
Drones, Swarm Intelligence, and the Future of Cyber-Physical Societies
Digital Humanism Lecture
Vienna University of Technology
AUTONOMOUS AIRSPACE
U-SPACE INTEGRATED
AI & DISTRIBUTED INTELLIGENCE
· SWARMS
· EDGE AI
· DECISION SYSTEMS
RESPONSIBLE GOVERNANCE FOR HUMAN-CENTRIC AIRSPACE
• Human-Centric Governance
• Ethical AI & Human Oversight
• Accountability & Liability
• Public Interest & Safety
• Transparency & Trust
• Sustainability
REAL-TIME DATA
SENSORS · AI · ANALYTICS
CONNECTIVITY
5G / 6G
IoT
SATELLITE
DIGITAL TWIN
MODELING
SIMULATION
PREDICTION
The sky is becoming programmable.
CONNECTIVITY 5G / 6G
EDGE & CLOUD COMPUTING
DATA INFRASTRUCTURE
CYBERSECURITY & TRUST
HUMAN-CENTRIC GOVERNANCE

Summary

- Overview of drone technologies
- Drone applications and dual use
- Overview of drone market
- Where the EU stands with drone regulation
- Outlook on future ‘drone society’

Why drones matter

AI IN PHYSICAL SPACE

- Real-time sensing
- Autonomous decision-making

CONVERGENCE OF TECHNOLOGIES

- AI
- 5G / 6G
- Edge / Cloud
- IoT
- Robotics

CRITICAL INFRASTRUCTURE

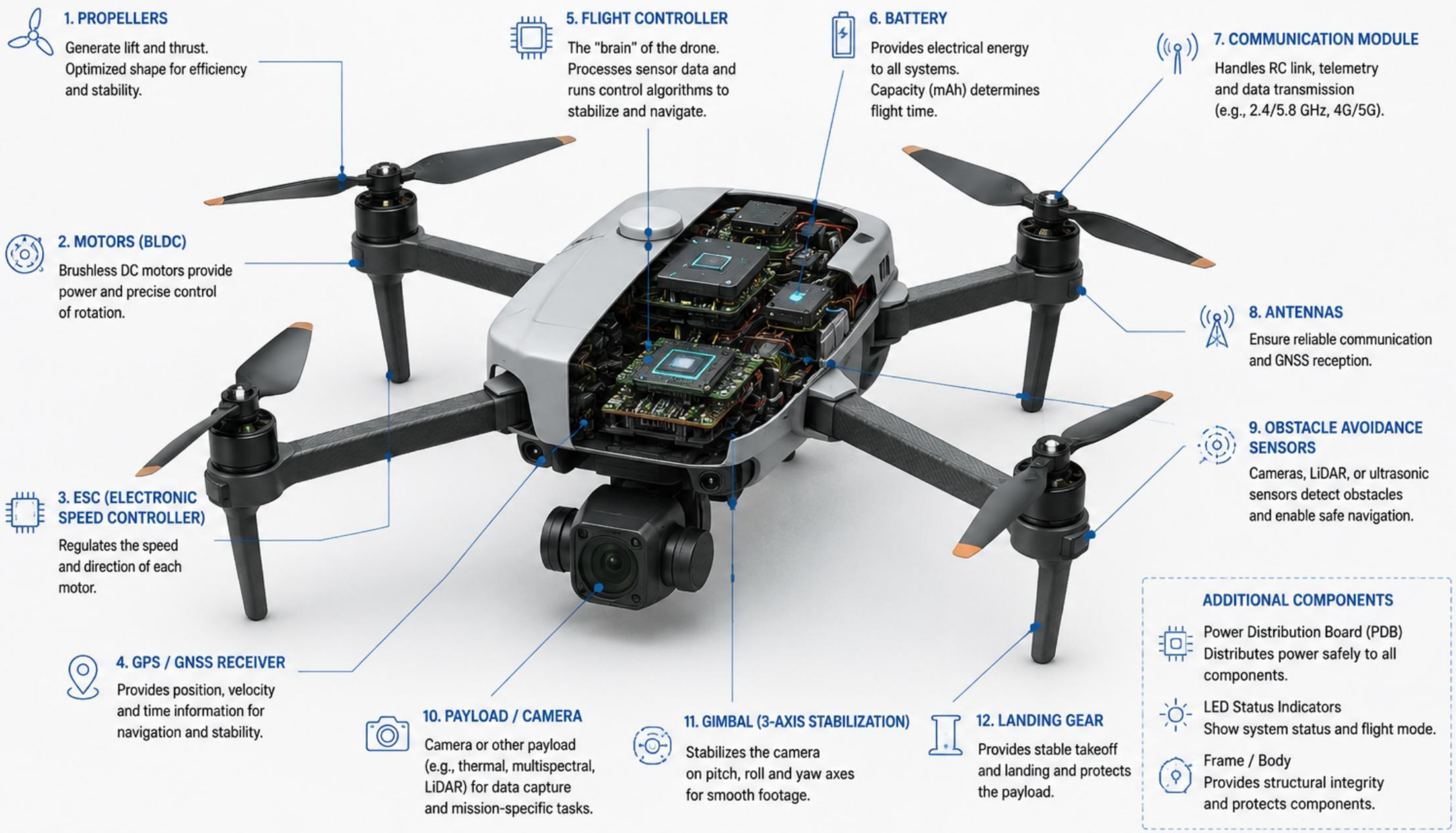
- Logistics
- Emergency response
- Humanitarian aid
- Agriculture
- Energy
- Security
- Defense
- Health
- …

