# ADAPTING MARTIAN ROVER TECHNOLOGY FOR TERRESTRIAL DISASTER RESPONSE AND EXTREME TERRAINS

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## ABSTRACT

Rovers have transformed planetary exploration by enabling autonomous, intelligent operation on alien terrains. From the Soviet Lunokhod 1 to NASA's Perseverance, rover technology has evolved to include advanced mobility systems, AI-driven navigation, autonomous decision-making, and onboard scientific instruments. This paper examines how these innovations, originally developed for Mars, can be adapted to solve real-world challenges on Earth, particularly in disaster-prone and inaccessible regions. We designed and 3D-printed a rover prototype, informed by Martian mobility principles, and analyzed its potential for navigating extreme terrain. Using global disaster datasets and a review of current aerial and terrestrial solutions, we evaluated rover applicability to scenarios such as floods, landslides, wildfires, and harsh geographical regions. Our results indicate that ground-based rovers, leveraging autonomous navigation and robust suspension systems, could complement drones and helicopters to improve disaster response and accessibility. Future work will explore multi-agent coordination, hybrid aerial-ground systems, and adaptive AI algorithms to enhance rover efficiency and resilience in complex Earth environments.

## INTRODUCTION

The story of rovers begins with a pivotal shift in how we explore other planets—not simply from orbit, but by touching and traversing their surfaces. This idea gave rise to a new type of mission: one that aimed to land mobile machines capable of operating autonomously on alien terrain. The Soviet Union's Lunokhod 1, launched in 1970, was the world's first successful remote-controlled rover to land on the Moon. Decades later, NASA's Sojourner rover, part of the 1997 Pathfinder mission, became the first to operate on Mars. These pioneering efforts answered a critical question: can we engineer systems that not only survive in hostile extraterrestrial environments, but also move across them, make decisions, and return valuable data independently? [1]

As missions evolved, so did the design and expectations of rovers. Spirit and Opportunity, launched in the early 2000s, brought significant upgrades in navigation and durability. A key innovation during this period was the rocker-bogie suspension system—a springless, passive design that gave rovers an uncanny reptilian adaptability. It allowed them to climb over obstacles twice the diameter of their wheels and maintain traction and balance on slopes of up to 45°, all without complex mechanical parts [5][7]. This simple but powerful design remains in use today, underscoring its long-term reliability and effectiveness [5].

With the arrival of Curiosity in 2012 and Perseverance in 2021, the rover's role transformed from being a mechanical explorer to becoming a fully capable scientist. These newer generations were not just robust vehicles, but fully equipped mobile laboratories. Their onboard technologies include X-ray spectrometers, laser ablation systems for chemical analysis, and atmospheric and environmental sensors. These advancements allowed them to perform detailed scientific investigations on-site, without needing to send samples back to Earth. Another revolutionary leap was the integration of artificial intelligence and autonomous navigation. Given the communication delay between Earth and Mars, these systems enabled rovers to make real-time decisions about terrain navigation, hazard avoidance, and data collection without waiting for human input [2][6]. Curiosity introduced autonomous navigation software that allowed it to create 3D maps from stereo images and chart safe routes through rocky terrain [39] .This reduced dependence on daily commands from Earth and increased the efficiency of long drives. Perseverance built on this with a more advanced system known as AutoNav [40], which processes images much faster using dedicated onboard processors. This allowed it to detect hazards, avoid obstacles such as boulders or sand traps, and select optimal driving paths without stopping for instructions. In practice, this meant that Perseverance could cover distances in a single day that would have previously taken multiple sols for Curiosity. AI also supported science operations, with algorithms prioritizing targets of interest, optimizing the use of power, and even assisting in scheduling instrument use. These capabilities made the rover not only a mobile laboratory but also an independent field scientist, capable of adapting its behavior to unpredictable Martian conditions.

Today, rover research is rapidly evolving to embrace new concepts rooted in simulation, machine learning, and immersive human-robot interaction. Sophisticated simulation environments such as NASA's ROAMS or MIT's Mars Surface Exploration (MSE) platform now allow engineers to test rover behavior, optimize performance, and anticipate real-world challenges before launch [2][3][6]. These tools simulate Martian terrain physics, wheel-soil interaction, and rover dynamics under various constraints. At the same time, extended reality (XR) interfaces—such as VR overlays or immersive teleoperation systems—enable scientists and engineers to visualize and interact with rover environments in real time. These technologies help operators rehearse mission procedures, improve situational awareness, and develop more intuitive methods of controlling robots across vast distances [3][6].

