Chapter Outline

Capability Development Along Three Routes

Chapter 1 Introduction

1.1 Concepts and Applications

1.2 History and Trends

1.3 Components and Architecture

1.4 Coordinate Systems and Control Principles

1.5 Assembly and Debugging

1.6 RflySim Toolchain

1.7 Learning Path and Experiments

1.8 Exercises and Discussion

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Textbook: Sec. 1.1.2 Introduction

1.2.1 Robotics: Cultural Imagination

Robot: Visions of Replacing Labor

Note: Robots still struggle with general tasks such as housework. Continued exploration yields advances: the beauty of research.

Mechanisms serve tasks.
Feedback improves control.
Adaptation broadens the task range.



R.U.R. production, New York, 1922

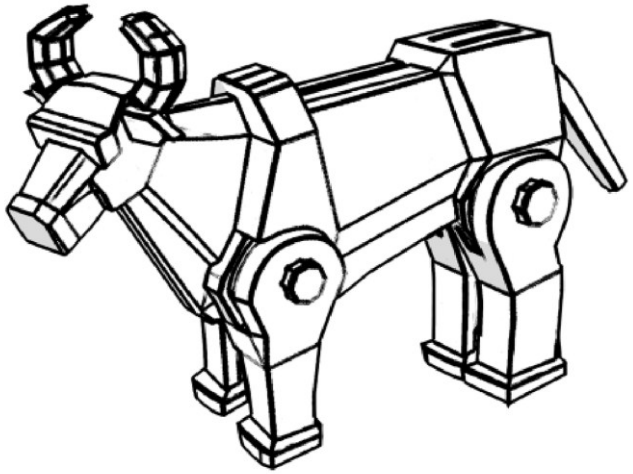
- **Etymology:** Robot comes from Czech writer Karel Čapek's R.U.R. (Rossum's Universal Robots), first staged in 1921; robota means labor or drudgery.
- **Practical need:** Repetitive, heavy and dangerous work motivates mechanical alternatives. Transport, handling and manipulation require different mechanisms and power sources.
- **Broad definition:** Robots are automated machines serving human needs, usually able to act autonomously. They need not be humanoid or self-aware like those in the play.

The wish to replace human labor drove exploration of mechanisms and control for different tasks.

1.2.1 Robotics: Transport Aspirations

Wooden Ox and Flowing Horse

Note: The original construction and control are untraceable. The story reflects ancient China's wish to ease manual labor with machinery.



(a) Wooden Ox and Flowing Horse

Fig. 1.5(a) Later reconstruction

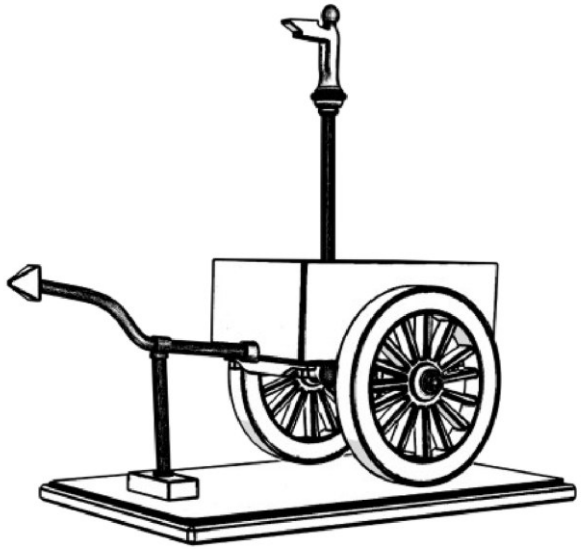
- **History:** Records of the Three Kingdoms credits Zhuge Liang with improving repeating crossbows and devising the Wooden Ox and Flowing Horse. The two carried grain on northern expeditions in Jianxing years 9 and 12, respectively.
- **Engineering:** Power input, load support, force transmission and continuous motion must cooperate. Roads, slopes, grain weight and operator numbers affect feasibility.
- **Reconstruction:** This later model's mechanism remains unproven. Load-carrying robot dogs continue the wish to ease transport labor.

From the Wooden Ox and Flowing Horse to load-carrying robot dogs, the wish to ease transport labor moves toward reality.

1.2.1 Robotics: Automatic Direction Keeping

South-Seeking Chariot: Direction Keeping

Note: Artificial intelligence (AI) broadens access to technology and helps realize ideas: an opportunity and a challenge.



(b) South-Seeking Chariot

Fig. 1.5(b) Reconstruction

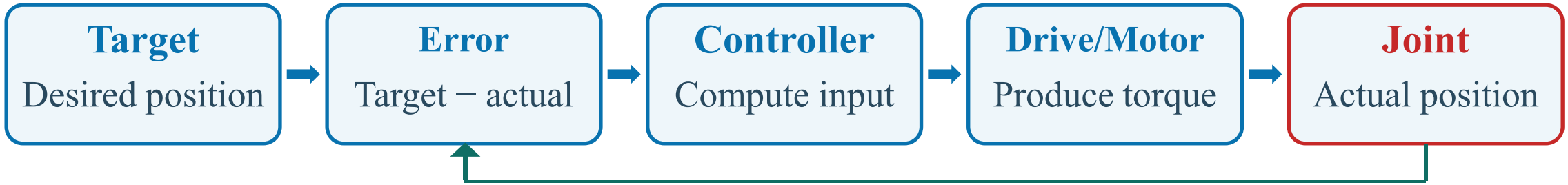
- **Historical context:** Gujin zhu (Western Jin) records the South-Seeking or Sinan Chariot. Legends credit the Yellow Emperor or Duke of Zhou; Ma Jun of Wei (Three Kingdoms) later improved it. Its construction remains uncertain.
- **Common reconstruction:** Unequal wheel travel in a turn drives differential gears; these turn the figure to help keep its initial direction.
- **Automation:** Fixed gearing performs the pointing task without magnetic poles. Human initialization and mechanism motion jointly determine the output.
- **Error sources:** Initial alignment, wheel slip and transmission errors cause drift; the device cannot detect or correct these errors.

