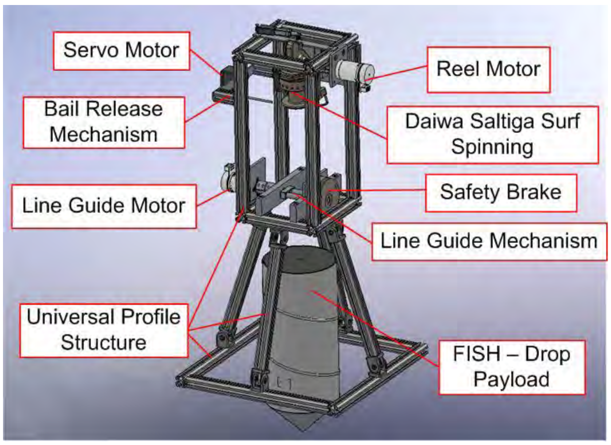

Figure 2. Mechanical System

The reel.SMRT system was designed for two modes of operation: a "Drop Mode" and a "Slow Reel Mode". When the Drop Mode is initiated the FISH starts inside the MAIN Payload and is designed to fall 30m before the tether is caught and decelerated. The FISH is then reeled up to the same position for possible repetition of the process.

The Slow Reel Mode is similar to the Drop Mode but the

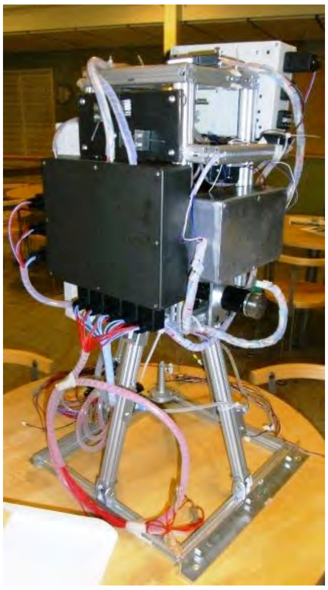

Figure 3. Photograph of the assembled reel.SMRT MAIN Payload with the insulation removed and the electronics boxes distributed around the frame

free-fall is replaced by a reel-down of the FISH. This requires a system to control the descent of the FISH from the MAIN Payload, thus enabling sample collection from different altitudes below the gondola. The FISH is lowered by a motor which reels down the line by rotating the handle forward. In this way, the speed of the reeling and the line tension may be varied to achieve such effects as simulated Martian gravity, UAV safety lines or vertical sampling resolution for payloads.

3.2. Mechanical

The Mechanical Subsystem was designed to withstand all mechanical and thermal loads and enable operations of the mechanisms. The MAIN Payload mass was 23kg and the FISH mass was 1.8kg at launch.

The FISH houses the mission critical payload, which is aimed at measuring a milligravity environment using its own power, thermal system, data storage, sensor suite and safety parachute. The mechanical connection between the FISH and the MAIN Payload is a high strength *Dyneema*™ fishing line. Although the fishing reel is equipped with a mechanical brake, there is also a short segment of elastic rope to reduce the jerk and a swivel system to prevent the twisting of the tether from impacting the FISH dynamics.

The MAIN Payload is divided into two main segments: the Reel Mechanism and the Line Guide Mechanism. The Reel Mechanism consists of a high strength COTS *Daiwa Saltiga Surf 6000* fishing spinning reel specifically designed to release a line from the spool with minimal friction and then catch the line whilst enduring high loads. A spinning reel mechanism is preferable as the spool itself does not turn, meaning that there is no drag due to bearing-friction or kinetic energy while turning the spool or alternatively no variable motor required to turn it at accelerating rates. For the reel to function, a DC motor is rigidly coupled to the winding mechanism. The bail arm of the fishing reel is operated via a servo motor connected to a bail release fork, which is able to move the bail rearwards thus unspooling the tether. This arrangement of the reeling mechanism is displayed in Fig. 4.

