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OPTIMIZATION OF DATA ACQUISITION SYSTEM FOR CUBESATS USING DELTA ENCODING AND HEATSHRINK COMPRESSION TECHNIQUES

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Abstract: CubeSats, being compact and resource constrained satellites, require highly efficient systems to handle data collection and transmission. This project focuses on optimizing the Data Acquisition System (DAS) in CubeSats by implementing a dual-stage compression strategy using Delta Encoding and the Heatshrink compression algorithm. Delta Encoding minimizes redundancy by recording changes between successive sensor readings, while Heatshrink, a lightweight and real time compression library, further reduces the data size suitable for embedded systems. The optimized DAS is designed to reduce onboard memory usage and downlink bandwidth requirements, thereby enhancing overall system performance. Proposed approach was evaluated in a simulated CubeSat environment which used real time sensor data, and we saw that there was a large improvement in compression ratio and transmission efficiency. This work puts forward that we have extended the what CubeSats can do in space missions by improving data handling at the same time maintaining reliability.

***IndexTerms* - CubeSat, Sensors Unit (DHT22, MPU9250, QMC5883L, BMP280, NEO-6M-0-001), Data Acquisition System, Delta Encoding, Heatshrink Compression, ESP32, Micro USB Cable, NRF24I01 (RF Module), Ground station (Computer).**

I. INTRODUCTION

CubeSats are in the field of very small satellites which has seen great adoption in academic, research, and commercial settings because of what they bring to the table in terms of price, form factor, and how quickly they can be put into service [1]. While that is true, what they lack in size they also bring in terms of powerful onboard processors, large storage tanks, and high bandwidth for communications [2]. In that which they do present in terms of challenges is the issue of getting out what is acquired from the telemetry and scientific data out of the system they are in [3]. The Data Acquisition System (DAS) is a very important sub system which plays the role of collecting from the onboard sensors what we need -- temperature, pressure, inertial measurement units (IMUs) and GPS which it then formats and sends off to the ground station. Since in the field of CubeSat which have a typical issue of low energy and narrow band communication we put forth that which is of great importance for mission success and performance [4]. This work puts forth an optimized DAS architecture which we did via the use of Delta Encoding and Heatshrink Compression which are very light weight and resource friendly data compression solutions for embedded systems [5], [6]. Delta Encoding what we did is we put in to practice which is a method to reduce redundancy by only coding the difference between successive data values which makes it very effective for slowly changing telemetry data. Heatshrink is a real time compression library we used which is designed for microcontrollers that have very little memory and computing resources.

By combining these methods, the system significantly reduces telemetry packet sizes, which results in:

- Improved data transmission speed
- Reduced power consumption
- Increased throughput of scientifically relevant data Such optimizations are vital for modern small satellite missions, where efficient use of limited bandwidth and power can directly impact mission success.

II. RELATED WORK / LITERATURE REVIEW

CubeSats and other small satellites operate under strict constraints of power, size, and bandwidth, necessitating efficient data acquisition and compression strategies. Recent advancements in onboard telemetry systems and embedded compression algorithms have laid the foundation for optimizing such systems.

J. Smith et al. [1] discussed the use of miniaturized and low power sensors for CubeSat missions. Their work in the IEEE Sensors Journal highlighted the trade-offs between sensor resolution, data rate, and power consumption, which are central to onboard data acquisition system (DAS) design. R. Kumar et al. [2] demonstrated the application of multi-sensor data fusion techniques in CubeSats, improving both redundancy and data reliability, while also increasing the data volume, thereby justifying the need for onboard compression. L. Wang et al. [3] evaluated telemetry system designs using UHF/VHF, S-band, and X-band communication protocols. They emphasized the importance of reducing telemetry payloads due to limited downlink windows, a key challenge addressed by onboard data compression in our work. P. Davies et al. [4] proposed an FPGA-based onboard processing architecture that enabled real-time telemetry formatting and prioritization. This aligns with our project's goal of embedding efficient, real-time delta encoding and lightweight compression into a microcontroller-based DAS. S. Tanaka et al. [5] explored the integration of edge computing in space systems, applying machine learning techniques for autonomous data reduction. While powerful, these approaches may not be feasible on ultra-low-power platforms. Instead, lightweight techniques such as delta encoding and Heatshrink—used in this work—strike a balance between efficiency and implementation simplicity. The Heatshrink compression algorithm, introduced by E. Evenchick [6], provides a minimal-memory LZSS implementation suitable for microcontrollers. Delta encoding, when combined with Heatshrink, can significantly reduce the entropy of sensor telemetry data, enabling higher compression ratios with minimal CPU usage.

