Airbag equipped smart helmet for prevention of cervical spine injury

S Tharun[*], *G Vishal* Vaishnav, and *M Sangeetha*

B.E.Mechatronics, Sathyabama Institute of Science and Technology, 600119, Chennai, India

Abstract. One of the most severe consequences of two wheeler accidents is the occurrence of head and spinal injuries, which often cause long term disability or even death. The cervical spine, located in the neck area, is particularly at risk, and existing helmets mainly focus on protecting the skull rather than the neck. This project proposes the development of a smart helmet that includes an airbag system, specifically designed to protect the cervical spine. The system utilizes an inertial measurement unit (IMU) sensor, such as the BNO055, to continuously monitor acceleration, orientation and rotational movement. When the Arduino microcontroller detects unusual motion that indicates a fall or collision, it initiates the activation process. A solenoid valve, connected to a CO_2 cartridge, is triggered by a threshold based algorithm, causing a U shaped airbag either built into or attached to the helmet to inflate rapidly. This inflation provides essential neck support and occurs within milliseconds, ideally before the impact occurs. The design also considers the potential for reuse and compact integration, addressing the challenges of pre-crash detection and fast airbag deployment. The systems reliability and responsiveness are validated through hardware prototypes and simulations using Tinkercad and MATLAB Simulink. In addition to improving safety, this smart airbag helmet presents a scalable solution for practical application, aiming to reduce the severity of spinal injuries in motor vehicle accidents.

1 Introduction

Head and spinal injuries are among the leading causes of death or permanent disability in motorcycle accidents, which constitute a significant share of all traffic related injuries worldwide [8][9].

Traditional helmets offer little to no protection for the cervical spine during sudden falls or collisions, even though they do help prevent direct impacts to the skull. Because of its flexibility and sensitivity, the neck is especially prone to fractures, whiplash, and spinal cord injuries when exposed to sudden force. Recent innovations in rider safety, such as motorcycle airbag jackets, are often too costly or overly complex for everyday use. To address this gap, the Smart Helmet Airbag System has been developed as a cost effective, portable, and efficient solution for protecting the cervical spine [10].

* Corresponding author: tharunselva4@gmail.com

The system integrates a motion sensor, the BNO055, to record acceleration and orientation in real-time. This sensor data is analysed by an Arduino microcontroller, which is programmed to identify abnormal motion patterns that may indicate a collision or fall. Upon detection, a relay controlled solenoid valve releases compressed CO_2 from a cartridge, inflating a TPU coated nylon airbag. This airbag, positioned to support the neck, inflates within milliseconds, ideally before the rider makes contact with the ground. The design represents an important step forward in enhancing rider safety by emphasizing real-time detection, rapid deployment, and effective integration into standard helmet designs.

2 Existing system

2.1 Smart helmet integrated with Airbag system

Airbags are integrated into smart helmets to protect the head and neck during an accident. A prototype of this project. Acceleration and tilt angles are continuously measured by an MPU6050 sensor [7]. A microcontroller triggers the opening of a solenoid valve to release CO2 which inflates airbag installed in the helmet, when threshold values are exceeded. This is in contrast to the traditional shell and foam helmet, which provide fast impact absorption. The system's quick deployment and localize head protection are its main advantages. However its drawbacks are the need for precise threshold value, weight distribution problems for the comfort of the rider and difficulty of manufacturing mini airbags in a helmet. Its design is creative in converting automobile airbags to rider personal protective gear.

Fig. 1. Smart airbag with compressor [7]

2.2 Airbag protection and alerting system for elderly people

This wearable belt system protects senior citizens from fall related injuries. For monitoring acceleration and angular speed gyroscope and accelerometer sensors are integrated [6]. A CO2 cartridge is triggered to inflate an airbag around the abdomen to support the hips and spine when irregular patterns of value indicate a fall. A GSM module alerts caregivers in real time. Both physical protection and communication support are provided by the device. To of its advantages are reduced fractures and instant monitoring for elderly safety. The belt's short battery life, discomfort when it is used continuously, and false alarm during rapid movement are its disadvantages. The device illustrates the wearable airbags can move automotive safety into health, in spite of this limitations.

