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AI-Enabled UAV-Based Landmine Detection and Classification Systems: The Next Battlefield Imperative for India

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Abstract

AI-enabled UAV based landmine detection and classification can be a major advantage for the Indian Army. By combining technologies like thermal imaging, ground-penetrating radar (GPR), magnetometry and edge AI processing on an autonomous system such as the UAV Mine Detection System (UMDS) can survey large areas from a safe distance. It can create real-time maps showing mine risks and share this threat information directly with battlefield networks. Given India's security challenges on two fronts, along with lessons learned from recent conflicts like Ukraine and Nagorno-Karabakh, there is a clear need for faster and safer mine detection. At the same time, the push for self-reliance under Atmanirbhar (self-reliant India) Bharat makes it even more important to develop such systems within the country. Therefore, UMDS should not be treated as a future idea but as an urgent operational need.

Keywords: UAVs, AI, Siachen, Landmines, New Age Battlefield

Introduction

Landmines have influenced military tactics for more than a century El Alamein to the defended approaches of the Siachen Glacier they have repeatedly restricted movement, disrupted supply lines and imposed heavy losses in both personnel and equipment. Yet, despite decades of technological progress, the core challenge of detecting and classifying landmines in a contested, time sensitive battlefield environment has remained stubbornly unresolved.

Recent wars have compelled us to rethink about this problem. The Russia-Ukraine conflict has produced the most heavily mined theatre of operations since the Second World War, with both sides deploying mines at a scale that has effectively stalled armoured movement. The 2020 Nagorno-Karabakh war also showed just how decisive a well-prepared minefield can be when combined with UAV-based ISR and loitering munitions, capable of destroying a numerically superior mechanised force within hours. These are not distant lessons. For the Indian Army, which must remain operationally prepared to fight across the deserts of Rajasthan, the high passes of Ladakh and the riverine plains of Punjab at the same time, the ability to quickly detect, classify and map minefields before and during combat is a capability of the first order.

The convergence of artificial intelligence, miniaturised sensor technologies and tactical UAV platforms now offers a credible solution for the first time. AI-enabled UAV-based landmine detection and classification systems, integrating thermal imaging, ground-penetrating radar (GPR), magnetometer arrays and edge AI processing could transform a task that has traditionally been slow, casuality prone and manpower-intensive into one that is rapid, autonomous and conducted from a safe stand-off distance. This article examines why such systems are strategically important for India, draws lessons from recent conflicts, outlines a qualitative operational architecture, and makes the case for an indigenous development pathway under the Atmanirbhar Bharat framework.

The Future Battlefield in the Indian Context

India is a continental power whose main security concern lie along its land borders. The two front environments—a belligerent China in the north & east and a Pakistan that maintains sub-conventional activity in the west sets the operational priorities for the Indian Army. Any future conflict, whether conventional, hybrid or mixed, will be fought mainly on land across highly varied and often harsh terrain.

On the northern front, the Line of Actual Control (LAC), from Ladakh to Arunachal Pradesh, presents a uniquely difficult operational environment. High altitude terrain above 14,000 feet, sub-zero temperatures all-round the year, rarefied atmosphere that reduces human performance, restricted vehicle movement and vulnerable communication lines all place severe limits on conventional engineer operations. In such conditions, a minefield laid at a forward pass or a logistics chokepoint cannot practically be cleared by traditional hand methods under fire, as the manpower required would be excessive. Since the Galwan Valley clash in June 2020, both sides have strengthened their defensive positions and accelerated border infrastructure development. It would therefore be unwise to assume that future standoffs will not include the mining of key terrain and approach routes.

The Indian Army's Corps of Engineers currently relies on a combination of handheld metal detectors, prodding rods, mine-protected vehicles and limited mechanised breaching assets such as the Combat Engineer Tractor (CET) and the Armoured Vehicle-Launched Bridge (AVLB). While these systems are effective in their intended roles, they are slow, offers limited stand-off, and becomes highly vulnerable in fire-contested environments. The integration of AI-enabled UAV mine detection into the engineer support chain would not only augment these capabilities—it would fundamentally alter the tactical options available to the battlefield commander.

