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Low-Cost Integrated Airbag Safety System in IoT-Based Smart Wearables

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***Abstract*— Drowning is one of the major causes of accidental death around the world, especially where there is no access to a rapid rescue system. The conventional life jackets provide buoyancy but are insufficient in critical situations when the victim is unconscious or is not able to call for help. To overcome this shortcoming, this study presents an independent wearable safety device that can sense underwater distress and activate immediate rescue services. The system is set to automatically react to real-time physiological and environmental conditions without any user intervention for personal protection and child safety. It combines a live server-based alerting system and dual-function design, unlike the current solutions, but cost effective for widespread availability. Currently available technologies tend to be limited by expense, single use design, or absence of communication capability, and thus are not usable to extensive application. This study presents an innovation that fuses smart sensing, real-time notifications, and low cost which sets it apart from available commercial systems. In comparison with the similar easily accessible alternatives, it estimates to be around 47% cheaper without compromising performance. It has been field tested and assessed under a wide range of weights to ensure efficiency. The end product is a working, scalable, and cost-effective solution that can easily lower drowning rates, especially in the aquatic environment with limited resources.**

Keywords—Drowning Prevention, Arduino, Wearable Safety, Automated Airbag, IoT, Dual-Function Design.

I. INTRODUCTION

In the era of rapid innovation, wearable safety systems are redefining how we approach drowning prevention and aquatic health emergencies [1]. Traditional life jackets only keep a person afloat but they do not have the ability to sense trouble or to act automatically when there is a need [2]. Recent advances in wearable tech have allowed for real-time physiological and environmental monitoring to be actual components of personal safety devices [3]. Though researchers have already delved into heart rate and pressure sensors for emergency detection, implementation on a broader scale has been minimal due to factors that include lack of proper water resistance, absence of multi-sensor systems, hardware costs, and weak real-time communication.[4]. The development of this study arose from addressing those inadequacies, especially in a high risk, low resource setting. With the introduction of a cost effective smart small-sized wearable airbag life jacket, the proposed system tries to bridge the gap between passive flotation and active life-saving technologies [5]. This innovation has been built around an ESP32 microcontroller that takes inputs from sensors MAX30102 for heart rates and MS5837-30BA for pressure and depth to evaluate a swimmer's condition at that moment. If any critical condition is detected, an automatic inflation of the airbag is done through solenoid valve. GSM also sends an emergency message. It also has an emergency panic button and LED alert strips for better visibility and manual control.

This project will have a core attribute of functioning both versions, that is, a child version with a water detection sensor to enable safety mechanisms upon accidental entry into the pool, and an integrated sensor version for adults to focus on medical emergencies while swimming. Unlike most present models, this model provides safety for both supervised and unsupervised swimmers and it also has a centralized server interface to monitor data in real time and trigger intervention at a distance when needed. All these feature places the proposed system as a reliable, scalable, and cost efficient innovation for drowning prevention and aquatic safety in personal as well as institutional settings [6]. This wearable system keeps track of real-time body signs and surroundings, and it automatically inflates an airbag in serious situations. The development showcases innovation in low-cost wearable safety technology, particularly for drowning prevention in under resourced and high risk environments.

II. LITERATURE REVIEW

In wearable safety technology, various research efforts paved the path towards drowning protection systems. One such study designed an airbag system using pressure sensors and smartphone gyroscopes for sensing abnormal underwater situations and inflating flotation support accordingly. Effective for simple situations but lacking in real-time communication for external rescue assistance [7]. Another study proposed a wearable system to track depth and heartbeat levels to identify possible drowning cases in swimming pools and alert if there are abnormal readings. Most of these devices are depended on additional hardware modules or are not multi-functional and thus less useful for practical applications [8].