2.3 An automatic air inflated tubeless safety for motorbike rider

By inflating airbag while there is a collision, this jacket attempts to save motorcycle rider. It identifies sudden impact or free-falling situations with the help of piezo electric and accelerometer sensors [12]. When triggered, a CO2 inflator rapidly fills the chamber of the jacket which helps to protect the neck, spine and chest. The system operates independently, improving safety in real-world conditions compared to tethered designs. Advantages are autonomy from outside connections and more protection than alone with helmet. The disadvantages include additional weight, reduced comfort in warm conditions, and dependence on accurate sensor calibration. Regular replacement of CO2 cartridges also increases operational cost. The jacket still faces challenges in balancing safety, comfort, and cost effectiveness.

2.4 Wearable airbag technology: A study

Girish, et.al [13] have explained the wearable airbag used in vests, belt and jackets, highlighting their uses for industrial safety, elderly care and motorcycle use. To identify falls or collision, this systems samples MEMS motion sensors at high frequencies (up to 1000 Hz). Alpinestars Tech Air and Dainese Smart jacket are two market When triggered CO2 or helium fills airbags in 20 to 45 ms, covering vital areas like the collarbone, chest and spine as depictes. Examples that have proven to reduce injuries. High precision and multi-area coverage are some of their advantages. High accuracy and multi-area protection are among their benefits. The risk of false activations, replacement after deployment is drawback, though the research found that wearable airbags are effective but must be enhanced prior to being extensively employed.

3 Limitations of existing system

Although wearable protective technologies, like airbag-equipped motorcycle jackets and traditional helmets, have advanced, there are still a number of drawbacks that limit their usefulness in actual collision situations. The following are the main problems found:

3.1 User discomfort and bulky design

Much of the protective equipment and airbag jackets available in the present day are bulky, cumbersome, and unpleasant to wear on a daily basis. They are inappropriate for riders in hot, humid areas such as India because they are stiffly designed, restricting ventilation and mobility. Since users often resort to prioritizing comfort over security, it hampers adoption.

3.2 Delayed deployment time

Most commercial airbag systems employ tethered to the ground mechanical triggers or crash detection modules that are relatively slower. Since serious cervical spine injuries can happen milliseconds after impact, this inflation delay (typically 100-200 ms) decreases effectiveness.

3.3 Cervical spine limited coverage

The guarding of the thorax and chest is the main concern of existing systems. But too often, there is inadequate guarding for the cervical spine and neck, some of the most vulnerable areas in two-wheeler crashes. This imbalance creates the potential for severe or permanent damage.

3.4 Issues with accessibility and high cost

The majority of riders in developing countries cannot afford commercially available wearable airbags such as the Dainese D-Air or Alpine stars Tech-Air due to their prices being several tens of thousands of rupees. Widespread adoption is also hindered by expensive maintenance and cartridges replacement.

3.5 Sensor restrictions and false triggers

Many existing systems depend on basic accelerometers or tethers systems, which can lead to spurious deployments in sudden braking, hard cornering, or free fall without an impact. Such false alarms increase maintenance costs and reduce confidence of users.

4 Proposed system

4.1 Introduction to proposed system

The proposed system is an airbag helmet specifically designed to protect the cervical spine during two wheeler accidents. It integrates ESP32 microcontroller, BNO055 motion sensors, and a CO2 inflation system to deploy airbags in milliseconds to provide the user with maximum protection. The 9-axis IMU sensor in the helmet constantly monitors orientation, angular velocity, and acceleration. A solenoid valve is actuated by the system to release compressed CO2 into a semi U and T shaped TPU coated nylon airbag. When a change in motion patterns is detected, such as excessive tilt or sudden deceleration beyond the threshold, the airbag covering the neck and spine is actuated. The protective mechanism reduces the chance of spinal damage by immobilizing the cervical region. This system is particularly beneficial in two-wheeler accidents as it protects the spinal cord along with the head, while conventional helmets can only dissipate impact to the head [4]. The reusable airbag design of the system, low production costs, and compact electronics make it favourable for practical application. The helmet represents a significant breakthrough in motorcycle personal protective equipment as it integrates wearable safety technology with smart crash detection.