Lessons from Recent Wars

The Russia-Ukraine War (2022–Present)

Ukraine has become, in the assessment of most Western military analysts, the most comprehensive test of combined arms doctrine in decades. The use of mines by both Russia and Ukraine has been extraordinary in scale and methodology. Russian forces have employed the POM-3 and TM-62 series mines extensively, including variants delivered remotely by artillery and aviation, thus creating minefields that are irregular in shape, mixed in type and difficult to map using conventional reconnaissance. Ukrainian counter-offensive operations in 2023, especially the thrust towards Robotyne and Tokmak, were stalled by the density of mine destroying the armour such as Leopard 2 tanks and Bradley IFVs destroyed or disabled before reaching the first defensive line.

The tactical lesson drawn is very clear: in a symmetric or near-symmetric conflict, minefield reconnaissance by ground troops under fire is not a survivable mission. UAVs, already widely used in the Ukrainian theatre for ISR and strike roles, have also been used in experimental configurations to detect mines, though no dedicated AI-enabled mine-detection UAV has yet been fielded at scale. The operational need is clear, but technological solution is still catching up.

The Nagorno-Karabakh Conflict (2020)

The forty-four-day war between Azerbaijan and Armenia in 2020 showed the decisive potential of UAV integrated operations against a conventionally equipped army. Armenian armoured formations were systematically destroyed by Azerbaijani Bayraktar TB2 drones and Harop loitering munitions operating in a permissive air environment. Equally important, though less highlighted was the way Armenian defensive minefields laid along traditional axes of approach were bypassed through UAV ISR, which identified gaps and alternative routes and allowed Azerbaijani ground forces to manoeuvre around, rather than through prepared defences. In that sense, the mine was tactically neutralised not by breaching, but by the battlefield transparency created by UAVs. For the Indian Army, the lesson is clear: UAVs used for minerelated operations need not be limited to clearance alone; mapping and route circumvention, supported by accurate AI-generated threat overlays, may be just as valuable.

Israel-Gaza Operations (2023–Present)

Israel's operations in Gaza since 2023 have highlighted the difficulty of dealing with complex IED and mine threats in an urban setting, where traditional clearance methods cannot keep pace with tactical tempo. The Israel Defence Forces have used a range of robotic and unmanned systems, including the D9 armoured bulldozer with sensor suites, the Jaguar autonomous patrol vehicle and small UAV platforms, to preserve mobility in contested urban terrain. A notable feature of Israeli engineer operations has been the integration of data from multiple sensors and platforms into a common operational picture. The combination of thermal imagery, ground-penetrating radar data and AI-assisted anomaly detection into a single threat map at the company and battalion level is the architectural model the Indian Army should aim to replicate.

Why Landmine Detection Remains a Critical Challenge

Despite decades of international pressure, investment in humanitarian demining and the Ottawa Treaty regime, the global landmine problem remains acute. From a strictly military perspective, setting aside humanitarian concerns, landmines are still one of the most cost-effective tools of area denial available to any army. A TM-62 anti-tank mine, which may cost only forty to sixty US dollars, can disable a main battle tank worth tens of millions. The economics of mine warfare remain highly asymmetric in the defender's favour.

For the Indian Army, the challenges of mine detection may be grouped into four broad categories. Operations become difficult because the environment changes a lot from place to place. Deserts, high-altitude rocky areas, alluvial plains and thick vegetation each creates different problems for sensors. A metal detector that works well in open plains may fail in mineral rich Himalayan rocks, while a GPR system that works in desert sand may create too much noise in laterite soil.

Another challenge is the type of mine itself. Modern armies often use low metal or minimum metal mines, which are designed to avoid detection by standard metal detectors. In a high intensity conflict, minefield clearing also has to happen very quickly, sometimes within hours instead of days. In addition to above, mine clearance is still a dangerous job, even with protective equipment.

Because of these challenges, stand-off detection is not just useful, it is necessary. An AI-enabled UAV mine detection system is especially effective as it can cover large areas quickly from the air. It can also use multiple sensors together to handle different terrains better. Most importantly, it reduces the risk to people by keeping operators away from the minefield.

Role of UAVs in Modern Combat Engineering

UAVs are already being used in combat engineering, but adding AI-based onboard processing makes them much more useful. At present, engineers mainly use drones for ISR support during breaching operations. They fly over obstacle belts to find minefield edges, anti-tank ditches and enemy activity near crossing points.