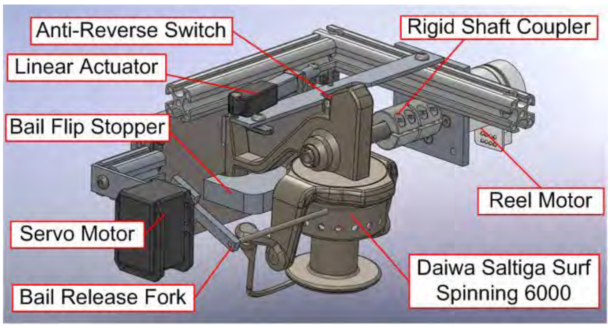

Figure 4. Bail Mechanism of the MAIN Payload

For minimal disturbances to the payload, the line needed a guide to ensure there were no major horizontal oscillations, akin to the loops on a fishing rod. This device consists of a gap in the middle of two smooth metallic rods through which the tether was fed. This line guide also acts as a key safety device: firstly, for the ascent phase, the line guide is locked to prevent potential unspooling of the line; secondly, if the bail fails to catch the line on a long drop, then the line guide would, after a critical time limit, rotate and entangle the line around itself. This guide is controlled by a rigidly coupled DC motor. The complete mechanism was then attached to a Safety Power-OFF Brake that can take the force of the line in case of a complete power failure. Fig. 5 displays the view from the reel down through the line guide within the MAIN Payload.

Figure 5. View from above the reel looking down through the MAIN Payload past the line guide

The operation of these mechanisms is as follows. When the drop mode is initiated, the line guide is unlocked and the reel is turned to align the bail with the bail opening mechanism using a hall sensor to determine correct positioning. The bail is then flipped using the servo motor, enabling the FISH to fall under gravity as the line spools off the reel. Once the appropriate distance is reached, as determined by the elapsed time, the bail mechanism is shut by turning the reel motor and thus forcing the bail past an angled, solid wedge that mechanically closes the bail. This ends the free-fall phase. In the deceleration phase, the internal reel brake is automatically applied after the bail is closed and the FISH is decelerated to a halt over approximately 20m (as set by the reel brake). In the recovery phase, the FISH is reeled up to the MAIN Payload until proximity sensors detect the presence of a marker above the FISH. The line locking mechanism may be applied between each drop, by spinning the line guide via a ground station command.

As the structure of the payload is exposed to the environment through a hole in the floor of the gondola, insulation is applied both externally to the system and around a series of electrical boxes dispersed on the structure, along with heaters and temperature sensors to maintain the components within their operating temperatures (inclusively between -10 °C and 20 °C).

3.3. Electrical

The MAIN Payload electronics provide and distribute power to the MAIN Payload, to ensure correct motor and sensor operations. The design consists of three PCB boards: a microcontroller, a power supply and a motion control board. The microcontroller board hosts the microcontroller that executes the on-board control software. The power supply board provides +24V, ±12V, +18V, +5V and +3.3V for motors, sensors and other electronics. The motion control board drives the actuators of the experiment. To deliver sufficient stall torque, this board is capable of delivering more than 250W peak power. It also controls the linear actuator and several heaters to keep the critical components within their operating temperatures.

The key task of the FISH electronics is to measure the quality of the reduced gravity environment during the drop. As such, a company pre-calibrated off-board set of high precision three-axis capacitive accelerometers and a 24-bit sigma delta 8-channel parallel Analog to Digital Converter were implemented to measure at 1MHz to an accuracy greater than $1x10^{-3}$g. The FISH electronics is mounted on a single board that also contains an *ARM7* microcontroller, three gyros, an onboard three-axis backup accelerometer, a micro-SD storage memory card and a wireless communication radio to connect to the MAIN Payload. The sensor suite also includes a temperature sensor for the accelerometer bias compensation and so ultimately outputs the complete attitude and dynamics of the FISH. The FISH provides three different voltages: +1.8V, +3.3V and +5V, with a nominal power consumption of 800mW. Fig. 6 shows the internal layout of the FISH.