4.2 Novelty

Even though there are various commercial and research-based airbag protection systems [1] for the head, such as airbag collars and airbag helmets, which utilize pattern recognition of movements based on limited sensor parameters, the proposed Airbag-Equipped Smart Helmet for Cervical Spine Injury Prevention offers a unique helmet-based system that makes use of real-time inertial sensing and electronic control for faster crash detection [5]. The proposed system makes use of the BNO055 for real-time sensing of multiple parameters such as linear acceleration, angular velocity, and helmet orientation, which can be used for a multi-parameter crash detection algorithm, as opposed to only one parameter for crash detection. Moreover, the proposed system makes use of the airbag structure for cervical spine injury prevention by deploying the airbag structure around the helmet during crash events, making it a more focused protection system for head protection as opposed to other airbag protection schemes for the head, which may be expensive for the same functionality.

4.3 Working principle of proposed system

Real-time motion sensing and threshold detection form the basis of the operation. Accelerometer (linear motion), gyroscope (angular velocity), and magnetometer (orientation) data are continuously recorded by the BNO055 sensor. An Arduino microcontroller filters and processes this raw data. The system flags a possible collision if it detects abrupt deceleration of more than 6g or an abnormal angular tilt of more than 60°. The relay module is then triggered by a decision making algorithm, which opens a solenoid valve that is attached to a $CO2$ cartridges. The high-pressure gas inflates the TPU coated nylon airbag in 100 to 200ms in which the airbag will give a support to the neck and the spine in which it absorbs the impact and distributes it to reduce the risk of injuries.

Table 1. Traditional and proposed systems

Aspect	**Traditional Helmet**	**Proposed Smart Airbag Helmet**
Protection	Only head protection (hard shell foam	Head + cervical spine protection
Impact Absorption	Foam absorbs limited energy	Airbag deploys instantly, dissipating force
Detection	No crash detection	Real time motion sensing(BNO055)
Deployment timing	None	Airbag deploys in <200 ms
Reusability	Fully reusable	Reusable electronics replaceable CO_2 cartridge
Cost	Low	Slightly higher, but practical with low cost sensors