Although this information is valuable, it still has to be checked by a human analyst before it is passed to the breaching team. This creates delay and in fast moving operations, even a small delay can be a serious problem. AI processing on the drone can reduce this gap by giving quicker, more direct information.

The integration of AI into the UAV platform will shorten this observe-orient-decide-act (OODA) loop. An AI-enabled UAV conducting a minefield reconnaissance mission does not merely collect imagery for later analysis—it processes the sensor returns in real-time, classifies anomalies as mine-probable or mine-improbable, assigns confidence scores to each detection, and generates a continuously updating threat map that is transmitted to the ground commander's digital command system. By the time the UAV returns from its mission, the tactical commander has already received and acted upon the intelligence.

Beyond detection, UAVs offer two more engineer-relevant capabilities. *First* is precision marking: once an UAV identifies a mine, it can mark the location with a small dye package or a GPS-based digital tag, allowing follow-on breaching forces to move through the minefield far more accurately than traditional prodding and marking methods permit. *Second*, is route proving: a swarm of UAVs scanning multiple route options can quickly identify the least mine-contaminated axis, helping mechanised columns choose the best line of advance with much better information than was previously available.

The scientific basis for AI-enabled landmine detection rests on combining multiple sensing technologies, since no single sensor can provide enough discrimination to be tactically dependable. These sensing inputs are then processed with machine-learning algorithms trained to recognise mine signatures across different environmental conditions. The main sensing modalities relevant to UAV-based detection are thermal infrared imaging, ground-penetrating radar, magnetometry, and hyperspectral imaging, with each contributing a different piece of the detection problem.

Thermal infrared imaging works by detecting the difference in heat retention between a buried mine and the surrounding soil. A mine, especially one with a plastic or rubber casing, absorbs and releases heat differently from undisturbed ground. This thermal contrast is usually strongest at dawn, when the surface temperature gradient is at its maximum and diminishes as the day warms. In a UAV-based system, a forward-looking infrared (FLIR) camera on a stabilised gimbal captures the thermal image and an AI algorithm then scans it for anomalies with the right size, shape and heat signature.

Ground-penetrating Radar (GPR) working is based on sending electromagnetic pulses into the ground and analysing the reflected signals to detect objects below the surface. A mine typically produces a distinctive radar return, often seen as a hyperbolic reflection pattern, which differs from normal variations in soil. The main limitation for UAV use has been standoff distance, since conventional GPR works best when the antenna is very close to, or in contact with, the ground. However, advances in ultra-wideband GPR and AI-based clutter suppression have gradually increased the usable standoff distance, making low-altitude UAV-mounted GPR a practical option.

Magnetometry detects disturbances magnetic field caused by ferrous material buried underground. Although, it is less effective against minimum-metal mines, it remains highly reliable for the large share of mine stocks that still contain substantial metal components. A miniaturised fluxgate or optically pumped magnetometer mounted on a UAV, with the aircraft's own magnetic signature compensated for, can produce high-resolution magnetic anomaly data at low flight speeds.

The strength of sensor fusion lies in the AI system's ability to correlate detections across multiple modalities. An object that produces a thermal anomaly but no radar return may simply be a surface stone; one that shows a radar return but no thermal signature may be a root or other natural feature; but one that triggers anomalies in all three channels, with the right spatial dimensions and confidence levels, can be classified as mine-probable with much greater certainty. Modern convolutional neural networks, trained on large datasets of mine signatures across different soil and vegetation conditions, have reportedly achieved classification accuracies of above 90 percent in controlled trials.

Components of the Proposed UAV Mine Detection System (UMDS)

UAV Platform

The optimal platform for the mine detection role is a multi-rotor or hybrid VTOL (Vertical Take-Off and Landing) UAV in the Class I (sub-150 kg) category. VTOL capability is non-negotiable given the operating environment; a runway-dependent system is tactically unusable in high-altitude terrain or in the forward areas of a desert battle. The UAV must be capable of operating at altitudes up to 5,000 metres AMSL to cover LAC proximate operational areas, must be resistant to the wind conditions characteristic of high-altitude passes (sustained speeds of 30–35 km/h with gusts up to 50 km/h) and must carry a sensor payload of 8–12 kilograms with an endurance of 45–60 minutes at operational altitude. Battery propulsion is preferred for the noise-sensitive counter-infiltration and ISR roles; a hybrid electric-IC engine option may be warranted for high-altitude sustained endurance missions.

