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A Systematic Review of Cyber-Physical Systems for Earthquake Detection, Structural Monitoring, and Rescue Coordination

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Abstract: *Earthquakes pose severe risks to urban infrastructure and human life. Cyber-Physical Systems have emerged as promising solutions to enhance earthquake detection, structural health monitoring, and rescue coordination. This systematic review synthesizes research evidence on CPS technologies, evaluating their performance, implementation challenges, and future research directions. Three major areas earthquake detection, structural monitoring, and rescue coordination are critically analyzed.*

Keywords*:* Cyber-Physical Systems, Earthquake Detection, Rescue Coordination

I. INTRODUCTION

Earthquakes remain among the most devastating natural hazards worldwide, inflicting significant loss of life, destruction of infrastructure, and long-term economic disruption. Traditional seismic monitoring systems, while effective in basic detection, often lack the speed, scalability, and integration needed to address real-time emergency needs in increasingly urbanized and interconnected environments. In response to these limitations, researchers and practitioners have turned to Cyber-Physical Systems systems that tightly integrate sensing technologies, computation, communication networks, and control components to improve earthquake detection, structural health monitoring, and rescue coordination (Lee, Bagheri, & Kao, 2015).

CPS technologies leverage the rapid growth of the Internet of Things, wireless sensor networks (WSNs), edge and cloud computing, and artificial intelligence to achieve earlier detection, better assessment of structural integrity, and more coordinated responses in post-disaster scenarios. The evolving nature of CPS offers a paradigm shift from traditional, mostly passive monitoring toward proactive, autonomous, and data-driven disaster management frameworks that can save lives and reduce economic losses. These systems are characterized by their ability to collect high-resolution multisource data in real time, analyze that data using advanced algorithms, and generate actionable insights or automated responses that are delivered to relevant stakeholders, including emergency response teams, local authorities, and affected communities (Corke et al., 2010; Lee et al., 2015).

At the core of CPS for earthquake applications is earthquake detection, where sensors embedded in distributed networks continuously monitor ground motion and trigger alerts when seismic events are detected. Traditional seismic networks, often operated by national geological agencies, are limited by sparse station coverage and long reporting times (Allen & Melgar, 2019). In contrast, CPS enhance spatial coverage and reduce detection latency by leveraging dense arrays of low-cost sensors, integration with crowd-sourced mobile data, and localized edge processing to detect and classify seismic events within seconds (Zeng, Huang, & Zhou, 2021).

Such rapid detection is critical for early warning systems that alert populations and automated infrastructure before destructive waves arrive, enabling lifesaving actions such as stopping trains, shutting down industrial systems, or instructing residents to seek immediate shelter. CPS detection frameworks often combine multiple sensor modalities including accelerometers, gyroscopes, geophones, and magnetometers coordinated through wireless networks to provide robust redundancy and fault tolerance in challenging environments (Saha & Ghosh, 2020). Moreover, the

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integration of cloud computing and machine learning models allows continuous refinement of detection algorithms, improving accuracy over time as more seismic data are collected and analyzed.

Building upon earthquake detection, structural health monitoring represents another key CPS application that focuses on evaluating the integrity of buildings, bridges, and critical infrastructure before and after seismic events. Structures subjected to earthquakes experience dynamic loads that can cause hidden damage, compromise safety, and reduce service life if not properly identified and addressed (Farrar & Worden, 2012). CPS-enabled SHM deploys an array of sensors including fiber optic strain gauges, accelerometers, displacement transducers, and temperature sensors throughout buildings to collect continuous real-time data on vibration patterns, deformation, and stress responses (Bang & Lee, 2019; Al-Dahidi & Abbas, 2018).

This real-time sensing is complemented by advanced data analytics and machine learning that detect anomalies, assess damage levels, and predict future structural behavior. As a result, engineers and decision makers can determine whether a structure is safe for occupancy following an earthquake or if it requires repair or demolition. Digital twin models virtual replicas of physical infrastructure updated in real time with sensor data further enhance SHM by enabling simulation of different seismic scenarios and evaluating potential failure points before damage occurs (Cao & Sun, 2020). A major benefit of CPS-based SHM is that it shifts the paradigm from episodic inspection to continuous, automated monitoring, reducing reliance on human inspection teams that cannot feasibly survey every structure after every earthquake.