In another more recent attempt, researchers presented a waterproof wearable system with heart rate, blood oxygen saturation, activity, and depth sensing, along with a Wi-Fi module for remote alerting in real time. Although the system features enhanced sensing capability, it relies strongly on continuous network connectivity, which restrict its use in remote locations [9]. Another experiment employed a motion-stabilized pulse oximeter to measure oxygen saturation and heart rate in low movement situations, with the ability to identify drowning in its initial stages without generating too many false alarms [10]. In addition, researchers developed some sensor based drowning protection systems and established that recent advancements have greatly enhanced response latency, the possibility of integrating tiny sensors, and the affordability of systems [11]. Vision based drowning detection systems were also developed with AI-powered surveillance, radar, and computer vision. While highly accurate, these systems are plagued by privacy issues and ongoing environmental calibration needs and thus are less suitable for wearable personal devices [12].

III. METHODOLOGY

This paper describes the principle of a smart life jacket system that is built for quicker and automated responses during water related incidents. The system operates on a microcontroller as a Central Processing Unit, taking different sensor inputs with corresponding outputs in the actuation of life-saving systems. The system uses a pressure sensor to detect water pressure and thus estimate the depth to which the user is being immersed. A heart rate sensor monitors the condition of the swimmer, and a water sensor found only in the child model of the jacket, which detects continuous contact with water, and assists in establishing possible accidental falls.

The microcontroller analyzes these inputs relative to preprogrammed thresholds and triggers the emergency sequence if the measured values exceed the threshold. Upon the confirmation of emergency, the GSM sends SMS alerts to preprogrammed phone numbers to inform the rescuers about the situation. In addition, it triggers the opening of the solenoid valve for releasing the compressed air from the CO_2 cylinder, inflating the airbag within the prescribed time intervals, while a visual LED alert system simultaneously provides immediate onsite indication even when the GSM connectivity is weak. GSM module was utilized in place of GPS since it is low-cost, easy to operate, and efficient in closed areas such as indoor swimming pools where GPS signals would be weak or absent. Nevertheless, GPS can be incorporated in future outdoor models for location tracking.

The system is developed with a dual nature to help in a better way. It contains a water sensor for children's safety jacket to make its operation automatic, even when a child falls into the water without being supervised. To reduce false alarms in children's jackets due to brief splashes or accidental water contact, the water sensor is adjusted to react only if water contact exceeds 3 seconds. The delay is set based on tests, which indicated that accidental splashes or momentary water contact lasted less than 3 seconds. The delay eliminates unwarranted inflation without inhibiting the system from responding rapidly to actual emergencies. The inflation process is governed by the valve activation duration:

$$T_{inflate} = \frac{V_{airbag}}{Q_{flow}} \quad (1)$$

Where,

$T_{inflate}$: Inflation time

V_{airbag}: Volume of airbag

Q_{flow}: Flow rate of CO_2 gas

The total response time, or Time to Swell (TTS), is calculated as the sum of the detection time, T_{detect}, and inflation time, $T_{inflate}$:

$$TTS = T_{detect} + T_{inflate} \quad (2)$$

While testing and recording data, the lowest TTS was recorded as 2.17 seconds, ensuring rapid deployment of the airbag for optimal safety. There is also a manual push button so that the safety features can be operated manually for redundancy in case of sensor malfunction or unforeseen conditions.

A. Block Diagram

Fig. 1 represents the block diagram of an improved life jacket system to enhance safety during water emergencies. The system consists of several sensors, a microcontroller, and several actuators for fast detection and actuation of possible drowning incidents. The microcontroller is the centerpiece of the system, which collects all the input data and drives suitable outputs. Depth and pressure sensor keeps a watch on the water depth and pressure, water sensor detects the presence of water, heart rate sensor inputs vital physiological data; and a length detector to measure certain distances during operation are the main inputs to the microcontroller. It also connects an emergency panic button that may be manually turned on in case of any critical instance. The microcontroller gives a number of outputs for the safety of the user based on the input data. Outputs are lighting up the red LEDs as a means of visual indication, a solenoid valve for releasing CO_2 gas to inflate the airbag, and a GSM module to send emergency SMS to the registered contact numbers. The airbag inflates instantly and provides buoyancy for safekeeping. Precise timing mechanisms underpin the reliability of the system.