Sensor Suite

The UMDS sensor suite should integrate (as a minimum): a stabilised FLIR camera with thermal resolution, better than 50 milli-Kelvin; an ultra-wideband GPR system with ground penetration depth of at least 300 mm and a usable standoff altitude of 1–3 metres; a three-axis fluxgate magnetometer array compensated for UAV magnetic interference; and a high-resolution electro-optical camera for visible spectrum imagery. A hyperspectral sensor, while adding weight and cost, should be incorporated in the advanced variant to detect soil disturbance signatures and explosive residue traces associated with recent mine-laying activity.

Edge AI Processing

The most defining feature of an operationally useful UMDS is onboard AI processing or edge AI, wherein the processing is performed on the UAV itself rather than sending raw data to a ground station for analysis. This reduces latency, preserves tactical momentum and makes the system far more useful in a contested environment where the time delay is tactically unacceptable. This is operationally critical for two reasons. *First*, it eliminates the delay in data transmission and remote analysis, enabling real-time threat mapping. *Second*, it provides operational resilience against electronic jamming or communication disruption; if the data link is cut, the UAV continues to collect, process and store detection data for transmission when communication is restored. The processing unit should be radiation hardened, ruggedised AI inference chip capable of running multi-modal sensor fusion algorithms in real time.

Ground Control and Data Management

The Ground Control Station (GCS) for the UMDS should be man-portable, operable by a two-person team at section or troop level, and integrated with the Army's tactical communication network. The GCS receives processed detection data from the UAV and displays it on a digital map overlay—the Battlefield Management System (BMS) or the Tactical Command, Control, Communication and Intelligence (Tac C3I) platform—showing mine-probable locations with associated confidence scores. This threat overlay should be shareable across the combat net to all elements of the formation, enabling the armoured regiment commander, the mechanised infantry battalion, and the supporting engineer troop to operate from a common recognised mine picture (CRMP). The GCS should also support mission planning, route optimisation, and swarm coordination functions.

Swarm Coordination Module

For large-area coverage, particularly in the context of a formation-level deliberate attack, a single UAV is insufficient. The UMDS should be configurable as a coordinated swarm of 4–8 UAVs operating simultaneously, each allocated a scanning lane and automatically de-conflicting their flight paths. Swarm coordination algorithms, running on the GCS, should enable the concurrent scanning of a front of 2–4 kilometres in a single mission of 45–60 minutes—sufficient to survey the mine threat ahead of a brigade attack.

Desired Operational Specifications

Essential Qualitative Requirements (QRs)

- **Atmanirbhar Compliance.** Must conform to indigenous development requirements. All critical sub-systems viz. sensors, processing units, data links, are to be sourced from Indian manufacturers or approved technology transfer partners. Import content to be restricted to components that cannot be produced domestically and only sourced from countries on the Government of India's approved vendor list.

- **VTOL Capability.** It must be capable of vertical take-off and landing from unprepared surfaces, with no runway dependency. It should also be recoverable by net or hand-catch in emergency.
- **High-Altitude Operation.** It must remain operationally effective at altitudes up to 5,000 metres above the mean sea level in sub-zero temperatures (−20 degrees Celsius to +45 degrees Celsius at sea level) and sustained winds of up to 35 km/h.
- **Multi-Sensor Payload.** It must carry integrated FLIR, UWB-GPR, and magnetometer sensors simultaneously, with provision for hyperspectral sensor in advanced variant.
- **Edge AI Processing.** It must process sensor data onboard in real-time. Threat map must be available for transmission within 30 seconds of each detection pass.
- **Secure Communications.** It must use encrypted, frequency-hopping, anti-jam data links for all control and data transmission and must also have a Return to Home (RTH) function in the event of link loss.
- **BMS/Tac C3I Integration.** Threat overlay data must be compatible with existing Indian Army digital systems including BMS, Tac C3I and CIDSS (Command Information and Decision Support System).
- **Swarm Capable.** It must be capable of coordinated multi-UAV operation (minimum 4-UAV swarm) with autonomous lane allocation and collision avoidance.