Predictive algorithms powered by machine learning are also playing a growing role. Systems like CosmosPathNet and MLNav train rovers to detect and analyze terrain features, calculate the most efficient path, and reduce energy consumption during operations. These algorithms not only make rovers more intelligent, but also more resource-efficient—an essential quality for long-term missions with limited power and high risk. Research is increasingly focused on sim-to-real transfer, ensuring that AI-driven models behave consistently both in simulation and under real planetary conditions [2][6].

Looking ahead, the future of rover missions will likely depart from the lone explorer model altogether. Instead, missions will involve swarms of heterogeneous robots: Wheeled rovers, flying drones, and sub-surface crawlers working together will create a complementary system where each platform addresses the limitations of the others. Wheeled rovers are best suited for carrying heavy instruments and traveling long distances across stable terrain. Flying drones, like the Ingenuity helicopter, can quickly scout areas ahead, map routes, and access regions that are too steep or fractured for rovers. Sub-surface crawlers or burrowing robots could reach beneath the Martian surface to investigate soil layers, ice deposits, or sheltered environments where signs of past or present life might be preserved. These robots will form a multi-agent ecosystem—an intelligent network that shares data, adapts roles, and makes joint decisions on the fly. Collaboration among them will allow a mission to distribute tasks dynamically, with one robot acting as a scout, another as a carrier of instruments, and another as a specialist for detailed analysis. By combining their unique strengths, the robotic swarm can achieve broader and deeper scientific coverage than a single platform ever could and will rely heavily on distributed AI systems and robust communication architectures. In this paradigm, the rover is no longer a stand-alone machine, but a critical node in a broader web of machines—each performing tasks too dangerous or complex for humans alone [3][6].

While rovers were initially designed for space, their core technologies are finding potential new applications here on Earth. As climate events grow more extreme and unpredictable, rovers may one day be deployed to navigate disaster zones—such as wildfires, floods, and landslides—where conventional vehicles fail. Their rugged mobility systems, autonomous decision-making, and ability to operate in dangerous or unstable terrain make them ideal candidates for next-generation search-and-rescue operations [2][6]. As our ambitions grow—to explore further, adapt faster, and collaborate smarter—so too does the role of the rover, from solitary scout to adaptable agent in a global, and even interplanetary, system.

In this paper, we will explore how the advanced technologies developed for Martian rovers—such as autonomous navigation, AI-driven decision-making, multi-agent coordination, and rugged mobility systems—can be adapted to address real-world challenges on Earth. We will examine specific rover capabilities, including obstacle negotiation, hazard detection, and environmental sensing, and analyze how these can be applied to natural disaster scenarios such as floods, landslides, and wildfires. The discussion will highlight both the technological transfer from space to

Earth and the potential for rovers to enhance efficiency, safety, and reach in disaster response operations, demonstrating the broader societal benefits of extraterrestrial robotics research.

## Rover Design

The rover, as illustrated in Figure 1, is a sophisticated machine engineered for extreme extraterrestrial environments, particularly Mars. Its chassis is typically constructed from lightweight yet durable materials like aluminum or titanium alloys, which allow it to endure significant temperature fluctuations from −140°C to 20°C and resist mechanical stresses caused by impacts or terrain irregularities [8]. The mobility system is based on a rocker-bogie suspension, a passive, springless design that allows each wheel to independently conform to the surface. This enables the rover to climb over obstacles as high as twice its wheel diameter—roughly 25–30 cm in rovers like Spirit and Opportunity—and maintain stability on slopes up to 45°, without tipping [9]. The wheels are fitted with cleats or grousers to maximize traction on loose regolith or sand, and are often made of aluminum with titanium treads. For instance, Curiosity's wheels are 50 cm in diameter and 40 cm wide, while Perseverance uses slightly smaller but more rugged wheels to resist wear [10]. The power system relies on either solar arrays, which generate around 140 watts of electricity during peak daylight (as with Spirit and Opportunity), or a radioisotope thermoelectric generator (RTG)—used in Curiosity and Perseverance—which provides a constant 110 watts of electrical power and heat from plutonium decay [11]. Its electronic systems include navigation cameras, panoramic cameras, spectrometers (such as Alpha Particle X-Ray and Mössbauer), microscopic imagers, and tools like rock abrasion instruments. These allow the rover to analyze mineral composition, texture, and elemental content of Martian rocks and soil with precision [12]. Communication is handled through a UHF antenna for relaying data to Mars orbiters, a low-gain antenna for basic telemetry, and a high-gain antenna for direct Earth contact, enabling data rates of 2–256 kbps depending on the antenna and distance from Earth [13]. Together, these systems allow rovers to act as autonomous laboratories, capable of long-term exploration in one of the harshest environments known to humanity.