The modular design makes the operation in emergency situations fast and effective. Adding optical indicators, that is, LEDs, make this system more effective when warnings are there, thus viable even in regions having poor GSM connectivity. Advanced sensors and actuators in a compact design make this system a significant leap forward in wearable safety technology.

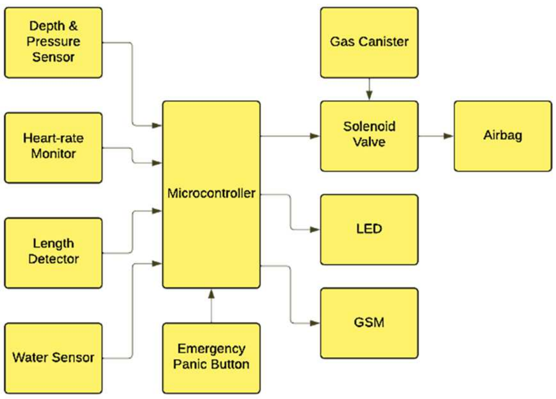


Fig. 1. Block diagram of the proposed prototype airbag safety system.

B. System Flowchart

The flowchart in Fig. 2 illustrates the functional structure of a sophisticated water safety system. The microcontroller-based system starts with initializing all the sensors, including the MS5837-30BA pressure sensor that is constantly measuring water pressure. Once the pressure goes above a predefined set point, suggesting a possible emergency, the system activates an inflation mechanism. A panic button provides a manual override of the safety systems during emergencies. On activation, floatage is enhanced through inflation of the airbag using a CO_2 cartridge, and red LEDs flash to indicate the emergency and guide rescuers to the user. Meanwhile, the GSM module transmits the SOS message to preprogrammed numbers. The visual warning system eliminates GPS, and it is a low-cost option. The system resets itself upon completion of the emergency response.

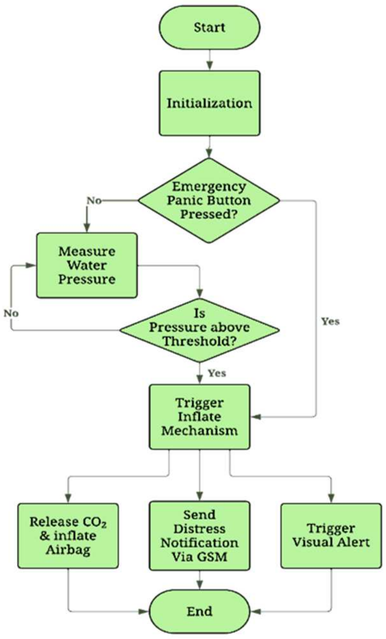


Fig. 2. System flowchart of the prototype airbag safety system.

C. Safety Mechanism and Dual-Function Design

The proposed system incorporates a multi-level safety mechanism to ensure quick and consistent response in case of any emergency condition, including severe system failure. Using built-in sensors, it continuously measures depth, water pressure, and heart rate. Automatic deployment of the airbag occurs if any reading surpasses safety standards.

An emergency panic button serves as a manual override to assist automatic detection, allowing swimmers to initiate the rescue mechanism on their own if they feel uneasy or frightened. The remote server adds an extra layer of protection as the server end staff keeps an eye on those data in real time so they can respond right away. Rescue personnel may attempt to remotely activate the airbag via the server if airbag inflation is unsuccessful, because of hardware malfunction or connection problems. The system requires one last failsafe, and that is human intervention. Even in the event of a critical failure in the system, guaranteed safety is provided by the instant arrival of rescue personnel in the vicinity of the swimmer's position to deliver immediate assistance.

