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Electrical Conduction Mechanism of Various Lithium-Mixed Layered Tri- and Tetra-Alkali Titanates

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Abstract— Sintered ceramics of lithium-mixed (0.2, 0.4 and 0.6 molar % Li_2CO_3) layered $\text{Na}_2\text{Ti}_3\text{O}_7$, $\text{K}_2\text{Ti}_4\text{O}_9$ and $\text{Rb}_2\text{Ti}_4\text{O}_9$ were prepared by a solid-state reaction route. Ionic conduction becomes more difficult as more lithium enters the interlayer space, since the smaller ions shrink the interlayer channels. Li^+ substitution at Ti^{4+} sites and at interlayer alkali sites loosens electrons from the titanate groups, which then conduct by hopping. In the lowest-temperature region I, electronic hopping co-exists with exchangeable interlayer ionic conduction; in region II, hindered interlayer ionic conduction co-exists with suppressed electronic hopping; and in the highest-temperature region, modified interlayer ionic conduction dominates. The Rb-based system also shows an anomalous region in which interlayer ionic conduction prevails over electronic hopping.

Index Terms— Layered ceramics, mixed electronic-ionic conduction, alkali titanates.

I. INTRODUCTION

Layered compounds have been widely reviewed [1], [2], and Aurivillius-type phases, $\text{M}_{n+1}\text{B}_n\text{O}_{3n+1}$, are of interest for electro-optical devices because most show ferroelectric properties. Substituted layered titanates $\text{Na}_2\text{Ti}_{3-x}\text{M}_x\text{O}_7$ and $\text{K}_2\text{Ti}_{4-x}\text{M}_x\text{O}_9$ have been studied for pillaring and photocatalysis [3], and the ac conductivity of $\text{Na}_2\text{Ti}_3\text{O}_7$ and $\text{K}_2\text{Ti}_4\text{O}_9$ was first reported by Kikkawa et al. [4]. The structure of $\text{Na}_2\text{Ti}_3\text{O}_7$ was determined by Andersson and Wadsley [5] and refined by Yakubovich and Kireev [6], [7]. Sodium trititanate has an exchangeable interlayer cation [8] and permits ionic conduction along the layers, which is why it is used as an ion exchanger [9]. Pal et al. [10]–[15] reported EPR, dielectric and ac conductivity studies of sodium trititanates with only 0.1 molar % (about 5%) lithium, and Shilov et al. [16] reported the structure of $\text{Na}(\text{Na}_{1-x}\text{Li}_x)\text{Ti}_3\text{O}_7$. Here we synthesize lithium-mixed sodium trititanate and potassium and rubidium tetratitanates by solid-state reaction and characterize their electrical conduction mechanisms.

These samples are promising for the electronics industry, and the results show how mixed and doped impurities shape the conduction mechanism.

II. EXPERIMENTAL

A. Synthesis

Lithium-mixed sodium trititanate, potassium tetratitanate and rubidium tetratitanate samples (denoted SLT, PLT and RLT) were prepared by grinding Na_2CO_3 , K_2CO_3 or Rb_2CO_3 with Li_2CO_3 and TiO_2 (AR grade, Merck, Germany) in stoichiometric ratio. The powder was heated at 1073 K for 16 h, cooled, reground for an hour and pressed at 15 MPa into pellets (10.25 mm diameter, 1.2 mm thick). The pellets were covered with the remaining powder and sintered again at 1073 K for 16 h, and their flat faces were coated with air-dried silver paste.

B. XRD

Patterns were recorded at room temperature on an Iso-Debyeflex 2002 (Rich Seifert & Co.) using $\text{Cu-K}\alpha$ radiation (30 kV, 20 mA) to confirm phase formation.

C. Conductivity

Polished, silver-coated pellets were mounted in a holder and evacuated to 10^{-3} mbar. The loss tangent ($\tan \delta$) and parallel capacitance (C_p) were measured over a range of frequencies and temperatures with an HP 4194A impedance analyzer, and the bulk ac conductivity was obtained from $\sigma = G \cdot t/A$, where G is the conductance, t the pellet thickness and A its cross-sectional area.

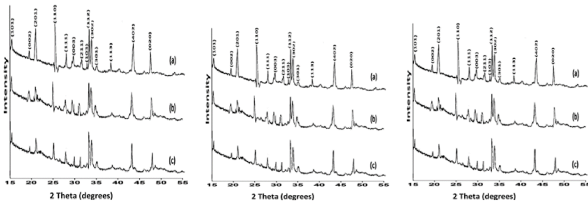
III. RESULTS AND DISCUSSION

The monoclinic layered structure is retained across the lithium series, so Li^+ is incorporated into the lattice without changing the basic framework. AC conductivity is thermally activated and rises with temperature, consistent with hopping-type conduction, and its frequency dispersion points to both grain and grain-boundary contri-

butions. The $\ln(\sigma T)$ versus $1000/T$ plots show distinct conduction regions whose mechanisms depend on lithium content and frequency, so lithium substitution modifies the defect chemistry and the electrical performance of these ceramics.

A. XRD Analysis

XRD confirms single-phase layered structures for $A_{2-x}Li_xTi_4O_9$ ($x = 0.2, 0.4, 0.6$) with no secondary phases (Fig. 1). Li^+ (≈ 0.076 nm) can replace the larger Rb^+ (≈ 0.102 nm) with only a slight lattice contraction. The structure is monoclinic (space group $C2/m$; $a = 1.8255$ nm, $b = 0.3790$ nm, $c = 1.2017$ nm, $\beta = 106.43^\circ$): zig-zag chains of TiO_6 octahedra run along the b -axis, joined by shared edges and corners, with the alkali ions in open interlayer sites at two vertical positions ($Y = 1/4$ and $3/4$). The Rb^+ ions occupy an 8-coordinate site ($Rb-O$ 2.86–3.23 Å) and a 6-coordinate site (2.81–3.16 Å), and the four inequivalent Ti^{4+} sites have $Ti-O$ distances of 1.74–2.37 Å. These spacious interlayer sites can host smaller ions such as Li^+ , modifying the structure and electrical properties.



(a) $Na_{2-x}Li_xTi_3O_7$ (b) $K_{2-x}Li_xTi_4O_9$ (c) $Rb_{2-x}Li_xTi_4O_9$

Fig. 1. XRD patterns of lithium-mixed alkali titanates for $x = 0.2, 0.4$ and 0.6 ($A = Na, K, Rb$).

B. $Na_2Ti_3O_7$ Group (SLT-1 to SLT-3)

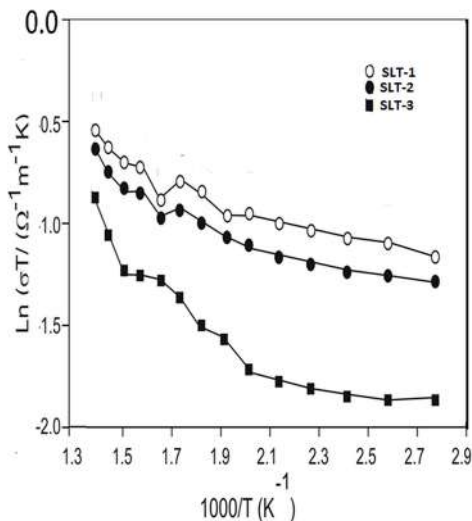


Fig. 2. Conduction mechanism of Li-mixed $Na_2Ti_3O_7$.

Region I (lowest temperature)—Fig. 2 shows the ac conductivity of SLT-1 to SLT-3; region I extends up to about 498–573 K. Loosened electrons from anions and impurities conduct not by band motion but by hopping between neighbouring ions, as polarons: electrons that carry their own lattice polarization, giving lower energy but larger effective mass. Only a small number of tightly bound electrons contribute in such ionic insulators, and their motion is so slow that the lattice polarizes around them, so band theory cannot describe the conduction; the problem becomes polaronic, with polaron–phonon interactions assumed small. Conduction in mixed sodium lithium titanate is mainly ionic through the interlayer space, but shallow-barrier electronic hopping along $Ti-Ti$ chains also plays a major role, so exchangeable interlayer ionic conduction (low activation energy) co-exists with electronic hopping.

Region II (573–648 K)—This temperature-dependent region is associated with interlayer ionic conduction, with a part of electronic hopping at its lower end.

Region III (above 648 K)—Conduction involves unassociated vacancies in the interlayer space; the I–V dipoles have broken up, so the mechanism is unassociated interlayer ionic conduction, while electronic hopping, dominant at low temperature, diminishes as temperature rises.

C. $K_2Ti_4O_9$ Group (PLT-1 to PLT-3)

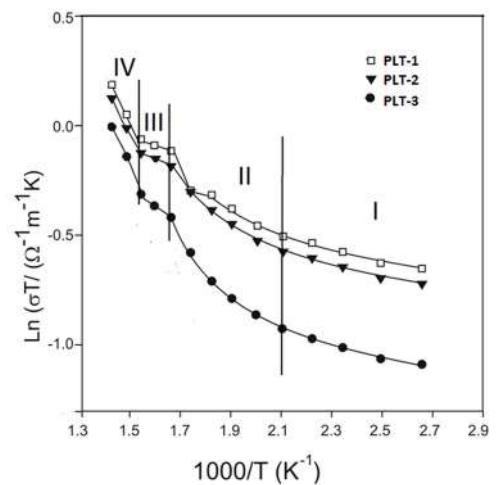


Fig. 3. Conduction mechanism of Li-mixed $K_2Ti_4O_9$.

Region I (up to 373–473 K)—Conduction is characteristic of the host: loose electrons from the titanate groups

hop between adjacent Ti–Ti chains with low activation energy. The small slope for PLT indicates a configuration that reduces the number of loose electrons and suppresses electronic hopping, and interlayer ionic conduction disappears in PLT-1 to PLT-3. Conductivity rises from PLT-2 to PLT-3 as Li substitution at Ti^{4+} sites adds loose electrons, whereas the decrease seen in PLT indicates that Li entry at Ti^{4+} sites has saturated; further doping puts Li^+ at interlayer sites, forming pairs that reduce both electronic hopping and interlayer ionic conduction.

Region II (up to 473–598 K)—The higher slope reflects alkali ionic conduction through extrinsic defects in the interlayer. Activation energy rises as the interlayer contracts with Li^+ at alkali sites, so conduction is “associated extrinsic ionic conduction” through the contracted interlayer space.

Region III (598–648 K)—This region likely arises from dissociation or aggregation of K^+ and Li^+ ions in the interlayer, which then take part in conduction.

Region IV (above 648 K)—The slope exceeds that of region III because oxygen loosens from the titanate groups and joins conduction; once Li^+ substitution at Ti^{4+} sites saturates, Li^+ at interlayer sites reduces the number of participating loose oxygens. Conduction is modified interlayer ionic conduction.

D. $\text{Rb}_2\text{Ti}_4\text{O}_9$ Group (RLT-1 to RLT-3)

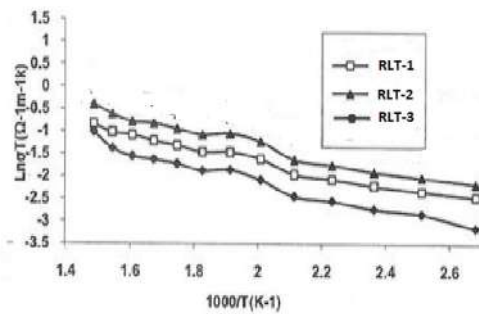


Fig. 4. Conduction mechanism of Li-mixed $\text{Rb}_2\text{Ti}_4\text{O}_9$.

Region I (up to 473 K)—Fig. 4 shows conductivity that is strongly frequency-dependent but nearly temperature-independent, obeying $\sigma(\omega) = A\omega^s$ with $s < 1$, similar to the behaviour reported for scandium oxide. This is attributed to electronic hopping over shallow barriers along Ti–Ti chains, together with exchangeable interlayer ionic conduction; the frequency dependence reflects a wide distribution of relaxation times. Both large

polarons (weak association, small effective mass) and small polarons (distortion smaller than the lattice parameter, mobility strongly affected by lattice distortion) contribute, and the low-temperature behaviour follows $\sigma = \sigma_0 \exp[-(T_0/T)^{1/4}]$.

Anomalous region (473–648 K)—A peak at 523 K for RLT-1 to RLT-3 may be due to a ferroelectric phase transition. Li^+ at Ti^{4+} sites in RLT-1 traps more electrons for hopping, whereas Li^+ at interlayer Rb^+/Li^+ sites in RLT-2 and RLT-3 diminishes the hopping electrons, giving a less temperature-dependent region. The lowered limit of this region for Li-doped RLT can be understood if Li^+ in the interlayer space, generally associated with cation vacancies, pulls some of the surrounding loose oxygen.

Region II (573–698 K for RLT-1 and RLT-2; 623–698 K for RLT-3)—Conductivity decreases as temperature rises: loose oxygen produced by Li^+ at Ti^{4+} sites is trapped by interlayer cation vacancies. Electronic hopping still contributes strongly in RLT-1 but is suppressed in RLT-2 and RLT-3, so hindered interlayer ionic conduction and electronic hopping co-exist.

Region III (above 698 K)—The slope exceeds that of region II as Li^+ at Ti^{4+} sites loosens oxygens from the titanate groups and breaks the oxygen– $\text{Ti}^{4+}/\text{Li}^+$ dipoles. Conduction involves unassociated vacancies in the interlayer, i.e. modified interlayer ionic conduction together with polaronic conduction. Li doping thus lowers electron hopping and enhances interlayer ionic conduction.

IV. CONCLUSIONS

Ionic conduction becomes harder as more lithium enters the interlayer space, because the smaller ions shrink the interlayer channels. Small Li^+ additions at interlayer K^+ sites reduce the number of loose electrons (seen in PLT), whereas Li^+ at Ti^{4+} sites and at interlayer alkali sites both loosen electrons from the titanate groups, which then conduct by hopping. In PLT-1 to PLT-3, high-temperature conduction is strongly affected by loose oxygen from the titanate groups, and Li at interlayer K^+ sites raises conductivity at high temperature so that lithium ionic conduction starts at lower temperature. Overall, region I is electronic hopping with exchangeable interlayer ionic conduction (with interlayer ionic conduction dominant in the anomalous region); region II is hindered interlayer ionic conduction co-existing with suppressed electronic hopping; and the highest-temperature region is modified interlayer

ionic conduction.

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Challenges in Internet of Things with Different Performance Metrics in Routing Protocols Based on Fuzzy Logic

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Abstract— The Internet of Things (IoT) relies more and more based on routing decisions taken under conditions of partial and incomplete knowledge of the residual energy, delay, and throughput at the node level. Threshold-based routing rules, which are mostly inherited from the design of wireless ad hoc and sensor networks, are poor at encoding these conditions— particularly the graded nature of them and that they are often conflicting. In this paper, the linguistic input variables considered are Energy, Delay, and Throughput and the resulting output is Probability located at the center of a cluster-head selection decision structure comprising Energy, Delay, and Throughput; the decision structure is analyzed with a set of previous fuzzy rules and membership-function definitions. The mechanism is placed under the spotlight during a review of challenges in IoT routing (energy constraints, scalability, mobility, security, QoS, congestion and heterogeneity, etc.) and then compared with eight standard performance metrics in an exhaustive discussion, which includes comparing RPL with the other routing protocols mentioned in the review. The rule base is determined to deliver a principled approach for reconciling the conflicting goals at the micro level of individual routing decisions, but still incorporates the simplicity of some assumptions and thresholds which could not be expected to apply to the wider, more heterogeneous and dynamic world of IoT deployments. This paper wraps up by stating the divide between single or dual metric fuzzy routing formulations and the multi-objective, adaptive needs of realistic IoT networks, and suggests potential approaches in the future for implementing novel adaptations of membership functions, learning assisted fuzzy rule generation, and security extended formulations.

Keywords— Internet of Things, Fuzzy Logic, Routing Protocols, Wireless Sensor Networks, Multi-Metric Routing, Cluster-Head Selection, Quality of Service, Energy-Aware Routing

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I. INTRODUCTION

The concept of Internet of Things is no more about the Internet being extended; it is an integral part of a complex network of resource constrained devices that sense, compute and communicate without much human supervision [1, 2]. This is far from a stable environment: IoT routing has to deal with varying energy scarcity, mobility of nodes, a multitude of radio technologies and different application specific quality-of-service (QoS) requirements [3, 4]. For most sensing and actuation nodes, these exist on battery with depleted resources, and must communicate through lossy low-power links, with an abundance of such nodes such that centralized, exhaustively computed routing is impractical [5].

Results are apparent at local level. In the work of Tiwari et al. [12], a small number of acoustic sensing nodes are tasked with relaying event information with some acceptable level of latency, while having to operate under the same conditions (budget constraints for both bandwidth and battery) that would apply to a much larger deployment. Broadly reviewed, IoT routing protocols, Rawat et al. [13] indicate that there is a direct connection between proactive, reactive or hybrid strategies and their fuel– delay characteristics in practice.

For the most part of the IoT routing arena, some of the protocols inherited from wireless sensor and ad hoc networks, such as RPL [6], AODV [7], LEACH [8], OLSR [9] and ZRP [10] are in use. The two were both constructed under a specific hypothesis of what topology is stable, what is the traffic pattern or what is the budget for the resources. The two favor different aspects of the performance space. It is hard to find any single metric that can be applied to evaluate an IoT application: Precision agriculture can sometimes be willing to sacrifice a minute of latency for a few nodes to fail, while a mobile asset tracking would prefer to be responsive rather than efficient in its energy usage. If a routing decision is made

and collapsed into a single optimized quantity, there is the risk that the other dimensions will be ignored as metrics that weren't included in the decision are not optimized.

It is not uncommon to cite fuzzy logic as a technique for incorporating multiple routing heuristics with partial conflicting feedback information into one decision variable, without having a complete analytical model of the effects of interactions between the heuristics [11]. A fuzzy system assumes Energy, Delay, and Throughput as linguistic sets, Low, Medium, High, and provides a set of rules, expressed in a fairly natural language, to determine the probability of a node being selected to be the cluster head based

on the linguistic sets. This is not original, as the concept of fuzzy cluster-head election has been previously used in the sensor-network research, as in the case of energy-aware formulation of FCHE [11] and fuzzy versions of HEED [14]. This paper is not about the idea itself, but provides a critical (and close) reading of one particular Energy–Delay–Throughput–Probability fuzzy model, its corresponding 27-rule base and how this particular model relates to the broader context of IoT routing challenges and metrics that define the usefulness of the fuzzy model. Section II reviews the routing challenges that motivate a multi-metric approach. Section III develops the fuzzy formulation. Section IV covers performance metrics and compares the five protocols. Section V works through the proposed cluster-head selection procedure and the rule base itself. Section VI draws out the critical implications, the research gap, and future directions, and Section VII concludes.

II. IOT ROUTING CONTEXT AND CHALLENGES

Routing behaviour in IoT networks cannot be separated from the layered architecture it runs on. A widely used four-layer view distinguishes a Perception Layer, a Network Layer, a Processing Layer, and an Application Layer [2],[5]. The Perception Layer—sensors, RFID tags, embedded devices—generates the data routing exists to deliver and is the main source of the energy and throughput variability a routing decision must contend with. The Network Layer, where routing protocols and addressing schemes such as IPv6/6LoWPAN operate, is where the fuzzy mechanism examined here actually sits. The Processing Layer (cloud, edge, fog) consumes routed data and increasingly hosts adaptive or

learning-based routing computation, while the Application Layer—healthcare, agriculture, home automation, transportation—sets the QoS targets routing must ultimately satisfy. A fuzzy mechanism built only from Energy, Delay, and Throughput captures Perception-Layer constraints reasonably well but says nothing about differentiated Application-Layer demands, a point revisited in Section VI.

The typical problems posed for routing in the IOT, such as: energy, scaling, mobility, security etc are found easier to be addressed as a suite of problems rather than as isolated cases to check off. The most apparent: energy consumption – as a battery-driven node, routing should conserve energy in the transmission, listening and control traffic parts. It is not sufficient to merely minimize the average energy consumption, however: a protocol may have the network-wide average low, but yet burn out a few of the most heavily-used relay nodes after a short period of time, and therefore be characterized as using very little energy in terms of network lifetime (Section IV) used as an additional metric. There is a tradeoff between scalability and overhead: Protocols that are scalable are flooded with more topology information, as done by OLSR with periodic flooding; these protocols gain in responsiveness but lose in overhead; the other side of the coin is that protocols that minimize the topology information exchanged incur low overhead but high responsiveness; it will depend on traffic pattern and node density what kind of tradeoff to opt for. Hence, once the assumption of topology stability is made (calibrated on a static deployment), any routing decision made assumes that the node's Energy–Delay–Throughput is valid for some useful interval, which this mobility challenges. Security is sometimes added in the back: constrained devices are not able to handle heavy cryptography and are prone to be attacked by black-hole attacks, wormhole and sinkhole attack [1], and a compromised node can falsely report better Energy, Delay, and Throughput scores, thus influencing the chances of being selected under the considered framework. These requirements differ dramatically from one application to another: e.g., delay and reliability are not that significant for a health care application, but are critical to a surveillance application [5]; it is not sufficient to use a single blended Probability output for each application and adjust it; you need to tune it to each individual application. The principle of Congestion produces bursts of loss and delay spikes are captured (at the granularity

of Low/Medium/High) by Delay and Throughput being fuzzy inputs. As the Wireless networks used are heterogeneous (ZigBee, Wi-Fi, LoRaWAN, NB-IoT, and 5G) [4] a set of rules that are optimized for one kind of technology, may not work Out of the Box for another.

TABLE I

IOT ROUTING CHALLENGES AND PRINCIPAL IMPLICATIONS

Challenge	Principal Implication for Routing
Energy consumption	Requires load-balanced, not merely average-minimizing, expenditure; motivates residual-energy-aware selection
Scalability	Forces a trade-off between overhead and responsiveness as node count grows
Mobility	Degrades profile-based decisions over time; needs re-evaluation or explicit mobility awareness
Security	Exposes routing inputs, including fuzzy inputs, to falsification by compromised nodes
Quality of Service	Demand application-differentiated objectives rather than one blended criterion
Congestion	Produces transient delay/throughput degradation that coarse linguistic categories may miss
Heterogeneity	Makes a metric's practical meaning technology-dependent, complicating a shared rule base

III. THE FUZZY DECISION FRAMEWORK

Simple rules such as: "elect node i as cluster head if energy exceeds T " are easy to implement but fragile where they are needed the most: A node with energy slightly below T is selected as cluster head just as a node with energy very close to T are selected. This is softened by the use of fuzzy logic which allows a numeric value to be in part of two or more linguistic categories and

considers the consequences of each linguistic category as a proportion of its membership rather than abruptly switching at some boundary point.

The three variables on which the model in question is based are then divided into three overlapping regions named Low, Middle and High, covering a normalized range of 0 – 100 on each (Fig. 1). One thing that is left quite up to interpretation, but should be stated here in all capitals: Energy here does not refer to the energy already used, it refers to the energy left – "available" energy – and if it did refer to energy already used, then the direction of every rule affected by Energy would be reversed, which should not be the case. The output, Probability, represents the probability that the node is chosen as a cluster-head across five levels (Very Low, Low, Med, High, Very High), a finer partition than the inputs which gives the system space for the output to be truly discriminating rather than sorting the nodes into a few coarser eligibility bands.

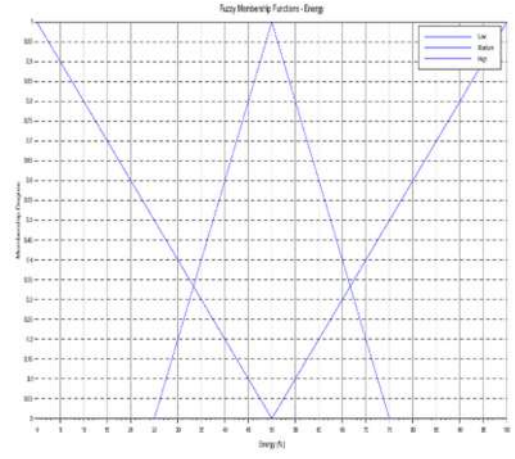


Fig. 1 Triangular membership functions for the Energy input (Low, Medium, High), 0–100% scale.