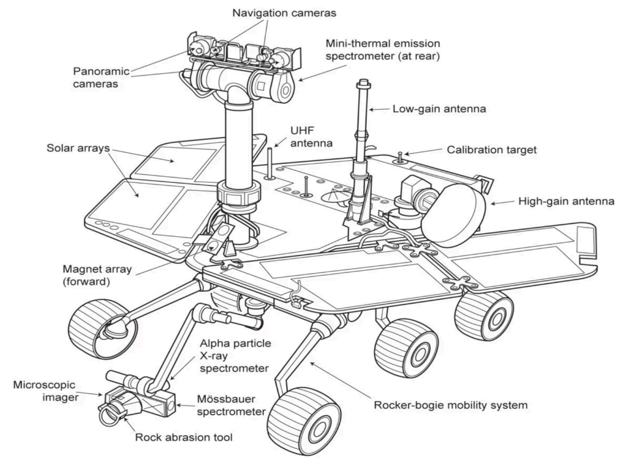


**Figure 1:** Schematic diagram of a typical martian rover
(https://www.planetary.org/space-images/mer-diagram)

## Sketching and 3D-Printing a Rover Prototype

In order to develop a rover prototype, we produced orthographic sketches to define the vehicle's overall proportions and structural layout (Figure 2). These included top, side, front views, and isometric sketches to better visualise the 3D configuration. The key structural components are the central rectangular chassis, a six-wheel rocker-bogie suspension system, a front-mounted robotic arm, solar panels on top, and a mast with cameras and sensors. Approximate dimensions and functional considerations were carefully evaluated during the conceptual phase.

The hand-drawn sketches were imported into Fusion 360 as reference images to guide the CAD process in creating a scaled model relative to the prototype, at approximately a 1:8 ratio. The main chassis was modeled first, extruded from a rectangular base, and fillet tools were used to smooth edges while maintaining proportional accuracy to the prototype. The rocker-bogie suspension system was designed so the linkages matched the prototype's ratio, ensuring wheel contact and stability on uneven terrain. Wheels were built with a tread pattern scaled according to the prototype to preserve grip and realism. A modular robotic arm was constructed with segments and rotational joints, keeping the dimensions proportional to the full-scale design, and a sampling tool was added at the end. The mast with mounted cameras and a solar panel array was positioned on the chassis, scaled to maintain the correct ratio. Each component was assembled, movement tested, and constraints applied to refine the design while ensuring printability at the model's scale.