Desired Technical Specifications

- **Endurance:** 45–60 minutes at 4,500 m AMSL.
- **Operational radius:** 5 km from GCS.
- **All-Up Weight (with sensor payload):** less than 25 kg.
- **Sensor payload capacity:** 8–12 kg.
- **GPR standoff altitude:** 1–3 metres AGL.
- **Detection confidence threshold:** greater than 85 per cent true positive rate at less than 10 per cent false positive rate.
- **Area coverage rate:** minimum 0.5 sq km per hour per UAV.

- **Threat map update latency:** less than 30 seconds.
- **Propulsion:** hybrid electric/IC engine with battery-priority mode for noise-sensitive missions.
- **Mode of operation:** fully autonomous waypoint scanning with manual override option.
- **GCS:** man-portable (less than 15 kg), two-operator crew, ruggedised for battlefield environment.

Possible Battlefield Scenarios

Scenario One: Mechanised Operations — Western Front

Consider an armoured brigade tasked to penetrate a defended sector in the Cholistan-Thar sector in the initial phase of a conventional conflict. The axis of advance is known; intelligence indicates that the forward defended localities are protected by a mixed anti-tank and anti-personnel minefield, some 2–3 kilometres in depth. A conventional deliberate breach would require the forward deployment of mine-protected vehicles, combat engineer tractors and hand-clearance parties under cover of fire—a time-consuming, casualty-prone operation that surrenders surprise and cedes initiative.

Under the UMDS concept, a section of four UMDS UAVs is launched from the assembly area, 8–10 km behind the forward line of own troops (FLOT), during the night preceding H-Hour. The swarm autonomously scans the designated lane—600 metres wide by 3 kilometres in depth—over a 90-minute window, transmitting a continuously updated threat overlay to the brigade commander's BMS terminal. By first light, the brigade has a mine probability map of the entire intended breach zone, identifying the two or three corridors of least mine density. The armoured regiment's assault plan is adjusted accordingly: the main effort is directed through a lower-threat corridor identified by the UMDS, and the engineer breach support is concentrated where the threat is highest. The result is a faster, more predictable breach with reduced risk to both engineer and assault elements.

Scenario Two: Mountain Warfare — LAC Sector

An infantry brigade, holding a defensive sector on the LAC in central Ladakh, receives intelligence that the adversary has initiated mining of an approach route to a key pass that serves as the brigade's primary logistics corridor. Physically reconnoitring the route under observation is not possible without risking an incident, and laying a counter-minefield to deter further activity requires first confirming the threat. Two UMDS UAVs are then tasked to overfly the route at high altitude conditions of 4,800 metres AMSL, scanning a 400-metre corridor along the suspected axis. In GPR and magnetometer fusion mode, the onboard AI identifies eighteen discrete mine-probable locations in a pattern consistent with a deliberate anti-vehicle minefield. The GPS-referenced threat overlay is transmitted to Brigade Headquarters within two hours of tasking. The brigade commander now has the evidence needed to redirect logistics along an alternate route, brief higher HQ on the adversary's intent and initiate diplomatic escalation procedures. Hence, no soldier has entered the contested area, no casualty has been incurred and the intelligence has been obtained at stand-off distance.

Scenario Three: Counter-Infiltration — Jammu and Kashmir

A counter-infiltration grid in a forward sector of the LC receives reports of an IED laid on a patrol track. The traditional response is to send a bomb disposal team to carry out a hazardous physical search is slow, dangerous and disruptive to operations. A UMDS UAV, kept at readiness at the company operating base, is launched within fifteen minutes of the report. It can fly just 2 to 3 metres above the ground along the suspected route and scan a 500-metre stretch in one pass. The AI system can then spot an unusual object at 340 metres that looks like an IED because of its irregular shape, shallow burial and small amount of metal. The location is GPS tagged and sent to the unit commander. The Bomb Disposal team is then directed to the exact spot, hence cutting clearance time from hours to minutes and restoring operational tempo.

Tactical and Strategic Advantages

The introduction of AI-enabled UMDS into the Indian Army's order of battle would create advantages at multiple levels of war.

At the tactical level, the most immediate benefit is preservation of combat power. Mine clearance is among the most casualty-intensive tasks an engineer can undertake and removing the human operator from the detection phase directly reduces the cost of a mine encounter. Just as important is the time advantage: a UAV swarm can survey in two hours what a hand-clearance party might take two days to cover. In a high-intensity war, where operational tempo is decisive, that difference may shape the outcome of an engagement.