SOCIETAL TRANSFORMATION

- Privacy
- Governance
- Human agency
- New dependencies

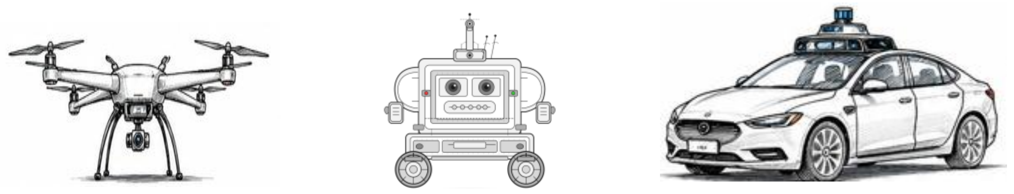
Drones are among the first large-scale cyber-physical systems operating directly in public space

Anatomy of drones: key components and functions



Autonomous system architecture — on-board stack & off-board ecosystem

On-board



Drone (air) · Robot (ground) · Autonomous car (land)

5 DATA
Real-time environment mapping, situational awareness & decision-making

- 3D mapping — airspace / road environment
- Object detection & tracking
- Route/path planning
- Decision — navigate, avoid, yield, turn

4 CONTROL
Autonomous behaviour & vehicle/flight control

- Flight / driving control algorithms
- Trajectory & path tracking
- Stability / speed & steering control
- Autonomous mission / behaviour planning

3 COMPUTE
Onboard AI processing & edge computing

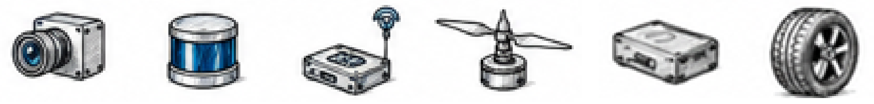
- Onboard flight / vehicle computer
- Sensor fusion & state estimation / localisation
- AI inference — object detection & tracking
- Edge processing for low latency

2 CONNECTIVITY
Data, commands & coordination

- 5G / LTE · Satellite (backup)
- U-space / UTM (drones) · V2X (cars)
- Remote ID & command link
- Cloud & traffic systems