The two systems interface with the *XBee-PRO® 868* modules, through which data from the FISH is transferred to the MAIN Payload for duplicate storage and transmission to the ground station. To log all of the data redundantly, the sampled data is sent in packets to the MAIN

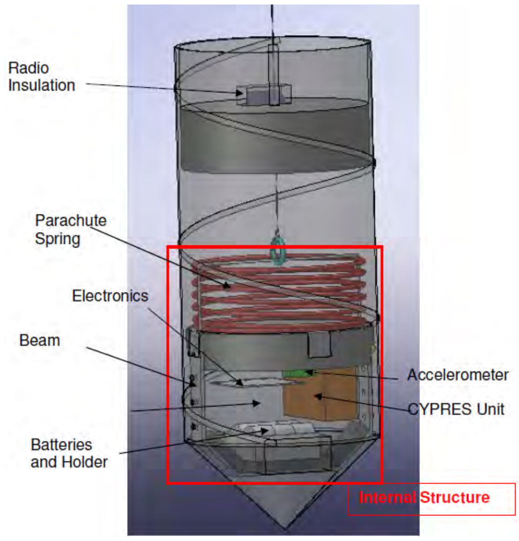

Figure 6. The positioning of key mechanical and electronic systems within the FISH

Payload prior to storage in the local memory. The MAIN Payload saves all the data and transmits it to the ground station. The camera is a secondary system and so has its own independent power, thermal and communication system. It is mounted onto the MAIN Payload to monitor the status of the FISH and hence help the operator to control the experiment and diagnose its behaviour.

3.4. Software

The primary task of the control software is to operate the mechanisms of the system, including the servos and motors. The secondary task is to control the communication between the FISH, the MAIN Payload and the ground station.

The communication protocol allows the operation of the experiment in real-time from the ground. The control of actuators and mechanisms, as well as thermal regulation, is achieved through effective use of feedback sensors. A real-time operating system is employed to cope with the demanding requirements.

There are two modes of data sampling rate: "high" during drops and slow reel (10^6 samples/s) and "low" during standby (1 sample/s). To support data transfer in the high mode, the key limitation was the amount of memory available to cache the acquired data before downlink to the ground station. The memory of the microcontroller is not sufficient, so the data is stored in a SD card as cache memory as well as permanent storage onboard. The cache mechanism is implemented both on the FISH and on the MAIN Payload for increased redundancy. The ground station receives the data via TCP packets then parses it according to the communication protocol and saves the data on the hard drive for further analysis.

Due to strict requirements regarding system responsiveness the control software was implemented using a real-time operating system, *FreeRTOS*. Fig. 7 shows the task design of the MAIN Payload, which handles the most demanding tasks both for data transfer with caching and actuator control.The *FreeRTOS* tasks in the FISH are very similar to the MAIN Payload tasks, with less complexity: the actuator control and TCP network tasks are not required.

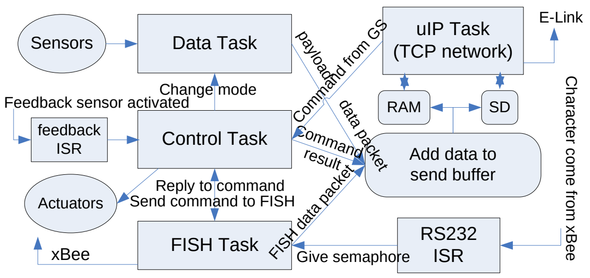

Figure 7. Task Diagram for MAIN Payload software

4. FLIGHT PERFORMANCE ANALYSIS

The experiment demonstrated full functionality of all systems, passed the Mission Interference Test and Experimental Acceptance Review and flew in this condition. During the flight, however, the system did not reach full functionality due to rupture of the line.

4.1. Launch Campaign

The launch campaign involved many final tests: a challenging process which necessitated the solution to many problems and rigorous work.