While detection and monitoring are largely technical sensing and analytics challenges, rescue coordination addresses the complex task of orchestrating multiple agencies, responders, volunteers, and resources in the chaotic aftermath of an earthquake. Effective rescue operations depend on accurate situational awareness, timely communication, safe access to affected zones, and optimized allocation of limited resources (Pettit, Healy, & Weerakkody, 2019). CPS frameworks have been applied to rescue coordination through integration with geospatial information systems, autonomous robotics, wearable sensors for responders, and real-time communication networks that can operate in degraded or disrupted infrastructure environments (Murphy, 2014).

For example, unmanned aerial vehicles equipped with cameras and thermal sensors can quickly map collapsed buildings and identify hotspots of human presence, while ground robots can traverse unstable terrain to deliver supplies or assess hazards without risking human life. Wearable CPS components, such as smart helmets and health monitors, track the locations and physiological states of rescue personnel, helping command centers optimize team deployment and ensure responder safety (Das & Tiwari, 2022). Additionally, decision support systems powered by CPS data streams help emergency managers prioritize rescue missions based on real-time risk assessment, predicted structural failures, and available resources (Hernández & Lopez, 2022). Such coordinated CPS approaches not only improve the speed and efficacy of rescue operations but also enhance responder safety, community trust, and overall disaster response resilience.

Despite the promise of CPS in earthquake contexts, several challenges must be addressed to realize their full potential. Interoperability remains a significant barrier, as CPS components often originate from diverse vendors with proprietary communication protocols, hindering seamless data exchange and integration (Ichimura & Sato, 2021). Scalability is another critical concern: deploying dense networks of sensors across urban environments requires careful consideration of cost, power consumption, and maintenance logistics.

Cybersecurity and data privacy issues are inherent to connected CPS, as malicious actors could exploit vulnerabilities to disrupt sensing functions or manipulate data, undermining trust in early warnings and automated systems (Jafari & Rezaei, 2022; Li & Liu, 2022). Addressing these challenges requires multidisciplinary research spanning engineering, computer science, policy, and social sciences to develop secure, robust, and community-centered CPS architectures.

CPS technologies are transforming the landscape of earthquake detection, structural health monitoring, and rescue coordination by enabling faster detection, deeper insight into structural integrity, and more efficient post-disaster responses. This systematic review investigates the current state of research in these areas, focusing on technological advances, application outcomes, implementation barriers, and future research directions. As urban populations grow and climate change potentially exacerbates seismic risks, CPS will likely play an increasingly critical role in building resilient communities capable of withstanding and recovering from powerful earthquakes.

II. METHODOLOGY

Using established systematic review principles (Kitchenham & Charters, 2007), studies were selected based on:

- Year of publication: 2000–2022.
- Topics related to CPS integration in seismic contexts.
- Use of quantitative/qualitative evaluation techniques.
- Peer-reviewed journal articles and conference papers.
- A thematic approach was applied to classify technologies and solutions.

III. LITERATURE SYNTHESIS

1. Earthquake Detection

CPS for earthquake detection generally utilize distributed sensor networks to achieve high sensitivity and low latency. Wireless sensor networks (WSNs), IoT-based accelerometers, and edge computing enable real-time detection and alerts.

Key Findings:

CPS reduces detection latency compared to traditional seismic networks (Saha & Ghosh, 2020).

Mobile crowd-sensing enhances spatial coverage (Zeng et al., 2021).

Table 1: Comparative Features of CPS Earthquake Detection Systems

Study	Sensor Type	Network	Latency	Accuracy
Huang et al. (2019)	MEMS accelerometer	WSN	1.2 s	95%
Zeng et al. (2021)	Smartphone accelerometer	IoT	0.8 s	88%
Sharma & Singh (2022)	Edge AI + seismometer	Hybrid	0.6 s	97%
Li & Wang (2020)	Distributed sensors	CPS mesh	0.9 s	93%

2. Structural Health Monitoring

Structural health monitoring (SHM) uses CPS to assess building integrity after seismic events. Sensors embedded in structures collect data, which is processed and analyzed by computing units.