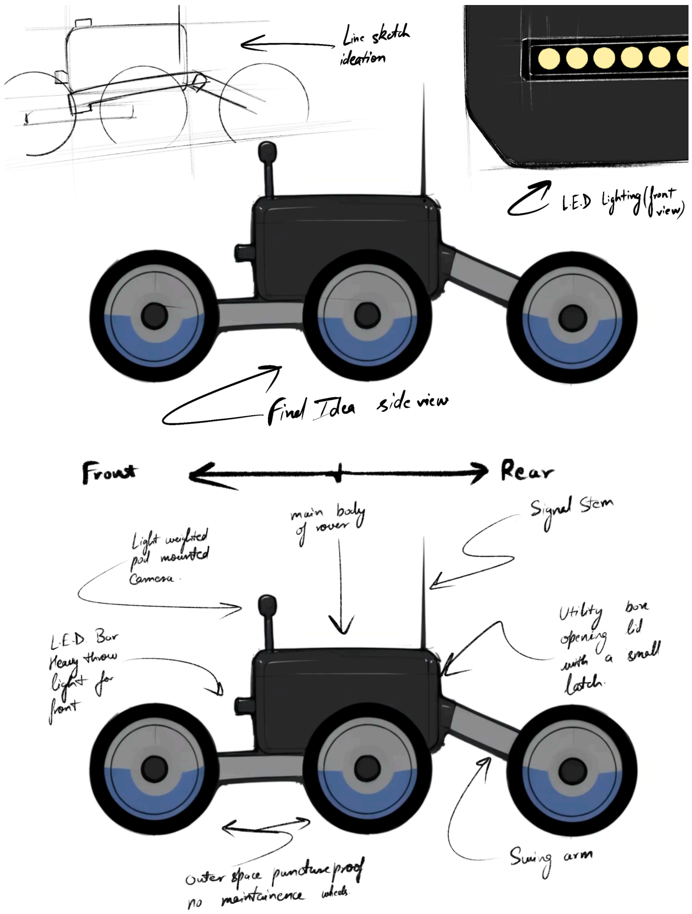


**Figure 2:** Orthographic sketches of the rover prototype

To transform the CAD model into a physical prototype, the design was prepared for 3D printing by exporting each component as STL files. The chassis, suspension arms, and wheels were printed separately to preserve detail and allow for easy assembly. PLA filament was chosen for its balance between strength and printability. Once printed, the parts were cleaned, sanded, and fitted together using screws and adhesive where necessary. The rocker-bogie joints were printed with tolerances that allowed rotational movement without additional machining, enabling the suspension to function as designed.

The rover was enhanced with practical details. The front-mounted light bar was printed as a hollow component to allow small LEDs to be fitted inside, creating functional headlights for low-light testing. The solar panel was represented by a textured 3D-printed plate on the top surface, and could be swapped for a functional photovoltaic sheet in future iterations. Together, these elements gave the prototype both realism and potential utility, helping the model serve as a testbed for mobility, stability, and energy concepts.