These prior works collectively emphasize the need for realtime, embedded, low-complexity compression techniques precisely what this project aims to optimize for CubeSat applications

III. THE SYSTEM ARCHITECTURE AND DESIGN

The design of a Data Acquisition System (DAS) for CubeSats must consider multiple constraints such as limited power, low memory, reduced bandwidth, and the need for real-time operation. The proposed system integrates efficient data compression into the DAS to optimize performance for CubeSat missions.

A. System Architecture

BLOCK DIAGRAM

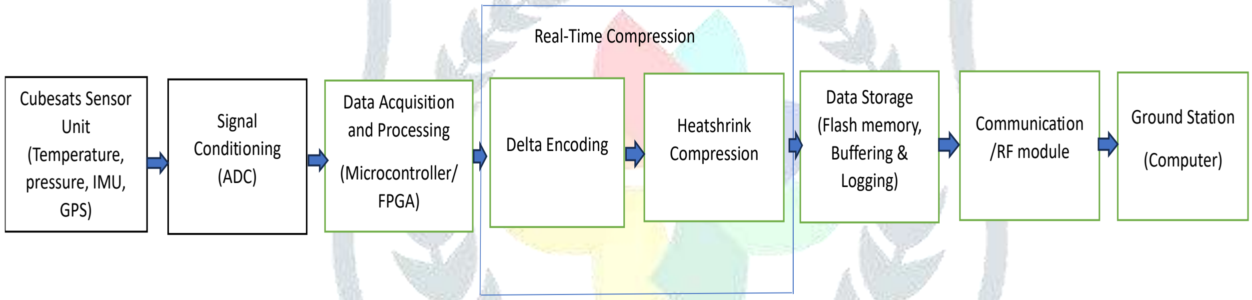


Fig 1.1: Optimization of Data Acquisition System for CubeSats

The system is divided into the following major functional blocks:
1. **Sensor Interface Unit:** Collects real-time data from onboard sensors (temperature, pressure, orientation, etc.).
2. **Microcontroller Unit (MCU):** The central controller that handles data acquisition, delta encoding, Heatshrink compression, and communication.
3. **Delta Encoder:** Computes the difference between successive sensor values to reduce redundancy.
4. **Heatshrink Compressor:** Compresses the delta encoded data using the Heatshrink algorithm, which is lightweight and suitable for embedded systems.
5. **Data Storage / Buffer:** Temporarily stores compressed data before transmission.
6. **Communication Module:** Sends out compressed data to the ground station via RF or which is also to use other CubeSat protocols for communication (for instance UHF, S-band).
7. **Ground Station (Computer):** Receives, decompresses and displays telemetry. Also run scripts to monitor CubeSat health or mission performance.
8. **Power Supply:** Gives regulated power to all components, designed to do so very efficiently in space.

IV. IMPLEMENTATION

Compression Methodology

Delta encoding then which we apply to Heatshrink Compression. We chose this approach for its performance in constrained resource embedded systems.

4.1 Delta Encoding;

Delta Encoding is out method of transforming which reports the difference between consecutive sensor measurements instead of the full values. This method is very efficient when sensor data changes slowly or is mostly the same over time.

a. How it Works:

Original Data:

• Let's say you have a temperature sensor that outputs:

• D = [100,102,104,107,109]

• Delta Encoding Result:

• ΔD = [100,+2,+2,+3,+2]

Explanation:

• First value is unchanged: it acts as a reference.

Then we store:

• $d1=D1-D0=102-100= +2$
• $d2=D2-D1=104-102= +2$
• $d3=D3-D2=107-104= +3$
• $d4=D4-D3=109-107= +2$

b. Delta Encoding Formula

Let:

• D = [D0,D1,D2,...,Dn] be the original data sequence.
• ΔD = [D0,d1,d2,...,dn] be the delta-encoded data.

Then:

• $d_i = D_i - D_{i-1}$ for i = 1 to n
• This is the forward (encoding) transformation.