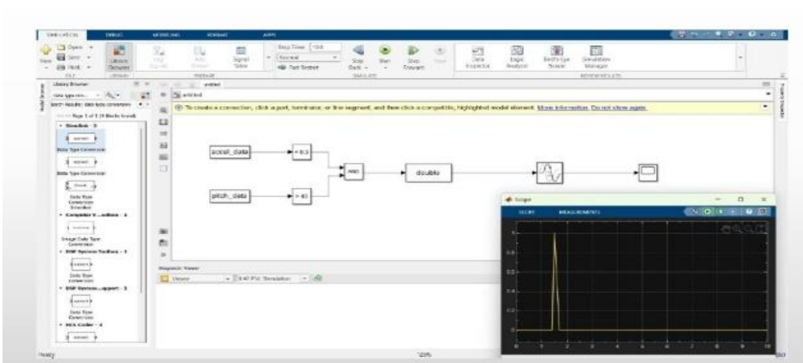

Fig. 2. Ideology of Sensor working

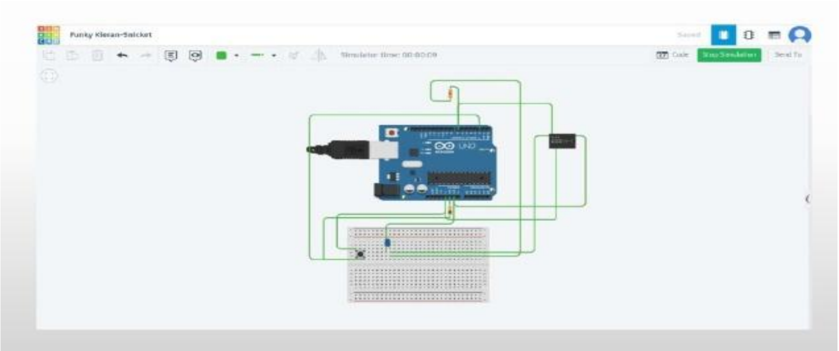

Fig. 3. Circuit connection.

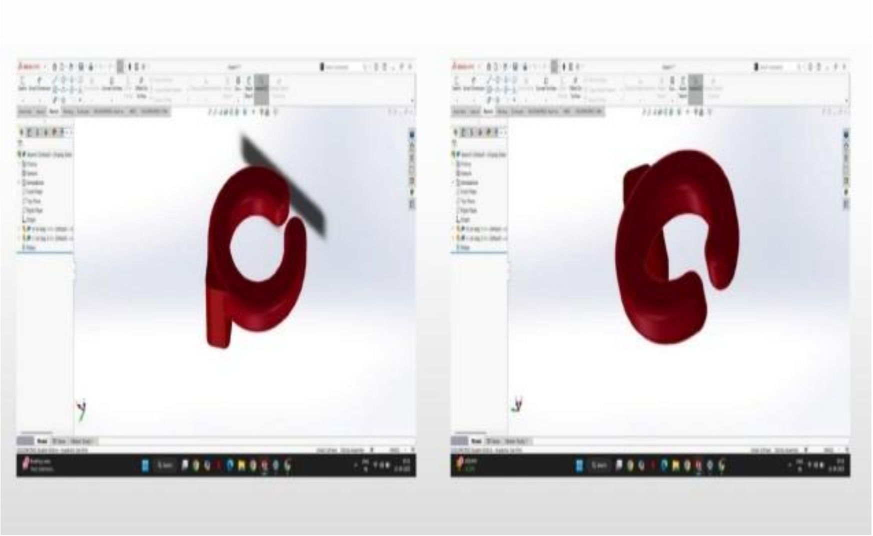

Fig. 4. Model of Airbag

5 Methodology

5.1 Sensor integration

The BNO055 sensor which is embedded in helmet continuously monitors the head orientation, acceleration and angular velocity. The placement of the sensor is to be accurate. The integration allows real time data of the riders head to detect the crashes which forms the foundation for effective crash detection.

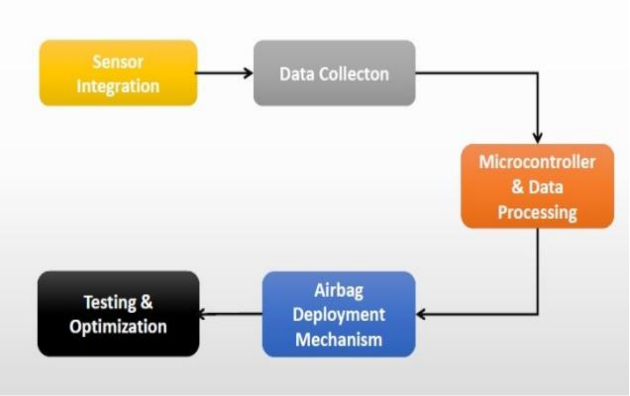

Fig. 5. Block diagram

5.2 Data collection

The real time data which is transmitted by the sensors which senses the riders acceleration, angular rate and orientation angles are collected. The microcontroller processes the acquired data by comparing with the threshold values and is used to determine the crash.

5.3 Microcontroller & data processing

The microcontroller will collect the incoming data through programming algorithms and it compares the values with the threshold values. If it detects any abnormal changes beyond the safety thresholds and detects the crash. Then the microcontroller activates the airbag mechanism for deployment.