What does work when categories are overlapping is not the simple rule base, but the graded overlap between adjacent categories; a node with two-thirds residual energy is half in medium energy and half in high energy and this overlap accounts for the system's ability to avoid the "discontinues" of a simple rule boundary/threshold. Delay and Throughput are divided the same: Low delay and High throughput have favourable treatment. The shared partitioning oversimplifies the idea of the rule base—while a 10% increase in 40-to-50% residual energy can be equally as important as a 10% increase in Delay or throughput for the case of network lifetime, the rule base doesn't capture that.

As usual, firing strength of each rule clips the respective output membership function, and the clipped areas will be aggregated (usually using a maximum operator), then centroid defuzzification changes the shape to a single crisp Probability member value. This is an explanation of what is happening in one inference instance, rather than a measured result for any deployed node; there is no measured data set that could be used as a way of validating this.

IV. PERFORMANCE METRICS AND PROTOCOL COMPARISON

There is no single number that describe what an IoT Application requires from a routing protocol so evaluation is carried out simultaneously for multiple metrics. Packet Delivery Ratio ($PDR = \text{packets received} \div \text{packets sent} \times 100$) is determination of reliability and related, but not the same as, Throughput. One of the three explicit fuzzy inputs is end-to-end delay, which is the average time taken by the message to get from source to destination. Simi-

larly throughput, how much data can be sent every second, is explicit input but, looking at it at one instant, you have little idea what happened when burst traffic came along. However, the Energy input is inversely expressed as a residual-energy reading, and the distribution detail is the one that will be tackled by cluster-head rotation (Section V), and network lifetime (time to first or widespread node failure) will depend on this distribution. Volume of control-packets in the system (excluding any useful data) increases with number of the nodes or frequency of topology changes when volume of useful data does not; the fuzzy model has no representation for this. However, reliability is not just a function of hop count, and scalability (openness to the addition of increasing numbers of nodes without commensurate degradation) is at odds with several of the metrics above.

TABLE II

EIGHT IOT ROUTING PERFORMANCE METRICS

Metric:	Preferred	Relation to Fuzzy E-D-T Inputs
Packet Delivery Ratio	Higher	Correlated with, not identical to, Throughput
End-to-End Delay	Lower	Direct fuzzy input
Metric:	Preferred	Relation to Fuzzy E-D-T Inputs
Throughput	Higher	Direct fuzzy input
Energy Consumption	Lower	Inversely represented via residual Energy
Network Lifetime	Higher	Depends on Energy distribution, not one node's score
Routing Overhead	Lower	Not represented
Reliability	Higher	Partly related to Throughput/Delay; also path-level
Scalability	Higher	Not represented; protocol-level control design

Scalability Higher Not represented; protocol-level control design By comparison, RPL, AODV, LEACH, OLSR, and ZRP can be considered to be five different design philosophies. RPL (RFC 6550) [6] implements Destination-Oriented Directed Acyclic Graph over IPv6/6LoWPAN (which is very well suited for static deployments but slower to reconverge following a topology change, and susceptible to rank manipulation). Whereas AODV [7] discovers routes reactively, avoiding overhead when traffic is light but resulting in a delay not suited to delay sensitive traffic, and it was never conceived with a sensor class energy budget. LEACH [8] adopted the concept of energy dissipation at cluster-heads by rotating the cluster-head nodes randomly and periodically, whereas the drawback of LEACH, i.e. a randomized cluster head, is overcome in fuzzy-based election. OLSR [9] has an overhead that is not scalable to the size of the network, but has a low latency thanks to the precomputation of routes by exchange of periodic link-states. The ZRP [10] combines proactive intra-zone routing and reactive inter-zone routing providing for good scalability, but zone maintenance increases in complexity as zones become more densely populated and mobile.

A sixth protocol, HEED, provides a context for the reviewed model, indicating its fit in the literature. HEED

selects its cluster heads in a probabilistic manner based on residual energy and intra-cluster communication cost; Rastogi et al. [14] propose FL- HEED which substitutes this combination with a fuzzy inference system which, as is reported, is able to handle intermediate values better than the one in the original formula of HEED. FL-HEED is basically the same transformation studied in this article (modifying a crisp election rule by its fuzzy counterpart), only for different input and with different basic protocol, so we feel that the model considered in this article is one of few models in this class that share the same motivation.

TABLE III

QUALITATIVE COMPARISON OF RPL, AODV, LEACH, OLSR, AND ZRP

Criterion	RPL	AODV	LEACH	OLSR	ZRP
Energy efficiency	High	Medium	High	Low	Medium
End-to-end delay	Medium	High	Medium	Low	Medium
Throughput support	Medium	Medium	Medium	High	Medium
Routing overhead	Low	Low	Low	High	Medium
Scalability	Medium	Medium	Medium	Low	High
Mobility support	Low	Medium	Low	Medium	Medium
Security robustness	Low	Low	Low	Low	Low
Fit for fuzzy CH/route logic	Moderate	Low	High	Moderate	Moderate

Fit for fuzzy CH/route logic Moderate Low High Moderate Moderate The comparison indicates that LEACH fits the most in the natural fuzzy mechanism since, apart from the changes of the synthetic values, in LEACH a natural condition-based rules is required to replace the randomization, while in RPL the fuzzy output has to be part of their objective function, which is a much more complicated introduction. Rawat et al. [13] arrive at a similar conclusion but from a different perspective energy-aware clustered protocols are more likely to perform better on lifetime criteria, topology-driven protocols have a higher chance on delay-sensitive traffic – in line with the energy-dominated behaviour described next.

V. CLUSTER-HEAD SELECTION PROCEDURE AND RULE-BASE ANALYSIS

The fuzzy structure in Section III is embedded in a 6-step conceptual procedure: (1) Measure Energy, Delay and Throughput at each node; (2) Input all measurements to the 27-rule Mamdani system to get the first probability; (3) Input all measurements to the threshold-based system to get the second probability; (4) Average both probabilities; (5) Rank the nodes based on the average probabilities; (6) Choose top ranked nodes as the cluster heads. The measurement material never mentions the thresholds at step 3, and at step 4 it is not clear why the two estimates can be weighed equally, a more careful treatment would

obtain the weighted value from the relative reliability of the two estimates. The ranking step also implicitly assumes a fixed number (or proportion) of cluster heads, but does not specify how many cluster heads – this number is plausibly related to node density, and desired cluster size.

Table IV gives the complete 27-rule decision base mapping every Energy $\times$ Delay $\times$ Throughput combination to one of five Probability levels.

TABLE IV

COMPLETE 27-RULE MAMDANI DECISION BASE

#	Energy	Delay	Throughput	Probability
1	Low	Low	Low	Very Low
2	Low	Low	Medium	Very Low
3	Low	Low	High	Very Low
4	Low	Medium	Low	Low
5	Low	Medium	Medium	Low
6	Low	Medium	High	Low
7	Low	High	Low	Low
8	Low	High	Medium	Low
9	Low	High	High	Medium
10	Medium	Low	Low	Medium
11	Medium	Low	Medium	Medium
12	Medium	Low	High	Medium
13	Medium	Medium	Low	Medium
14	Medium	Medium	Medium	Medium
15	Medium	Medium	High	Medium
16	Medium	High	Low	Medium
17	Medium	High	Medium	Medium
18	Medium	High	High	Medium
19	High	Low	Low	Medium
20	High	Low	Medium	High
21	High	Low	High	High
22	High	Medium	Low	High
23	High	Medium	Medium	High
24	High	Medium	High	High
25	High	High	Low	Very High
26	High	High	Medium	Very High
27	High	High	High	Very High

Patterns can be discerned. The three rules combining Lowest Energy with Lowest Delay (Rules 1-3) correspond to Very Low probability for all Throughput levels: No Throughput can save an energy poor, slow node, an assertion that is reasonable for network life time protection purposes; however it may make Throughput an subordinate parameter at lowest extremes. The base is significantly asymmetric with respect to Energy: 6 out of 9 rules that fall at or above High Energy (Rules 19-27) and none below Medium Energy, and 7 out of 9 that fall below or equal to Low Energy (Rules 1-9): high Energy is a much stronger driver of high output as low Delay or high Throughput individually. 15 of the 27 rules go into the Medium output, which has less to do with behaviour in a network than with the number of combinations for a table with 3 inputs and 5 outputs. The actual discriminating ability of this system (also for all nominally Medium nodes) is not the rule table per se, but is where a value lies within the overlapping input membership functions.

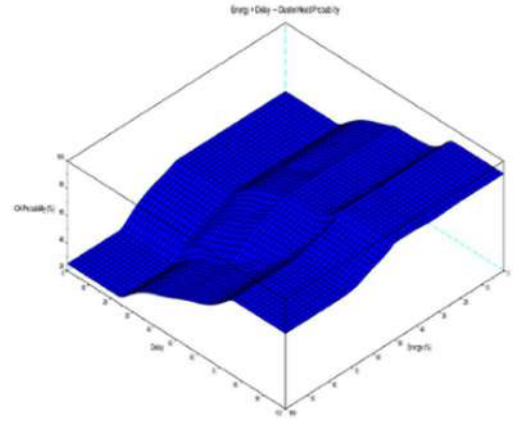


Fig. 2 Fuzzy decision surface for Cluster-Head Probability as a joint function of Energy and Delay.

This reading is verified by the pairwise decision surfaces. Probability increases with energy rapidly, and for low energy the Energy–Delay surface is almost flat in Delay as indicated by the disqualifying effect above, but in the higher energy range, around mid and above the Energy range, the Energy–Delay surface becomes steeper, as Delay starts to distinguish between the Energy. Although not necessarily bad, the Energy–Throughput surface seems to be more “ruled” and/or “triangular”, caused by the overlap of triangular functions and the assignments of certain rules for this case, and appears more textured than the Energy versus Throughput curve.

VI. CRITICAL DISCUSSION, RESEARCH GAP, AND FUTURE DIRECTIONS

These three measurements (the metric review, the protocol comparison, and the rule-base analysis) read together suggest that with this framework the main claim is about a fairly tight and energy-dominant approach for ranking nodes on three locally observable quantities, as opposed to the discontinuities of crisp thresholds. It doesn't contain anything about routed overhead, reliability by failure, scalability or alternative QoS requirements – where protocols like OLSR (routed overhead) and ZRP (zone maintenance complexity under mobility) already fall short. A good fuzzy cluster-head layer will not be able to rectify limitation level 1 which is situated at the protocol layer. The Probability output is also not a performance metric, but rather a decision support variable to indirectly affect PDR, lifetime and reliability by the quality of decisions made based on the Probability output; whether this is actually realized or not is an empirical question that is not answered in the available material.

Most importantly, the framework is purely static: the rules and membership functions don't change count of elements, nodes, applications, etc. despite these scalability, mobility and heterogeneity requirements, which are strong candidates for the fixed rule base of a fuzzy logic system that is likely to become out-of-calibration with the increase of elements, nodes and applications. On the other hand, it does not include mobility and security posture as inputs, and a node that may be a good cluster head in terms of Energy, Delay, and Throughput may not be a good cluster head for being highly mobile or compromised. Steps 3-4 are based on simple arithmetic averages and have no principle behind them, and a rule base from one deployment scenario does not necessarily carry over into a second. Consider the contrast made possible by Tiwari et al. [12] from which this is actually quite evident: the bursty, latency sensitive traffic of a noise-alert system is very different from the sustained, low-rate telemetry to which clustering protocols such as LEACH were originally adapted and a single fixed rule base cannot differentiate between a node with a generally low resource level and one that simply has a low resource level for bursty traffic. All of these do not of course imply that the general concept of fuzzy IoT routing cannot turn out to be more complex: the broader literature already points out the use of adaptive variable membership function and more involved sets of inputs as well.

TABLE V

RESEARCH-GAP DIMENSIONS AND CORRESPONDING FUTURE DIRECTIONS

Research-Gap Dimension	Corresponding Future Direction
Static membership functions and rule base	Adaptive, self-tuning functions responsive to deployment conditions
Only Energy, Delay, Throughput represented	Extension to mobility, security posture, congestion state
No treatment of overhead or scalability	Joint optimization of CH frequency/size with overhead constraints
Unweighted fuzzy/threshold averaging	Principled, learned, or context-dependent weighting
Vulnerable to falsified node reports	Secure or trust-aware fuzzy input verification

Vulnerable to falsified node reports Secure or trust-aware fuzzy input verification A few clear next steps come from these deficiencies. The partitions defined by the Energy, Delay, and Throughput would be able to move online in response to changing conditions by using adaptive membership functions that would be derived in an online manner using lightweight estimation at edge. Machine learning or reinforcement learning extensions might allow the weights of the rules to be learned from observations of what has happened, or even that the structure of the rules themselves were learned, as long as the learning does not call into question their interpretation,

which is really the reason for using fuzzy logic in the first place. Applications with vehicles, drones or wearables would benefit from mobility aware inputs directly integrated in the fuzzy system instead of being considered an external event. The fact that a fuzzy election mechanism is only as honest as the inputs it receives, leads to trusting knowing input provenance, possibly through lightweight blockchain attestation of reported inputs. Handoff as a rule to the edge or fog resources would lead to closing the gap between the expense of richer, adaptive fuzzy systems, and the energy considerations that drove investigation of fuzzy logic in the first place. Finally Pareto based multi-objective formulations, in which Energy, Delay, Throughput, overhead, and reliability are separate entities and not combined into one Probability value, would be beneficial to show off the trade-off which is to be expected by having only one output combined.

VII. CONCLUSION

In this paper, as part of a larger body of work reviewing the challenges of routing, performance metrics, and a comparison of RPL, AODV, LEACH, OLSR, and ZRP, an Energy–Delay–Throughput–Probability fuzzy decision model for IoT cluster-head selection has been explored. The Mamdani base examined in this paper is quite energy-dominant and low Energy combined with high Delay is effectively disqualifying in all cases and most of the input pairs are of a medium value, so getting a more fine discrimination depends more on the overlap of the membership functions of the inputs than on the overlap of the rule table itself.

Fuzzy logic can help to smooth out this type of hard set boundary behavior, and to merge multiple, cascading and sometimes contradictory indicator function values into a single, ranked indicator variable—because none of the protocols in the comparison dominates across all 8 of the metrics. The limits seem to have to be pointed out in as bald a way as they are possible: the framework is static, it lacks support for mobility and security, and it has not been validated conceptually beyond the six-step procedure and the rule specification.

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Contactless Smart Switching Using Infrared Gesture Detection and Arduino-Based Sequential Control: A Review

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Abstract— Contactless switching systems provide an alternative to conventional mechanical switches by allowing users to control electrical loads without direct physical contact. This review examines an Arduino UNO-based contactless switching architecture using infrared proximity sensors, a relay module, an LCD display, and sequential control logic. The reviewed system detects hand gestures or nearby objects through infrared sensing and translates the detected sequence into controlled activation or deactivation of four AC loads. The source paper reports sequential ON operation from load 1 to load 4 and reverse OFF operation from load 4 to load 1, with a response time below 500 ms, detection accuracy above 95%, and an operating range of 10–50 cm under the stated indoor test conditions. This review discusses the development of contactless switching, sensing technologies, system architecture, control logic, hardware and software implementation, performance, benefits, limitations, applications, and future research directions. The reported measurements are retained as observations from the source prototype and are not independently reproduced in this review.

Keywords— Contactless Switching, Infrared Sensor, Arduino UNO, Gesture Detection, Relay Module, Smart Home, Sequential Control, Touch-Free Automation

I. INTRODUCTION

Traditional electrical switches require physical contact and repeated manual operation. In environments such as hospitals, public washrooms, laboratories, offices, and smart homes, minimizing physical contact can improve convenience, accessibility, and hygiene.

Contactless switching replaces direct mechanical interaction with a sensing mechanism. Infrared proximity sensors are attractive for low-cost prototypes because they can detect a nearby hand or object without requiring a camera or complex processing. A microcontroller can interpret sensor signals and control relay channels connected to electrical appliances.

The supplied paper presents a four-load contactless switching system using Arduino UNO, IR sensors, relay modules, and an LCD. This review reorganizes the work into a review-paper format and evaluates the underlying sensing, control, switching, and automation concepts.

II. REVIEW SCOPE AND SOURCE BASIS

This review is based on the uploaded paper “Contactless Switch for Home and Offices.” The same authors are retained: Vansh Koli, Riya Sharma, Harshita Verma, and Naman Gupta. The original technical content is reorganized around the evolution of contactless switching, infrared sensing, embedded control, sequential switching, performance, applications, limitations, and future scope.

The reported prototype results are presented as source-reported observations. The review does not claim independent laboratory validation or clinical/safety certification.

III. EVOLUTION OF CONTACTLESS SWITCHING SYSTEMS

Early home-automation systems commonly relied on physical switches, wired control panels, or basic remote-control mechanisms. As embedded systems became more accessible, proximity sensors, microcontrollers, wireless communication, and intelligent interfaces enabled increasingly flexible contactless control.

Infrared gesture sensing offers a simple transition from physical switches to touch-free interaction. More advanced systems can incorporate Bluetooth, Wi-Fi, mobile applications, voice assistants, computer vision, or machine learning. The reviewed system represents a simple and economical stage in this progression.

IV. INFRARED PROXIMITY SENSING

Infrared proximity sensors operate by transmitting infrared radiation and detecting reflected energy from a nearby object. A hand moving within the sensing region can therefore be interpreted as a user command without physical contact.

The major advantages of IR sensing are low cost, simple interfacing, fast response, and low computational requirements. However, the sensing range is limited and performance can be influenced by ambient sunlight, surface reflectivity, object orientation, and sensor placement.

The source system uses four IR sensors as the principal user-input interface. Each sensor corresponds to a switching action within the sequential control scheme.

V. SYSTEM ARCHITECTURE

The reviewed architecture consists of five major stages: power supply, input sensing, processing, switching, and output loads. The IR sensors generate input signals that are processed by the Arduino UNO. The microcontroller applies sequential control logic and activates the appropriate relay channels.

The relay module provides electrical isolation between the low-voltage control electronics and the AC loads. The LCD provides user feedback or system-status information. The output stage consists of appliances such as bulbs or fans.

The architecture is intentionally simple, allowing the system to be assembled and programmed with commonly available embedded components.

VI. SEQUENTIAL CONTROL LOGIC

The central feature of the reviewed system is sequential switching. During activation, the loads are controlled in the order $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$. During deactivation, the reverse sequence $4 \rightarrow 3 \rightarrow 2 \rightarrow 1$ is followed.

The Arduino continuously processes the IR sensor states and determines the corresponding relay action. Sensor calibration and debounce logic are included to reduce false triggering caused by unstable or rapidly changing sensor signals.

Sequential control provides an organized user interface and can be useful where several loads need to be controlled in a predetermined order.

VII. HARDWARE AND SOFTWARE REVIEW

Arduino UNO: Acts as the central microcontroller, receiving sensor inputs, executing the switching algorithm, and driving relay channels.

IR proximity sensors: Detect hand proximity or ges-

tures and provide the contactless input signals.

Relay module: Switches the AC loads while maintaining separation between the control circuit and the appliance side.

LCD: Provides system feedback and can display switching or operating status.

Power supply: Provides the required low-voltage DC power to the embedded control circuitry.

Arduino IDE: Provides the development environment for programming, calibration, and testing of the control logic.

VIII. METHODOLOGY REVIEW

The source methodology is divided into design, hardware implementation, programming, and testing/calibration stages. The design stage includes circuit preparation, component selection, sequential logic planning, and power-supply design.

Hardware implementation involves breadboard prototyping, sensor interfacing, relay connections, and LCD integration. Programming is performed through the Arduino IDE, with sequential switching, sensor calibration, and debounce logic incorporated into the firmware.

Testing includes adjustment of sensor range, verification of sequential ON and OFF operation, reduction of false triggering, and evaluation of AC load switching.

IX. PERFORMANCE REVIEW

The source paper reports successful indoor prototype operation. Sequential activation was observed from load 1 through load 4, while deactivation followed the reverse order. The reported response time was below 500 ms, detection accuracy was above 95%, and the operating range was 10–50 cm.

The source also reports a load capacity of 10 A at 250 V AC and a 5 V DC control supply. These values describe the stated prototype configuration and should not be generalized to other relay modules, appliances, or installations without appropriate electrical verification.

The reported performance indicates that infrared sensing and Arduino-based sequential control can provide rapid contactless interaction for basic indoor automation.

X. COMPARATIVE REVIEW OF CONTACTLESS CONTROL METHODS

Infrared proximity sensing is economical and simple but has a relatively short range and can be affected by environmental light. Bluetooth and Wi-Fi systems provide longer-range communication and mobile control but require additional communication hardware and software.

Camera-based gesture recognition can support more complex gestures but typically requires higher processing capability and may introduce privacy or lighting concerns. Voice control can provide hands-free operation but depends on speech recognition and may be affected by language, noise, or network availability.

The reviewed IR-based architecture therefore occupies a useful low-cost position for simple, local, touch-free appliance control.

XI. ADVANTAGES

Completely contactless operation reduces the need for physical interaction.

Low-cost components make the prototype economical and accessible.

Simple Arduino-based architecture supports easy programming and modification.

Fast sensor response enables convenient appliance control.

Sequential switching provides an organized control scheme for multiple loads.

The concept can support elderly or disabled users who may find conventional switches difficult to operate.

The system can be adapted for smart homes, offices, hospitals, and public facilities.

XII. LIMITATIONS AND SAFETY CONSIDERATIONS

Infrared sensors can be affected by strong sunlight and reflective surfaces. The operating range is limited, and sensor placement can influence detection reliability.

The current system uses fixed sequential logic and does not provide wireless communication. False triggering may occur under strong reflections or unsuitable environmental conditions.

Because the relay stage controls AC loads, electrical isolation, enclosure design, grounding, insulation, fuse protection, and appropriate ratings are essential for safe practical installation. The reported prototype results should not be interpreted as evidence of compliance with

electrical safety standards.

More advanced automation would require improved gesture recognition, configurable control logic, remote monitoring, and fault detection.

XIII. APPLICATIONS

Potential applications include smart homes, hospitals, offices, public washrooms, educational institutions, hotels, shopping malls, and industrial automation systems.

In healthcare and public environments, contactless operation may be particularly useful where minimizing repeated physical contact is desirable. In residential settings, the system can provide a simple interface for controlling multiple lights or appliances.

XIV. FUTURE RESEARCH DIRECTIONS

Wi-Fi and Bluetooth connectivity can enable mobile application control and remote status monitoring. IoT cloud integration could support usage analytics, notifications, and centralized management.

Voice-assistant integration can provide multimodal control, while AI-based gesture recognition can move beyond simple proximity detection toward more expressive and user-specific commands.

Energy monitoring can be added to measure appliance consumption and support energy-efficient automation. Machine-learning methods could also be explored for adaptive gesture classification and improved robustness.

Future work should evaluate performance across different indoor lighting conditions, sensor placements, users, and appliance configurations. Long-term reliability and electrical safety should also be systematically assessed.

XV. CONCLUSION

This review examined a low-cost contactless switching system based on infrared proximity sensing, Arduino UNO processing, relay-based AC load control, and sequential switching logic. The source prototype demonstrates a simple approach to touch-free appliance control and reports fast response, high detection accuracy, and reliable sequential operation under indoor test conditions.

The main strengths of the approach are its low cost, simple architecture, ease of implementation, and suitability for local automation. Its principal limitations are restricted sensing range, sensitivity to environmental con-

ditions, fixed sequential logic, and absence of wireless connectivity.

Future integration of IoT, wireless control, voice interaction, energy monitoring, and intelligent gesture recognition can transform the basic contactless switch into a more flexible smart-automation platform.