Reconstructing the Original Data (Decoding)

• To recover original data from delta:
• D0 = ΔD0 (Initial full value)
• D1 = D0 + d1
• D2 = D1 + d2 • …
• Dn = Dn−1 + dn [2]

• So, cumulative addition gives you back the full sequence.

Advantages:

- Reduces data redundancy.
- Ideal for real-time, continuous data.
- Increases compression efficiency in the next stage.

4.2 Heatshrink Compression

Heatshrink is a lightweight and efficient real-time compression algorithm designed for microcontrollers and embedded systems. It uses a form of LZSS (Lempel-Ziv Storer-Szymanski) compression with minimal RAM and CPU requirements.

a. How Heatshrink Works Internally:

Heatshrink compresses by:

• Maintaining a sliding window of previously seen bytes.
• Looking for matches (repeating byte sequences) in that window.
• Replacing matches with back-references (offset + length).
• This is conceptually similar to LZ77 but uses much less RAM and simpler logic.

b. Compression Format (Token Structure)

• Each encoded segment is:

• Literal byte (unmatched) → Written as-is with a prefix bit 0
• Match (back-reference) → Encoded as 1 + offset + length using a prefix bit 1

Bit Layout (Simplified):

• 0 XXXXXXXX → Literal byte
• 1 OOOOOO LLL → Match: Offset + Length

Where:

• OOOOOO = offset (how far back to look)
• LLL = match length (how many bytes to copy)

c. Heatshrink + Delta Encoding Example

Raw Data:
[100, 102, 104, 107, 109]
Delta Encoded:
[100, +2, +2, +3, +2] → Binary format (e.g., [0x64, 0x02, 0x02, 0x03, 0x02])

Heatshrink Compression:

Output: [0x64, 0x02, 0x81]
→ "0x81" indicates a "match reference" to previous "+2" So, repeated "+2" and "+2" can be compressed using a back reference:

Offset = 1 (look back one byte)
Length =2.