1 HARDWARE
Physical platform, sensors & actuation

- Cameras · LiDAR · Radar · IMU / GNSS
- Batteries & power management
- Frame / chassis & drive system
- Actuators — motors, rotors, steering, brake



Off-board

Satellites
GNSS · Earth observation · connectivity backup

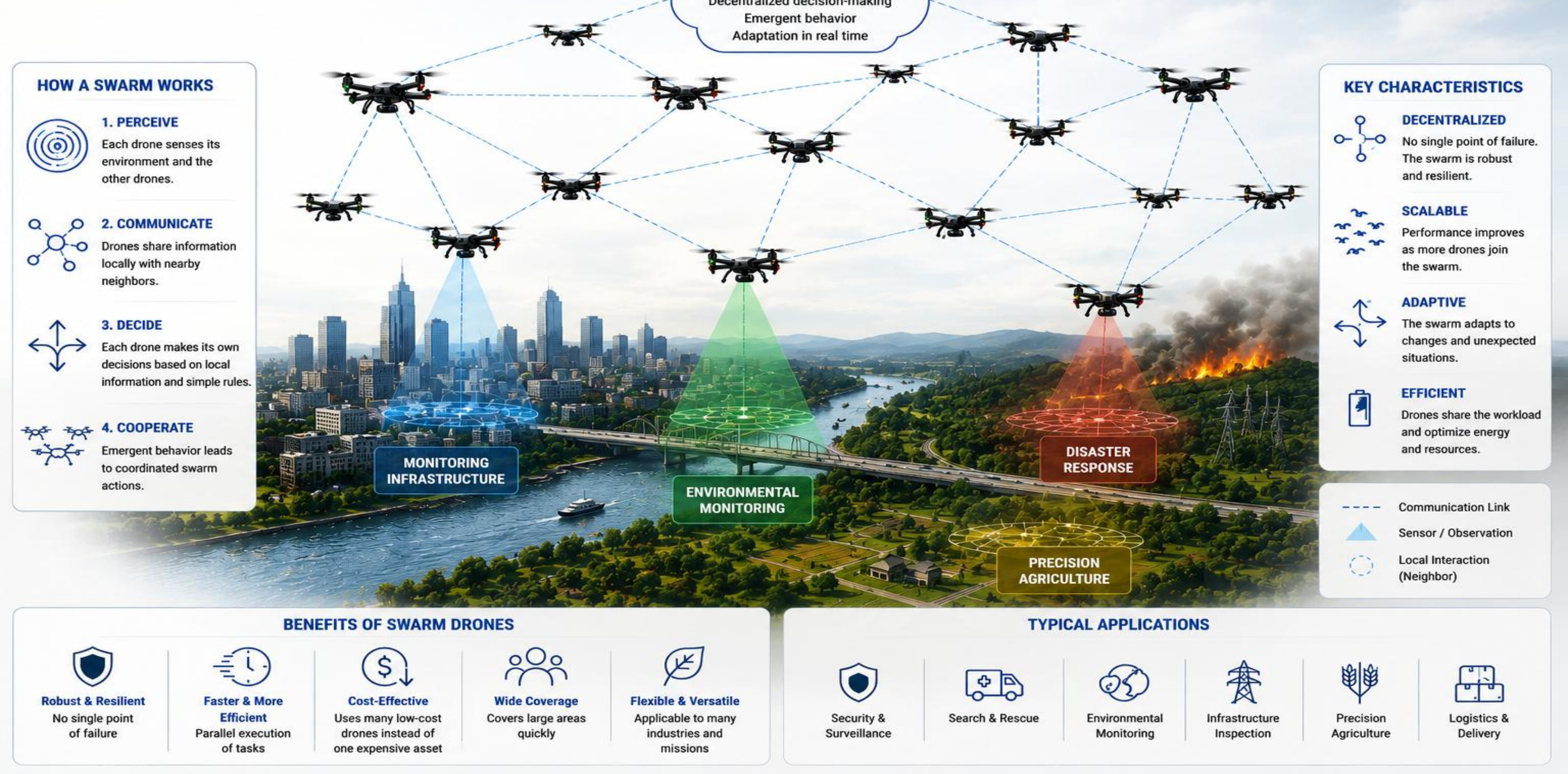
Edge nodes
MEC servers · roadside units · U-space