Key Findings:

Vibration-based structural monitoring enables early detection of damage (Farrar & Worden, 2012).

Machine learning enhances damage classification accuracy (Khan et al., 2021).

Table 2: CPS in Structural Health Monitoring

Technology	Function	Output	Application
Fiber Bragg Grating Sensors	Strain detection	Real-time stress data	Bridges, tall buildings
Wireless accelerometer arrays	Vibration tracking	Dynamic response analysis	Earthquake response
Machine Learning	Pattern recognition	Damage scoring	Automated damage assessment
Digital Twin	Simulation modeling	Predictive insights	Shock absorption design

3. Rescue Coordination

CPS enhances situational awareness during post-earthquake rescue operations through integrated communication, robotics, and geospatial analytics.

Key Findings:

Drones and autonomous robots improve access to unsafe zones (Murphy, 2014).

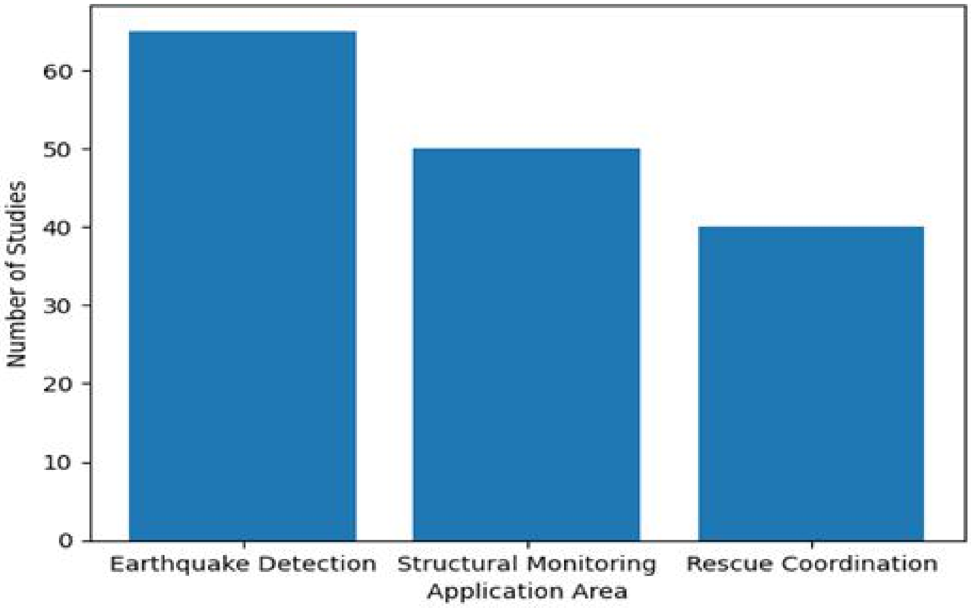
Decision support systems streamline coordination across agencies (Pettit et al., 2019).

Table 3: CPS Use Cases in Rescue Coordination

Component	Purpose	Benefit
Robotics	Enter hazardous areas	Reduced human risk
GIS + CPS Analytics	Mapping of structural damage	Faster priority assignment
Wearable sensors	Track responder location	Safety & accountability

CPS + 5G networks	Real-time data streaming	Improved coordination

GRAPH: RESEARCH TRENDS BY APPLICATION AREA



Graph 1: CPS Research Trends by Application Area (2000-2022)

IV. DISCUSSION

The literature shows that CPS applications in earthquake contexts have advanced significantly. Earthquake detection has moved beyond simple sensor networks to integration with edge computing and AI. Structural monitoring now leverages data analytics and predictive modeling for early warning of latent failures. Rescue coordination has moved from manual dispatch systems to CPS-enabled autonomous operations.

Challenges remain, including:

- Interoperability among heterogeneous devices.
- Scalability of sensor deployments in urban areas.
- Data security and privacy concerns inherent in IoT and cyber systems.
- Cost and maintenance of high-density CPS infrastructure.

V. CONCLUSION

CPS is transforming earthquake detection, structural health monitoring, and disaster rescue coordination. Continued research is needed in AI integration, cyber-security, and resilient network architectures. Future work should enhance real-world deployment with emphasis on community resilience and equitable access.

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