It is the dual-functionality model of this system, developed for personal as well as family security, that makes it so efficient. The main function for regular users responds to panic button presses or extreme pressure levels. But a unique sub-function has been introduced with children's security in mind. To reduce false alarms due to water splashes or exposure to light, the water sensor within the life jacket is designed to automatically trigger safety mechanisms upon detecting constant contact with water for a minimum of 3 seconds. This feature secures children from falling into the water accidentally or against parental instructions. Even without adult supervision, immediate safety precautions are ensured, proving the system's design not only protect users but also strengthens the device itself as one of the best family-oriented water security solutions out there.

IV. Simulation and Hardware Models

A. Simulation Model

The simulation model of Proteus, showing the operating structure of the intelligent life jacket system, including Arduino Uno, GSM module, and water sensor, demonstrates the transitions between its states to realize the key functionalities in case of water detection. Fig. 3(a) is the system at its inactive stage. In such a mode of operation, no presence of water is detected by the water sensor, and therefore, the entire system remains at rest. The inactivity of the system is confirmed by the display attached to the system. Fig. 3(b) depicts the case when water has been detected and the system switches automatically into operational mode. The water sensor sends a signal to the Arduino Uno, thus triggering the safety features. An LED is used to represent the visual warning system. Meanwhile, the system send notifications via the GSM module. Fig. 3(c) shows the critical situation where the detection of water automatically sends distress notifications via GSM to a pre-set number. The simulation's virtual terminal confirms emergency messages are sent, enabling real-time communication. This is helpful for children, as the water sensor attached to their safety jacket triggers the safety mechanism and notifies guardians or emergency services upon water contact detection. This simulation provides evidence for two functionalities, the default action of regular emergencies and the special action for child safety along with a GSM module for communication, combined to a visual alert system, which serves as an effective and efficient means to approach potential water hazards.

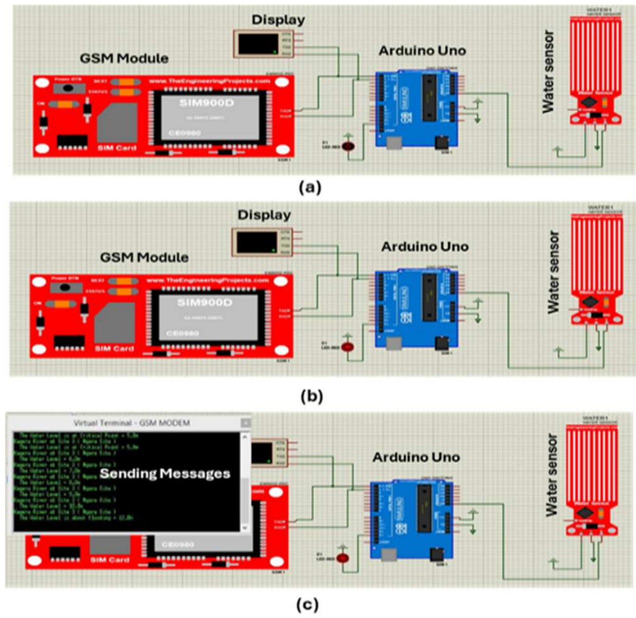


Fig. 3. (a) Simulation model of proposed airbag safety system (off) condition, (b) Simulation model of proposed airbag safety system (on) condition, (c) Sending messages after accident detection.

B. Hardware Model

As indicated below in Fig. 4 is the hardware implementation model that houses several components which provide aquatic safety for the entire project. In it, the microcontroller is situated centrally within the entire system to control all functionalities. Depth and pressure are measured by the MS5837-30BA depth and pressure sensor, which assists in the detection of a potential emergency.

For the dual-function design, a water sensor is implemented only in the kids' safety jacket to detect water contact, and after a short delay, runs protection mechanisms to keep children safe in unexpected situations. In case of any emergency, the system triggers a solenoid valve actuated airbag inflation mechanism through which compressed gas is discharged to inflate the airbag. The GSM module used for communication sends the critical alerts to target receivers, like parents or any rescue workers, to act accordingly. Red LEDs are used in this system to act as an easily visible kind of visual alarm. The integrated design shall combine advanced pressure monitoring, robust communication, and life-saving features to provide an effective response in case of a drowning emergency. The addition of dual-functionality design meets the peculiar safety needs of children, hence extending the usability and impact of the project in aquatic environments.