5G / 6G network
Base stations · antennas · private 5G

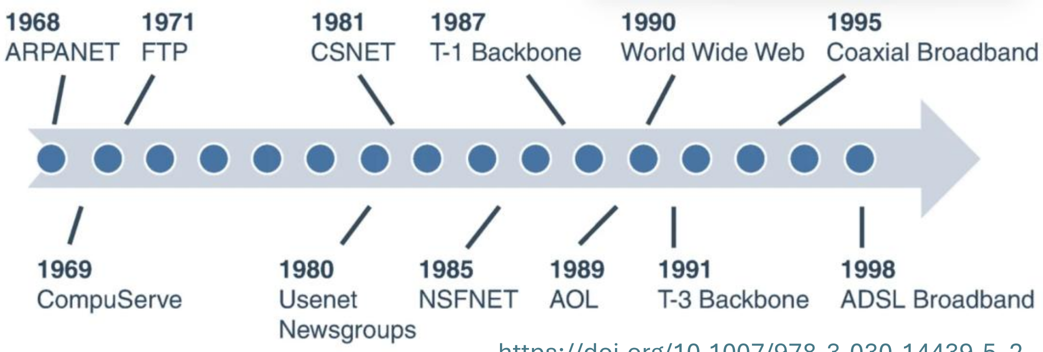
Cloud infrastructure
Orchestration · data lakes · digital twins

AI Factories / Giga-factories
Model training · simulation · fleet/swarm learning

Drone Swarm: many drones, one intelligence



Dual use: (un)known pattern in IT development?



Timeline of Internet milestones

https://doi.org/10.1007/978-3-030-14439-5_2

Civilian adaptation of capabilities that defence investment has accelerated:

- secure communications
- resilient navigation
- better thermal and multisensor payloads
- weather-hardening
- modular open architectures
- autonomous logistics
- interoperable command-and-control

European Defence Agency

UNMANNED AIRCRAFT SYSTEMS

Unmanned Aircraft Systems (UAS) technology has been rapidly advancing in recent years, having become increasingly popular in both military and civilian applications. UAS can be used for a variety of applications such as intelligence, surveillance, and reconnaissance (ISR), search and rescue (SAR) operations, disaster response, monitoring natural disasters and border patrol.

EDA funding of UAS: 11 ongoing projects, EUR 15 million

Drones for European Humanitarian Assistance and Civil Preparedness

A **public-interest infrastructure** in the sky, on the ground, and on the water.

Drones as **“first on scene”** use cases reaching an emergency area before responders, collect early information and report, bring aid equipment, and can warn people about imminent danger or support remote messaging before teams arrive.

Drones for common good

When governed properly, drones can **reduce time to action, reduce risk to responders**, improve **access for remote communities**, and **maintain a thread of communication** when the rest of the system is failing.

Drones are **delivering blood**, **vaccines**, **diagnostic samples**, **defibrillators**, **nutrition supplies**, **network infrastructure for communication**. They **collect information** for maps and emergency situational awareness.

COLLARIS Network

COLLARIS Network: Collaborative network on unmanned Aerial Systems.