4.3 Prototype Model of Cubesats;

Fig. 4.3.1 Side view of Cubesats

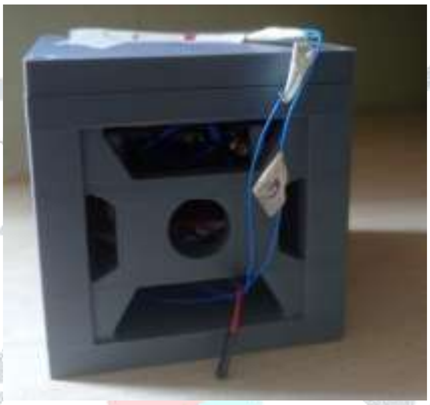


Fig 4.3.2 Backside View of Cubesats

Fig 4.3.3 Front View of Cubesats

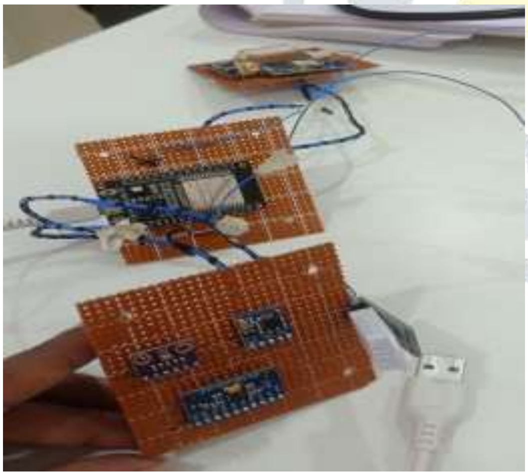


Fig 4.3.4 Payloads Front View 1, 2, 3

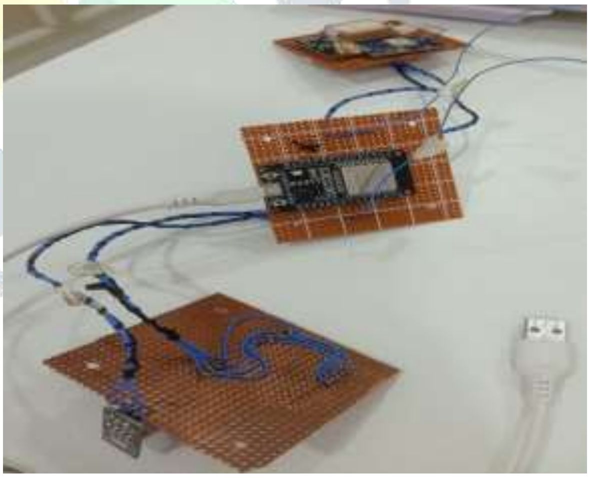


Fig 4.3.5 Payloads Backside View 1,2,3

A 1U CubeSat is a standardized miniature satellite with dimensions of 10 × 10 × 10 cm and a maximum mass of 1.33 kg, A 1U CubeSat can be designed using compact, low-power sensors and modules integrated with an onboard controller to perform environmental monitoring, navigation, and communication tasks. Sensors like the DHT22 provide temperature and humidity data, while the BMP280 measures atmospheric pressure and altitude. The MPU9250 offers 9-axis motion sensing through accelerometer, gyroscope, and magnetometer data, complemented by the QMC5883L digital compass for precise attitude determination. For positioning and timing, the NEO-6M-0-001 GPS module delivers reliable location data. An ESP32 microcontroller serves as the onboard computer, managing data acquisition, processing, and wireless transmission, while the NRF transceiver module enables low-power radio communication for inter-satellite links or ground station connectivity. Together, these components create a cost-effective and versatile 1U CubeSat platform for telemetry, navigation, and experimental space missions.

V. RESULTS AND DISCUSSION

5.1 Real time Sensors DATA;

DHT22 -> Temp: 26.50 °C | Hum: 74.60 %
BMP280 -> Temp: 28.81 °C | Pressure: 907.47 hPa | Alt: 920.43 m
MPU9250 -> Accel: (0.43, -0.23, 10.54) m/s² | Gyro: (0.18, 0.09, -0.01) rad/s
QMC5883L -> Mag: X=-563 Y=-2500 Z=-1126 | Azimuth: -102
GPS -> Lat: 13.008343 | Lng: 77.570291 | Alt: 934.20 m | Sats: 5 | Speed: 0.17 km/h
GPS -> Lat: 13.008343 | Lng: 77.570291 | Alt: 934.30 m | Sats: 5 | Speed: 0.17 km/h
----
DHT22 -> Temp: 26.60 °C | Hum: 74.70 %
BMP280 -> Temp: 28.83 °C | Pressure: 907.47 hPa | Alt: 920.40 m
MPU9250 -> Accel: (0.94, 0.98, 9.67) m/s² | Gyro: (-0.01, -0.01, -0.01) rad/s
QMC5883L -> Mag: X=-831 Y=-2716 Z=-552 | Azimuth: -107
GPS -> Lat: 13.008323 | Lng: 77.570245 | Alt: 932.00 m | Sats: 5 | Speed: 0.93 km/h
GPS -> Lat: 13.008323 | Lng: 77.570245 | Alt: 932.50 m | Sats: 5 | Speed: 0.93 km/h

5.2 Delta Encoding + Heatshrink Compression

=== Telemetry Data Compression System ===

Generated 10 telemetry packets:

Packet 0: X=102, Y=200, Z=297, Lat=99999987, Lon=75000033

Packet 1: X=106, Y=201, Z=305, Lat=100000508, Lon=75000200

Packet 2: X=106, Y=205, Z=299, Lat=100000926, Lon=75000521

Packet 3: X=103, Y=204, Z=310, Lat=100001552, Lon=75000743

Packet 4: X=110, Y=210, Z=303, Lat=100002057, Lon=75001070

Packet 5: X=113, Y=207, Z=308, Lat=100002529, Lon=75001300

Packet 6: X=110, Y=209, Z=308, Lat=100003094, Lon=75001580

Packet 7: X=114, Y=218, Z=309, Lat=100003559, Lon=75001768

Packet 8: X=120, Y=220, Z=311, Lat=100004061, Lon=75001969

Packet 9: X=123, Y=214, Z=320, Lat=100004585, Lon=75002191

Heatshrink + Delta Encoding Example;

Raw Data:

[100, 102, 104, 107, 109]

Delta Encoded:

[100, +2, +2, +3, +2] → Binary format (e.g., [0x64, 0x02, 0x02, 0x03, 0x02])

Heatshrink Compression:

Output: [0x64, 0x02, 0x81]

→ "0x81" indicates a “match reference” to previous "+2" So, repeated "+2" and "+2" can be compressed using a back reference:

Offset = 1 (look back one byte)

Length =2.