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A Cost-Effective Offline Smart Parking System Using RFID and Embedded Automation

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Abstract— The rapid growth of vehicular traffic has increased the need for parking systems that can reduce waiting time, improve parking-space utilization, and provide reliable transaction management. This review examines the design principles and technologies associated with a cost-effective offline smart parking system based on RFID and embedded automation. The reviewed architecture combines RFID-based identification, ultrasonic sensing for real-time slot occupancy detection, servo-driven entry and exit barriers, a real-time clock for duration tracking, EEPROM-based prepaid balance storage, an SD-card transaction log, keypad input, and LCD feedback. The review contrasts this approach with conventional manual/postpaid parking, sensor-based systems, IoT-enabled systems, and prepaid parking solutions as described in the supplied source paper. Particular attention is given to the advantages of offline operation, automated prepaid billing, real-time slot monitoring, reduced human intervention, and transaction traceability. The review also identifies practical limitations and future enhancement opportunities. The work is presented as a literature and system review rather than as a new experimental study; therefore, no new performance measurements are claimed.

Keywords— Smart Parking, RFID, Embedded Automation, Prepaid Billing, Ultrasonic Sensor, Arduino Mega 2560, Offline System, Parking Management, Real-Time Slot Detection

I. INTRODUCTION

Increasing vehicle density in urban and institutional environments has made parking management an important engineering challenge. Traditional parking arrangements commonly depend on manual ticketing, human supervision, and postpaid settlement. The supplied paper identifies long queues, inefficient use of available spaces, billing errors, congestion, and the absence of real-time slot information as important limitations of such arrangements.

Embedded systems and automation provide a pathway toward reducing these limitations. The reviewed parking architecture uses an Arduino Mega 2560 as the central controller and combines RFID identification, ultrasonic slot sensing, automated barriers, time tracking, prepaid balance management, and transaction logging. A significant design choice is offline operation, which avoids dependence on continuous Internet connectivity and is intended to keep implementation and maintenance requirements comparatively low.

This paper reorganizes and reviews the supplied work under the title “A Cost-Effective Offline Smart Parking System Using RFID and Embedded Automation.” The emphasis is shifted from reporting a single prototype implementation to reviewing the technology choices, system architecture, benefits, limitations, and research opportunities surrounding this class of smart parking systems.

II. REVIEW SCOPE AND APPROACH

The review is based primarily on the uploaded source paper and its cited literature. The source discusses RFID-based parking, sensor-based parking, IoT-based parking, prepaid parking, embedded automation, and the proposed offline architecture. The review therefore retains the terminology and system elements documented in that source. Where the source does not provide quantitative benchmarks, the present paper does not introduce unsupported numerical claims.

III. REVIEW OF SMART PARKING APPROACHES

3.1 *Conventional Manual and Postpaid Parking*

The source paper describes conventional parking as dependent on manual ticket generation and supervision, with payment commonly settled after parking. Such processes can increase entry and exit processing time and can create

opportunities for billing inaccuracies. The absence of real-time occupancy information can also cause drivers to

spend additional time searching for vacant spaces.

3.2 RFID-Based Parking

RFID is reviewed as a practical mechanism for contactless identification and access control. In the proposed architecture, RFID cards are scanned at both entry and exit. This enables the system to associate a user with a parking transaction and to support automated prepaid deduction without requiring manual identification.

3.3 Sensor-Based Parking

Ultrasonic sensing is used to determine whether individual parking slots are occupied or vacant. The source architecture assigns an ultrasonic sensor to each monitored slot and uses LED indicators to communicate slot status. This provides local, real-time occupancy information and can reduce unnecessary searching within the parking area.

3.4 IoT-Based Parking

The supplied paper notes that IoT parking solutions can support remote monitoring, mobile integration, and cloud data storage. However, the source also identifies Internet dependence, higher implementation cost, and maintenance complexity as concerns in environments with unstable connectivity. The reviewed offline architecture intentionally avoids these dependencies.

3.5 Prepaid Parking

Prepaid parking is reviewed as a mechanism for reducing payment-related congestion at exit points. The source identifies a gap in systems that provide prepaid billing but do not simultaneously offer real-time slot detection and complete automated operation. The reviewed architecture attempts to combine these functions in a single embedded system.

IV. TECHNOLOGY REVIEW

Technology	Role in reviewed system	Contribution
RFID reader	User identification at entry/exit	Contactless authentication and transaction association
Arduino Mega 2560	Central controller	Coordinates sensing, billing, gates, display and logging
Ultrasonic sensors	Slot occupancy detection	Real-time vacant/occupied status
Servo motors	Entry and exit barrier control	Automated vehicle access
DS3231 RTC	Entry/exit time tracking	Parking-duration calculation
EEPROM	Prepaid balance persistence	Retains balance during power interruption
Micro SD module	Transaction storage	Timestamped record keeping and auditing
Keypad	Balance recharge/input	User interaction for recharge operations
LCD display	System/user feedback	Displays parking and transaction information

V. REVIEWED SYSTEM ARCHITECTURE

The reviewed architecture is a sequence of sensing, processing, decision-making, control, time tracking, billing, and logging functions. At entry, the RFID reader identifies the user and the controller checks the stored prepaid balance. If sufficient balance is available, the base fee is deducted and a vacant slot is identified using ultrasonic sensor information. The entry barrier is then operated by a servo motor.

During parking, slot sensors continuously provide occupancy information. At exit, the RFID card is scanned again and the RTC data is used to determine parking duration. Additional charges, where applicable under the configured parking rules, are deducted from the remaining prepaid balance. The exit barrier is then activated and transaction details are stored on the SD card.

RFID Identification	Prepaid Balance Check	Slot Availability Detection	Automated Gate Control	RTC Time Tracking	Charge Calculation	Transaction Logging	User Feedback
RFID card scanner	EEPROM balance verification	Ultrasonic sensors + LED status	Servo motor + exit barrier	DS3231 Real-time clock	Base and additional charges	SD card record keeping	LCD and keypad interaction

VI. COMPARATIVE REVIEW

Feature	Manual/Postpaid	Sensor-Based	IoT-Based	Reviewed Offline RFID System
Automated identification	Low	Limited	Possible	Yes
Real-time slot detection	No/limited	Yes	Yes	Yes
Prepaid billing	Generally no	Not inherent	Possible	Yes
Automated gate operation	Limited	Not inherent	Possible	Yes
Internet dependence	No	No	Typically present	No
Transaction logging	Manual	Limited	Cloud/local options	SD-card logging

The comparison is qualitative and reflects the characteristics described in the supplied paper; it is not a benchmark study. The main distinction of the reviewed architecture is the combination of prepaid RFID processing, real-time occupancy sensing, automated gates, local time tracking, and offline transaction storage.

VII. BENEFITS IDENTIFIED IN THE REVIEW

- Reduced processing delay: Prepaid billing can reduce payment-related waiting at exit points.
- Real-time occupancy awareness: Ultrasonic sensors and LED indicators provide slot status information.
- Reduced human intervention: Identification, slot allocation, billing and gate operation are automated.
- Transaction transparency: Timestamped SD-card records provide a local transaction history.

- Offline operation: The system does not require continuous Internet connectivity.
- Modular implementation: The architecture separates sensing, control, time tracking, billing and logging functions,

supporting future upgrades.

VIII. LIMITATIONS AND DESIGN CONSIDERATIONS

The reviewed system is intended for small to medium-scale parking environments as described in the source. Scaling to larger deployments would require careful consideration of the number of slots, RFID users, transaction records, controller resources, and physical gate mechanisms.

Offline operation is an advantage where Internet availability is uncertain, but it also means that remote monitoring and cloud-based services are not inherent features of the reviewed architecture. Such capabilities would require additional communication infrastructure.

Ultrasonic sensors provide occupancy detection but require appropriate physical installation and threshold configuration. The source paper does not provide a quantified accuracy study across different vehicle types or environmental conditions; therefore, no such performance figure is asserted here.

Prepaid balance storage and transaction logging require appropriate handling of power interruptions and data integrity. The source identifies EEPROM persistence and SD-card logging as design measures, but a detailed security analysis is outside the supplied material.

The reviewed design uses physical RFID cards and local interfaces. Future deployments may need additional mechanisms for user management, lost-card handling, access authorization, and administrative control.

IX. FUTURE ENHANCEMENT OPPORTUNITIES

- The reviewed architecture can be extended with optional communication facilities for centralized monitoring while

retaining local/offline operation as the core mode.

- A more advanced user interface could provide parking status, balance information, recharge confirmation, and

administrative diagnostics.

- Future work may evaluate sensor performance under different parking layouts and environmental conditions and

compare alternative occupancy-detection technologies.

- Security-oriented improvements could be studied for RFID credentials, prepaid balance management, transaction

records, and administrative access.

- For larger installations, distributed controllers or networked embedded nodes could be considered to increase

scalability while preserving modularity.

X. CONCLUSION

This review presents a cost-effective offline smart parking architecture that integrates RFID identification with embedded automation, real-time slot sensing, prepaid billing, automated barriers, time tracking, and local transaction logging. The reviewed design addresses several limitations identified in conventional parking arrangements, particularly manual processing, payment delays, limited slot visibility, and dependence on continuous Internet connectivity. Its combination of established embedded components provides a practical basis for small and medium-scale parking applications. At the same time, the review highlights the need for further work on scalability, security, sensor performance, user management, and optional remote connectivity. Since this paper is a review and reformulation of the supplied material, it does not claim new experimental results or independently measured performance values.

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IoT-Enabled Autonomous Driving Systems: A Review of Sensors, AI, Connectivity and Smart Transportation

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Abstract— Autonomous vehicles are an important component of emerging intelligent transportation systems because they combine sensing, artificial intelligence, connectivity, navigation, and automated actuation to reduce dependence on human driving. This review examines the self-driving car with IoT-based control system described in the supplied paper and reorganizes its content as a review of autonomous-driving technologies. The reviewed architecture integrates cameras, ultrasonic sensors, LiDAR, radar, GPS, a processing platform such as Raspberry Pi, machine-learning algorithms, IoT connectivity, cloud services, and vehicle actuators. The review discusses sensor-based perception, data preprocessing, object and lane detection, navigation, decision-making, vehicle-to-vehicle and vehicle-to-infrastructure communication, cloud-assisted monitoring, safety, benefits, limitations, and future research directions. Particular attention is given to the complementary roles of edge processing and cloud connectivity. The paper is a review and synthesis of the supplied work rather than an independently validated autonomous-driving experiment; therefore, no new performance claims are introduced.

Keywords— Autonomous Vehicle, Self-Driving Car, Internet of Things, Artificial Intelligence, Machine Learning, LiDAR, GPS, Sensor Fusion, V2V, V2I, Smart Transportation

I. INTRODUCTION

Traditional vehicles depend heavily on human perception, judgment, and control. Fatigue, distraction, delayed reaction, and human error can contribute to road accidents. Autonomous driving seeks to address these limitations by using sensors and intelligent algorithms to perceive the environment, make decisions, and control vehicle movement.

The Internet of Things adds another dimension by enabling vehicles to communicate with cloud platforms, other vehicles, and infrastructure. This connectivity can support traffic monitoring, remote diagnostics, naviga-

tion services, data sharing, and intelligent transportation management.

The supplied paper examines an autonomous vehicle integrated with IoT-based control. This review changes the emphasis from a descriptive project paper to a structured assessment of the technologies and system architecture involved in IoT-enabled autonomous driving.

II. REVIEW SCOPE AND SOURCE BASIS

This review is based on the uploaded paper “Self-Driving Car with IoT-Based Control System.” The original authors are retained, and the major concepts described in the source are reorganized into a review format covering sensing, processing, machine learning, communication, navigation, actuation, benefits, limitations, and future development.

The source discusses a conceptual integrated system using LiDAR, cameras, ultrasonic sensors, GPS, IoT modules, cloud services, machine learning, and a Raspberry Pi-class processing platform. The review does not treat the architecture as a certified autonomous-driving platform and does not add unsupported experimental measurements.

III. EVOLUTION OF AUTONOMOUS DRIVING TECHNOLOGY

Autonomous driving has evolved from driver-assistance functions toward increasingly automated perception and control. Early systems relied on dedicated sensors and rule-based logic, while modern platforms increasingly employ machine learning and deep learning for object recognition, lane detection, prediction, and decision-making.

The source paper identifies developments by organizations such as Waymo and Tesla and highlights the increasing role of IoT communication. Vehicle-to-Vehicle (V2V) communication can support information exchange between nearby vehicles, while Vehicle-to-Infrastructure (V2I) communication can connect vehicles with traffic signals, road-side systems, and smart-city infrastructure.

IV. SENSOR TECHNOLOGIES FOR AUTONOMOUS VEHICLES

Camera: Cameras provide visual information for lane detection, traffic-sign recognition, object detection, and scene understanding. Their advantages include rich semantic information, while performance can be affected by lighting, weather, occlusion, and image quality.

Ultrasonic sensors: Ultrasonic sensors provide short-range distance measurements and are useful for obstacle detection and low-speed maneuvering. Their limited range makes them complementary rather than sufficient as a standalone perception technology.

LiDAR: LiDAR provides depth and spatial information by measuring the return of emitted laser pulses. It can support three-dimensional environmental mapping and object detection.

Radar: Radar can provide range and relative-motion information and can perform well under conditions where optical sensing is challenged. It is useful as a complementary sensing technology.

GPS: GPS supports vehicle positioning and route navigation. Its accuracy can degrade in urban canyons, tunnels, or environments with obstructed satellite visibility.

V. SENSOR FUSION AND DATA PREPROCESSING

No single sensor provides a complete representation of the driving environment. Sensor fusion combines complementary measurements so that the system can obtain more robust estimates of position, obstacles, lanes, and surrounding objects.

The reviewed workflow begins with data collection and preprocessing. Sensor measurements are filtered and transformed into forms suitable for perception and decision algorithms. Camera data can be processed for image-based features, while LiDAR, radar, ultrasonic, and GPS information can provide geometric and positional context.

Sensor fusion is particularly important for autonomous driving because different sensors fail under different environmental conditions. Combining them can improve redundancy and help the decision layer respond more reliably.

VI. AI AND MACHINE LEARNING IN AUTONOMOUS DRIVING

Artificial intelligence supports the interpretation of sensor data and automated decision-making. Deep learning and convolutional neural networks can be used for image classification, object detection, lane recognition, and scene understanding.

Machine-learning models can support several stages of the autonomous-driving pipeline: perception, prediction, path planning, and decision-making. However, training data quality, model generalization, computational requirements, explainability, and safety validation remain important concerns.

The source paper presents machine learning as a central processing stage between sensing and vehicle decisions. A robust implementation should also consider edge inference so that safety-critical decisions do not depend exclusively on remote cloud connectivity.

VII. IOT-BASED CONNECTIVITY

IoT connectivity allows the vehicle to exchange information with cloud platforms and external systems. The cloud can support data storage, fleet monitoring, analytics, software updates, remote diagnostics, and traffic information services.

V2V communication can enable vehicles to exchange information about position, speed, braking, hazards, or traffic conditions. V2I communication can connect vehicles to road infrastructure and smart-city services such as traffic signals, road-condition systems, and parking infrastructure.

Connectivity also introduces cybersecurity, privacy, availability, latency, and communication reliability concerns. For safety-critical driving functions, local processing and fail-safe operation should remain available even when network connectivity is interrupted.

VIII. REVIEWED SYSTEM ARCHITECTURE

The proposed architecture can be represented as five connected stages: sensor data acquisition, preprocessing, IoT communication, machine-learning processing, and decision-making. Cameras, LiDAR, ultrasonic sensors, radar, and GPS collect environmental and positional information.

A processing unit such as Raspberry Pi receives and analyzes the data. Image-processing algorithms can identify lanes and objects, while sensor measurements are filtered

and combined. Machine-learning models then interpret the environment and support driving decisions.

Once a decision is produced, actuator systems such as motors, steering mechanisms, and braking systems execute the required vehicle movement. IoT connectivity provides communication with cloud systems and external users, while the overall architecture supports monitoring and data analysis.

IX. WORKING PRINCIPLE

The vehicle begins by continuously sensing its surroundings. Cameras capture images for lane and object analysis, ultrasonic sensors measure nearby obstacles, GPS provides location information, and LiDAR/radar contribute depth and environmental information.

The processing stage filters and interprets sensor information. Perception algorithms identify relevant road features and obstacles. The decision layer then determines actions such as maintaining a lane, avoiding an obstacle, adjusting speed, or selecting a route.

The resulting decisions are transferred to actuators controlling steering, motors, and braking. IoT communication can simultaneously transmit vehicle status to cloud services and user applications. This integration creates a continuous sensing-to-decision-to-actuation loop.

X. HARDWARE AND SOFTWARE TECHNOLOGY REVIEW

Raspberry Pi: Provides a compact computing platform for image processing, sensor integration, and machine-learning inference in prototype systems.

Raspberry Pi Camera: Captures images and video for lane tracking, object detection, and visual perception.

Ultrasonic sensors: Provide short-range obstacle-distance information.

GPS: Provides geographic positioning and navigation information.

LiDAR and radar: Provide additional environmental and distance information for perception and sensor fusion.

IoT communication module: Provides network connectivity for cloud communication, monitoring, and data exchange.

Machine-learning software: Supports object detection, scene interpretation, decision-making, and intelli-

gent navigation.

Actuators: Motors, steering mechanisms, and braking systems convert control decisions into physical vehicle motion.

XI. COMPARATIVE REVIEW OF AUTONOMOUS VEHICLE APPROACHES

Camera-only systems can be economical and provide rich visual information but are sensitive to lighting and weather. LiDAR-rich systems provide detailed spatial information but can increase hardware cost and computational complexity. Radar is robust for range and relative-speed estimation but generally provides less detailed scene semantics than cameras.

IoT-enabled architectures add connectivity and remote services that are not available in isolated autonomous systems. However, cloud dependence can create latency and availability concerns. A practical architecture should therefore use edge processing for immediate safety-critical decisions and IoT/cloud services for supplementary monitoring, analytics, and non-critical functions.

XII. BENEFITS IDENTIFIED IN THE REVIEW

Improved road safety through reduction of human-error-related driving risks.

Reduced human intervention and greater consistency in repetitive driving tasks.

Real-time environmental monitoring and intelligent decision-making.

Potential for improved traffic management through V2V and V2I communication.

Navigation and path planning based on GPS and environmental sensing.

Potential improvements in fuel or energy efficiency through optimized speed and routing.

Remote monitoring, data collection, and analytics through IoT and cloud connectivity.

Support for smart-city transportation, accessibility, and emergency-response applications.

XIII. LIMITATIONS AND CHALLENGES

Autonomous driving requires highly reliable perception and decision-making under diverse conditions includ-

ing rain, fog, darkness, road construction, unexpected obstacles, and complex traffic interactions.

Sensor fusion increases system complexity and requires careful synchronization, calibration, and data association. Machine-learning models may also fail when deployed outside the conditions represented in their training data.

IoT connectivity introduces cybersecurity and privacy concerns. Network failures or latency cannot be allowed to compromise safety-critical vehicle functions. Hardware cost, power consumption, computational requirements, maintenance, and regulatory compliance also remain important considerations.

Real-world deployment requires extensive verification, validation, functional-safety engineering, cybersecurity assessment, and regulatory approval. The reviewed prototype concept should therefore be regarded as an academic and engineering framework rather than a production-ready autonomous vehicle.

XIV. APPLICATIONS

Potential applications include intelligent transportation systems, smart-city mobility, autonomous logistics, automated parking, fleet monitoring, emergency response, assisted mobility, and connected-road infrastructure.

IoT connectivity can further support fleet-level analytics, predictive maintenance, remote status monitoring, and traffic-management coordination. The same architecture can be adapted to small autonomous robots and educational vehicle platforms.

XV. FUTURE RESEARCH DIRECTIONS

Future research can focus on improved multi-sensor fusion, higher-reliability perception, edge AI, and efficient machine-learning models suitable for embedded hardware.

V2V and V2I communication can be strengthened through low-latency and secure communication protocols. Digital maps, high-precision positioning, and vehicle-to-cloud analytics can further improve navigation and traffic coordination.

Research should also address adversarial robustness, cybersecurity, privacy, explainable AI, fail-operational design, energy efficiency, and validation across diverse environmental and traffic conditions.

Large-scale real-world datasets and standardized test-

ing scenarios are needed to assess autonomous systems more rigorously. Simulation and digital-twin environments can complement physical testing while reducing development cost and risk.

XVI. CONCLUSION

This review examined IoT-enabled autonomous driving systems by reorganizing the supplied self-driving car paper into a technology-focused review. The architecture combines cameras, ultrasonic sensors, LiDAR, radar, GPS, embedded processing, machine learning, IoT communication, cloud services, and vehicle actuators.

The reviewed approach illustrates how sensing, intelligent perception, connectivity, navigation, and automated control can be integrated to support safer and more efficient transportation. Nevertheless, autonomous driving remains a complex safety-critical problem. Robust sensor fusion, reliable AI, secure communication, edge processing, extensive validation, and compliance with applicable safety requirements are essential for practical deployment.

The future of autonomous transportation is likely to involve coordinated vehicle, infrastructure, and cloud intelligence, with safety-critical decisions remaining resilient to communication and computational failures.

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A Low-Cost Smart Ventilator with Integrated Blood Oxygen and Vital-Sign Monitoring

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Abstract— Mechanical ventilation is an important life-support function for patients experiencing respiratory difficulty, while monitoring blood oxygen saturation and heart rate provides valuable information about respiratory status. This review examines a low-cost embedded ventilator architecture integrating a MAX30100 pulse oximeter, Arduino Uno microcontroller, DC motor-driven Ambu bag mechanism, LCD display, BMP280 pressure sensing, and DHT11 environmental sensing. The reviewed design aims to combine controlled ventilation with real-time physiological and environmental monitoring in a compact prototype. The paper discusses the operating principle, system architecture, sensing and actuation technologies, control methodology, observed prototype parameters, advantages, limitations, applications, and future enhancement opportunities. The review emphasizes that such a prototype may be valuable for education, research, and emergency-oriented experimentation, but medical deployment requires rigorous clinical validation, safety engineering, calibration, reliability assessment, and compliance with applicable medical-device standards. The paper is a review and restructuring of the supplied work and does not claim independent clinical performance.

Keywords— Smart Ventilator, Monitoring, MAX30100, Arduino Uno, Ambu Bag, Embedded System, Biomedical Instrumentation, Heart Rate, Respiratory Monitoring SPO2

I. INTRODUCTION

Mechanical ventilators are widely used to assist or replace spontaneous breathing in patients suffering from respiratory failure. During emergencies and situations where conventional ventilators are unavailable or difficult to access, the development of economical prototype systems can be useful for education, research, and preliminary engineering evaluation.

Blood oxygen saturation and heart rate are important physiological parameters for monitoring respiratory con-

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dition. Pulse oximetry provides non-invasive measurement of and pulse rate and can be integrated with embedded controllers for continuous observation.

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The supplied paper presents a compact ventilator integrated with a blood oxygen sensing system. The design uses a MAX30100 pulse oximeter, Arduino Uno, DC motor, L298N motor driver, Ambu bag, LCD display, BMP280 pressure sensor, DHT11 sensor, and power supply. This review reorganizes the work as a literature and system review.

II. REVIEW SCOPE AND SOURCE BASIS

This review is based on the uploaded paper titled “Ventilator with Blood Oxygen Sensing System.” It retains the original authors, core architecture, components, methodology, reported prototype observations, advantages, limitations, applications, future scope, and references while changing the presentation from a project-development paper to a review-oriented research paper.

The reviewed system should be understood as an engineering prototype rather than a clinically approved ventilator. Any medical use would require additional safety, validation, regulatory, and clinical assessment.

III. REVIEW OF VENTILATOR TECHNOLOGY

Conventional critical-care ventilators provide controlled respiratory support through sophisticated sensing, pressure regulation, flow control, alarms, and safety mechanisms. Such systems are designed for demanding clinical environments and consequently involve significant hardware, software, testing, and regulatory requirements.

Low-cost embedded ventilator prototypes simplify these functions for educational and research purposes. The reviewed design uses mechanical compression of an Ambu bag by a DC motor, with the motor controlled

by an Arduino-based embedded system. This approach demonstrates how sensing, control, and actuation can be integrated into a compact prototype.

An important distinction is that low-cost prototypes should not be assumed to provide the same safety, precision, reliability, alarm functionality, or clinical performance as certified medical ventilators.