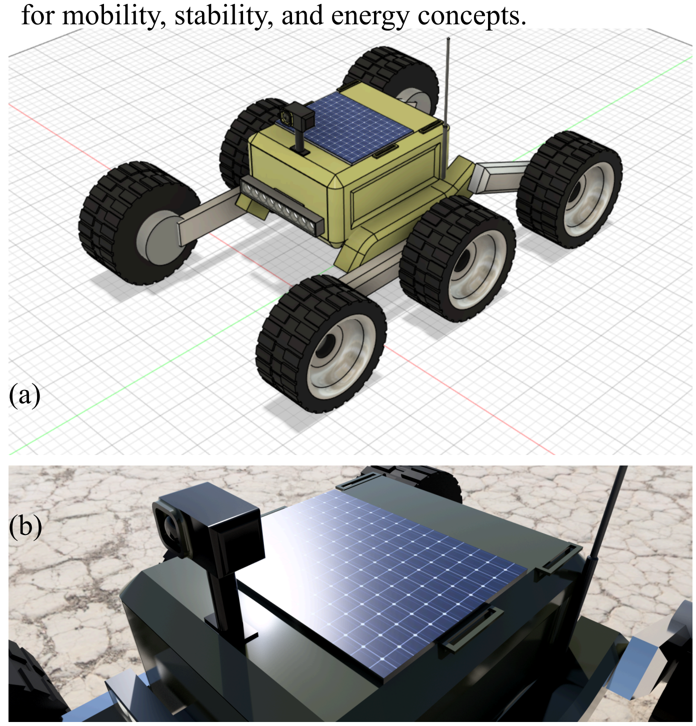


**Figure 3:** (a) Sketch of 3D printed rover with (b) photovoltaic solar panels

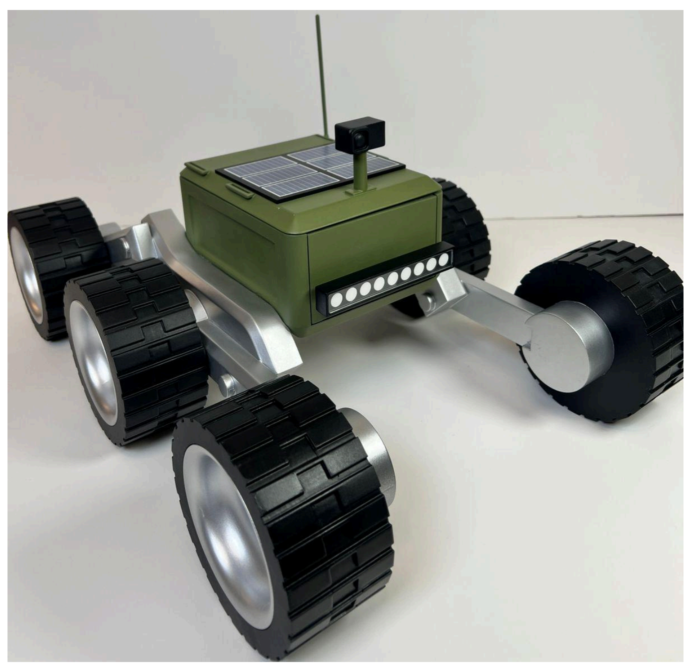

**Figure 4:** 3D-printed rover

| Parameter | Observed Characteristics on Mars | Challenges for Rovers |
|---|---|---|
| Surface Temperature Range | The Martian surface experiences dramatic fluctuations in temperature, ranging from a maximum of around +20°C (68°F) during midday at the equator, to lows of approximately -140°C (-220°F) at night, especially near the poles [41]. These fluctuations can happen over short timescales within a single sol (Martian day). | Such extreme thermal cycling causes mechanical stress on rover components, including expansion and contraction of joints, cracking of composite materials, and degradation of onboard batteries. Electronics must be housed in temperature-controlled compartments, and insulation systems must be designed to withstand both searing day heat and bitter night cold. |
| Atmospheric Pressure | Mars has a thin atmosphere composed mostly of carbon dioxide, with an average surface pressure of only about 6 millibars — just 0.6% of Earth's at sea level. Pressure can vary slightly depending on elevation and season, from around 2 to 12 millibars [41] | The near-vacuum environment creates difficulties in thermal regulation and mechanical sealing. Traditional convection-based cooling systems don't work, so rovers must rely heavily on radiation and conduction for heat dissipation. Pressure-sensitive equipment must be hermetically sealed to prevent malfunction. |
| Dust Storms | Dust storms are frequent on Mars, ranging from small localized events to massive planet-wide storms, such as the one in 2018 that ended the Opportunity mission after nearly 15 years. These storms can block sunlight for weeks and reduce visibility to near zero [42]. | Thick atmospheric dust reduces the efficiency of solar panels by blocking light and coating their surfaces. It can also interfere with optical sensors and spectrometers, clog moving parts, and create static buildup. Rovers must have dust-resistant components and alternate power sources like radioisotope thermoelectric generators (RTGs) to maintain operations. |
| Wind and Dust Transport | While wind speeds on Mars can reach up to 100 km/h (60 mph), the low atmospheric density means they exert only about 1% of the force that similar winds would on Earth [43]. However, they are still capable of lifting fine dust particles and creating massive dust clouds. | Dust particles, often finer than talcum powder and electrostatically charged, can penetrate seals and joints. Over time, this can lead to abrasion of materials, jamming of mechanical parts, and obscuring of cameras and solar panels. Rovers require specially designed dust-tolerant actuators and regular calibration of optical instruments. |
| Ultraviolet and Cosmic Radiation | Mars lacks both a strong magnetic field and a thick atmosphere, meaning its surface is exposed to intense ultraviolet (UV) radiation and high levels of cosmic rays — up to 200 times the dose experienced on Earth's surface [44]. | Prolonged exposure to UV radiation can degrade polymers, optical filters, and circuit boards, while cosmic rays can cause single-event upsets (bit flips) in microprocessors. Radiation shielding, radiation-hardened electronics, and software error-checking are essential for long-term reliability |
| Soil Composition and Abrasiveness | The Martian regolith contains sharp basaltic particles, sulfates, and perchlorates. Its oxidizing nature and fine granularity pose significant hazards for surface interaction. In-situ analysis by Curiosity has confirmed the presence of reactive chemicals [44]. | The abrasiveness of Martian soil leads to wear and tear on wheels and drilling equipment. For example, Curiosity experienced early wheel damage due to repeated traversal of sharp rocks. Engineers must use hardened materials, treads, and advanced path-planning algorithms to mitigate erosion and maintain traction. |
| Terrain Diversity | The Martian landscape includes a wide range of features: volcanic plains, dune fields, rocky outcrops, steep slopes (up to 45°), and deep craters. Loose regolith, dust-covered slopes, and jagged rocks present unpredictable hazards [45]. | Rovers must be able to navigate uneven terrain without toppling or becoming immobilized. This requires advanced suspension systems such as the rocker-bogie design, real-time hazard detection, and autonomous navigation software capable of responding to sudden changes in terrain conditions. |