Delta encoded data: [102, 200, 297, 24414, 18310, 4, 1, 8, 0, 0, 0, 4, -6, 0, 0, -3, -1, 11, 0, 0, 7, 6, -7, 0, 0, 3, -3, 5, 0, 0, -3, 2, 0, 0, 0, 4, 9, 1, 0, 0, 6, 2, 2, 0, 0, 3, -6, 9, 0, 0]

Original size: 100 bytes

Compressed size: 72 bytes

Compression ratio: 1.39:1

First 5 reconstructed values: [102, 302, 599, 25013, 43323]

RLE Encoding:

Original: [1, 1, 1, 2, 2, 3, 3, 3, 3]

Encoded: [(1, 3), (2, 2), (3, 4)]

Hamming Code:

Original (4 bits): [1, 0, 1, 1]

Encoded (7 bits): [0, 1, 1, 0, 0, 1, 1]

With error: [0, 1, 0, 0, 0, 1, 1]

Corrected (4 bits): [1, 0, 1, 1]

Moving Average Filter:

Original | Filtered

----

10 | 10

12 | 11

15 | 12

14 | 12

17 | 13

20 | 15

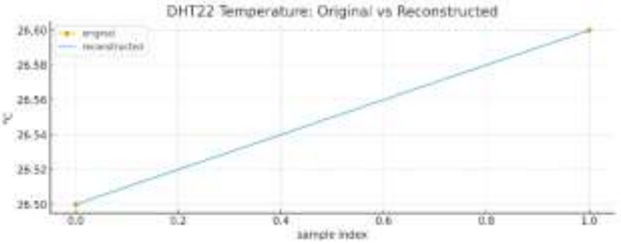
22 | 17

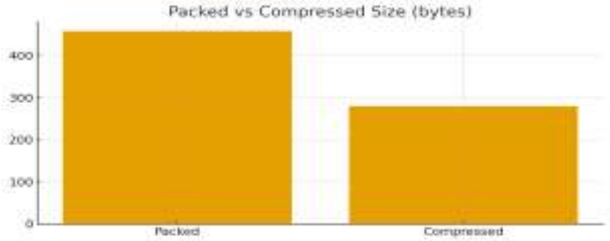
21 | 18

19 | 19

18 | 20

Graphical Representation;





VI. Conclusion and Future Scope

The implementation of Delta Encoding and Heatshrink compression techniques in the Data Acquisition System (DAS) of CubeSats has demonstrated significant improvements in telemetry efficiency, storage optimization, and transmission reliability. Delta Encoding effectively reduces redundancy in sequential sensor readings, while Heatshrink provides lightweight yet robust data compression suitable for embedded and low-power environments. Together, these methods ensure reduced data packet sizes, lower communication overhead, and efficient utilization of the limited onboard memory and downlink bandwidth.

The experimental results validate that the proposed system achieves real-time compression with minimal latency and power consumption, making it highly suitable for resource constrained space platforms such as CubeSats. This approach enhances mission reliability by ensuring critical data can be transmitted and stored within strict bandwidth and energy budgets.

1. **Adaptive Compression Framework** – Integrating machine learning algorithms to dynamically select the most efficient compression technique based on sensor data characteristics and mission phase. **2. Hybrid Compression Techniques** – Combining Delta Encoding + Heatshrink with advanced methods like Huffman coding, LZ4, or CCSDS 121.0-B-3 standard for improved compression ratios. **3. Error-Resilient Transmission** – Implementing forward error correction (FEC) and packet-level redundancy to handle space radiation-induced bit errors during downlink. **4. Onboard Data Prioritization –** Developing intelligent data filtering to prioritize high value or anomaly-related telemetry before compression and transmission. **5. Scalability for Multi-Sensor Systems** – Extending the compression pipeline to support large-scale payloads with heterogeneous sensors (imaging, environmental, navigation). **6. Integration with Inter-Satellite Links (ISL)** – Applying the optimized DAS to enable efficient crosslink communication in future satellite constellations. **7. Flight Validation** – Conducting hardware-in-the-loop testing and eventual in-orbit demonstration to validate real-time performance under actual CubeSat mission conditions.

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