Multi-hazard

ASPRID

ResponDrone

AiRMOUR

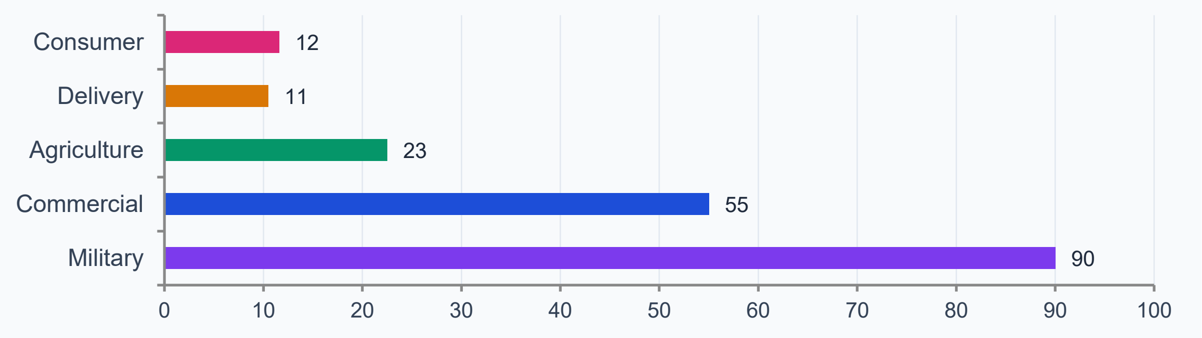
FASTER

SYNERGISE

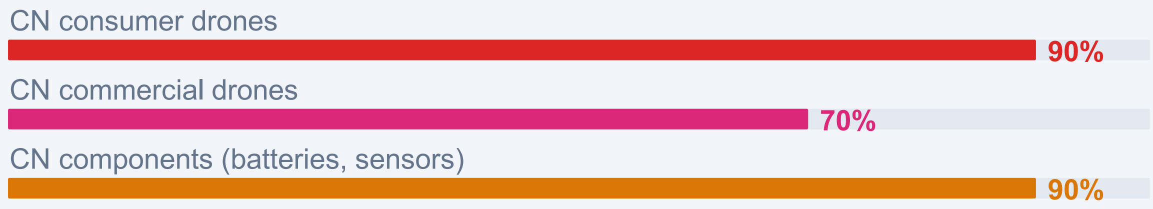
GLOBAL DRONE MARKET — SIZE, SEGMENTS & SUPPLY

~€73B	~24%	~€164B	2.8M	~70%
Global market 2024	**EU share of global**	**Forecast 2030**	**Commercial units 2024**	**CN global share of supply**
total incl. military		CAGR ~14%	connected drones	consumer & commercial

Market Segments (2030 projection, €B)