5.4 Airbag deployment mechanism

Once the microcontroller sends the signal to release the airbag the solenoid valve is powered by activating a relay circuit upon the detection of crash. Upon crash detection, the solenoid valve releases compressed CO_2 gas, which inflates the airbag within milliseconds. The airbag which is made with TPU coated nylon expands across the neck areas protects the riders from neck cervical spine injury.

5.5 Testing and optimization

During the testing stage repeated crash tests take place so it can be modified and optimized for unnecessary explosion of the airbags. For this the inflation rate, algorithm thresholds and sensors sensitivity are all adjusted. High responsiveness, safety and practical usability are achieved in the final optimized design for everyday motorcycle use.

6 Threshold and Calculation

6.1 Acceleration Threshold Using BNO055

The BNO055 provides Linear Acceleration (m/s²) after removing gravity internally.
The crash detection is based on resultant acceleration magnitude.
Resultant acceleration equation [3][11]:

$$A = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

Where:
a_x= acceleration in X-axis
a_y= acceleration in Y-axis
a_z= acceleration in Z-axis
All values are obtained from the linear acceleration register of BNO055.
Crash acceleration threshold
Research on helmet impact detection shows head impact acceleration typically ranges between 5g – 10g.
For reliable detection without false triggering:

$$Threshold = 6g$$

Convert g to m/s²

$$1g = 9.81\, m/s^2$$
$$6g = 6 \times 9.81$$
$$A = 58.86\, m/s^2$$

Final acceleration condition

$$A \geq 58.8\, m/s^2$$

6.2 Orientation Threshold (Tilt Detection)

The BNO055 directly gives Euler angles:
Roll
Pitch
Yaw
These represent helmet orientation.
During normal riding:
Head tilt ≈ 0° – 30°
During a crash or head fall:
Tilt often exceeds 60°.
Orientation threshold

$$|\, \theta \,| \geq 60^{\circ}$$

Where:
θ= pitch or roll angle.

6.3 Time Threshold

To avoid false triggering due to bumps or vibrations, a time condition is added.
Typical crash duration:

$$t \geq 100\, ms$$

6.4 Final Deployment Logic

The airbag deploys only if all three conditions occur:

$$A \geq 58.8\, m/s^2$$

$$|\, \theta \,| \geq 60^{\circ}$$

$$t \geq 100\, ms$$

The crash detection algorithm utilizes the linear acceleration and orientation data provided by the BNO055 sensor. The resultant acceleration magnitude is calculated using the vector sum of the three acceleration components. A crash event is identified when the acceleration exceeds 6 g (58.86 m/s^2) and the helmet orientation angle exceeds 60°, indicating a potential head impact. To prevent false triggering due to transient vibrations, the condition must persist for a minimum duration of 100 ms before activating the airbag deployment mechanism [2].

7 Conclusion

The proposed smart helmet with a cervical spine airbag provides an effective solution for improving two-wheeler rider safety. Unlike existing systems that mainly focus on chest and head protection, this system specifically targets cervical spine protection, which is often neglected by conventional helmets. The integration of the BNO055 sensor enables accurate motion tracking, while the threshold-based detection algorithm ensures reliable crash detection. The solenoid-controlled CO_2 inflation mechanism enables rapid airbag deployment within milliseconds, providing immediate support to the neck and cervical region. The system is compact, cost-effective, and suitable for real-world applications. Overall, the proposed design offers a practical and efficient solution to reduce cervical spine injuries in motorcycle accidents.