On the mechanical side, several tests were performed during the launch week in preparation for flight. Using the facilities at Esrange such as the MAXUS tower, the experiment was raised to 12m and several full system tests were performed by dropping or reeling at lengths constrained by the available drop heights. The team monitored the condition of the reel and it was found that it was wearing out quickly and only a minimal number of tests were possible. Several critical issues were encountered and solved during these tests, including setting the reel-brake to a proper level, securing the interfaces of the line to both the reel and the FISH and determining the reasonable total line length.

Electronics and software also incurred a great deal of final adjustments. The printed circuit board of the FISH caused many last minute problems for both software and hardware. Many software changes were needed as the integration tests revealed problems with sensors and a few reliability issues with the electro-mechanical systems. All issues were resolved prior to flight.

During the flight, the mechanisms of the MAIN Payload were largely successful, both electrically and mechanically. The line guide mechanism was able to secure the FISH without any visible disturbances and operated as expected. The reeling operation was also successful in reeling the FISH up to a good pre-drop position. Then,

Figure 8. View from onboard camera looking down on the FISH and line-guide stopper

the bail release mechanism worked and successfully released the FISH into a free-fall which was, according to the video streamed to the ground, of very good quality. Fig. 8 shows a still from this video and Fig. 9 shows the FISH hanging below the gondola shortly after launch. The bail closing operation was executed successfully but the tether ruptured and the FISH was lost.

Figure 9. View of the FISH hanging below the gondola from the ground shortly after launch

Furthermore, it was realised on the morning of the launch that an incorrect software version had been loaded into the MAIN Payload microcontroller. This was not resolved as it was deemed too risky to dismantle the experiment to change the flight software. The consequence was that data during the high data rate mode, which was automatically triggered by a drop command, was unable to be transferred to the MAIN Payload and remained stored only on the FISH. A trajectory analysis was conducted and searches were conducted for the FISH, however it and the drop data remain unrecovered at the time of writing.

4.2. Diagnosis

The inability for the system to meet all of its objectives during the flight was due to a rupture of the line. After many careful steps to extract the payload, somewhat mangled and damaged after the landing and subsequent transport back to Esrange, initial inspection of the reel and the remaining line showed two obvious facts: the line broke and it broke before it ran out, both at the attachment to the barrel of the reel and at the bail. What were not immediately obvious were the reasons why it broke during the flight but survived the system tests.

Figure 10. Close-up of the broken line as it was stuck on the bail when recovered

Firstly, the breakpoint on the bail, as seen from Fig. 10, shows the line literally encrusted in the aluminium of the bail. Moreover, there were several line fragments visible and dents on the bail, which were not present pre-flight. This is a witness to the extreme frictional events that occurred when closing the bail. This corroborates with the audio recordings, demonstrated in Fig. 11, which suggest violent impact as the line jumped on the bail as it was forced shut. One possible cause for such discontinuous jumps would be the snagging of the line on itself causing discontinuous tension. Secondly, the breakpoint of the line at its interface to the reel barrel is also of interest.

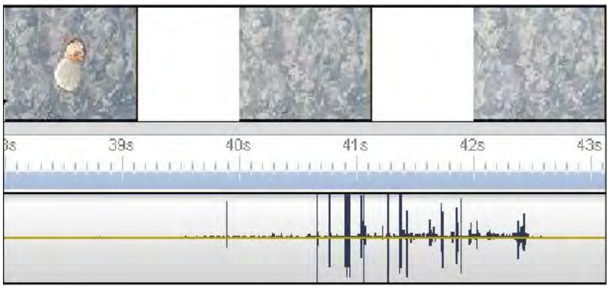

Figure 11. Audio graph from the FISH drop video

Fig. 12 shows temperature readings between 5°C and 10°C, which rules out thermal issues as system tests demonstrated safe operation down to -15°C for the relevant components. Still, for the line to break at its attachment point requires the propagation of the tension along its entirety. This is surprising as one would expect the tension to tighten the line on the barrel and in doing so enforce the grip and absorb the tension.