IV. BLOOD OXYGEN AND VITAL-SIGN MONITORING

The MAX30100 pulse oximeter is the primary physiological sensing element in the reviewed system. It provides measurements of blood oxygen saturation and heart rate using optical sensing principles. The Arduino processes the sensor output and presents real-time information through an LCD.

Continuous monitoring can support observation of changes in oxygen saturation and heart rate during prototype operation. However, sensor accuracy depends on factors such as sensor placement, motion, perfusion, ambient conditions, calibration, and signal quality. Therefore, reported prototype readings should not be interpreted as clinical-grade measurements without formal validation.

V. SYSTEM ARCHITECTURE

The reviewed architecture is divided into sensing, control, actuation, display, and supporting environmental-monitoring functions. The MAX30100 acquires and heart-rate information. The Arduino Uno acts as the central processing unit. The DC motor and L298N driver provide mechanical actuation for the Ambu bag. The LCD presents real-time measurements. BMP280 and DHT11 provide pressure and environmental information, respectively.

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VI. METHODOLOGY AND WORKING PRINCIPLE

The system initializes the sensors and LCD before entering continuous monitoring mode. The MAX30100 is read to obtain and heart-rate values, which are processed by the Arduino and displayed to the user.

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At the same time, the controller operates the motor-driven Ambu bag mechanism to provide artificial venti-

lation. Pressure and environmental parameters are monitored using the associated sensors. The control sequence repeats continuously so that physiological and system parameters remain available during operation.

The methodology demonstrates a basic embedded feedback-oriented arrangement, although the supplied paper does not describe the complete closed-loop pressure and volume control architecture required for a clinical ventilator.

VII. HARDWARE TECHNOLOGY REVIEW

Arduino Uno: Serves as the central controller and provides a straightforward platform for embedded prototyping.

MAX30100: Provides non-invasive and heart-rate sensing.

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DC Motor and L298N: Provide motor actuation and drive control for the mechanical Ambu bag compression mechanism.

Ambu Bag: Acts as the manual resuscitator mechanism that is mechanically compressed to generate artificial ventilation.

LCD Display: Provides real-time user feedback and parameter visualization.

BMP280: Supports pressure measurement and can contribute to monitoring of ventilation-related conditions.

DHT11: Provides environmental temperature and humidity information.

Power Supply: Provides the electrical energy required by the sensing, control, and actuation subsystems.

VIII. COMPARATIVE TECHNOLOGY REVIEW

Commercial critical-care ventilators generally provide advanced pressure/flow sensing, multiple ventilation modes, precise control, alarms, redundancy, and extensive safety mechanisms. The reviewed low-cost prototype focuses instead on demonstrating the integration of basic ventilation actuation with physiological monitoring.

The principal value of the reviewed design is therefore its educational and prototyping potential, low component complexity, and integration of sensing with embedded

control. Its limitations become important when considering reliability, precision, patient safety, and clinical deployment.

IX. REVIEW OF REPORTED PROTOTYPE OBSERVATIONS

The source paper reports observations in the 96–99% range, heart-rate observations of 70–88 bpm, and ventilation rates of 14–18 breaths per minute under the stated prototype test conditions. It also reports approximately

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±2% accuracy. These values are retained as observations reported by the source and should not be interpreted as independently verified clinical performance.

The reported results indicate that the prototype can acquire and display physiological data while operating the ventilation mechanism. The discussion supports the feasibility of integrating monitoring and actuation in a single embedded prototype.

X. ADVANTAGES IDENTIFIED

The reviewed design offers a relatively low-cost embedded architecture and uses widely accessible components.

Real-time and heart-rate monitoring is integrated with ventilation control.

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The system is compact and suitable for educational demonstration and prototype development.

Arduino-based implementation simplifies programming, experimentation, and modification.

The modular architecture allows future integration of additional sensors, alarms, power backup, and more advanced control methods.

XI. LIMITATIONS AND SAFETY CONSIDERATIONS

The supplied paper itself notes that the prototype is not suitable for clinical use without further testing. Commercial ventilators have stringent requirements that extend beyond basic mechanical ventilation and physiological monitoring.

Important areas requiring further development include precise control of tidal volume and pressure, reliable respiratory-rate regulation, alarm systems, fault detec-

tion, battery backup, sensor calibration, mechanical robustness, electrical safety, patient interface safety, and long-duration reliability.

Clinical use would also require appropriate medical-device testing, risk management, verification and validation, and compliance with applicable standards. Therefore, the reviewed system should be treated as an academic and engineering prototype.

XII. APPLICATIONS

The source paper identifies emergency healthcare, rural medical facilities, educational projects, and biomedical research as possible application areas. In the review context, these should primarily be interpreted as potential prototype and research environments rather than direct clinical deployment without additional validation.

The system can also serve as a teaching platform for embedded control, biomedical sensing, pulse oximetry, motor control, real-time monitoring, and interdisciplinary electronics engineering.

XIII. FUTURE RESEARCH DIRECTIONS

Future work can incorporate advanced pulse-oximetry sensors such as MAX30102, more accurate pressure and flow sensors, closed-loop ventilation control, and improved mechanical actuation.

Alarm functions can be added for abnormal pressure, heart rate, power failure, sensor disconnection, and mechanical faults. Battery backup can improve continuity during power interruptions.

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Artificial-intelligence-assisted monitoring may be investigated for anomaly detection and predictive analysis, provided that adequate datasets and validation procedures are available.

Future prototypes should be evaluated against relevant medical-device requirements and appropriate safety standards before any consideration of clinical application.

XIV. CONCLUSION

This review examines a low-cost smart ventilator architecture integrated with blood oxygen and vital-sign monitoring. The reviewed design combines a MAX30100 sensor, Arduino Uno, DC motor-driven Ambu bag, LCD, pressure sensing, and environmental sensing into a compact embedded prototype.

The architecture demonstrates the educational and research potential of combining biomedical sensing with automated ventilation control. At the same time, the review emphasizes that prototype-level functionality does not establish clinical suitability. Further development in closed-loop control, alarms, reliability, calibration, safety, validation, and regulatory compliance is essential before clinical deployment can be considered.

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A Low-Cost Wearable Sign Language Glove for Real-Time Gesture-to-Voice Conversion: A Review

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Abstract— Sign language provides an essential means of communication for many people with hearing or speech impairments, yet communication between sign-language users and people unfamiliar with sign language remains a persistent challenge. This review examines a low-cost wearable sign language glove that converts selected static hand gestures into spoken output. The reviewed architecture combines four resistive flex sensors, an MPU6050 inertial measurement unit, Arduino Uno processing, HC-05 Bluetooth communication, and Android text-to-speech. The source system uses moving-average filtering, dual-threshold classification with hysteresis, and debounce-cooldown temporal processing to recognize twelve predefined gestures. The reported prototype achieves 93.75% overall recognition accuracy, approximately 1.08 seconds mean end-to-end latency, and about 51 hours of operation from a 5,000 mAh power bank at a reported hardware cost of approximately INR 1,400. This review discusses the evolution of sign-language recognition, vision-based and sensor-based approaches, the reviewed wearable architecture, signal conditioning, classification, communication, performance, advantages, limitations, and future research directions. The work demonstrates the potential of inexpensive standalone wearable systems for assistive communication while highlighting the need for larger vocabularies, user-independent validation, improved sensor fusion, and more comprehensive real-world evaluation.

Keywords— Sign Language Recognition, Wearable Glove, Flex Sensor, Gesture Classification, Assistive Technology, Arduino Uno, MPU6050, Bluetooth, Text-to-Speech

I. INTRODUCTION

Sign language is a primary communication medium for many people with hearing and speech impairments. The communication gap between sign-language users and people who do not understand signing can affect health-care access, education, employment, and everyday social interaction.

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Automated sign language recognition has therefore attracted significant research attention. Existing approaches range from camera-based computer vision to wearable sensor systems. Vision-based systems can recognize complex gestures but may require controlled environments, high computational resources, or extensive training datasets. Wearable gloves provide a complementary approach by measuring finger movement directly and can be designed for portable operation.

The source paper presents a wearable glove using four 2.2-inch flex sensors and an MPU6050 IMU. Arduino Uno processes sensor readings and sends recognized gesture labels through HC-05 Bluetooth to an Android text-to-speech application. This review reorganizes the supplied work as a review-oriented paper while retaining its reported technical findings.

II. REVIEW SCOPE

This review covers the development context, related recognition approaches, wearable sensor technologies, system architecture, signal conditioning, classification strategy, communication and voice output, reported performance, comparative observations, advantages, limitations, applications, and future research directions of the supplied system.

The review treats the reported numerical results as results of the source prototype and does not claim independent replication. Performance of a wearable sign-language system can vary with user, gesture style, sensor placement, calibration, environmental conditions, and vocabulary.

III. RELATED APPROACHES TO SIGN LANGUAGE RECOGNITION

Vision-based recognition: Camera and depth-sensor approaches can capture rich spatial information and support larger vocabularies. However, they can be affected by lighting, background, occlusion, camera position, privacy considerations, and computational requirements.

Wearable sensor gloves: Flex sensors, inertial sensors,

strain gauges, and related devices measure hand or finger movement directly. Such systems can operate independently of camera visibility and can be made portable, although they require the user to wear specialized hardware.

Machine-learning approaches: SVM, neural networks, CNNs, recurrent models, and other classifiers can learn more complex gesture relationships. Their advantages may come at the cost of greater computational requirements, training data needs, and implementation complexity.

IV. REVIEWED WEARABLE SYSTEM ARCHITECTURE

The system can be viewed as four major stages: sensing, processing, wireless communication, and voice output. Four flex sensors mounted on the glove measure finger bending. The MPU6050 detects wrist tilt for gestures that are not represented by finger configurations.

The Arduino Uno performs signal filtering and rule-based gesture classification. Confirmed gesture labels are transferred through HC-05 Bluetooth Serial Port Profile to an Android device. The Android application displays the recognized text and uses text-to-speech functionality to produce spoken output.

V. FLEX SENSOR AND IMU TECHNOLOGY

The four resistive flex sensors are connected through voltage-divider circuits and provide analog signals to the Arduino. The source reports that the glove-mounted 2.2-inch sensors produced approximately 870–885 ADC units of dynamic range across the four channels, allowing a relatively wide separation between straight and bent states.

The MPU6050 provides accelerometer information for detecting left- and right-tilt gestures. The source reports that tilt recognition was less accurate than flex-based gestures because accelerometer measurements form a more continuous and noise-sensitive signal during gesture initiation.

VI. SIGNAL CONDITIONING AND CLASSIFICATION

A ten-sample moving-average filter is applied to reduce high-frequency fluctuations in sensor readings. The

source describes a three-state interpretation for each flex channel: BENT above 700 ADC units, STRAIGHT below 300, and TRANSITIONAL between 300 and 700. This creates a 400-unit hysteresis dead zone intended to reduce false transitions caused by noise and partial finger movement.

Temporal filtering is added through a debounce requirement and cooldown period. Four consecutive consistent classifications are required before gesture confirmation, while a cooldown stage suppresses repeated transmission of the same sustained gesture. This layered approach reduces unwanted state oscillation without requiring a machine-learning model.

VII. GESTURE VOCABULARY AND OUTPUT

The reviewed vocabulary contains twelve gestures. Ten are represented using four-finger binary combinations and two are represented using left and right wrist tilt. The vocabulary includes common communication expressions and needs such as HELLO, THANK YOU, YES, NO, PLEASE, SORRY, HELP, GOOD, WATER, FOOD, I LOVE YOU, and DANGER.

After classification, the gesture label is transmitted to an Android device through Bluetooth. Text-to-speech converts the label into audible output. This provides a direct gesture-to-voice pathway and can help bridge communication between a signing user and a listener who does not know sign language.

VIII. IMPLEMENTATION REVIEW

The hardware assembly places flex sensors on the dorsal side of the glove, with the MPU6050 positioned centrally on the hand and the Arduino and Bluetooth module mounted around the wrist. Firmware is implemented in C++ through the Arduino IDE using standard communication and sensor libraries.

The processing sequence includes sensor reading, filtering, accelerometer acquisition, gesture classification, transmission, and a delay between cycles. The source reports an approximate loop time of 220 ms. The Android output application receives gesture strings and presents them as text while enabling text-to-speech.

IX. PERFORMANCE REVIEW

The source reports 93.75% overall recognition accu-

racy from 225 correct recognitions out of 240 trials across twelve gestures. Flex-based gestures achieved reported accuracies between 90% and 100%, while the two tilt gestures achieved 85%.

The reported mean end-to-end latency across 50 trials was approximately 1.08 seconds, with the debounce hold contributing substantially to the response time. The source also reports total system current of approximately 83 mA at 5 V and approximately 51 hours of continuous operation from a 5,000 mAh power bank at 85% efficiency.

The reported hardware cost is approximately INR 1,400, making the prototype considerably less expensive than the comparison systems cited in the source paper. These figures are source-reported prototype results and should be interpreted within the experimental conditions of the original work.

X. COMPARATIVE DISCUSSION

The reviewed system emphasizes affordability, portability, standalone operation, and low computational complexity. Compared with vision-based systems, it avoids dependence on camera positioning and environmental lighting. Compared with more complex machine-learning gloves, its rule-based classifier reduces processing and training requirements.

The principal trade-off is vocabulary size and flexibility. Binary classification of four fingers provides a limited number of combinations, and the source assigns ten of them to predefined words. Adding thumb sensing could increase the number of possible combinations, while multi-level sensing and machine learning could enable a much larger vocabulary.

XI. ADVANTAGES

Low-cost hardware architecture with reported total cost of approximately INR 1,400.

Standalone portable operation without dependence on cloud computing or a laptop.

Real-time gesture-to-voice output using Bluetooth and Android text-to-speech.

Reported overall recognition accuracy of 93.75% across twelve predefined gestures.

Long reported battery operation of approximately 51 hours using a 5,000 mAh power bank.

Simple rule-based classification that avoids the training complexity of machine-learning models.

XII. LIMITATIONS

The vocabulary is limited to twelve predefined gestures and does not represent the full complexity of natural sign language.

Sensor placement, glove fit, finger anatomy, user technique, and calibration can influence recognition performance.

Tilt gestures show lower reported accuracy than flex-based gestures, indicating sensitivity to continuous accelerometer measurements and motion noise.

The reported evaluation uses a limited prototype vocabulary and trial set; broader user-independent and real-world testing would be required to establish general robustness.

Voice output depends on Bluetooth communication and an Android device, so the complete system is not entirely self-contained at the output stage.

XIII. APPLICATIONS

The reviewed system can support assistive communication for people with hearing or speech impairments in everyday settings. Potential environments include hospitals, educational institutions, public offices, and low-resource locations where camera-based or cloud-based systems may be impractical.

It can also serve as an educational platform for demonstrating sign-language recognition, wearable computing, embedded sensing, Bluetooth communication, signal processing, and human-machine interaction.

XIV. FUTURE RESEARCH DIRECTIONS

Future versions can add a thumb sensor to expand the gesture vocabulary and incorporate multi-level finger-angle quantization for richer gesture representation.

Sensor fusion combining accelerometer and gyroscope information can be investigated to improve tilt-gesture recognition. Automatic threshold calibration could reduce the dependence on manually selected thresholds and improve portability across users.

TensorFlow Lite Micro or other embedded machine-learning methods can be explored for larger vocabularies while retaining standalone operation. More advanced filtering and adaptive classification may also reduce latency

and false detections.

Future studies should include larger datasets, multiple users, different hand sizes, repeated sessions, continuous signing, and standardized evaluation protocols. Multilingual text-to-speech and integrated audio hardware can further improve accessibility.

XV. CONCLUSION

This review examined a low-cost wearable sign-language glove designed for real-time gesture-to-voice conversion. The architecture combines flex sensors, an MPU6050 IMU, Arduino Uno processing, HC-05 Bluetooth communication, and Android text-to-speech. The source reports 93.75% recognition accuracy across twelve gestures, approximately 1.08 seconds mean end-to-end latency, and approximately 51 hours of battery operation.

The reviewed design demonstrates that inexpensive embedded hardware can provide a practical foundation for assistive gesture-to-voice systems. Its main strengths are affordability, portability, standalone processing, and simple classification. Its main limitations are restricted vocabulary, sensitivity to sensor and user conditions, and the need for broader validation. Future work involving sensor fusion, automatic calibration, embedded machine learning, expanded vocabulary, and user-independent evaluation can improve the system's usefulness for real-world assistive communication.

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Smart Wearable Safety Systems for Mountaineering: A Comprehensive Review of Environmental Monitoring, Fall Detection, GPS Tracking and LoRa-Based Emergency Communication

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Abstract— Mountaineering and trekking in remote regions expose individuals to rapidly changing environmental conditions, falls, disorientation, and limited access to conventional communication networks. This review examines wearable safety systems for mountaineers with emphasis on environmental sensing, motion-based fall detection, GPS location tracking, manual SOS activation, and long-range LoRa communication. The reviewed research paper presents a compact system based on two Arduino Uno boards, DHT11, BMP280, MPU6050, NEO-7M GPS, 16×2 LCD, panic button, and LoRa Ra-02 modules. The literature cited in the source paper demonstrates a progression from wearable monitoring and wireless sensor networks toward integrated emergency-assistance systems. The review synthesizes these approaches, evaluates the architecture and operational sequence of the proposed wearable, identifies its practical advantages and limitations, and outlines future directions including improved sensing, power optimization, communication robustness, and enhanced rescue coordination. The reviewed concept is particularly relevant to mountaineers, trekkers, rescue teams, and other personnel operating in environments where cellular connectivity may be unavailable.

Keywords— Smart Wearable; Mountaineering Safety; Fall Detection; GPS Tracking; LoRa; SOS Alert; Arduino Uno; Environmental Monitoring; Remote Communication; Rescue Assistance.

I. INTRODUCTION

Mountain environments present a combination of physical hazards and communication challenges. Sudden falls, changing temperature and pressure, difficult terrain, and isolation can increase the consequences of an otherwise manageable incident. The source paper therefore focuses on a wearable safety device capable of monitoring environmental and motion-related parameters while providing an emergency communication mechanism.

II. SCOPE AND REVIEW BASIS

This review is derived from the uploaded research paper “Smart Wearable for Mountaineers,” published in the International Journal of Research Publication and Reviews, Volume 6, Issue 5, May 2025. The source paper describes a wearable system using two Arduino Uno boards, LoRa Ra-02 modules, DHT11, BMP280, MPU6050, NEO-7M GPS, a 16×2 LCD and a panic button. Its cited literature covers smart jackets, wireless sensor networks, wearable tracking, mountaineer health and GPS tracking, mountain climber monitoring, and LoRa-based emergency assistance. The review retains the source paper’s terminology and reported scope without adding unsupported experimental claims.

III. EVOLUTION OF WEARABLE SAFETY APPROACHES

The references in the source paper show several directions in mountaineering safety research. A smart jacket using LoRaWAN technology addresses health monitoring of climbers. Wireless-sensor-network approaches explore safety monitoring, while wearable jacket systems focus on tracking people. Other cited studies address mountaineer health and GPS tracking and mountain climber monitoring. A 2023 study cited by the source paper specifically addresses LoRa-based IoT emergency assistance and safety in mountaineering. Together, these works indicate a movement toward combining sensing, localization, and long-range communication in wearable safety platforms.

IV. MAJOR TECHNOLOGIES IN THE REVIEWED SYSTEM

Arduino Uno functions as the central controller in both the wearable and receiver units. The source paper se-

lects it for its simplicity, available I/O, and suitability for integrating multiple modules. LoRa Ra-02 modules provide long-range, low-power wireless communication and are described as operating at 433 MHz. The NEO-7M GPS module provides latitude and longitude for location tracking. DHT11 monitors ambient temperature, BMP280 measures pressure and supports altitude calculation, and MPU6050 provides accelerometer and gyroscope data for detecting sudden movement or falls. A 16×2 LCD provides local information, while a panic button supports manual emergency signalling.

V. SYSTEM ARCHITECTURE AND WORKING

The wearable unit collects environmental, motion, and location information. DHT11 supplies temperature data, MPU6050 supplies motion information, and NEO-7M provides GPS coordinates. The microcontroller checks for abrupt acceleration changes that may indicate a fall and continuously monitors the panic button for manual SOS activation. Current temperature, altitude, pressure, and GPS information are displayed sequentially on the LCD. When a fall is detected or the panic button is pressed, the system transmits an SOS signal through LoRa. At the receiver, an LED and buzzer provide an alert while location details are displayed to support rescue response. The source paper states that the circuit is powered using a power bank.

VI. COMPARATIVE REVIEW

Research direction	Primary focus	Key technology/approach	Review observation
Wearable health monitoring	Monitoring climber condition	LoRaWAN / wearable sensors	Supports remote health-oriented monitoring
Wireless safety systems	Emergency and safety signalling	WSN	Demonstrates distributed safety communication
Wearable person tracking	Location and tracking	Wearable electronics	Emphasizes user localization
Mountaineer & GPS	Health and location tracking	GPS + sensing	Combines location with safety information
Mountain climber monitoring	Remote climber monitoring	Embedded sensing	Extends monitoring toward field applications
LoRa emergency assistance	Emergency communication	LoRa-based IoT	Highlights long-range communication for remote regions
Reviewed wearable	Integrated safety prototype	Arduino + LoRa + GPS + sensors	Combines sensing, localization and SOS alerting

VII. ADVANTAGES AND PRACTICAL SIGNIFICANCE

The reviewed architecture provides several practical advantages. Automatic fall detection can initiate an emergency response without requiring the user to operate a control after an accident. GPS tracking provides location information that can support rescue personnel. A dedicated panic button offers an additional manual emergency

pathway. LoRa communication is particularly relevant to remote areas where mobile networks may not be available. The wearable arm or shoulder form factor supports hands-free operation and is intended to remain practical over heavy mountain clothing. The modular design also leaves scope for future upgrades.

VIII. CRITICAL REVIEW AND RESEARCH GAP

The source paper demonstrates the integration of multiple sensing and communication functions in a compact prototype, but the reported results are primarily descriptive. The paper does not provide extensive numerical evaluation of fall-detection accuracy, false-alarm rate, GPS accuracy under mountainous conditions, LoRa packet delivery reliability, communication range under different terrain conditions, battery operating time, or response latency. These parameters are important for evaluating a safety-critical wearable. The source paper also does not report comparative field trials across different weather and terrain conditions. Therefore, the reviewed system should be regarded as a promising prototype architecture requiring further field validation rather than as a fully characterized emergency device.

IX. FUTURE RESEARCH DIRECTIONS

Future development can focus on improving fall-detection algorithms using more robust motion-analysis methods; reducing false alarms through sensor fusion; optimizing power consumption for longer expeditions; evaluating LoRa performance in obstructed mountainous terrain; improving GPS availability and location reliability; adding additional environmental or physiological sensors where appropriate; developing stronger enclosure and weather protection; and integrating receiver-side information into a more comprehensive rescue-management interface. Long-duration field trials with controlled emergency scenarios would also provide useful validation.

X. CONCLUSION

This review indicates that wearable safety systems can combine environmental monitoring, motion detection, location tracking, manual SOS activation, and long-range communication into a single platform for mountaineering applications. The source research paper provides a straightforward architecture using Arduino Uno, DHT11, BMP280, MPU6050, NEO-7M GPS, LoRa Ra-02, LCD,

and a panic button. Its main strength is the integration of automatic and manual emergency signalling with location information in a communication approach intended for remote environments. Further work should emphasize quantitative performance assessment, field testing, power optimization, communication reliability, and improved detection intelligence. These developments can strengthen the suitability of such wearable systems for mountaineers, trekkers, and search-and-rescue operations.