At the operational level, UMDS would transform the Corps of Engineers from a point-survey capability into an area-surveillance capability. A corps commander, conducting an offensive operation, could request a mine-threat assessment of the entire intended axis of advance, not just a narrow breach lane. That broader picture would support better route selection, better timing of manoeuvre and more precise allocation of engineer support to areas of prominent threat.

At the strategic level, a credible AI-enabled mine detection capability also has deterrent value. An adversary who knows that any minefield laid in contested border areas will be rapidly mapped and exploited loses one of the cheapest and most asymmetric tools in the defender's arsenal. In this context, UMDS is not only a system for detecting mines already laid; it is also a capability that can discourage mine laying in the first place.

Challenges and Limitations

An AI enabled UAV mine detection also have its current limits. Every technology has limitations and a commander who uses UMDS without understanding its limitations would not be able to exploit its advantages fully.

The biggest limitation is detection accuracy in certain environments. The create sensor noise produced by dense vegetation, standing water and some laterite or volcanic soil reduces the performance of both GPR and thermal imaging. It can produce too many false positives as AI models trained are mainly on open terrain until they are programmed with local data. This development challenge solved through testing across Indian terrain types.

Electronic warfare is another major challenge. The communication link between the UAV and the ground control station can be hacked/ jammed. AI, at the edge, helps because the UAV can keep working on its own and save data locally even if the link is lost.

However, a stronger enemy may also try GPS spoofing or block navigation signals, which can make automatic route scanning less reliable. To handle this, the system needs anti-jamming communication, navigation methods that do not depend only on GPS, and a Return-to-Home function.

Operational security is also important. A UAV,over a military area, is visible to the radar, observation posts and acoustic sensors, so UMDS used in contested forward areas, especially along the LAC, must be carefully managed to avoid revealing own positions or intent. Low-signature designs, acoustic suppression and missions during low-visibility periods are sensible mitigations.

Finally, the human factor should not be underestimated. AI-generated mine probability maps will be new to many tactical commanders and they will need training to interpret them correctly. Over-trusting an 85 percent confidence detection as a confirmed mine or under-trusting AI output out of scepticism can both be dangerous. A structured training and doctrine programme would be a necessary precondition for effective use.

Future Scope

The UMDS described in this article is best understood as a first-generation capability. The direction of future technology suggests that later versions will be much more capable. Quantum sensing, especially quantum magnetometers with far greater sensitivity than current fluxgate sensors, could extend detection to minimum-metal mines that today remains beyond reliable airborne detection. At the same time, advances in AI model compression and neuromorphic computing will allow more sophisticated sensor fusion at lower power, which should increase UAV endurance and make smaller platforms viable.

UMDS should not be seen as a separate system. Instead, it should work as part of the Indian Army's larger digital ecosystem. The information it collects about mine threats should move automatically into systems like the Artillery Fire Direction System, BMS and the Air Defence network. This would create a shared and clearer battlefield common operating picture, helping different arms make better decisions.

In the future, UMDS could also do more than detect mines. It may eventually help neutralise them using precision micro-munitions or directed energy, so the full process of detection, classification and neutralisation can be completed without sending troops into the minefield.

More broadly, autonomous engineer support should include more than mine detection. It can also be used for route clearance, checking obstacle placement and assessing battlefield damage. The Indian Army's future plans and capability development should make room for these technologies now, so the system and organisation are ready when the technology becomes mature.

Conclusion

The mine threat for the Indian Army is more serious today than ever before. India faces security challenges on two fronts and there is always the risk that enemy forces may lay mines in a conflict zone. Recent wars such as Ukraine and Nagorno-Karabakh have also shown how dangerous mine warfare can be. All of this makes it clear that action is needed now.

AI enabled UAV based landmine detection systems are not just a small improvement. They are a major leap forward. A system like this can scan a kilometre of minefield in minutes instead of days, keep soldiers away from danger during detection, and create a digital threat map that can be shared quickly across units. If it is affordable for brigade and division level use, it can solve one of the biggest problems in modern mine warfare.

UMDS should therefore be developed and fielded without delay because the need is urgent. India also has a chance to build this technology itself and it should take full advantage of that opportunity.

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