Thirdly, the line, as it was after retrieval, was significantly snagged and physically damaged. As such, the explicit attempt to avoid this issue by carefully hand-winding the line onto the barrel pre-flight did not succeed.

The hypothesis, then, is that as the tension was created from forcing the bail shut, the attachment to the barrel

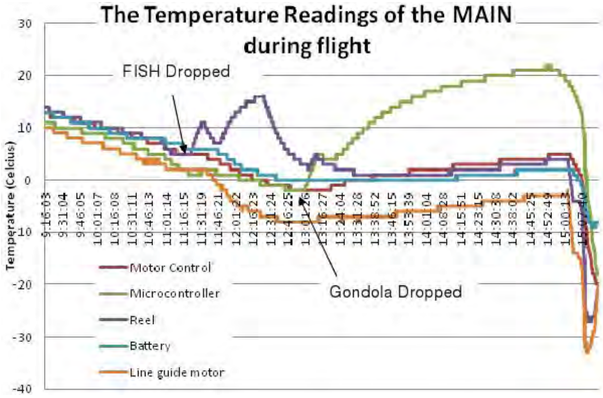

Figure 12. Temperature readings of the MAIN Payload during the flight

must have worn out, then, the tension build-up increased the snagging and damage to the line still wound on the barrel. In turn this made the force pattern on the line-to-bail contact more discontinuous and characterised by several impacts rather than a more gentle continuous tension. Those repeated impacts caused dents on the bail and pieces of line to wear off until eventually the line, weakened by intense snagging, ruptured. Although this seems like a reasonable hypothesis due to corroboration with the evidence, the evidence is not sufficient to prove this sequence of events. It was concluded, however, to be the simplest explanation.

5. CONCLUSIONS

Despite not achieving full functionality during the flight, the reel.SMRT experiment demonstrated that a low-gravity platform utilising a tethered repeatedly reeled and dropped payload is theoretically possible within the extreme environment of the Stratosphere. The system, however, is unable to provide a quantitative measure of the quality of the reduced gravity until the FISH and its acceleration data is recovered. Such data would provide information on the dynamics of the FISH throughout the tethered drop as well as the free-fall through the atmosphere to the ground. With this data, a quantitative outcome may ultimately be met. Nevertheless, the outcome of this experiment led to the following conclusions:

- The video capture of the flight suggests good stability of the capsule as it hangs below the gondola.
- The flight video in tandem with the integration tests shows that the spinning reel design is very good and fairly repeatable for dropping a capsule in near-freefall conditions multiple times.
- The design as it stands is fully operational for the reeling operation, for lowering and raising payloads from a balloon.
- Commercial fishing equipment is not strong enough for even a minimum weight capsule for dropping operations: a custom design is necessary.

Thus the partial success of all subsystems shows that the functionality of the designed system was achieved and that the ultimate feasibility of low-gravity experiments onboard balloons could perhaps be proven by a sturdier custom redesign of the reel.SMRT system. For higher payload masses the implementation of an up-scaled system would be necessary. Recommendations for customisation, particularly pertaining to the drop mode, include:

- A sturdier bail and reel mechanism.
- A higher-strength line that is resilient to multiple drops, such as a larger diameter *Dyneema*™ line.
- A mechanism to hold the FISH in place prior to the drop would optimise stability in the horizontal axis.
- A means to transfer power to the payload would enable lower mass for experimental payloads.
- A dynamic analysis of the balloon during the drop for a larger mass payload and system would be valuable.
- A greater level of performance and control could be obtained through use of a variable braking mechanism, which may be achieved through interfacing a motor to the variable brake of, for example, a mechanism akin to that within a spinning fishing reel.
- For long drops (kms), the line speed off the reel is limiting and alternate methods may be required, such as a single drop of slack line. Such a system might include a spinning reel with a pinched-in base, allowing the line to fall off it under gravity.

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EuroLaunch, a cooperation between the Esrange Space Center of the Swedish Space Corporation (SSC) and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from ESA, SSC and DLR provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from Esrange Space Center in northern Sweden.

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