Fig 4. The smart wearable prototype with an integrated airbag safety system.

V. Result Analysis

Tests were run at 3.5 ft to 7 ft water depth for five different weight groups to test the operation of the proposed smart airbag system. It was observed that the system operated consistently to detect water depth, measure pressure, and initiate the airbag inflation mechanism within seconds.
Results obtained from the MS5837-30BA sensor, as tabulated in Table I, show that pressure increases positively with water depth, from 20.7 kPa at 3.5 ft to 43.5 kPa at 7 feet of water depth. On the other hand, the detection time was inversely proportional to the pressure, and it ranged from 1.21 seconds by a 5 kg load at 3.5 ft depth to 0.77 seconds by a 25 kg load at 7 ft depth. Inflation time had minimal differences between various weight ranges, with the maximum recorded time of 1.5 seconds and the minimum at 1.2 seconds. The total response time, ranged from 2.17 seconds for a 25 kg load at 7 feet to 2.55 seconds for a 10 kg load at 4.5 feet, ensuring the system can respond rapidly within 3 seconds.
During the testing of child safety jacket, some false alarms were experienced due to splashes or shallow contact. To reduce unwanted deployments, the water sensor was set with a 3 second trigger delay, requiring ongoing exposure before inflation. No false activations were noticed with the adult model. However, in certain instances, the system did not respond due to hardware misreads or unstable power. This reinstated the importance of the emergency panic button and LED warning system, which functioned as expected and ensured safety despite the sensor failure.
Besides, practical effectiveness in swimming pool applications was assured by limiting the maximum test depth to 7 ft. Unlike other commercial life jackets that has delays or no flotation without manual operation, the proposed system was significantly faster and sensitive in providing safety.

TABLE I. Performance Analysis of Proposed Airbag System at Different Weights and Water Depths.

Weight (kg)	Water Depth (ft)	Pressure Detected (kPa)	Detection Time (s)	Inflation Time (s)	Total Time to Swell (s)
5	3.5	20.7	1.21	1.2	2.41
10	4.5	26.6	1.05	1.5	2.55
15	5.5	33.4	0.90	1.3	2.20
20	6.5	39.2	0.81	1.5	2.31
25	7	43.5	0.77	1.4	2.17

A. Graphical Result Analysis

The Weight vs. Water Depth vs. Detected Pressure graph, shown in Fig. 5, shows how increased weight results in deeper submersion and, therefore, higher detected pressure. From 5 kg to 25 kg, the increase in water depth goes from 3.5 ft to 7 ft, and the corresponding detected pressure rises from 20.7 kPa to 43.5 kPa. Hence, weight, depth, and pressure are directly proportional to one another. The second graph, represents Water Depth vs. Total Time to Swell vs. Weight, depicted in Fig.6, provides an overview of how total response time changes with depth and weight. Whereas, the detection time decreases by increasing depth, inflation time is still contained within a tight range of values for fast triggering. The system retains a total swelling time between 2.17 to 2.55 seconds, proving its efficiency in case of emergencies.