References

1. D. Zhao and W. Chen, "Design and Research of Smart Neck Helmets Based on the KANO QFD Model and TRIZ Theory," *Security and Communication Networks*, vol. **2021**, pp. 1–10, (2021). https://doi.org/10.1155/2021/4693719
2. D. Tang, A. B. Usman, and A. Abba, "Fall Detection System with Accelerometer and Threshold-Based Algorithm," *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, vol. **11**, no. 3, pp. 45–50, (2023).
3. E. R. Lin, "Airbag Helmet: Design and Analysis of Helmet Piezoelectric Accelerometer," *J. Phys.: Conf. Ser.*, vol. **1593**, no. 1, pp. 012038, Jul. (2020). 10.1088/1742-6596/1593/1/012038

4. H. Yhdego, C. Paolini, and M. Audette, "Toward Real-Time, Robust Wearable Sensor Fall Detection Using Deep Learning Methods: A Feasibility Study," *Applied Sciences*, vol. **13**, no. 8, article 4988, (2023) https://doi.org/10.3390/app13084988
5. L. Musenich, L. Strozzi, M. Avalle, and F. Libonati, "D-HAT: a Diatom-Inspired Structure for a Helmet Concept Against Trauma," *Adv. Intell. Syst.*, vol. **7**, no. 4, 2400419, Feb. (2025) https://doi.org/10.1002/aisy.202400419
6. M. Ibrahim, S. Shawish, S. Aldroubi, A. Dawoud, and W. Abdin, "Airbag Protection and Alerting System for Elderly People," *Applied Sciences*, vol. **13**, no. 16, art. no. 9354, (2023). https://doi.org/10.3390/app13169354
7. M. Kumar B., M. S., V. M., and A. K. G. R., guided by Prof. K. Sindhu, "Smart Helmet Integrated with Airbag System," *Int. J. Prog. Res. Eng. Manag. Sci.*, vol. **3**, no. 6, pp. 850–853, Jun. 2023. https://www.doi.org/10.58257/IJPREMS31560
8. O. Cherta-Ballester, M. Llari, T. Bros, V. Honoré, and P.-J. Arnoux, "Coupling a Wearable Airbag with a Back Protector: What are the Effects on Motorcyclists' Safety?" in *Proc. IRCOBI Conference 2023*, Florence, Italy, pp. 472–473, Sep. (2023).
9. O. Cherta-Ballester, M. Llari, V. Honoré, C. Masson, and P.-J. Arnoux, "Investigating the Effects of Inflating a Wearable Airbag Under a Motorcycle Jacket," in *Proc. IRCOBI Conference 2024*, Stockholm, Sweden, pp. 495–496, Sep. (2024).
10. P. Rodegast, S. Maier, J. Kneifl, and J. Fehr, "On Using Machine Learning Algorithms for Motorcycle Collision Detection," *Discover Appl. Sci.*, vol. **6**, art. no. 326, Jun. (2024). 10.1007/s42452-024-06014-w
11. S. M. K. M. Siam, K. I. Sumaiya, M. R. Al-Amin, T. H. Turjo, A. Islam, A. H. M. A. Rahim, and M. R. Hasan, "Real-time accident detection and physiological signal monitoring to enhance motorbike safety and emergency response," *arXiv*, vol. abs/2403.19085, Mar. (2024). https://arxiv.org/abs/2403.19085
12. R. L. Bulathsinghala, S. Fernando, T. S. S. Jayawardana, N. Heenkenda, S. Jeyakumar, P. Packiyarasa, G. Hemamala, and D. Wijesena, "An Automatic Air Inflated Tubeless Safety Jacket for Motorbike Riders," Research Journal of Textile and Apparel, vol. 25, no. 3, pp. 185–202, (2021). https://doi.org/10.1108/RJTA-01-2021-0002
13. A. Girish, V. N., H. C. B., S. M. K., H. P. Menon, and D. Devasia, "Wearable Airbag Technology: A Study," Grenze International Journal of Engineering and Technology, vol. 9, no. 1, pp. 3085–3088, Jan. (2023). https://thegrenze.com/pages/servej.php?fn=532_1.pdf&name=Wearable%20Airbag%20Technology:%20A%20Study&id=1750&association=GRENZE&journal=GIJET&year=2023&volume=9&issue=1