**Table 1**: Martian characteristics and subsequent rover design challenges

### Martian Weather

Rovers were specifically designed for Mars, a planet with extreme and unpredictable environmental conditions. To understand the challenges these machines face, it's important to examine the Martian weather and the conditions under which they typically operate. Temperatures on Mars can vary dramatically, ranging from about 20°C (68°F) during the day at the equator to as low as -140°C (-220°F) at night near the poles [14]. The surface pressure is extremely low, fluctuating between 2 and 12 millibars—roughly 1% of Earth's atmospheric pressure—making it a harsh environment for both electronics and mechanical systems [15]. One of the most significant challenges comes from frequent and sometimes planet-wide dust storms, which can reduce visibility and severely impact the performance of solar-powered equipment [16]. In addition, Martian winds are capable of lifting fine dust particles into the atmosphere, contributing to global dust coverage and further fueling storm formation [17]. These factors combined make Mars a uniquely demanding setting for rover operations. Martian characteristics and subsequent challenges for rover design are summarized in Table 1.

### Terrestrial Accessibility Challenges

Our aim is to identify how rovers—originally developed for extraterrestrial exploration—can be applied to terrestrial accessibility challenges, particularly in regions affected by extreme natural events and difficult geography. To begin, it's important to review what these challenges look like and the conditions they present. Natural disasters such as wildfires can obstruct ground routes and degrade air quality, directly impacting human health and damaging sensitive equipment [18]. Floods and landslides are responsible for destroying infrastructure and leaving entire regions inaccessible, with the World Bank reporting that floods alone affect more than 250 million people globally each year [19]. Snowstorms and avalanches limit visibility and mobility, posing serious risks to both manned and unmanned missions in mountainous or polar regions [20]. Hurricanes, with winds exceeding 150 km/h, bring heavy rainfall that can disrupt operations and destroy communication and monitoring systems [21]. In terms of geography, deserts pose challenges due to loose sand and extreme heat, which affect traction and stress vehicle cooling systems [22]. Mountainous terrain complicates navigation due to steep gradients and uneven surfaces, often requiring specialized mobility designs for stability [23]. Snowy areas reduce battery efficiency, stiffen mechanical parts, and impair sensor accuracy [24]. Jungles, with their dense foliage and persistent high humidity, interfere with electronic equipment and make signal propagation difficult [25]. Together, these conditions demonstrate the potential value of adaptive, rugged rover technology in addressing real-world accessibility issues, particularly in regions where traditional transport systems fail.

| Disaster Type | Total Deaths | Total Affected | Total Damage (billion US$) |
|---|---|---|---|
| Drought | 24,170 | 1,695,098,024 | 208.20 |
| Wildfire | 2,294 | 14,977,496 | 169.93 |
| Volcanic activity | 1,744 | 6,633,758 | 3.47 |
| Flood | 136,983 | 1,857,440,620 | 784.37 |
| Storm | 223,388 | 876,775,104 | 1,849.22 |
| Earthquake | 794,927 | 154,902,363 | 691.49 |
| Extreme Temperature | 289,981 | 133,910,173 | 50.87 |
| Mass movement (wet) | 21,973 | 8,817,248 | 5.46 |
| Explosion (Industrial) | 14,261 | 498,399 | 36.64 |
| Fire (Miscellaneous) | 10,938 | 672,158 | 1.79 |

**Table 2**: Most significant disasters in terms of total deaths, total population affected and total damage as of 2025-06-02. Blue shaded cells indicate maximum value for disaster metrics.