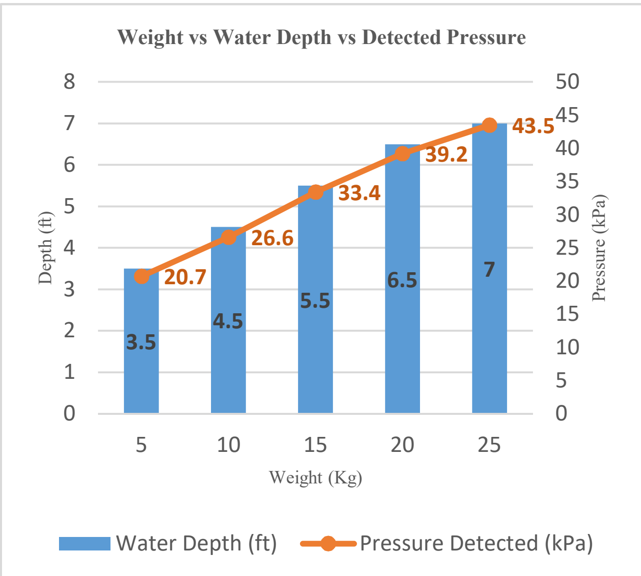


Fig. 5. Correlation between weight, water depth, and detected pressure in the proposed airbag safety system.

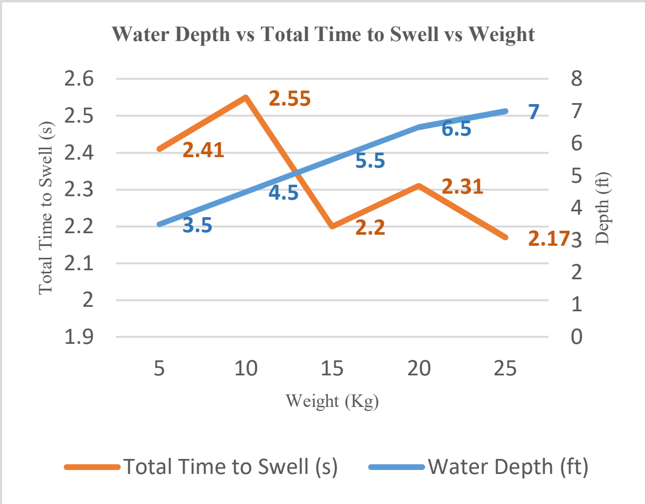
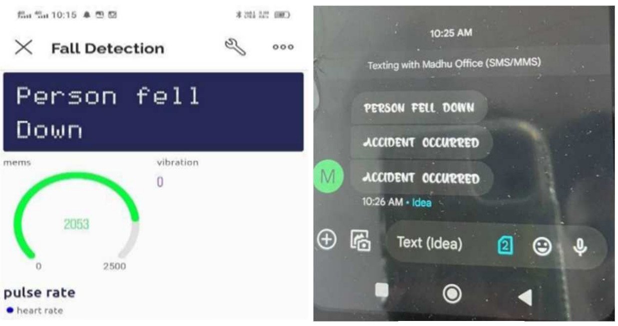


Fig. 6. Representation of water depth and total swelling time against the weight.

B. Server Integration

The proposed system integrates a server for real-time monitoring and actuation along with enhanced safety management. The system continuously monitors parameters such as heart rate, water depth, and pressure, and provides instant status in case any person falls into the water. Fig. 7(a) illustrates the "Fall Detection" interface, which reflects a "Person fell down" warning associated with the pulse rate for immediate evaluation. Fig. 7(b) illustrates an important dual alert mechanism that promptly conveys any message to the rescue team, thereby preventing accidents related to drowning. In the event of false alarms like those caused by water splashes on children's coats, the server assists in verifying genuine emergencies by analyzing all the sensor data before triggering the rescue signals. If a local sensor or device fails to trigger the response, the server offers a remote override system to deploy the airbag manually via the dashboard. Visual alert and emergency notification can also be activated remotely to provide an additional layer of safety in case of communication breakdown or equipment failure. Redundancy contributes to the reliability of the entire system and enables fast and precise emergency reaction.



(a) (b)

Fig. 7. (a) Heart rate observation on the server. (b) The SMS notification sent to the rescue team.

VI. Comparison Study and Analysis

Table II shows that the proposed system shows considerable enhancements over available solutions by incorporating a sophisticated depth monitoring mechanism, a low-cost high-performance microcontroller, and an innovative dual-function design appropriate for routine users and children. Compared to similar market available products, advanced depth monitoring up to 7 feet, and real-time dual communication through GSM and visual alerts, makes the system quicker and efficient, while market alternatives fall short during emergencies. These improvements directly contribute to safer real-world deployments, particularly in resource constrained environments, and positions the system as an excellent candidate to complement existing smart life-saving wearables.