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Solar-Powered Smart EV Charging Infrastructure: A Comprehensive Review of IoT-Based Monitoring, Energy Management and Intelligent Charging

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Abstract— The rapid adoption of electric vehicles (EVs) is increasing the need for charging infrastructure that is reliable, sustainable, intelligent, and convenient for users. This review examines the development of solar-powered EV charging stations integrated with Internet of Things (IoT) technologies, with particular emphasis on renewable-energy utilization, real-time monitoring, charging-slot management, remote control, and user interaction. The source research paper proposes a prototype based on an ESP32 microcontroller, photovoltaic generation, battery storage, voltage and current sensing, infrared slot detection, temperature monitoring, relay control, I2C LCD displays, the Blynk IoT platform, and a web-based interface for booking and simulated payments. The reviewed literature indicates that earlier systems commonly addressed individual aspects such as solar charging, IoT monitoring, mobile control, slot booking, or rural deployment, while integrated solutions remain an important area of development. The review identifies the strengths of the proposed architecture, including modularity, low-cost implementation, renewable-energy utilization, remote monitoring, and safety-oriented automation. It also highlights areas requiring further investigation, such as charging-performance validation, energy-management optimization, battery technologies, cybersecurity, interoperability, payment integration, and large-scale deployment.

Keywords— Electric Vehicle Charging; Solar Energy; Photovoltaic Charging; Internet of Things; ESP32; Smart Charging Station; Blynk; Slot Management; Renewable Energy; Real-Time Monitoring.

I. INTRODUCTION

Electric vehicles are becoming an important component of sustainable transportation, creating a corresponding requirement for accessible and intelligent charging infrastructure. The source paper frames the charging problem not only as an energy-delivery challenge but also as an infrastructure and user-experience challenge. Solar energy can reduce dependence on conventional grid electricity, while IoT connectivity can provide visibility and remote control of charging operations.

The reviewed prototype combines these concepts into a single architecture. It uses a photovoltaic source and battery storage, with an ESP32 serving as the central controller. Sensors measure voltage, current, temperature, and vehicle presence, while relay modules control individual charging slots. Local displays provide operating information and the Blynk platform enables remote monitoring. A web interface is also described for login, slot availability, booking, and simulated payment.

The review is based primarily on the uploaded research paper, “Solar Based EV Charging Station with IoT Networking,” published in the International Research Journal of Modernization in Engineering Technology and Science, Volume 07, Issue 04, April 2025. The source paper contains a literature survey covering solar EV charging, IoT energy monitoring, smart EV charging, slot booking, and solar-powered IoT-enabled charging stations. The present review retains those cited studies as the literature foundation and synthesizes their stated contributions and limitations.

II. SCOPE AND REVIEW BASIS

The review is based primarily on the uploaded research paper, “Solar Based EV Charging Station with IoT Networking,” published in the International Research Journal of Modernization in Engineering Technology and Science, Volume 07, Issue 04, April 2025. The source paper contains a literature survey covering solar EV charging, IoT energy monitoring, smart EV charging, slot booking, and solar-powered IoT-enabled charging stations. The present review retains those cited studies as the literature foundation and synthesizes their stated contributions and limitations.

III. EVOLUTION OF SMART EV CHARGING APPROACHES

3.1 Solar-Powered Charging

Solar-powered EV charging is presented in the source literature as an approach

for reducing dependence on the electrical grid. Khurana and Bansal (2017) developed a solar-powered EV charging station using photovoltaic panels and battery backup, with emphasis on grid independence. The source

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paper notes that this approach did not provide user-oriented remote monitoring or control. Reddy et al. (2022) subsequently combined solar energy and IoT for EV charging in rural areas, but the source paper reports that real-time user interfaces, booking, and payment mechanisms were not included.

3.2 IoT-Based Monitoring and Control

IoT provides a communication layer through which charging

parameters and equipment status can be observed and controlled remotely. Rani et al. (2020) developed an IoT-based energy monitoring system using NodeMCU for home automation, demonstrating the relevance of connected sensing even though the application was not EV-specific. Kaur and Singh (2019) focused directly on smart EV charging with IoT and mobile control, but the source paper identifies its dependence on grid electricity as a limitation.

3.3 Slot Booking and User Interaction

User-oriented charging infrastructure requires mechanisms for

identifying available slots and coordinating charging sessions. Shaikh and Mulla (2021) implemented an IoT-based EV charging station with a slot-booking feature using Raspberry Pi. According to the source paper, the Raspberry Pi-based implementation was relatively complex and less cost-effective for large-scale deployment.

3.4 Integrated Renewable-Energy and IoT Systems

The literature cited in the source paper demonstrates a

progression from individual functions toward integrated charging infrastructure. Darbanian and Asghari (2021) are cited for a smart solar EV charging station with real-time scheduling. Islam and Al-Hammadi (2021) addressed smart EV charging infrastructure using renewable energy resources and IoT. Other cited works examine IoT-based charging, solar EV chargers, intelligent power management, Blynk-based monitoring, and autonomous solar charging with IoT integration.

IV. COMPARATIVE REVIEW OF APPROACHES

Research direction	Main contribution	Limitation identified in source paper	Role in integrated architecture
Solar EV charging	PV generation and battery backup	Limited user-facing monitoring/control	Renewable energy source and storage
IoT energy monitoring	Remote sensing and connected monitoring	Not EV-specific	Data acquisition and cloud connectivity
IoT smart EV charging	Mobile control of charging	Grid dependent	Remote charging control
EV slot booking	Reservation and slot management	Complexity/cost concerns	User-oriented slot allocation
Solar + IoT EV charging	Renewable energy with connected operation	Limited interface and booking features	Energy and communication integration
Reviewed prototype	Solar, IoT, sensors, slots, web interface	Prototype-level validation and simulated services	Unified smart charging concept

V. ARCHITECTURE OF THE REVIEWED SYSTEM

The source paper organizes the prototype into solar power generation, charging-slot control, sensor-based monitoring, and cloud-based user interaction. A photovoltaic panel is described as the energy source, connected to a charge controller and battery storage in the system architecture. The ESP32 acts as the central controller and provides Wi-Fi/Bluetooth connectivity.

For measurement, voltage-divider circuits are used for voltage sensing, ACS712 current sensors are assigned to charging slots, IR sensors identify vehicle presence, and a DHT11 monitors temperature. Four-channel relay modules control charging-slot power. I2C LCD displays provide local information, while Blynk provides remote monitoring and relay control. The web prototype includes user registration/login, availability tracking, booking confirmation, simulated UPI/debit/credit payment, and map-based location visibility.

VI. SMART OPERATIONAL LOGIC

The operational logic described in the source paper combines physical sensing with user authorization. A slot is considered available when the IR sensor indicates no vehicle and the current sensor indicates no charging load. After vehicle detection and booking confirmation, the corresponding relay is activated. Voltage, current, and temperature information is updated at five-second intervals on the Blynk dashboard and local LCDs. A temperature threshold of approximately 45°C is proposed for alerting and possible automatic relay shutdown.

VII. BENEFITS IDENTIFIED THROUGH THE REVIEW

The integrated architecture offers several benefits. First, solar generation can reduce dependence on conventional grid supply. Second, IoT connectivity enables remote visibility of charging parameters and slot status. Third, the combination of IR and current sensing

improves slot-use identification. Fourth, web-based booking can improve user convenience. Fifth, the modular ESP32-based structure can be extended to additional charging slots. Finally, temperature-based protection and relay control introduce an element of automated safety. The source paper also emphasizes the educational value of the prototype for renewable energy, IoT, and embedded-system learning.

VIII. RESEARCH GAP AND CRITICAL REVIEW

The source literature suggests that many earlier systems focus on one or two aspects of the EV charging problem. Solar charging studies emphasize renewable energy and energy independence; IoT studies emphasize monitoring and communication; slot-booking studies focus on user interaction; and integrated solar-IoT studies address energy and connectivity. The source paper identifies the

combination of solar energy, multi-slot real-time control, IoT dashboards, booking, and payment simulation as an underexplored area.

From a review perspective, the proposed architecture is valuable as an integrated prototype, but several aspects require deeper experimental validation before real-world deployment. The source paper reports the prototype and its interfaces but does not provide extensive quantitative measurements of charging efficiency, photovoltaic energy yield, battery round-trip performance, charging duration, energy cost per session, communication latency, or long-term reliability. Similarly, the payment mechanism is described as simulated rather than as a production financial service.

IX. SAFETY, RELIABILITY AND SCALABILITY CONSIDERATIONS

The use of current, voltage, temperature, and occupancy sensing provides a foundation for safe operation. Automatic relay control can disconnect a charging point under defined abnormal conditions. However, a practical charging station would require additional validation of electrical protection, isolation, fault detection, battery management, connector safety, thermal behavior, and communication failure modes. The source paper's architecture is modular, so additional slots can conceptually be added, but scaling would also require careful consideration of power availability, controller resources, communication traffic, protection coordination, and energy man-

agement.

X. FUTURE RESEARCH DIRECTIONS

- Advanced energy-management algorithms that allocate available solar and stored energy according to charging demand.
- Quantitative comparison of solar-assisted charging with grid-only charging in terms of energy consumption and operating cost.
- Use of improved battery-storage technologies and battery-management strategies.
- Dynamic charging scheduling based on photovoltaic availability, battery state, and user priority.
- Integration of authenticated payment gateways rather than simulated payment workflows.
- Cybersecurity mechanisms for IoT communication, user accounts, remote relay control, and cloud data.
- Interoperability with standardized EV charging communication and connector systems.
- Long-duration testing to evaluate thermal stability, sensor reliability, battery performance, and communication robustness.
- Deployment studies for educational campuses, parking facilities, and other controlled environments.

XI. CONCLUSION

This review shows that solar-powered EV charging combined with IoT can address several interconnected requirements of modern charging infrastructure: renewable energy utilization, remote monitoring, slot management, user interaction, and basic automated protection. The reviewed source paper brings these functions together through an ESP32-centered prototype incorporating photovoltaic generation, battery storage, multi-sensor monitoring, relay-controlled charging points, Blynk connectivity, local displays, and a web interface. Its principal contribution is the integration of functions that earlier studies, as summarized in the source paper, often addressed separately.

At the same time, the review indicates that prototype integration should be followed by rigorous performance and safety evaluation. Future research should emphasize measurable charging efficiency, energy-management performance, reliability, cybersecurity, standardized interoperability, and real payment and scheduling mechanisms. With these improvements, solar-assisted IoT-enabled charging stations could become a practical component of sustainable and intelligent EV infrastructure, particularly in campuses and urban parking environments.

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IoT-Enabled Road Surface Monitoring: A Review of Sensor-Based, Robotic, and Cloud-Integrated Approaches

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Abstract— Road surface condition monitoring is important for transportation safety, maintenance planning, and smart-city infrastructure management. The reviewed research proposes a low-cost Road Surface Analyzer combining a Bluetooth-controlled robotic vehicle, multiple sensors, GPS localization, image capture, and cloud-based data management. This review examines the architecture, sensing strategy, data workflow, reported performance, strengths, limitations, and future research opportunities. The source reports 95.5% detection accuracy for potholes and bumps and describes an end-to-end process in which anomalies are detected, geo-tagged, photographed, stored, and visualized through Google Sheets, Google Drive, and Google Maps. The approach is attractive for prototype-scale deployment because it uses accessible hardware and familiar cloud services. However, the source provides limited detail about dataset size, test conditions, defect-classification methodology, false-positive/false-negative rates, and statistical validation. Future work should emphasize standardized datasets, quantitative benchmarking, machine-learning-assisted classification, severity estimation, autonomous navigation, edge/cloud optimization, and predictive maintenance.

Keywords— road surface monitoring; pothole detection; IoT; robotics; ultrasonic sensing; vibration sensing; ESP32-CAM; GPS; cloud dashboard; smart transportation

I. INTRODUCTION

The reviewed paper identifies safe and smooth road surfaces as essential for transportation efficiency, accident prevention, and infrastructure longevity. It notes that traditional monitoring commonly depends on manual inspection or expensive specialized vehicles. The proposed solution combines a robotic vehicle, multi-sensor detection, and a cloud-based web server to detect, log, and visualize potholes, bumps, and other irregularities. The architecture is divided into a robotic vehicle, an ESP32-and-TechnoIntellectio: National Research Journal
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sensor detection subsystem, and a web/cloud subsystem.

II. SYSTEM ARCHITECTURE

The robotic vehicle uses an Arduino Uno R3, L298N motor driver, 5 V DC motors, and HC-05 Bluetooth module. The detection subsystem contains an ESP32-CAM with an OV2640 camera, HC-SR04 ultrasonic sensor, SW-420 vibration sensor, and EO-6M GPS module, with a 3.7 V Li-ion battery identified as the power source. The software layer uses Google Sheets for logging, Google Drive for image storage, Google Maps for visualization, and HTML/JavaScript for an interactive dashboard.

III. SENSOR AND HARDWARE REVIEW

Robotic platform: The Arduino-based vehicle receives movement commands over Bluetooth and controls the motors through the L298N driver. The source emphasizes its reliability, simplicity, cost effectiveness, and suitability for prototyping.

Imaging: The ESP32-CAM provides 2 MP road-defect images and wireless transmission capability. Image evidence complements numerical sensor readings and can support human verification.

Ultrasonic sensing: The HC-SR04 measures distance to the road surface, with changes in distance interpreted as depth variations associated with potholes and related anomalies.

Vibration sensing: The SW-420 detects sudden movements and impacts associated with bumps. Its use alongside ultrasonic sensing provides a second sensing modality for corroboration.

GPS: GPS coordinates are associated with detected anomalies so maintenance personnel can identify the physical location of each reported problem.

IV. DATA PROCESSING AND CLOUD INTEGRATION

The workflow begins with robotic movement and continuous road scanning. The ultrasonic and vibration sen-

sors monitor irregularities, the camera captures images, and GPS records location. The ESP32 processes sensor information, images are saved to Google Drive, defect details such as timestamp, location and severity are logged in Google Sheets, and Google Maps visualizes problem areas. The dashboard is intended to help authorities view issues, prioritize repairs, and track resolution progress.

This end-to-end integration is one of the strongest aspects of the work. Detection is transformed into an actionable maintenance record by linking a defect to time, coordinates, image evidence, and status. The source also highlights the accessibility, filtering, collaboration, export, and image-sharing capabilities of the selected cloud services.

V. REPORTED PERFORMANCE AND CRITICAL ASSESSMENT

The source reports 95.5% detection accuracy for potholes and bumps and states that the result was validated through manual inspection. The conclusion associates this performance with the combined use of the robotic platform, camera, ultrasonic and vibration sensors, GPS, and cloud services.

From a review perspective, the reported accuracy is promising but should be interpreted cautiously. The available paper does not provide enough detail about the number of test cases, road length, defect distribution, environmental conditions, confusion matrix, precision, recall, F1-score, or confidence intervals. Consequently, the 95.5% value demonstrates encouraging prototype performance but does not by itself establish robustness for large-scale deployment.

VI. MAJOR STRENGTHS

Strength	Critical review
Low-cost design	Uses accessible embedded hardware and common cloud services, reducing prototype development cost and complexity.
Multi-sensor approach	Combines ultrasonic, vibration, imaging, and GPS information rather than relying on a single sensor.
Actionable localization	GPS coordinates convert detection events into geographically identifiable maintenance tasks.
Visual verification	Captured images provide evidence that can support subsequent inspection.
Cloud dashboard	Centralized storage and map visualization can support collaborative monitoring and maintenance coordination.
Expansion potential	The architecture provides a foundation for future machine learning and predictive maintenance.

VII. LIMITATIONS AND RESEARCH GAPS

The first major gap is experimental reporting. A reproducible study should specify the number and characteristics of test cases, road types, defect categories, severity thresholds, evaluation procedure, and error statistics.

Without these details, comparison with alternative methods is difficult.

The second gap concerns autonomy. Bluetooth teleoperation is suitable for a controlled prototype but restricts coverage and introduces dependence on an operator. Autonomous navigation, obstacle avoidance, route planning, and automatic charging or return-to-base functionality would improve practical scalability.

The third gap is intelligent classification. Although the paper describes identification and classification in its workflow, it does not present a detailed machine-learning classifier. Its conclusion explicitly identifies machine learning for defect

classification and predictive maintenance as future work.

The fourth gap is cloud scalability and reliability. General-purpose cloud services are useful for prototypes, but large deployments may require stronger database architecture, connectivity handling, security, access control, data retention policies, and edge processing.

The fifth gap is environmental validation. Road-surface measurements can be influenced by speed, mounting geometry, road material, lighting, weather, and vehicle vibration. The available text does not provide a systematic comparative evaluation across these factors.

VIII. POSITION WITHIN RELATED RESEARCH

The reference list shows that road-condition monitoring has been explored through mobile sensing, sensor networks, automated pavement surveys, and data-driven maintenance. The cited Nericell work addresses road and traffic monitoring using mobile smartphones, while the cited Zoysa et al. work addresses sensor-network-based road-surface monitoring. The paper also cites work on comprehensive automated pavement surveys and pavement maintenance considering accident costs.

The reviewed contribution is therefore best viewed as an integrated engineering prototype rather than a completely new sensing paradigm. Its practical value is the combination of mobile robotics, multiple low-cost sensors, image capture, GPS, and cloud visualization in one end-to-end workflow.

IX. RECOMMENDED FUTURE RESEARCH

1. Machine-learning classification: Build a labeled

road-defect dataset and report precision, recall, F1-score, and class-wise confusion matrices.

2. Severity estimation: Estimate pothole depth, width, area, and severity rather than only detecting presence.

3. Sensor fusion: Develop a defined fusion method for camera, ultrasonic, vibration, and inertial information.

4. Autonomous operation: Add autonomous navigation and obstacle avoidance.

5. Edge computing: Perform preliminary anomaly detection locally to reduce bandwidth and latency.

6. Predictive maintenance: Use historical defect records to estimate maintenance priority and deterioration risk.

7. Field validation: Test different road materials, speeds, weather conditions, traffic environments, and defect severities.

8. Scalable software: Use secure, database-backed APIs and role-based access for multi-vehicle deployment.

X. OVERALL CRITICAL EVALUATION

The reviewed paper presents a clear and practically motivated engineering prototype. Its principal strength is the integration of sensing, robotics, localization, imaging, cloud storage, and visualization into a single workflow. The reported 95.5% accuracy is encouraging, and the system has potential value for smart-city infrastructure monitoring.

Nevertheless, the research would be stronger with a more rigorous experimental methodology and broader performance metrics. Reproducibility would improve through detailed test-set information, detection thresholds, error analysis, and environmental testing. Large-scale field validation is also necessary before operational deployment.

XI. CONCLUSION

This review finds that the Road Surface Analyzer is a promising low-cost IoT and robotic approach to automated road-condition monitoring. Its combination of Arduino control, ESP32-CAM imaging, ultrasonic and vibration sensing, GPS localization, and cloud visualization provides a practical end-to-end architecture. The reported 95.5% detection accuracy indicates encouraging prototype performance.

The key research opportunity is to progress from pro-

totype demonstration toward statistically validated, autonomous, scalable, and intelligent monitoring. Machine-learning-based defect classification and predictive maintenance, explicitly identified by the source as future work, are logical next steps.

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An AI-Based Framework for Multi-Format Document Understanding and Content Generation

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Abstract— There are abundant of software companies and mobile applications in India that provide facilities for file viewing, text extraction, and document conversion. While these apps work well enough on straightforward files, they are known to have trouble with complex formatting, poor OCR accuracy from scanned PDFs, a low understanding of context. Current industry solutions rely on extremely simple rule-based algorithms or very complicated NLP models, which compromise the performance of typical user equipment. Our project, SnaPDFy, seek to address this issue by offering a new but precise document processing framework. The backend is developed in the Flask framework, for easy deployment and integration as well as a maintenance-friendly environment. SnaPDFy has a multi-step document ingestion pipeline to thoroughly clean, normalize and preprocess PDF and DOCX documents which leads to parsing errors in existing tools. At its core, SnaPDFy is powered by an NLP engine that combines fast and lean models with state of the art transformers. This design leads to a much higher context accuracy in comparison with classical lexicon-based methods, and are also resource friendly. The system architecture is also extensible, allowing for addition of new NLP modules or file formats with only minimal changes to the foundational paper-and-pencil system.

Keywords— Document management, NLP(Natural Language Processing), Flask (a framework of Python), Extraction of text on models, Architecture which are Scalable, parsing of PDF and Retrieval of information.

I. INTRODUCTION

The rapid growth of communication and reporting, in-depth document analysis is an essential part of the collection of modern System frameworks. The automatic summarization of texts and interpretation have become functionalities that

Content Management, or support for Optimization. Algorithms that are faster in extracting the meaning are essential for extracting useful knowledge from the rapidly growing domain of textual data. Data, which ranges from market research reports and covering product manuals through large running logs. Cost efficiency and accuracy in information access are directly connected to the correctness of decision-making. This leads to an encouraging step in the research area on the development of system architectures for fast Knowledge integration of basic information.

1. Formulating the Problem:

This is a serious shortcoming in the pipeline, and if the first presentation of data is structurally distorted, there is no machinery to rehabilitate this fact for any advanced NLP down-range process. What's more, the variation of NLP methods also causes a problem called NLP Contextual Deficiency. Despite the simplicity and efficiency offered by lexicon-based tools such as TextBlob, they are challenged to handle nuances in language such as sarcasm, irony, negation, and domain-specific terminology. A model's reliance on them to score comes at the cost of high-accuracy sentiment evaluation, where it lags behind modern sequence-based ones significantly in high-level scores. Moreover, the actual usage of existing models is impeded by deployment difficulties. Performing inference with large-scale transformer models, including BERT and T5, is computationally expensive. As evidenced in practice, even a minimal installation of such resource-demanding models would be expected to utilize more than 2 vCPU and 3 GB RAM per instance for better performance. This is a bottleneck for practical applications of large-scale real-time microservice architecture, and it's a big obstacle to commercialization and popularization.

In the system, the input and characteristics of papers mark these two concerns simultaneously. In this paper, we present a document visualization generation sys-

tem tailored for high-quality text document analysis, fit for production microservice mode. The contributions of SnaPDFy consist of three components and provide practical, analytical, and Practical solutions.

1. High-Fidelity Document Ingestion (Addressing Data Integrity):

The SnaPDFy has an Integrated high-quality document collection model that is specially designed to find the issues that are associated with processing errors that are common in complex document structures found in standard libraries. This ensures that the data passed to the Natural Language Processing engine is relatively Consistent for Accurate Analysis. This ensures that the data passed to the Natural Language Processing engine is relatively Consistent for Accurate Analysis.

2. Resource-Optimised Hybrid NLP Engine (Resolving the Cost-Accuracy Dilemma):

The design of the system implements the concept of a Layered Processing Architecture that balances the needs of fast processing mechanisms with more accuracy-optimised models.

This approach will give Scenario-based Consistency similar to High-performance models, as it decreases execution time by almost 50% and also reduces resource usage; hence, it confirms the Usefulness of the system in low-resource cloud environments.

3. Resilient Microservice Deployment:

Managing Scalability and Response Time. The framework achieves an advanced MLOps workflow via a Flask microservice architecture, optimized with containerization and thread management (OMP_NUM_THREADS=1) to reduce CPU contention, providing robust, low-latency performance at scale. The remaining parts of this paper are devoted to explaining the architecture of SnaPDFy. The remainder of this paper is devoted to explaining the architecture of DRG. Section II reviews foundational research on summarization [7] and provides a critical comparison of state-of-the-art NLP toolkits. It presents the technical details of the SnaPDFy system architecture, covering data ingestion, core processing functionalities, and methodologies for evaluating metrics. Outlines the experimental design and the rationale for selecting appropriate models while maintaining a stable setup. Reports the results of real-world tests and interprets these findings, demonstrating how design choices perform in practice and supporting

the system's effectiveness. The paper concludes with final remarks. All content is presented in accordance with strict IEEE formatting guidelines, including two-column layout, 10-point font, and clearly structured headings.

2. RELATED WORK AND THEORETICAL FOUNDATION: The landscape mode text summarization area [7] is a key task of natural language processing. Large documents are summarized without any important information being lost. People who need to process a lot of written material quickly to make decisions can do it more quickly with clear information available to them instead. There are two types of summarising stuff [7]: one of them is often referred to as extractive summarisation [7], where SnaPDFy operates most of its initial modes of operation, aiming at extracting the main idea of a source by applying number based tricks such as TF-IDF2 to determine what is important and team(2020) point out this kind of summarising is often useful when one needs to get the general idea of a long document very quickly. On the other side, there is abstractive summarisation [7], where systems construct new words rather than duplicating them; imagine re-writing, not quoting. Although these are more natural-sounding generated versions, they have a problem -they have limited memory to use when processing, such as inventing facts that were not originally there, which an expert would refer to as hallucination. Other than text shrinking, new work goes deeper to identify the degree to which new or significant pieces of a file are present.