### Dataset

We used the EM-DAT (Emergency Events Database) [30], a comprehensive global database maintained by the Centre for Research on the Epidemiology of Disasters (CRED). It systematically compiles data on the occurrence and effects of over 24,000 mass disasters worldwide from 1900 to the present. The dataset includes natural disasters—such as floods, earthquakes, storms, droughts, and epidemics—as well as technological disasters. For each event, EM-DAT records standardized information

| | Opportunities | Limitations | Lifecycle | Cost |
|---|---|---|---|---|
| Helicopters [46] | -Fast deployment in emergencies<br>-Can reach remote, high-altitude areas<br>-Ideal for aerial surveillance and evacuation | -Require skilled pilots-Weather-sensitive (wind, rain, low visibility)<br>-High operational risk<br>-Expensive maintenance | Medium (5,000–10,000 hours per unit; high wear) | Very high – Acquisition ranges from $2M–$20M; operating costs $1,000–$3,000+ per hour; high maintenance and pilot training required. |
| Drones (UAVs) [47] | -Versatile for search-and-rescue, mapping, and deliveries<br>-Can access tight or dangerous zones<br>-Lower risk to human life | -Vulnerable to extreme weather (wind, rain, dust)<br>-Limited payload and battery life<br>-Regulatory restrictions in populated areas | Short (typically <1,000 flight hours; battery-dependent) | Moderate to high – Entry-level drones cost $1K–$10K; industrial drones $50K–$250K+; low operation costs but frequent part replacement and regulatory costs. |
| Rovers (UGVs) | -Excellent for ground-based operations- High terrain adaptability (mud, rubble, snow)<br>-Operate in wind or low visibility without risk to life | -Slower than aerial tech-Limited in very steep or heavily vegetated terrain<br>-Still requires robust navigation AI | Long (depends on hardware; designed for rugged use) | High initial; low upkeep – Units cost $50K–$500K+ depending on hardware and autonomy; minimal fuel/operator cost; durable for long-term use. |
| ATVs (All-Terrain Vehicles) | -Human-operated and cargo-capable<br>-Widely used in rural or off-road rescue<br>-Can carry multiple passengers or heavy payloads | -Requires access roads or open terrain<br>-Cannot operate in landslides, floods, or unstable ground<br>-Risk to operator in dangerous zones | Medium (vehicle lifespan ~5–10 years with heavy use) | Moderate to high – Purchase cost $10K–$50K+; ongoing fuel and maintenance required; repair costs rise with heavy terrain use. |
| Airships Blimps | -High payload capacity- Long endurance flight times<br>-Low fuel consumption<br>-Can hover over a target for extended periods | -Vulnerable to high winds-Large size limits where they can land<br>-Very slow response time | Long (durable but limited by weather constraints) | Very high – Build and deployment can exceed $10M; slow speed reduces cost efficiency; ground handling and storage are costly. |
| Tunnel Boring Drones | -Can create temporary access routes under rubble or terrain<br>-Useful in landslides or collapsed infrastructure scenarios | -Extremely new and experimental<br>-Very slow speed<br>-High energy demand<br>-Not suitable for all ground types | Experimental (project-based deployment) | Extremely high – Still experimental; development and deployment costs often exceed several million; not yet commercially scalable. |

**Table 3**: Current technological solutions advantages and disadvantages

including the date, location, disaster type, number of people killed or affected, estimated economic losses, and key contextual variables. By analyzing the dataset, we were able to derive the ten most significant disaster types in terms of total deaths, total population affected and total damage as shown in Table 2.