TABLE II. Comparison Between Traditional and Proposed Systems in Water Safety Wearables.

Categories	[13]	[14]	[15]	[16]	[17]	Proposed System
High Accuracy Pressure Sensor	X	X	X	✓	X	✓
Depth Monitoring (up to 7 ft or more)	X	X	X	X	X	✓
Response Time (less than 3 seconds)	X	X	✓	X	✓	✓
Dual Communication Mode	X	X	✓	✓	X	✓
High Energy Efficiency	X	X	✓	X	X	✓
Versatility (Dual Functionality)	X	X	✓	✓	X	✓
Cost Efficiency	X	X	X	X	X	✓

VII. Project Finance

The summary in Table III provides a comprehensive overview of the key components needed for the integrated airbag safety system, along with their estimated costs.

TABLE III. The Final Cost For The Project And Analysis.

Name of Components	Quantity Used	Proposed Sensor Cost (BDT)	Equivalent Indian Sensors (BDT) [18] [19]
Arduino Uno	1	900	2125 (Arduino Compatible)
MS5837-30BA Depth & Pressure Sensor	1	3050	3000 (Ultra Small Gel Filled Pressure Sensor)
Heart-Rate Monitor	1	1000	3550 (Heart Rate Sensor with MAX32664)
Length Detector	1	3500	7000 (Length Measuring Sensor)
Water Sensor	1	450	2800 (Water Level Sensor & Transmitters)
Emergency Panic Button	1	550	450 (Panic Button Alarm)

Gas Canister	1	1250	2600 (Venus Yellow Chlorine Gas Mask with Canister)
Solenoid Valve (Built-in Regulator)	1	3000	8000 (Water Solenoid Valve)
LED Strip	1	350	450 (240 LED Strip Light)
GSM Module	1	450	425 (GSM Module (Sim 800L)
Airbag	1	3000	3000
Jersey/Vest	1	500	350
Resistor	1	5	5
12V Battery	1	100	320 (Lithium-ion)
5V Battery	1	80	100 (Lithium-ion)
Total (BDT)	**1 Unit**	**18185**	**34175**

The major objective of this project was to create a complete system, with the cost analysis focusing on the acquisition of major equipment for its effective implementation. In order to determine the estimated total costs of the project, there was an extensive research process involving a thorough investigation of components from different producers and suppliers in Bangladesh and India. This approach also included a thorough cost comparison between the selected sensors and their alternatives in the Indian market, offering a cost effectiveness of almost $\left(\frac{34175-18185}{34175} \times 100\%\right) = 46.78\% \approx 47\%$ with a clear understanding of the financial implications of acquiring the necessary resources for the project.

VIII. CONCLUSION

The proposed airbag safety system successfully met its goals through a combination of novel design, real-world testing, and inexpensive implementation. The system exhibited emergency response with detection in as short as 1.21 seconds and inflation within 1.5 seconds. In testing, there were occasional false alarms in children's safety mode caused by splashes, which led to the incorporation of a 3 second threshold. There were no false alarms in adult use, and manual override features averted rare system failures. These mechanisms provide continued protection even in the case of failure conditions, while a critical observation of its effect provided insights into future development, including the integration of machine learning for earlier detection for emergencies, poolside cameras for better monitoring, and GPS tracker for outdoor safety jacket models. Cost analysis demonstrated that the proposed system is 47% less expensive than comparable systems, which proves the affordability for large-scale implementation. The system's dual-function capability, real-time server monitoring, and small-scale integration qualify this as an outstanding candidate as a scalable drowning prevention system, especially for low-resource environments. This study takes wearable safety technology to the next level by providing an effective, accurate, and affordable method of real-time underwater emergency response.

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