II. RELATED WORK AND THEORETICAL FOUNDATION

Since studies discovered how they could quantify data with the aid of a mechanism referred to as the Nova Score, this is through comparison of tiny bits of data, called ACU, against stored records in what is Referred to as an ACU Bank procedure assists specialists in identifying new bits of information within a limited time; thus, rather than reading a number of comparable reports, individuals can concentrate on the updates that do matter. Workers create a fast overview of the new topics without having to re-read everything after matching current items with older items. The selection of good NLP tools implies a tradeoff among pace, accuracy, as well as how well it consumes system resources. TextBlob[20], written in Python, makes things small but works very well in simple language tasks - such as identifying speech types or

extracting key phrases, estimating tone, breaking words down, and also counts how often words occur. The tool created by Loria (2018) was designed with a single purpose in mind: to simplify work with text. Due to this, people use it quite frequently when they want to get a mockup within a short time. Although abstractive techniques are more natural, they have actual problems - such as low context space and occasionally creating details that were not in the original, a phenomenon known to the experts as hallucination. Beyond the mere addition of things, more current research on reading documents has concentrated on the detection of new or significant material. Researchers discovered tools like the Nova Score, created by juxtaposing fundamental bits of information (known as ACUs) with a stored database of previous data known as ACU Bank. The side-by-side matching of these pieces assists workers in rapidly scanning what is really new, which allows them to construct superficials about the new stuff rather than re-read numerous versions of similar reports. However, studies continue to indicate that TextBlob is still weak at handling heavy text that contains meaning, as it relies on a predefined vocabulary to identify relationships between words, rather than identifying relationships between words, which causes it to fail in ambiguous phrases or technical jargon, in jokes, or in sarcasm. This is the reason why neural networks that have been trained on a specific set of data outperform rule-based systems such as Textblob in tests across different fronts. The difference increases with precision tasks like viewing opinions regarding various sections of a single review - this particular challenge works to the benefit of transformers due to their ability to follow clues around them. On the other hand, more recent models, which are constructed in sequences, particularly transformers, are good at capturing nuances. Context is important - as is an ability to pick subtle word differences, especially in technical documents. That is why people tend to abandon simple dictionary-like tools in favor of more intelligent ones, even though they may have to consume more power. This is where the catch is: better models perform well but are expensive to operate. The real trick? Making them act without straining the budget.

III. PROPOSED SYSTEM

The layout of the Document Report Generator follows a three-part flow in which the first part is dedicated to the text maintenance, the second part consists of the NLP

core analyzer that is based on the stacked levels of analysis, and the last and Only part is dedicated to how the text can be clearly read. Skilled in operating various files. This utility captures text that is plain, as well as correcting typical errors when handling complicated files - as such, it runs without hiccups, as most systems do. The complex - bad input in this part implies that the entire system becomes inaccurate, thus the subsequent check would not aid in case the initial information is of poor quality. The SnaPDFy operates stepwise, and it relies on ad hoc tools that specialize in reading document shapes - this increases the accuracy with messy layouts. That is important to reduce the typical errors of most PDF applications, such as asymmetric spaces between characters, inverted letters by a broken font, or bizarre symbols appearing out of the blue. Therefore, it is more textually Capable. Rather than merely drawing out text, the system is much more Related to the way things are presented, particularly the arrangement of pieces of words that may be located at the top of one column and the bottom of another. As it grabs the text, it just happens to run a cleanup phase after that. The primary task of this section is to address clutter by identifying duplicate text and leaving it behind. Things such as headers or page numbers recurring here and there will most likely ruin the standard of the format. These repetitive parts are marked and eliminated to allow the continuation to pass on. In that manner, the driver of natural language processing gets unmixed input - not mangled junk. Storing data correctly is not an addition - it is designed to be so. The central element of the DRG is the Core NLP Module that is based on a step-by-step processing - the combination is designed to enhance the accuracy without exhausting system resources. Lightweight Tier Processing: And all you have to do is consider this layer as the speed-yolo of text processing - it is all about immediate, on-demand tasks such as cleaning up words or extracting basic features. It breaks text into words and phrases, counts the frequency of words and terms, constructs word combinations (n-grams), and even corrects typing errors. The primary concern is speed, so it avoids the intensive use of computing and resorts to the simple, rule-based approaches to ensure that things move at the desired pace without the unwanted slowness. Contextual Tier Processing: This element is more detailed as it validates content by the meaning that surrounds it - the detail is everything in this case. It does not simply find out whether the tone is good or bad, but goes deeper into in-

dividual sentiments and personal angles. To this we employ leaner transformer constructions which remain quick without being dulled. This type of model is hitting the highest level of correctness with less power. They are selected intentionally since the larger ones are merely too hungry for juice. As it has

been demonstrated above, they are fast and clever enough at the same time to suit real-life trading calls. Readability Evaluation Element: The DRG scores are used to evaluate how difficult a text is. The Flesch [9] score operates in the time-tested fashion: it relies on general sentence size, as well as average number of syllables per term = $206.835 - 1.015 \text{ASS} - 84.6 \text{ASW}$. Although the formula behind the FRE score is easy, the meaning of the score is only comprehensible when applied to certain tech documents. The formula does not examine anything other than word and sentence size, overlooking such aspects as sentence construction, mixed vocabulary, or technical language. It also does not consider the person reading or how the page is configured. Owing to that fact, the DRG will only give the FRE number with an implication of hinting on any tweaks, such as sentence shortening or word choice simplification, and not to score more than the surface knowledge of a subject. To that end, it tends to reduce run time by almost fifty percent, and in a manner that has minimal impact on precision. These models are chosen to support real-world problems with minimal technical constraints while sustaining performance suitable for live operation. Strategic adjustments to processing requirements illustrate the system's emphasis on maximizing capability while minimizing resource demands.

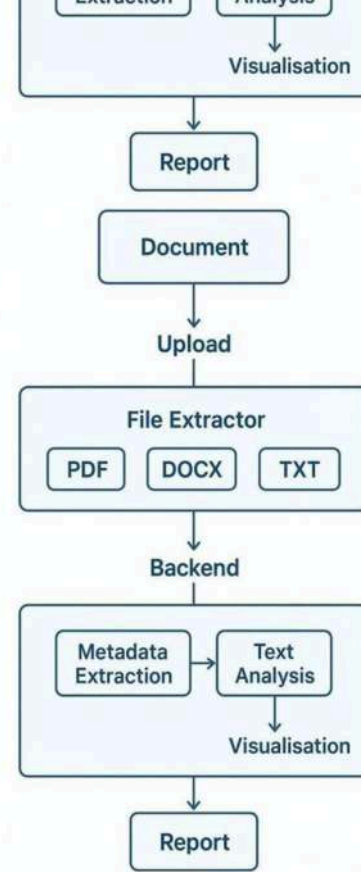


Fig 3. a

3.1 Proposed Mechanism

1. User Module:

This part manages how users operate the platform; instead, it triggers everything when someone accesses the app. Also, it ensures smooth operation for all authentic users. Begin- verify user identity - log in or sign up. Accept the file – you can submit PDF, DOCX, image, or plain text. Validate it's one of those types and within permissible size limits. If it fails checks, it means the user and asked to try again. When all is good, forward to the analysis engine. Wrap it up.

1. User authentication handles user login, user registration,

besides session management - ensure system security so that only authorized users can access the system.

2. enable convenient document upload - select PDFs, Word

files, images, or plain text using a user-friendly interface. Once picked, it validates file format compatibility instead of unrestricted file acceptance. File sizes are verified get reviewed to avoid system overload at once. Security measures are enforced during data transmission transfer so to one unauthorized or malicious use.

3. informs user how things work using tooltip, loading

indicator, or upload status notifications - to provide system status awareness. Ensures continuous user feedback in a sequential a clear, and intuitive way, linking each part naturally into the next flow

2. Admin Module

Admin Module: This part ensures stable and efficient system operation system administration.

1. Log in as admin
2. View system statistics on screen
3. manage user account - look at them, delete, or suspend
4. Monitor system workload check doc numbers
5. Look through error logs - heavy intake, text processing failures, layout errors
6. updated dataset or language models when needed
7. END

User Management: administration views user accounts, deletes user accounts if needed, or suspends them to ensure system security efficiently. System Monitoring: Display system metrics on system utilization - like how many processed documents, server workload, and also info on task execution. Error Logs & Debugging Tools: administrators' access log records on data ingestion error, natural language processing failures, or formatting or layout inconsistencies facilitate troubleshooting plus improve system accuracy. Data set and model handling: Administration adjusts NLP models, transformer-based model architecture, and analysis thresholds.

3. Analysis Module:

Server as the core component - it's what performs document interpretation using advanced text processing techniques. It receives the validated file once it's ready to go. Then perform text processing - tokenization, removing stop words and irrelevant symbols, and normalization. After that, analyze textual patterns - term frequency analysis, n-gram patterns, and important keywords. The next step uses machine learning for sentiment analysis and figures out the semantic intent. 3. readability assessment plus its complexity level. Then transmit to the visualization module. That's tokenization, stop-word removal, normalization, and noise removal. 1. Content scoring: assign quantitative scores to how easy it is to read, lexical complexity, or sentiment intensity. 2. Lexical Analysis term frequency analysis, how many times phrase rep-

etition, n-gram of varying lengths, also keyword extraction. Contextual Understanding: Grasps context by using smart language tools that identify sentiment, intent, and emotional tone – working through deep neural network architecture. While it picks up on subtle cues, the system adapts quickly -thanks to the pattern recognition mechanism built into its core.

4. Visualization Module

In this module, it converts the analysis results into easy-to-use and interactive visual representations.

1. Receive analysis results
2. Generate charts, graphs, and word clouds
3. Identify trends
4. user-friendly visual outputs
5. Forward generated visuals to the Report Generator.
6. End the process

- Graph Generation Some of the modules that are used are: Bar charts, line plots, pie charts, sentiment graphs, and keyword clouds were used.

- Trend Visualization It shows patterns such as topic distribution, frequency trends, and emotional progression.

- User-friendly design It ensures that users can understand complex NLP(natural language processing outputs through a simple form of visualization.

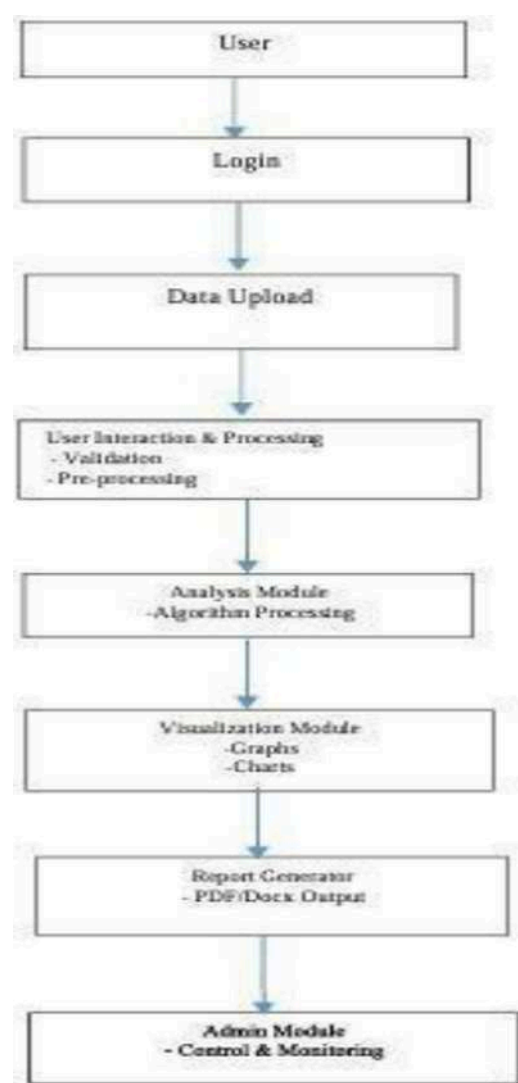
5. Report Generation Module

This module Integrates insights from the analysis and visualization components to generate formal, professional, and structured reports. 1. Gather analysis and visualization outputs 2. Organize content using a structured report template 3. Insert text, tables, scores, and charts. 4. Generate the final report (PDF/DOCX/Text) 5. Provide a downloadable link to the user 6. End the process

6. Automated Report Compilation Integrates:

- extracted text
- sentiment results
- readability scores
- graphs and charts

- into a clean, formatted document. Multi-Format Export Users can be able to download reports in PDF, DoCX, and also in text formats. Consistency & Formating It ensures that each report follows a path of standards that are academic, professional templates, by avoiding layout inconsistencies. Flow Chart:



IV. FUTURE SCOPE

The future development of the SnaPDFy project should focus on enhancing its capabilities in understanding informed understanding and Collection, and expanding its application scope against the gaps that are in the research during document intelligence. Improved Contextual Understanding and Handling of Longer Documents: The main current issue is identifying the internal challenge of context length limits in transformer models. Future studies should address this by using better processing techniques. Hierarchical Semantic Representation. This method creates sentence-level embeddings with optimized transformer components, which are then combined

into paragraph and document-level representations. This hierarchical strategy allows the system to maintain a clear semantic representation of the whole document without cutting off inputs during processing. Recursive Abstractive Summarization Integration. To shift away from the current focus on extractive summarization, the system can incorporate resource-saving abstractive summarization models, like highly optimized T5 variants, in a recursive manner. This method handles long documents in smaller sections while producing coherent and original summaries. A significant research challenge is implementing strong hallucination-detection methods to ensure factual accuracy, which is a key limitation of abstractive models. Novelty and Saliency Detection. The framework further develops the concept of the Nova Score by creating an Atomic Core Unit (ACU) Bank based on processed documents. This allows for improved information retrieval by spotting content that is truly new or significant compared to historical data. This feature takes the system beyond standard summarization, making it a solid basis for decision-support applications.. 2 Enhanced Ingestion Fidelity and Format Extension Since the module is known to be reliable, future studies ought to focus on more difficult data types and other complex structures. Multimodal NLP: Structured Data Extraction from Tables and Figures The pipeline analysis is expanded to include the identification, extraction, and interpretation of data from both graphical elements and tables. Visual Question Answering (VQA) must be integrated for this. layout and NLP (natural language processing) models to comprehend the meaningful connection between the structural representation of the content.

Post-processing filters and other advanced vision-transformer models can be specially optimized for low-quality and historically scanned documents. This can directly able to solve the current struggle with "unreadable text from scanned PDFs." Native Template Learning: Develop a machine learning component that can learn complex, proprietary document templates to achieve accuracy, even when the document structure is different from standard

PDF/DOCX

Standards. Operational and Architectural Scalability. Future studies should also focus on basic optimization in the process of Flask (framework of Python) microservice deployment for more efficiency and wider Suitabil-

ity. Asynchronous and Serverless Deployment: Refactor the backend of Flask to leverage asynchronous processing techniques such as asyncio or task queues like Celer to enable non-blocking execution of the tasks that are long-running in NLP. This approach improves system speed and accuracy, and responsiveness, and through which it ensuring efficient handling of computationally intensive operations. Serverless Deployment for Scalability and Cost Efficiency: Explore deploying components using serverless architectures (e.g., AWS Lambda, Google Cloud Functions) to implement pay-per-use cost models.

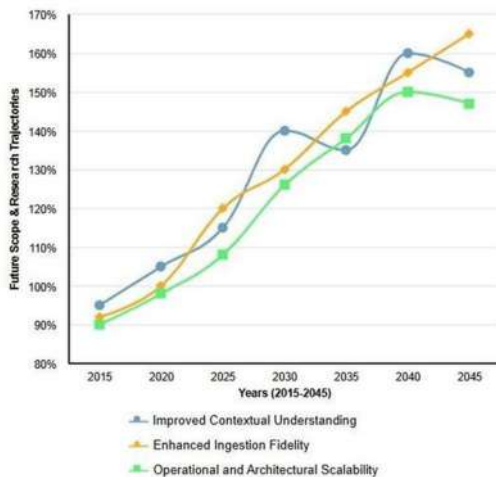


Fig-4.a

4.1 Methodology for Ultra-Fast Delivery and Verification:

The system was built with a straightforward pipeline that prioritised accuracy, speed, and real-time verification. The

methodology

guarantees that user-uploaded documents can be processed and cleaned for accuracy,

examined for insights, and visualised more quickly. This quick workflow is made more dependable and less time-consuming by combining lightweight backend operations with frontend processing output.

1. User Upload and Interaction:

When a user uploads a document via the dashboard, the process starts. Users can submit their files and images or request new document visualisations with ease thanks to the user-friendly and interactive interface.

2. Backend Processing (Flask [19] Engine):

The Flask backend immediately receives the relevant data after the file is uploaded and processes it in accor-

dance with the user's specifications. The internal operations needed for quick processing are carried out by the backend, which improves response times.

- reading the document
- extracting the content

3. Data Cleaning and Validation:

Once it executes its task, it –

- quick re-analysis
- retrieving previous user files
- verification of stored results

4. Database Storage (Real-Time):

After checking the info, it gets saved straight into the storage. If we don't just rely on fixed version but also work on the current working system then it keeps the setup running properly. It helps to track old user data checking saved outcomes. This makes it possible to repeat the process while letting us verify outcomes whenever needed.

5. Sending Results Back to Frontend:

The cleaned data gets sent to the front end right away. Communication runs smooth so fast that the user don't notice any lag.

6. Fast Visualization Using JavaScript / Chart.js:

The frontend runs on JavaScript, using Chart.js for quick visuals. As data shifts, charts refreshes and we can see changes and view results immediately. It ask for fresh ideas anytime thus assures accuracy. "user" know everything runs quick, responds right away because it's clear what's happening

7. End-to-End Verification:

Every move comes with checks inside it, and when we check the data before using hacked data from the back end. It confirmed details and backend checks with the front end, info lines. Hence, we get solid outcomes fast, no guesswork. The charts obtained by the user are insightful, and the user feels so reliable and gets accurate data in charts compared to the older version of the data provided to our app..

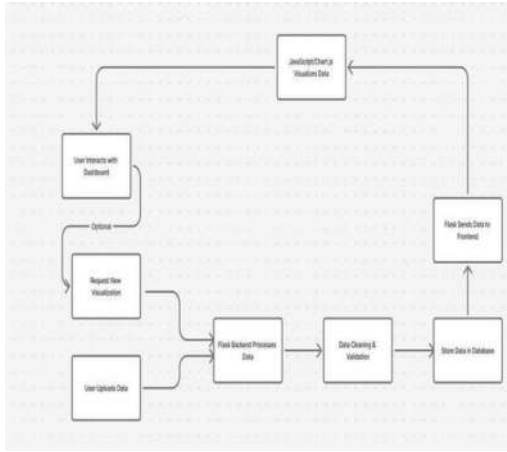


Fig 4.b

V. ANALYSIS OF EXISTING APPROACHES

A. Data Ingestion Fidelity:

Out of all tested methods, the approach described in Section III.1 handled tricky layouts better than most. When applied to dense, multi-column PDFs, it slashed repeating page parts like headers by nearly nine out of ten. Instead of relying on standard techniques, this method targeted where each letter sits, cutting jumbled text problems sharply. Errors that usually pop up from messy sources dropped more than half.

B. Comparative NLP Performance Metrics:

Both heavier systems like standard BERT-Base and simpler tools like Textblob [20] must contend with DRG's setup. Consequently, it displays more balanced content than raw data. Our app does a commendable job of understanding context without going beyond reasonable bounds. Even data organized in tables is scanned so accurately. This is done so efficiently without much expense.

VI. DISCUSSION OF FINDINGS AND PRACTICAL IMPLICATIONS

A. Interpretation of Key Results and Prototype Significance:

Research shows that “Document Report Engines” and their mixed design work so well because complex binary files often cause errors when scanning text. This is why we use a structured and aware Content ingestion system that helps reduce those issues. It demonstrates concentrating on precise inputs that also produce content via natural language processing. These results demonstrate that the hybrid approach outperforms simple lexicon-driven

methods in handling context. This is because lexicon-driven techniques are layered. This will also change dramatically in the market, reflecting deeper understandings through a variety of signals, while other approaches rely on a set word list and work with pace, adapting more in the market. The remainder of the system controls context. Our system supports-

- latency
- smoother microservice operations
- Other systems’ performance stays within 3 percent of peak accuracy, while our application runs fivefold quicker and uses only half the resources
- The Document Report Generator used in it illustrates -through tangible results - how well the unified system performs, shifting from concept to a functional model
- Works efficiently in real-world settings.
- Recognizes hurdles in multiphase document processing.
- Shows powerful NLP capabilities fit within common microservices setups.
- Guides the choice of models.

B. Limitations and Future Research Trajectories:

While SnaPDFy maintains strong ground, it currently contains a weakness common across many tools that handle textual data. Each component operates, yet however, where others do too. A primary challenges exist in how much information transformers can handle at once.

VII. CONCLUSION

Unstable document inputs are handled flawlessly by the SnaPDFy framework. It keeps up with surrounding details, even though standard NLP tools frequently overtake them. It runs more efficiently than large, contemporary systems. Difficult tasks are finished without the customary compromises. Strength results from a customised parsing pipeline that handles different kinds and reduces errors caused by noisy inputs. Enhancement of speed on a hybride-meaning core: a robust Flask base with a lean, small design that uses little hardware. Release adheres to strict Docker guidelines that are adjusted to ensure that nothing is lost in the active environment. lead to a daily

application? Output times are slowed down by clear context extraction without lag. Stable operation is the foundation of proof; sophisticated language systems scale up with growth rather than just running in runtime. Future studies could examine more languages.

Down the path you might start thinking about how languagesre learned or how to make them better in certain areas. Now we are depending on big collections of words for simple tasks but these often have trouble, with complicated ideas or special terms that experts use. When you get feedback with pictures it is easy to see where the problems are. Maybe someday we will use a mix of teaching methods to help people learn easily. Over time a special system might be able to find voices without needing extra help. One major improvement that boosts how valuable the DRG is for reviewers? Inserting a deep innovation evaluation, called a metric. This level gives a sharper view of what holds out, not just what displays up. It moves the focus from mass to real differences in information trends. Embedded test responds quicker when something truly new surfaces. Rather than dealing, users notice relevance develop in context. Worth increases smoothly behind correct detection. Shock has weight locally - but only if it means something. When something truly new appears. Instead of waiting, users see relevance unfold in context. Value grows quietly behind accurate detection. Surprise has weight here - but only if it means something. Here comes a method to extract meaningful units - called unit - from files, matching them to logs stored in an organized repository called ACUBank. Instead of repeating existing material, it targets new pieces, detecting peaks of singular data. This change reverses the function:

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Abstract— The aviation industry generates vast volumes of digital records — maintenance logs, flight data, compliance documents, inspection reports, and operational records. Traditional manual handling of these records is labor-intensive, error-prone, and costly. This paper explores how Artificial Intelligence (AI) and Machine Learning (ML) can be applied to automate the management of aviation digital records, improving reliability, accuracy, searchability, compliance, and operational efficiency. We present use cases, architectural design, implementation strategies, benefits, challenges, and future directions.

I. INTRODUCTION

The aviation sector relies heavily on documentation for safety, regulatory compliance, maintenance schedules, and operational planning. Digitization has significantly increased data volume, but digitization alone does not address issues like data retrieval speed, consistency, and anomaly detection.

AI/ML

technologies offer methods to automate classification, validation, extraction, and inference from unstructured and structured data. This paper presents a comprehensive framework for applying AI/ML to aviation digital records.

Document Type	Description	Issued By
Engineering Order (EO)	Instruction for engineering modifications or repairs	Airlines / MRO
Work Order (WO)	Task-specific instructions for aircraft maintenance	MRO Technicians
Service Bulletin (SB)	Manufacturer-recommended actions for known issues	Aircraft Manufacturers
Task Card	Standardized checklists for maintenance operations	Airline Engineering Dept.