### Current Technological Solutions

As shown in Table 3, current technological solutions to accessibility in challenging environments include helicopters and drones, both of which have proven useful significant limitations. Helicopters are commonly used but come with for firefighting, terrain scouting, and rescue missions in areas that are difficult to reach by land [26]. However, they require clear airspace, skilled pilots, and substantial maintenance, and are often grounded in severe weather conditions such as high winds or heavy rain. Drones have become increasingly popular for surveillance, search-and-rescue operations, and emergency deliveries in disaster zones [27]. While they offer flexibility and can access tight or hazardous areas, their performance is often hindered by unpredictable weather. On Earth, extreme conditions such as high winds, moisture, dust, and sudden temperature swings reduce the effectiveness and reliability of current drone technology [29]. These limitations highlight the need for more adaptive AI, autonomous control systems, and robust hardware that can endure environmental stressors without constant human intervention. This is where rover technology could provide a complementary solution. Unlike aerial vehicles, rovers are ground-based and can maintain stability in high winds, operate for extended periods with fewer safety concerns, and be equipped with advanced sensors for terrain classification and navigation. Their ability to traverse difficult terrains—mud, sand, rubble, or snow—while carrying equipment or supplies makes them ideal for supporting emergency responses and accessibility efforts in areas where helicopters and drones fall short. By integrating rover systems with existing aerial solutions, a multi-modal approach could offer a more resilient and comprehensive response to Earth's accessibility challenges.

## Future Directions

Recent advancements in multi-agent systems and autonomous robotics have paved the way for AI-driven cooperation between rovers in complex terrains. Projects like CISRU demonstrate how modular software frameworks can enable real-time interaction between rovers and astronauts through autonomous planning and perception modules [31]. A schematic representation of this interaction would show astronauts providing mission-level goals that feed into CISRU's modular framework, which includes autonomous planning, perception, and task allocation. Sensor inputs such as cameras, LiDAR, and spectrometers connect into the perception module, while outputs guide rover control systems for navigation, hazard detection, and scientific operations. Multiple rovers are linked through peer-to-peer data sharing, forming a decentralized network that allows them to collaborate, distribute tasks, and adapt to environmental conditions in real time. This structure highlights two-way communication between astronauts and rovers, distributed decision-making among agents, and the ability of each rover to function as an autonomous node while contributing to the larger mission. Inspired by drone swarm research, vision-based decentralized control using convolutional and graph neural networks allows ground vehicles to make collective decisions without centralized input [32][33]. Communication remains a challenge, especially in GPS-denied or signal-obstructed environments, but recent studies integrating LoRa mesh networks with ROS-based systems show promise in maintaining robust inter-agent connectivity [34]. Additionally, swarm intelligence frameworks originally developed for drone formations—like DFA$^{3+}$—offer scalable, fault-tolerant coordination that could be adapted for cooperative rover convoys or search formations [35]. Future directions will likely focus on hybrid frameworks combining sensor fusion, resilient hardware, and adaptive swarm logic, allowing rovers to self-organize, collaborate on mission goals, and respond dynamically to environmental challenges.

The University Rover Challenge (URC), organized annually by The Mars Society, is a leading international robotics competition that challenges university teams to design Mars-capable rovers for simulated missions in the Utah desert. The competition emphasizes real-world applications by assessing rover performance across tasks like autonomous navigation, terrain traversal, scientific analysis, and equipment delivery. Recent URC iterations have focused heavily on improvements in autonomy, modularity, and terrain adaptability, encouraging teams to integrate AI systems that can classify terrain, perform autonomous sampling, and aid in mission planning without direct human control. For instance, the Cal Poly SLO team developed a modular chassis with server–client-based control to enhance flexibility and allow future integration of autonomy features [36]. The RUDRA team from SRM University introduced an active adaptive suspension system controlled by AI algorithms for chassis stabilization on rugged terrain [37], while BRAC University's Mongol Tori rover demonstrated autonomous scientific capabilities such as soil analysis and weather detection, blending tele-operation with intelligent decision-making [38]. These student-led innovations are not only pushing the boundaries of educational robotics but also bridging the gap between academic research and field-ready rover prototypes, with many teams adopting techniques like machine learning, edge computing, and real-time control architectures that mirror trends in cutting-edge aerospace and terrestrial robotics.

Rovers were first developed for Mars missions, built to survive extreme temperatures, rough terrain, and restricted communication with Earth. Their ability to operate autonomously, adapt to unpredictable conditions, and maintain reliability under stress makes them valuable beyond space exploration. The same design principles can be applied to real-world challenges such as disaster response, supply delivery to isolated communities, environmental monitoring, and operations in hazardous areas like mines or nuclear zones. With advances in swarm intelligence, AI-driven autonomy, and modular design, rover technology is moving from planetary survival to practical terrestrial applications. These systems show how innovations born for space can evolve into tools that address pressing human needs on Earth.

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