SUPPLY: CHINA'S STRUCTURAL DOMINANCE



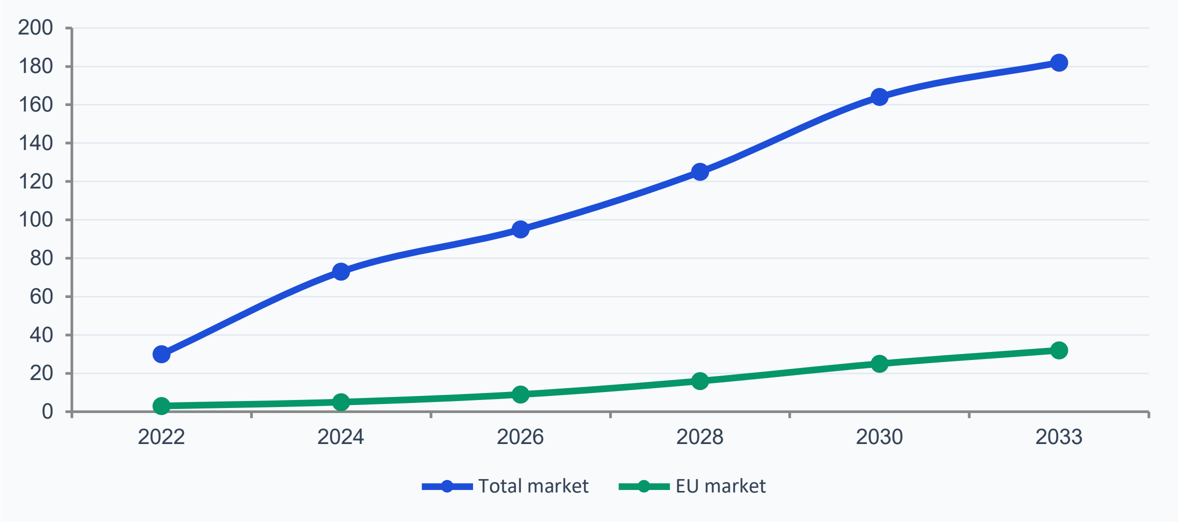
Key demand drivers

- **Defence & ISR**
- **Precision Agriculture**
- **Infrastructure Inspection**
- **Logistics & Delivery**
- **BVLOS & Connectivity**

Sources: Grand View Research, MarketsandMarkets, Technavio, ResearchAndMarkets (2024–2025)

Future Perspectives - Trends, Risks & Opportunities 2030+

Global market trajectory ($€)



Key trends shaping demand

Autonomy & AI

Optionally autonomous systems projected majority of new EU UAV purchases by 2028. Sensor-to-shooter loops shrunk from 20 min → <3 min.

BVLOS & U-space

Regulatory corridors opening. Delivery drones growing from €0.5B (2022) to €10B+ by 2030.

Defence surge

EU military drone market: €4.1B (2024) → €25B (2033). Ukraine conflict accelerating design cycles to weeks.

Counter-drone market

C-UAS growing at 25% CAGR to €20.3B by 2030. EU allocated €30M for joint counter-drone buys 2026–27.

▲ OPPORTUNITY

- EU sovereign supply chain investment surge
- EASA framework enabling cross-border commercial operations
- Defence-civil dual-use technology synergies
- Delivery & inspection BVLOS corridors opening

▼ RISK

- Structural cost/scale gap vs. Chinese manufacturers
- Critical component dependency (batteries, chips)
- US-style CN ban could disrupt EU operators
- Regulatory fragmentation across member states

◆ WATCH

- China supply chain restrictions (Ukraine precedent)
- Swarm & autonomous weaponization governance
- Satellite bandwidth constraints for BVLOS scale
- Privacy & surveillance regulation tightening

Sources: EU Perspectives, EUISS, MarketsandMarkets, Grand View Research, European Commission, DroneLife (2025–2026)

EU policies and legislation on drones: a complex landscape

FOUNDATION — AVIATION SAFETY FRAMEWORK

- Reg 2018/1139 - Basic Regulation — EASA authority over UAS
- Reg 2019/945 (amend. 2020) - UAS product regulation — design & manufacturing
- Reg 2025/870 - Delegated regulation — latest amendment to 2019/945

OPERATIONAL RULES — OPEN, SPECIFIC & CERTIFIED CATEGORIES

- Reg 2019/947 (amend. 2020/2021) - UAS operational rules — Open, Specific, Certified
- PDRA / STS (2021 onwards) - Predefined & Standard Risk Assessments
- Reg 2020/639 + 2021/1166 - Amendments to operational rules & class requirements
- EASA Easy Access Rules (Rev. July 2024) - Consolidated operational guidance (UAS)

HORIZONTAL LEGISLATION WITH DIRECT DRONE RELEVANCE

- GDPR 2016/679 (2018 applicable) - General Data Protection Regulation
- NIS2 Directive 2022/2555 (Oct 2024 transposition) - Network & Information Security Directive 2
- AI Act 2024/1689 (phased to 2027) - EU Artificial Intelligence Act
- CRA 2024/2847 (phased to 2027) - Cyber Resilience Act
- RED 2014/53/EU + delegated acts (2022) - Radio Equipment Directive — drone connectivity
- REACH / RoHS / Battery Reg - Product safety: chemical, materials & batteries

AIRSPACE INTEGRATION & TRAFFIC MANAGEMENT (U-SPACE)

- Reg 2021/664 - U-space regulatory framework
- Reg 2021/665 - Surveillance & common information services (U-space)
- Reg 2021/666 - Manned aviation access to U-space
- Remote ID (Art. 14, 2019/947) - Remote identification — mandatory from Jan 2024
- Geo-awareness (2019/947 + updates) - Geo-awareness & geofencing requirements