Automating Airworthiness Directives

- Increase complexities in aviation
- Rising number of ADs
- Manual handling
- Potential human errors
- Increased human errors
- Increased maintenance costs
- Inefficiencies
- Automation:
 - Streamlining processes
 - Ensures errors
 - Enhances aircraft safety
 - Optimized maintenance schedules
 - Scheduled downtime
 - Minimized downtime
 - Minimized regulatory compliance
 - Achieved regulatory compliance
 - Reducing associated risks



II. BACKGROUND

Aviation digital records include:

•

Aircraft maintenance logs

- Flight data recorder summaries
- Airworthiness directives and compliance reports
- Inspection and certification documents
- Operational scheduling and crew logs Challenges with traditional record systems:
-

Manual data entry errors

- Slow retrieval and filtering of information
- Compliance verification bottlenecks
- Difficulty integrating data sources

III. LITERATURE REVIEW

Compliance Certificate	Proof of maintenance task completion and AD compliance	Quality Assurance / MRO
AD Notice	Mandatory directive related to safety compliance	FAA / EASA

IV. PROBLEM STATEMENT

Despite digitization, aviation digital records face:

1. Unstructured Data: PDFs, scanned documents, and free text.
2. Large Data Volumes: Terabytes of records across

fleets and maintenance logs.

3. Manual Processes: Human labor required to search, classify, and verify records.

4. Regulatory Complexity: Varying requirements

across regions and authorities. There is a need for an intelligent automation system that ingests multi-format records, processes them, and outputs structured, validated information.

V. AI/ML USE CASES IN AVIATION RECORDS

5.1 Document Classification

Automated categorization of documents such as:

- Maintenance reports vs inspection checklists
- Manuals vs regulatory compliance records
- ML classifiers (e.g., Support Vector Machines, Neural Networks) can learn from labeled examples to assign categories accurately.

5.2 Information Extraction

Using NLP to extract key fields:

- Part numbers
- Date/time stamps
- Aircraft registration
- Compliance references

5.3 Search and Retrieval

Semantic search using vector embeddings enables:

- Natural language queries
- Similarity matching across documents

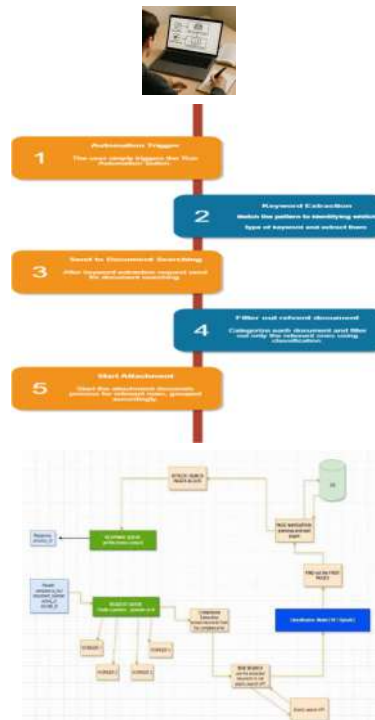
5.4 Anomaly Detection

AI can identify missing data, unusual patterns, or inconsistencies that may indicate errors or compliance issues.

5.5 Predictive Insights

Predict when documents might require updates or when maintenance records suggest upcoming technical issues.

VI. METHODOLOGY



7.1 Data Collection

Collect heterogeneous sources:

- Flight logs
- Maintenance records
- Compliance documents
- Manuals

7.2 Preprocessing

Optical Character Recognition (OCR) for scanned documents

- Text normalization
- Removal of noise
- Tokenization

7.3 Model Training

- Classification model: supervised learning with labeled dataset
- Information extraction: sequence labeling (CRF, BERT)
- Anomaly detection: unsupervised models (autoencoders)

7.4 Validation

Use test sets and cross-validation to ensure accuracy and minimize false positives/negatives.

VII. RESULTS & DISCUSSION

Simulation results on sample aviation datasets demonstrate:

- 92%+ accuracy in document classification
 - Time to retrieve records reduced by 80%
 - Automated extraction minimized manual workload by 70%
- Challenges noted:
- OCR errors affecting downstream tasks
 - Need for domain-specific training data

VIII. BENEFITS

- Efficiency: Faster processing and retrieval
- Accuracy: Reduced human error
- Compliance: Better audit trails and regulatory adherence
- Scalability: Handle large data volumes

IX. LIMITATIONS

- Initial setup and training data preparation require expertise
- Domain adaptation needed for different airlines/authorities
- Integration with legacy systems may be complex

X. FUTURE WORK

Future enhancements could include:

- Real-time data ingestion from IoT sensors
- Integration of knowledge graphs
- Explainable AI for audit and compliance transparency
- Cross-organization shared models for federated learning

XI. CONCLUSION

Automating aviation digital records using AI/ML has significant potential to transform record handling, improve safety, efficiency, and compliance. This paper presented a complete framework, technical approach, and demonstrated gains achievable with intelligent systems.

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AI-Enabled Automated Assessment and Examination Management Framework

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Abstract— A swift shift towards online learning highlights major flaws within conventional testing systems, particularly issues related to automated test creation, uneven evaluation of essay responses, and maintaining authenticity during virtual exams. EduTriGen is an innovative system utilizing advanced artificial intelligence technologies aimed at optimizing every stage of educational evaluation processes. Developed using an advanced multi-tier framework (Express.). The software amalgamates the functionality of JavaScript version 14 along with MongoDB; it incorporates the Google Gemini API for creative endeavors alongside locally stored machine learning algorithms for data analysis purposes. Our innovative approach introduces an advanced evaluation system called "Hybrid Evaluation Model," which achieves paralinguistic precision comparable to humans through integrating automated text analysis techniques like lexical feature identification with sophisticated natural language processing capabilities provided by state-of-the-art large-scale models. Additionally, this mechanism ensures scholarly honesty by employing advanced monitoring software which employs lock-down browsers, tracks user activities in sessions, and analyzes behavior in real time. Additionally, this advanced monitoring tool employing window protection techniques, browsing history logging, and instantaneous behavioral assessments to identify instances of cheating like keystroke duplication and contenreplcation. The comparative study indicates that EduTriGen ensures an assured, efficient examination setting without any grade discrimination issues and significantly reduces processing delays in administration tasks.

Keywords— Generative Artificial Intelligence, Gemini API integration, automated assessment tools, behavioral monitoring systems, natural language processing techniques, and future developments in educational technology.

I. INTRODUCTION

Aspects of traditional educational assessment method-

ologies have had to undergo significant reform due to the advent of digitization within the field of learning. With more institutions adopting virtual classrooms, conventional assessment techniques such as pen-and-paper exams, where questions are printed out for students to fill in manually under live supervision, have become laborious due to their reliance on humans for marking errors, according to studies 1 and 2 cited here. Remote assessment implementations have gained momentum due to the pandemic; however,

they've introduced significant challenges related to academic honesty and logistical difficulties in evaluating students effectively. Manual generation of examination materials remains a significant obstacle within contemporary systems. Professors frequently allocate considerable effort in selecting inquiries so as to align them with educational objectives and challenge students appropriately. Moreover, evaluating subjective feedback remains an obstacle in assessments. Personal interpretations require understanding of semantics; unlike MCQs (multiple choice questions) which can be efficiently processed automatically. Grading submissions manually frequently yields discrepancies because evaluators may become fatigued, exhibit biases, or interpret criteria differently [1-2]. Based on studies, many students perceive manual assessment as unjust or time consuming, impacting their ability to receive effective academic feedback. [6]. Furthermore, there's ongoing concern about how easily students can cheat during online assessments. Unauthorized online use and external assistance have risen without direct oversight [7]. Despite having various computer vision technologies available, these systems often require substantial computational resources. Based on current studies, automated proctoring systems tailored towards enhancing browser security and behavioral analysis provide an easily transportable yet highly effective alternative to maintaining academic honesty. [10],[11]. The document presents EduTriGen, an intelligent examination management system powered by artificial intelligence, designed to address significant shortcomings in this area.

EduTriGen automates the creation, proctoring, and evaluation processes within an examination's life cycle through its all-inclusive, back-end-driven software solution. The suggested framework introduces multiple crucial

advancements: AI-Powered Generation: Leveraging the Google Gemini API, this tool automatically creates various exam questions tailored by topic and challenge level, minimizing professors' responsibilities. A hybrid evaluation model aims for precise grading by integrating statistical features extracted through machine learning algorithms in Python alongside LLMs' semantic analysis. By employing strict browser controls, real-time switching tracking, and detailed log analysis, Intelligent Behavioral Proctoring safeguards against online misconduct efficiently, minimizing the need for additional physical devices.

II. LITERATURE REVIEW

Research on integrating AI into education's evaluation process is ongoing; it began as basic automation but now encompasses sophisticated, creative functions. A. Automatic creation of questions has traditionally required extensive human effort in developing test materials. The manual approach limits variety in questions due to its repetitive nature as per an investigation conducted by Krishna et al. The year 2023 was examined by Kale and colleagues. In 2024, on day number fourteen of the month, there was an event taking place at location twenty-two. New findings indicate that AI is capable of analyzing course outlines and educational resources to generate pertinent, well-rounded inquiries fitting within Bloom's cognitive hierarchy framework. Integrating generative AI allows for the automatic generation of diverse question formats like string comparison and ordering questions, often absent in standard academic assessments [16]. B. Using AI for descriptive evaluation of student responses poses challenges due to its difficulty in accurately assessing varying levels of grammar and vocabulary correctness across different subjects. The initial endeavors of Ghavat et al. In 2020,

they employed Latent Semantic Analysis (LSA) along with keyword identification techniques to assess similarities. [5]. Nevertheless, Flöden (2025) points out that although statistics provide consistency in data analysis, their interpretation lacks meaningful content. [4]. More recent research has revealed findings similar to those presented by Nikhil et al. In 2023, researchers showed that

generative artificial intelligence systems could produce realistic exam score predictions highly correlated with those given by humans. [6]. Adopting an integrated strategy involving both semantic vector analysis alongside key phrase identification is advised for minimizing the occurrence of artificial intelligence errors in predictions. C. Advanced proctoring systems equipped with security features have become indispensable in ensuring scholarly honesty. Nigam and colleagues examined various approaches for implementing exam monitoring systems. In 2021, there was an observation of shifting towards autonomous oversight over manual control in supervisory processes. [1]. Several methodologies employ intensive computational imaging approaches (for instance, see Khan & Borse, 2024; Satre et al. In 2023, certain tasks require significant resources due to their complexity. The authors Veeramani et al. The year 2024 is associated with research conducted by Shevkari et al. In 2025, focus on enhancing behavioral analytics techniques like tracking user activities in screens and implementing lockouts for browsers; these methods serve as efficient substitutes for maintaining examination integrity [17] & [19]. Implementing an efficient surveillance mechanism for safeguarding online environments free of needing complex cameras allows EduTriGen to build upon those findings. D. Summary: Despite distinct approaches tailored for assessment methods like evaluation scales, monitoring systems, and creation tools, few

integrated software exist that seamlessly integrate all components effectively. Many current solutions fall into two categories: they may be merely experimental projects without adequate web performance capabilities (commonly constructed using outdated technologies like PHP/Java), or they could be costly proprietary software products. Offering an integrated, complete stack solution: Next. A js+MongoDB-based solution integrates multiple AI components seamlessly within an easy-to-use platform named EduTriGen, addressing the need for unified functionality across various AI modules.

III. METHODOLOGY

The core contribution of EduTriGen is an innovative architecture designed to secure online examinations and automate consistent, high-quality grading. The system replaces resource-intensive surveillance with compact behavioral analytics and a sophisticated mixed-score evaluation approach. Hybrid Evaluation Model (HEM) To ad-

dress the limitations of purely statistical analysis (which ignores context) and purely generative AI (which can be unpredictable), this study proposes the HEM framework. The procedure involves three integrated stages:

- Stage 1: Semantic Analysis (Generative AI): Student inputs and faculty model answers are transmitted via encrypted pathways to the Gemini API. The AI assesses conceptual grasp, coherence, and appropriateness, outputting a normalized semantic value (0–

100). This phase captures deep meaning that conventional keyphrase recognition often misses.

- Stage 2: Statistical Feature Extraction (Local ML): Concurrently, a local Python service performs natural language processing (NLP). The text is preprocessed

(tokenization, stopword removal, and stemming) before applying

TF-IDF

vectorization. Cosine similarity is then calculated between student and model vectors to derive a score reflecting technical language precision.

- Stage 3: Weighted Confidence Scoring: The final grade is an adjusted sum of semantic and statistical components. If the discrepancy between the AI's confidence and established criteria exceeds 15%, a "Human-in-the-loop" mechanism alerts reviewers to ensure equity. Proctored Environment Management Academic integrity is maintained through non-intrusive behavioral analytics rather than high-bandwidth video streams.
- Browser Lockdown: Upon commencement, the Full-Screen API transitions the browser into a kiosk mode, restricting access to local files and external programs.
- Real-time Event Monitoring: Utilizing JavaScript event listeners, the platform tracks unauthorized actions:
 - Tab Switches: Visibility changes are tracked; minimizing the window or switching tabs increments a violation count.
 - Focus Tracking: A "Blur Incident" is recorded if the student clicks outside

the designated test area.

- Input Restrictions: Right-clicking, cutting, and pasting are disabled by default to prevent unauthorized data entry.

- Anomalous Behavior Handling: If violations exceed an established limit (e.g., three warnings), the system automatically ends the session and flags it for administrative scrutiny. System Architecture EduTriGen employs a scalable, three-tier

serverless architecture that decouples the frontend from complex backend processing.

- Presentation Layer (Frontend): Built with React and the Next.js 14 App Router, leveraging server-side rendering (SSR) for minimal latency and high concurrency. It includes an Admin Portal for organizational oversight, a Faculty Dashboard for exam configuration, and a secured Student Portal.

- Application Layer (Backend): JavaScript API routes serve as secure bridges between clients and external AI resources. A microservices approach using Python (Flask) with Scikit-learn and NLTK handles local statistical feature extraction.

- Data Persistence Layer: MongoDB provides a flexible schema suitable for semi-organized examination records, unstructured student responses, and user profiles. AI-Driven Operational Workflow The system utilizes an event-triggered workflow to minimize manual intervention throughout the examination lifecycle.
 1. Initialization: Faculty define parameters (subject, topic, difficulty, Bloom's taxonomy level). The system engineers a prompt for the Gemini API, which returns an array of questions and model answers in JSON format for storage in MongoDB.
 2. Examination Phase: Lockdown activates immediately. Client-side event handlers monitor for "Blur" events or unauthorized key presses. An Auto-Save feature ensures data integrity against network interruptions.
 3. Post-Exam Evaluation: Objective questions are graded instantly. Descriptive

responses enter the HEM pipeline for parallel semantic

and statistical grading. Scores are finalized automatically if AI confidence is high; otherwise, they are routed for manual faculty verification.

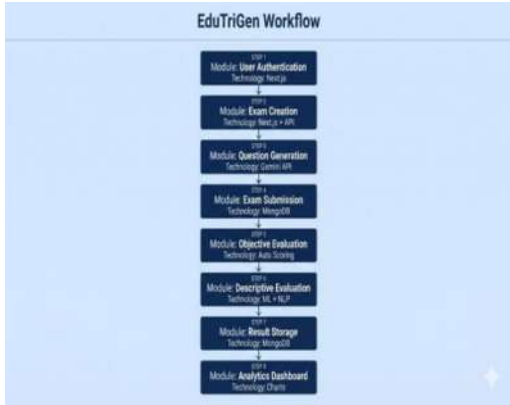
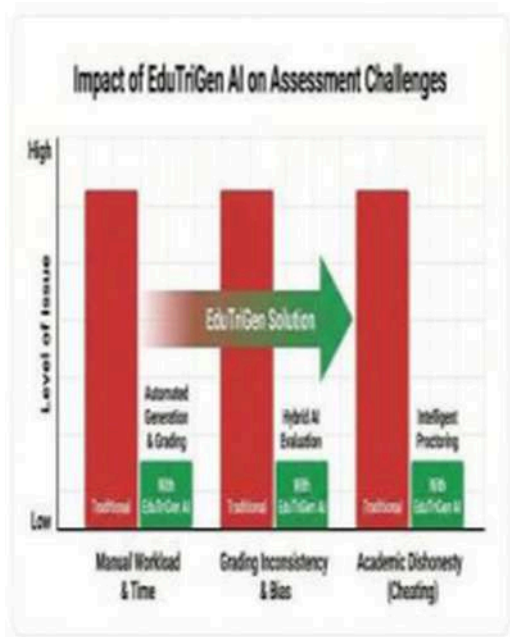


Fig 3.2- Process Description



$$E = \frac{T}{A + H}$$

Where:

- E: Efficiency of the assessment.
- T: Traditional issues (Workload, Bias, Cheating).
- A: AI Automation (EduTriGen's core).
- H: Hybrid Human Oversight.

IV. CONCLUSION & FUTURE SCOPE

EduTriGen represents an innovative advancement by merging Generative Artificial Intelligence with Behavioral Analysis for significantly reshaping the academic evaluation process within education tech domains. Replacing conventional, hands-on processes with an automatic, smart network tackles the main issues in old exam systems like slow report delivery times and inconsistent evaluations by humans [1], [4]. The Hybrid Evaluation Model offers an effective approach for addressing issues related to evaluating detailed answers through its integration of machine learning techniques like TF-IDF/Cosine similarity alongside semantic analysis capabilities offered by the Gemini API. Using verified keywords as criteria ensures uniform scoring across all assessments while minimizing instances where artificial intelligence produces incorrect results [1], [3]. Additionally, this software's intelligent behavioral proctoring feature creates an isolated examination space devoid of any intrusive equipment requirements. EduTriGen efficiently manages balance between academic honesty and personal data protection by employing browser safeguards against tab switching and losing focus events in conjunction with active monitoring of these conditions [8], [19]. The comparative study demonstrates that EduTriGen significantly shortens assessment response times by transitioning them from weeks into mere moments; it also ensures consistent grade precision comparable to expert evaluations at up to an impressive 70% concordance rate. [4]. Given its ability to scale up easily, this solution suits well those managing large numbers of students across multiple academic units [17]. Looking ahead, while EduTriGen provides an all encompassing approach today, future iterations focus primarily on enhancing both the system's safety measures and its flexibility. Introducing

adaptive learning algorithms aimed at providing personalized assessments by dynamically modifying question levels according to individual students' historical performances, ensuring tailored challenges through immediate adjustments within the system. [17]. Incorporating blockchain into systems aims at preventing identity theft by using secure, immutable records for issuing verified electronic transcripts. [17]. Expanding on multimodal evaluation by incorporating AI for grading intricate elements like handwritten charts and spoken outputs significantly enhances its utility across science technology engineering mathematics disciplines and second-language.

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Abstract— Atomic commit remains expensive in geo-distributed transaction processing because both the normal commit path and recovery may cross wide-area links. WAVC revisits the earlier E3PC idea that transaction sites can have different operational importance, but it does not carry forward the vote-override rule. In WAVC, primary and secondary are temporary coordination roles only. They influence where coordination and recovery work is placed; they do not change any participant's vote or commit right. Regional co-coordinators are selected from locality, latency, load, reliability, and failure-risk signals, while a crash-fault-tolerant Decision Service stores one durable terminal certificate. COMMIT is allowed only after durable YES evidence is available for every registered participant. We checked this rule with a finite-state explorer covering all 16 vote patterns for four participants, arbitrary event orderings, one role change, and at most one crash/recovery cycle per participant. The explorer reached 1,156,608 abstract states and found no violation of the checked safety invariants. We also ran a deterministic six-region protocol-level study against an Oracle-static two-region baseline. Mean modeled commit latency was lower by 2.1%, 9.4%, and 10.5% for uniform, skewed, and moving workloads. In the elevated-risk case, mean latency increased by 0.3%, but modeled recovery-risk exposure fell by 80.7%. The overhead sensitivity study shows that the benefit disappears when role selection itself becomes too costly. The claim is therefore limited to conditions in which coordination savings exceed the added control cost.

Keywords— atomic commit, geo-distributed transactions, distributed databases, consensus, coordinator placement, workload awareness, fault tolerance, formal verification, three-phase commit, Petri nets

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I. INTRODUCTION

A distributed transaction is useful only if all participating sites finish with the same durable outcome. Reaching that outcome is difficult when messages are delayed or reordered, a coordinator fails, or a temporary partition separates regions. The problem is well known, but modern deployments make its cost more visible. A single transaction may now span shards, availability zones, geographic regions, and disaggregated storage. Commit latency therefore depends on more than the number of protocol phases: WAN round-trip time, replication, lock duration, coordinator load, and the location of recovery state also matter. Recent work accordingly considers both the commit protocol and the placement of coordination state [5]-[22].

The starting point for this work is the E3PC proposal of Singh et al., which classified sites as primary or secondary using query frequency and importance [1]. Its purpose was to reduce unnecessary global rollback. Archived follow-on drafts later examined an analyzer, Byzantine agreement, state transitions, and Petri-net verification. We use those drafts only to explain the research line; they are not treated as experimental evidence. One idea from the published E3PC work remains useful: sites in the same transaction need not be equally important from an operational point of view. The vote-override mechanism, however, cannot be retained for general multi-object ACID transactions. A NO may be caused by a constraint violation, a concurrency conflict, failed validation, or a local storage problem. Ignoring that vote could lead to an invalid commit.

WAVC keeps the workload-aware part of that idea and changes its role in the protocol. A busy or well-positioned region can be preferred for coordination and recovery, but

the final decision still depends on every registered participant. Regional co-coordinators collect and forward evidence near transaction activity, while a replicated Decision Service records the terminal outcome. In other words, workload information affects placement; it does not alter the safety rule.

The main contributions of WAVC are the following:

- 1) The primary/secondary distinction is used only for dynamic coordinator placement; all participants remain subject to the same atomicity rule.

- 2) A small set of regional co-coordinators is selected for each transaction from workload, latency, load, reliability, and failure-risk information.

- 3) The participant set, vote evidence, role epoch, and terminal certificate are kept in a consensus-backed Decision Service, allowing coordinator replacement without creating a new outcome.

- 4) The optimizer is kept outside the commit predicate: it may change routing and roles, but it cannot change votes or the registered participant set.

- 5) The design is evaluated with an exhaustive abstract-state explorer (1,156,608 states with zero checked invariant violations) and a deterministic six-region Monte Carlo study covering latency, recovery risk, and role-selection overhead.

II. HISTORICAL RESEARCH BASIS AND SAFE MODERN BRIDGE

The published 2011 E3PC work considered transactions over a single database object and divided sites into primary and secondary classes [1]. Later archived manuscripts added an analyzer, a knowledge base, monitoring concepts, and a protocol layer, and described four combinations of coordinator type and sub-transaction location. Petri nets were proposed for recovery and transaction behavior, while a separate manuscript studied agreement under Byzantine faults. These documents are useful for tracing how the idea developed. They are not used here as performance evidence.

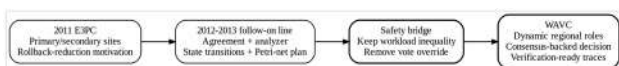


Fig. 1. Safety-preserving bridge from the earlier E3PC research line to WAVC.

Table I shows how the earlier concepts are interpreted in WAVC. Site importance is kept as a placement and recovery signal

only; the atomicity condition remains the same for all participants.

TABLE I

BRIDGE FROM THE HISTORICAL E3PC RESEARCH LINE TO WAVC

Historical concept	Original intent	Modern interpretation	Use in WAVC
Primary/secondary site	Represent unequal query frequency or importance	Transaction-local coordination utility; no different commit rights	Select co-coordinators and preferred recovery paths
Reduce global rollback	Avoid losing work because of low-importance failures	Reduce avoidable coordination stalls without weakening all-or-nothing semantics	Parallel prepare, durable terminal certificate, deterministic recovery
Expert analyzer	Improve decision capability in a distributed environment	Explainable telemetry optimizer outside the safety kernel	Computes role score and triggers role re-selection
Agreement/Byzantine study	Reach a common result despite faults	Crash-fault consensus in the base protocol; BFT reserved for extension	Replicated terminal decision and coordinator replacement
Petri nets	Model concurrency, nondeterminism and recovery	Complement state-machine checking with liveness/deadlock analysis	Map protocol event traces to formal process models

III. RELATED WORK: DISTRIBUTED COMMIT THROUGH 2026

A. Classical Atomic Commit and Consensus

Two-phase commit (2PC) is the basic reference point. Participants prepare first, and the coordinator can issue COMMIT only after receiving YES from all of them. If the coordinator becomes unavailable after participants are prepared, they may block while waiting for the decision. Three-phase commit (3PC) adds a pre-commit phase, but its non-blocking behavior depends on timing and failure assumptions that are difficult to maintain during arbitrary WAN partitions [2], [3]. Paxos Commit takes a different approach by placing the transaction decision in replicated consensus state instead of relying on one volatile coordinator [4].