SECURITY, DEFENCE & COUNTER-DRONE

- COM(2026) 81 - Action Plan on Drone & Counter-Drone Security
- COM(2023) 659 - EU policy on countering drone threats
- EDF 2021–2027 - European Defence Fund — drone & C-UAS grants
- SAFE Reg 2025/1106 - Security Action for Europe regulation
- Drone Strategy 2.0 - EU Drone Strategy 2.0

FORTHCOMING / PIPELINE (2026–2030)

- Drone Security Package: Updated registration, ID & C-UAS legislation, Exp. end-2026
- C-UAS Reg. framework - EU-level counter-drone regulatory framework, Target 2030
- EASA Cx rework - Revised EASA drone classification system, In progress 2026
- EU Counter-Drone CoE - Counter-Drone Centre of Excellence, Launch target 2027
- Certified Category regs - Regulations for air taxis & human transport UAS, Expected 2026–2027

Future Outlook: Challenges & Opportunities Ahead (1)

THE TECHNOLOGICAL HORIZON

Cyber-Physical Convergence

Drones exist simultaneously as physical objects, digital twins, and data sources. What we learn to govern here sets the template for every autonomous system that follows.

Simulated Worlds as Policy Tools

Digital twins let us run a drone corridor a thousand times before it opens. Powerful — but simulated environments can also be manipulated to justify decisions already made.

Sovereignty Across the Full Stack

Europe's challenge is not proving drones are useful. It is building sovereign capabilities at every layer: chips, software, connectivity, AI, orchestration.

Convergence Opportunity

Drones, autonomous vehicles, and robots share the same stack. Investment in one benefits all three — the case for European sovereign autonomous systems is economy-wide.

THE GOVERNANCE IMPERATIVE

Regulation as Differentiator

AI Act, NIS2, U-space, GDPR — used correctly, Europe's framework is not a burden. It is the only jurisdiction offering trustworthy, human-oversight-compliant autonomous systems.

Governance of New Airspace

How do you manage airspace that is simultaneously a public good, a commercial infrastructure, and a security asset? New governance models — not yet invented — are needed.

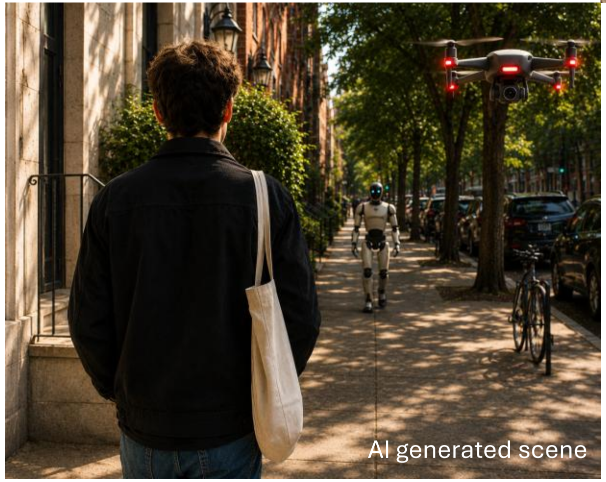
Social Legitimacy

Drones over homes and schools will face resistance unless communities are engaged and oversight is credible. Social acceptance is a governance design problem, not a communications problem.

Technology acceptance is not automatic — social legitimacy and sovereign capability must be built in parallel with the engineering.

Future Outlook: challenges & opportunities ahead (2)

- Gap between the new technical capabilities and the operational practices
- Legal and organisational obstacles
- Supply chain dependency and resource consumption
- Costs are underestimated
- Shared physical space (safety, privacy, liability)
- Illusion of super-power and new dependencies
- Erosion of jobs and skills



How can we integrate autonomous drones in our physical environment in a good way?

What world do we wish for?