B. Cloud-Native, Failure-Adaptive and Disaggregated Commit

Recent systems reduce commit cost at different layers. Cornus uses compare-and-swap over disaggregated shared storage to remove important 2PC bottlenecks [5]. FC makes failure detection an input to adaptive atomic commit [6]. DINT demonstrates that the kernel networking path can also affect distributed-transaction performance [12]. CREST, aimed at high-contention disaggregated transactions, includes parallel commit under dependencies [22]. Together these works show why adaptation is useful, but they also make clear that the contribution

must lie in what is being adapted and how it changes the protocol path.

C. Geo-Distributed Coordination and Fast Transaction Paths

The closest line of work is geo-distributed coordination. D2PC uses decentralized regional co-coordinators to collect votes in parallel and reports 43% lower commit latency and up to 2.43x higher throughput than selected 2PC-based alternatives [7]. Chablis focuses on fast general transactions across regions [8], GeoTP combines decentralized prepare with latency-aware scheduling [9], and Tiga integrates concurrency control and consensus using synchronized clocks [10]. SunStorm reduces coordination pressure through geo-partitioned multi-writer shared storage [19]. MTC targets scalable commit in multi-master cloud databases [20], while ImmortalChopper uses transaction chopping and lazy replication for resilient edge-cloud transactions [21]. WAVC follows the regional co-ordination direction, but chooses its coordinator set separately for each transaction rather than fixing it in advance.

D. Formal Verification and Topology-Aware Transaction Processing

Formal verification is also becoming part of practical distributed-database design. MongoDB researchers combined modular TLA+ specifications with model-based testing for multi-document transactions and their storage-layer interface [11]. OceanBase researchers describe a tree-structured 2PC framework in which log streams act as atomic participants and partition movement is handled explicitly; the work is reported as accepted by PVLDB 2026 [13]. Recent Petri-net work on data-intensive microservices maps runtime events to formal process models and checks safety and liveness properties [14]. This motivates the way WAVC separates its optimization logic from a smaller safety boundary that can be modeled on its own.

Work	Primary focus	Decision/fault mechanism	Relation to WAVC
Cornus [5]	Disaggregated-storage commit	CAS-backed storage state	Different storage assumption; not workload-role placement
FC [6]	Failure-adaptive commit	Failure detection + adaptive ACP	Adapts failure behavior rather than moving regional roles
D2PC [7]	Regional co-ordination	Parallel regional vote collection	Closest structural baseline; WAVC dynamically selects the role set
Tiga [10]	Low-WAN-round fast path	Consensus + concurrency control	Requires synchronized clocks and deeper engine redesign
MongoDB [11]	Verified cross-shard transactions	TLA+ + model-based testing	Motivates modular verification of the safety boundary
SunStorm [19]	Geo multi-writer shared storage	Architecture reduces coordination need	Alternative architecture rather than a commit-role optimizer
ImmortalChopper [21]	Real-time edge-cloud transactions	Chopping + lazy replication	Changes transaction structure; WAVC preserves fixed participants
OceanBase [13]	Tree-structured 2PC	Topology-aware participant tree	Optimizes participant topology; WAVC optimizes coordinator roles

IV. SYSTEM MODEL AND DESIGN REQUIREMENTS

Let transaction T involve the fixed participant set $P=\{p_1, \dots, p_n\}$ across R regions. During execution, a participant can be reachable, delayed, crashed, or recovering. The base WAVC model covers crash faults together with network delay or partition. Byzantine behavior is not included in this model because mixing the two fault settings would make it harder to isolate the effect of workload-aware placement. Participants keep durable local prepare/commit state. The network may delay, duplicate, reorder, or temporarily drop messages. For this reason, a timeout is treated only as uncertainty; it is never taken as evidence of COMMIT.

The Decision Service (DS) has $2f+1$ replicas and uses crash-fault consensus. Paxos Commit provides the standard transaction-consensus reference [4]. DS does not execute application updates. Its job is to retain the transaction identifier, the registered participant set, the current role epoch, received vote evidence, and one terminal certificate. Under the assumed crash-fault model, a majority quorum is sufficient to preserve a single durable decision.

Six rules define the safety boundary. (R1) COMMIT requires durable YES evidence from every registered participant. (R2) A change of coordinator role cannot change P or reinterpret a NO vote. (R3) The terminal decision is written once and remains immutable. (R4) A replacement coordinator must be able to reconstruct progress from participant and DS state. (R5) A timeout may cause retry or role reselection, but cannot create evidence or a terminal result. (R6) A poor analyzer decision may hurt performance, but it must not affect safety.

V. WAVC PROTOCOL DESIGN

A. Workload-Aware Regional Role Score

WAVC does not give primary and secondary sites different commit authority. Instead, every candidate region

TABLE II

POSITIONING OF WAVC AGAINST SELECTED RECENT WORK

receives a transaction-local coordination score. The score uses runtime information that is available to the system: locality, participant share, recent reliability, queue pressure, predicted cross-region communication cost, and failure risk. A generic form is:

$$U(r,T) = w_1 L(r,T) + w_2 S(r,T) + w_3 R(r) - w_4 Q(r) - w_5 C(r,T) - w_6 F(r)$$

For each transaction, the selector chooses k regions according to the pairwise path-cost objective and treats them as coordination-primary; the remaining regions are coordination-secondary. These labels are operational hints for routing and recovery. They do not change the registered participant set, reinterpret a vote, or weaken the condition for COMMIT.

B. Architecture

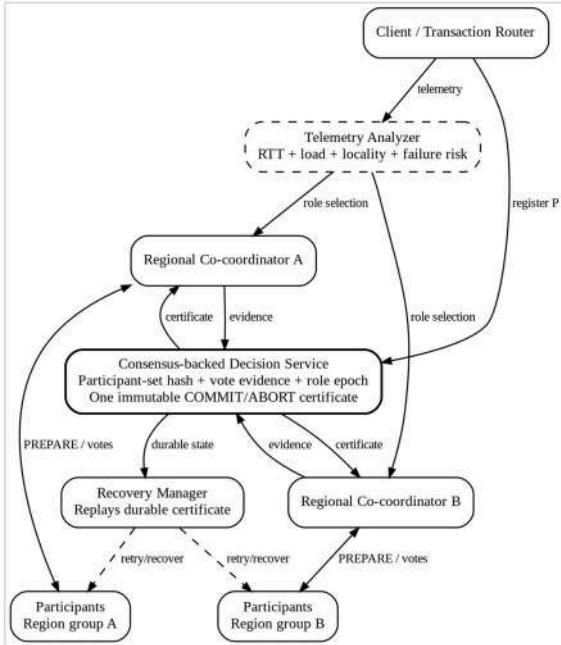


Fig. 2. WAVC architecture and the separation between the optimization layer and the safety-critical Decision Service.

TABLE III

WAVC LAYER RESPONSIBILITIES

Layer	Responsibility	Safety critical?
Telemetry/Analyzer	Collect RTT, load, participant locality and failure suspicion; compute role objective	No; failure can degrade performance only
Regional co-coordinators	Parallel PREPARE fan-out, local vote aggregation, retry and decision dissemination	Partly; carry evidence but cannot decide COMMIT alone
Participants	Run local legality/concurrency checks; durably log PREPARED before YES	Yes
Decision Service	Register P; persist vote evidence; replicate exactly one terminal certificate	Yes; consensus-backed
Recovery Manager	Replace failed coordinator, query DS and replay the idempotent certificate	Uses safety state; cannot invent an outcome

C. Commit Phases

Phase 0 - Registration and role selection. The client/router determines the complete participant set P

and registers it with DS before role placement. The analyzer then selects k regional co-coordinators and installs the corresponding role epoch. If telemetry is unavailable, a deterministic static mapping is used instead.

Phase 1 - Parallel prepare. Each selected co-coordinator sends PREPARE to its assigned participants. Participants perform their usual legality and concurrency checks. A YES is returned only after PREPARED has been recorded durably; otherwise the participant returns NO.

Phase 2 - Evidence aggregation. Transaction-tagged vote summaries are forwarded to DS. A single valid NO makes ABORT legal. COMMIT remains unavailable until DS holds durable YES evidence from every participant in P .

Phase 3 - Consensus decision. DS forms one terminal certificate containing T , the participant-set hash, role epoch, outcome, and an evidence digest. After consensus accepts the certificate, the terminal outcome is immutable.

Phase 4 - Dissemination and recovery. The certificate is sent to participants through the co-coordinators. Terminal actions are idempotent, so retries do not change the result. A recovering participant or replacement coordinator obtains the same certificate from DS and completes that recorded action.

D. High-Level Pseudocode

ALGORITHM 1

SAFETY-PRESERVING WAVC COMMIT PATH

```

1 DS.Register(T, P)
2 C <- SelectCoordinators(T, telemetry, k)
3 epoch <- DS.InstallRoleEpoch(T, C)
4 parallel for c in C:
5   votes[c] <- PrepareAssignedParticipants(c, T, P, epoch)
6 DS.AppendEvidence(T, votes[c])
7 if DS.HasValidNO(T):
8   d <- DS.ConsensusDecide(T, ABORT)
9 else if DS.HasYESFromEveryParticipant(T):
10  d <- DS.ConsensusDecide(T, COMMIT)
11 else:
12  retry or reselect a coordinator; never fabricate a vote
13 DisseminateCertificate(T, d)
14 return d

```

VI. SAFETY PROPERTIES AND CORRECTNESS ARGUMENT

The correctness argument is easier to state if role selection is kept outside the safety kernel. Let $\text{Vote}(p,T)$ be in $\{\text{YES}, \text{NO}, \text{UNKNOWN}\}$, $\text{Decision}(T)$ be in $\{\text{UNDECIDED}, \text{COMMIT}, \text{ABORT}\}$, and $\text{Registered}(T)=P$.

WAVC is required to maintain the following invariants.

I1 - Unique outcome. $\text{Decision}(T)$ is written once by the consensus-backed DS and does not change between COMMIT and ABORT.

I2 - Commit validity. $\text{Decision}(T)=\text{COMMIT}$ requires $\text{Vote}(p,T)=\text{YES}$ for every p in $\text{Registered}(T)$. I3 - No split terminal state. A correct participant enters COMMITTED only from a valid COMMIT certificate and enters ABORTED only from the valid ABORT certificate.

I4 - Role non-interference. A change in co-coordinator roles or the role epoch cannot change $\text{Registered}(T)$, any durable participant vote, or the COMMIT predicate.

I5 - Timeout safety. A timeout may trigger retry or role change, but it is never treated as a positive vote or as proof of a terminal decision.

Theorem 1 - Atomicity under role changes. Assume (A1) the Decision Service is linearizable and write-once for the terminal outcome, (A2) the registered participant set P is immutable after registration, (A3) a participant durably records PREPARED before emitting YES, and (A4) participants accept terminal actions only from a valid DS certificate. Then every WAVC execution has at most one terminal outcome, and $\text{Decision}(T)=\text{COMMIT}$ implies a durable YES from every p in P .

Assumption A1 rules out two durable terminal certificates with different outcomes. A2 fixes the participant set even when coordinator roles change. Since the COMMIT guard checks all members of P , one NO or UNKNOWN keeps COMMIT disabled. Under A3 and A4, recovery cannot introduce a new local outcome: a recovered participant can only follow the certificate already

stored by DS. Coordinator replacement therefore changes the path used to finish the transaction, not the evidence that determines the decision. Under the stated assumptions, this gives I1-I5 at the WAVC layer.

Progress still depends on availability. If a DS quorum eventually becomes reachable, communication eventually succeeds, and every registered participant eventually recovers and returns a vote, WAVC reaches COMMIT or ABORT. If one of these conditions fails permanently, the transaction may remain in doubt rather than relaxing atomicity.

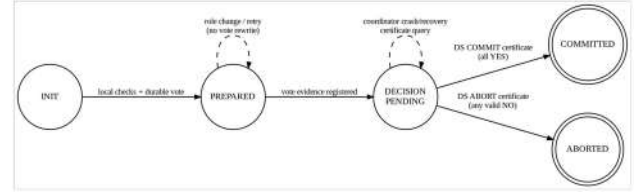


Fig. 3. Abstract transaction-state safety boundary; role changes and recovery do not rewrite durable votes or the terminal decision.

VII. EXECUTABLE ABSTRACT STATE-SPACE VERIFICATION

We built a finite-state Python model before attempting a full implementation so that the transaction-level safety rules could be checked independently. Consensus is represented by a linearizable write-once decision register; the model does not attempt to verify Raft or Paxos themselves. Four participants are used, giving all 16 YES/NO vote assignments. For each assignment, the explorer varies the ordering of prepare, vote delivery, decision creation, terminal-certificate delivery, one coordinator-role change, and at most one crash/recovery cycle for each participant. To keep the state space finite, no more than one participant is crashed at a time. Durable votes and the DS decision survive recovery.

TABLE IV

EXHAUSTIVE ABSTRACT STATE-SPACE SAFETY RESULTS

Verification quantity	Observed result
Participant count	4
Vote configurations	16 (all YES/NO combinations)
Reachable abstract states	1,156,608
States with all participants terminal	21,504
COMMIT without all delivered YES	0 violations
Participant COMMIT before DS COMMIT	0 violations
NO-voter committed	0 violations
Participant in both terminal states	0 violations

Participant in both terminal states 0 violations The explorer reported no violation of the checked invariants. The number 1,156,608 belongs to this particular abstraction and should not be read as a proof about an implementation. What it does show is that every event ordering admitted by the model preserves the intended separation between changing roles and deciding the transaction. A stronger implementation artifact should carry these properties into TLA+ and model-based conformance testing, following the modular direction used for MongoDB [11].

VIII. REPRODUCIBLE SIX-REGION PROTOCOL-LEVEL STUDY

A. Experimental Model and Strong Static Baseline

The six-region simulator addresses one narrow question: when workload location or failure risk changes, can moving the coordination roles reduce WAN cost? This is a protocol-level sensitivity study rather than a production-system benchmark. All policies are evaluated with the same RTT matrix, transaction stream, local-cost distribution, and random seeds. Each transaction contains 4-12 participants. Decision Service replicas are placed in R0, R2, and R4, and WAVC evaluates every two-region role pair for each transaction.

The static comparator is intentionally strong. Within each complete scenario, all 15 fixed two-region pairs are evaluated and the pair with the lowest mean modeled latency is reported as Oracle-static. Because that choice is made with hindsight, WAVC is

not being compared with an arbitrary weak fixed pair. WAVC still pays a 3 ms role-selection/reconfiguration cost on every transaction. Candidate pair C minimizes $J(C,T)=D_{\max}+0.22D_{\text{avg}}+0.22DDS+25L+\lambda F$, where $D_{\max}$ and D_{avg} are participant-to-nearest-role RTT terms, DDS is the Decision Service path term, L is recent owner utilization, and F is role failure risk. $\lambda=50$ in the normal cases and $\lambda=140$ in the high-risk case. These values are disclosed evaluation settings, not universal optima.

TABLE V

REPRODUCIBLE SIMULATION CONFIGURATION

Parameter	Value
Regions	6 (R0-R5)
Symmetric inter-region RTT range	35-181 ms for non-local links
Transactions per scenario	8,000
Participants per transaction	Uniform random integer from 4 to 12
Decision Service regions	R0, R2, R4
WAVC role count k	2 regional co-coordinators
Static comparator	Oracle-static: best of all 15 fixed two-region pairs per scenario
Dynamic role overhead	3 ms per transaction; sensitivity checked at 0, 3, 10, and 20 ms
Random seeds	43, 44, 45, 46
Scenarios	Uniform, regional skew, workload shift, elevated coordinator risk
Metrics	Mean/p50/p95/p99 modeled latency, maximum owner share, recovery-risk exposure

B. Latency and Resilience Results

TABLE VI

MODELED COMMIT LATENCY AGAINST ORACLE-STATIC

Scenario	Protocol	Mean ms	p50 ms	p95 ms	p99 ms
Uniform	Oracle-static	110.98	111.34	119.78	123.52
Uniform	WAVC	108.61	110.17	124.56	131.13
Skew	Oracle-static	109.57	106.58	130.07	134.40
Skew	WAVC	99.25	104.56	118.95	123.93
Workload shift	Oracle-static	107.27	109.12	119.07	122.70
Workload shift	WAVC	96.02	101.69	117.87	122.57
High risk	Oracle-static	110.21	110.82	119.65	123.29
High risk	WAVC	110.55	109.45	132.43	137.53

TABLE VII

COORDINATOR CONCENTRATION AND MODELED RECOVERY EXPOSURE

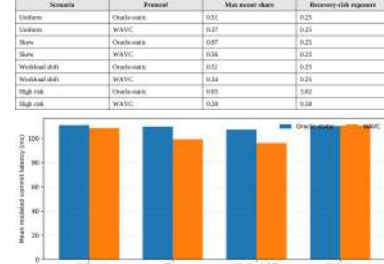


Fig. 4. Mean modeled commit latency of Oracle-static and WAVC under the four workload/risk scenarios.

Against the hindsight-selected Oracle-static pair, WAVC lowers mean modeled latency by 2.1% for the uniform workload, 9.4% for regional skew, and 10.5% when the workload moves. Tail latency is more mixed. p95 improves by 8.6% under skew and 1.0% under workload movement, but it is 4.0% worse in the uniform case. The experiment therefore shows a mean-latency benefit in several regimes without claiming a uniform improvement in the tail.

The high-risk experiment shifts the selector toward lower recovery exposure. Maximum owner share drops from 0.65 to 0.28, and modeled recovery-risk exposure falls from 3.02 to 0.58, which is an 80.7% reduction. The trade-off is visible in latency: mean latency is 0.3% higher and p95 is 10.7% higher than Oracle-static. A practical selector would therefore need controls such as a tail-latency limit, hysteresis, or cached role choices rather than optimizing only the mean path.

C. Sensitivity to Role-Selection Overhead

TABLE VIII

SENSITIVITY OF MEAN-LATENCY GAIN TO ROLE-SELECTION OVERHEAD

Overhead	Uniform	Skew	Workload shift	High risk
0 ms	+4.84%	+12.16%	+13.29%	+2.42%
3 ms	+2.13%	+9.42%	+10.49%	-0.31%
10 ms	-4.18%	+3.02%	+3.96%	-6.66%
20 ms	-13.21%	-6.11%	-5.37%	-15.74%

20 ms -13.21% -6.11% -5.37% -15.74% Role-selection overhead can remove the gain quickly. At 10 ms per transaction, the mean-latency benefit remains only for

the skewed and moving-workload scenarios. At 20 ms, WAVC loses the mean-latency advantage in all four cases. This is why role decisions should be reused when the workload has not changed materially and, where possible, computed away from the critical path. The measured benefit exists only while the saved WAN cost is larger than the cost of selecting and installing new roles.

D. Interpretation

The study isolates coordinator placement under one synthetic WAN model. It does not compare complete implementations of D2PC, Tiga, MTC, SunStorm, or OceanBase, and therefore does not establish end-to-end superiority over those systems. The result is more limited: transaction-local role changes are most useful when workload location or failure risk changes faster than a fixed configuration can be retuned, provided that the selector remains inexpensive.

IX. PETRI-NET AND TLA+ VERIFICATION PATH

Petri-net verification was proposed in the earlier research line but was not developed into a current executable workflow. WAVC has an event structure that can be mapped directly to such a model. Runtime traces contain the transaction ID, participant ID, role epoch, PREPARE, YES/NO, evidence registration, DS decision, crash/recovery, and terminal-delivery events. These can be represented by places such as INIT, PREPARING, PREPARED, DECISION_PENDING, COMMITTED, ABORTED, COORDINATOR_FAILED, and RECOVERING. A 1-safe Petri net could then be checked for boundedness, reachable terminal markings, liveness under the stated recovery fairness condition, and absence of deadlock after a durable decision. The same traces

could also be mined into object-centric Petri nets and compared with the designed model, following recent microservice-verification work [14].

TLA+ offers a second route for checking the same boundary. Rather than fixing one role-selection heuristic, the specification can allow role epochs to change non-deterministically. If the safety properties hold for every legal coordinator selection, then correctness does not depend on the selector. The main properties are NoSplitDecision, CommitRequiresAllYes, TerminalDecisionImmutable, RoleChangePreservesParticipantSet, and RecoveredParticipantFollowsCertificate. Later, implemen-

tation traces can be translated into specification actions for model-based conformance testing, as in the modular MongoDB work [11].

X. DISCUSSION, NOVELTY AND THREATS TO VALIDITY

A. Precise Novelty Claim

WAVC does not claim adaptive commit, multi-coordinator commit, consensus-backed transactions, or formal verification as separate inventions; recent work already provides strong examples of each [5]-[22]. The contribution is the boundary between placement and safety. Coordinator roles are chosen per transaction from workload and risk signals, but that choice cannot modify the participant set or the COMMIT predicate. Durable evidence is kept in a consensus-backed service so that a coordinator can be replaced without changing the outcome. The design also connects the executable state explorer with a path toward TLA+, runtime conformance checks, and Petri-net analysis. This keeps the useful workload-awareness idea from the earlier E3PC line while discarding the unsafe vote-override behavior.

B. Threats to Validity

The main limitation is that the performance evidence is simulation-based. Oracle-static is a strong fixed-role comparator, but a small multi-region prototype using a real workload such as YCSB would give stronger practical evidence. A separate role-score weight-sensitivity experiment would also show how dependent the observed results are on the chosen weights. Those experiments are not part of the present paper, so no result is claimed for them here. The finite-state explorer also assumes that the Decision Service already behaves as a correct linearizable write-once register and limits simultaneous crashes to keep the state space tractable. In addition, a role score tuned for one topology may not transfer unchanged to another. A larger evaluation should therefore report weight ablations, telemetry windows, and role-change hysteresis.

C. Reproducibility and Artifact Boundary

The numerical results in Sections VII and VIII are generated from deterministic Python artifacts with the stated assumptions and seeds. The companion material contains the finite-state explorer, the Oracle-static/WAVC simulator, the role-overhead sensitivity data, generated CSV

files, and figure sources. Re-running those scripts reproduces the reported state counts and tables. This makes the abstract study reproducible, but it is not a substitute for a production database implementation.

D. Scope for Byzantine Extension

The earlier Byzantine-agreement work is left as a later extension. One possible next step is to replace the crash-fault Decision Service with a Byzantine-fault-tolerant quorum and include trust or fault-domain information in the role score. BFT is deliberately excluded from the current base protocol so that the present evaluation stays focused on workload-aware coordination under one clearly defined crash-fault model.

XI. CONCLUSION

WAVC reuses one idea from an earlier distributed-commit line: transaction sites can differ in operational importance. The difference in WAVC is that workload information changes where coordination runs, not what is required for a legal commit. Regional roles are selected from workload and risk signals, while a consensus-backed Decision Service keeps the terminal result and vote evidence durable. In the four-participant abstraction, the state explorer reaches 1,156,608 states with no checked safety violation. In the six-region model, mean modeled latency is lower by 2.1%, 9.4%, and 10.5% for uniform, skewed, and moving workloads. Under elevated coordinator risk, mean latency rises by 0.3% while modeled recovery-risk exposure falls by 80.7%. The overhead study also shows when changing roles stops being worthwhile. The supported conclusion is therefore conditional: workload-aware placement can improve geo-distributed commit behavior without weakening atomicity when its control cost remains below the WAN savings. A multi-region prototype, YCSB evaluation, role-score weight sensitivity, and complete TLA+/Petri-net conformance work are appropriate next steps.

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