The Wooden Ox and Flowing Horse and the South-Seeking Chariot embody ancient ideas of automated machinery and early seeds of unmanned systems.

1.2.1 Robotics: Feedback Control

Measurement and Feedback Correction

Note: Norbert Wiener's Cybernetics (1948): feedback underpins modern automation and control engineering.



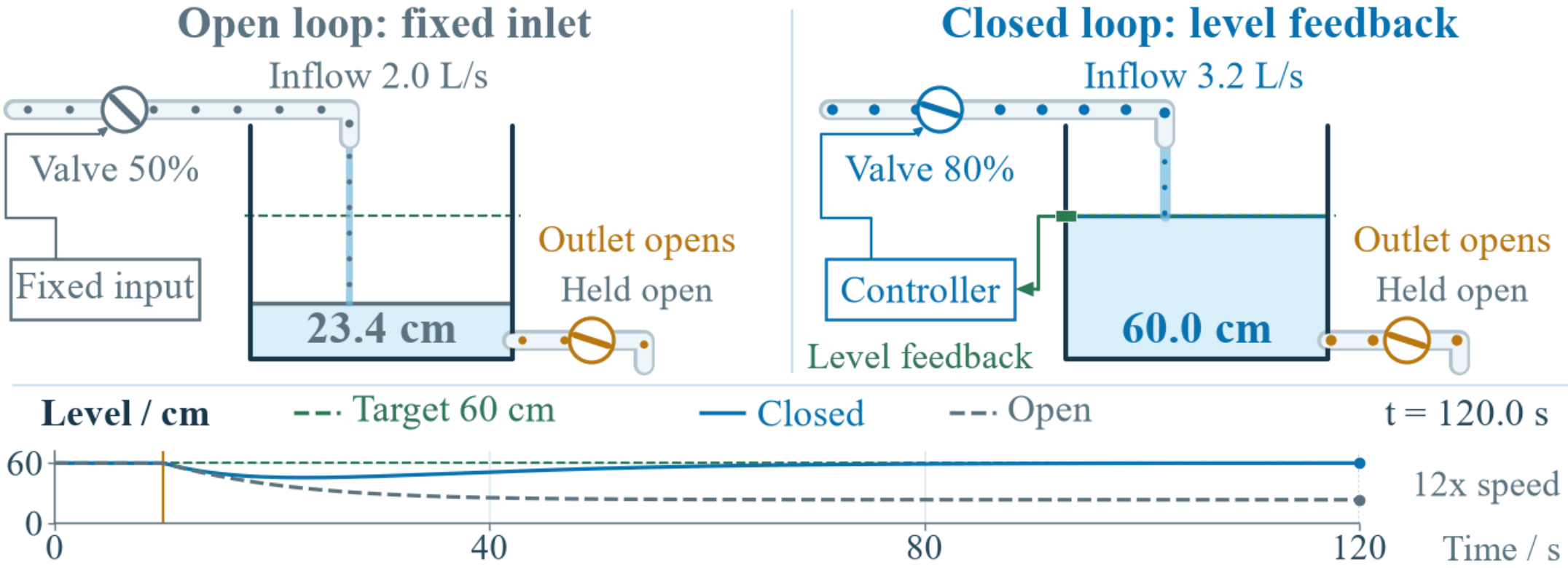
- **Measurement:** An encoder continuously measures joint angle; error = target − actual position (90° − 80° = 10°).
- **Control:** Larger errors produce stronger drive commands. Motor torque turns the joint toward its target; disturbances trigger new measurement and correction.
- **Limits:** Response speed, measurement error and actuator limits affect tracking. Feedback alone cannot select tasks autonomously.

Note: Claude Code, Codex and Qoder split goals, act, observe/verify and iterate via feedback: an analogy to task-level feedback control.

Feedback underpins automatic control and offers an analogy to Loop Engineering in AI agents.

1.2.1 Robotics: Feedback Control

How Feedback Restores Water Level as Demand Rises



Fixed inflow versus level feedback under the same outlet-valve change

1.2 History and Trends

1.2.1 Robotics: Industrial Robots

Actuation, Measurement and Control



Six-DOF arm on a production line

Note: Since the first robotics company (1956), integrating actuation, measurement and control has raised precision and efficiency, at a cost in integration and maintenance.

- **Mechanism:** Servo motors drive a multijoint arm; coordinated joints bring the end effector to its work position and perform the operation.
- **Measurement and control:** Encoders return joint states for drive-command adjustment. Measurement error and drive response jointly affect tracking accuracy.
- **Operating constraints:** Payload, speed and stiffness affect accuracy and repeatability. Travel limits, anomaly detection and safety responses define the operating range.

Industrial robots use specialized configurations for repetitive work, trading integration and maintenance effort for precision and efficiency.

1.2 History and Trends

1.2.1 Robotics: Platform Development

Dynamic Balance in Legged Platforms

Note: In 2004, Boston Dynamics introduced its first biomimetic quadruped, raising hopes that robots could match the locomotion of living creatures.



Quadruped Robot



Quadruped Robot



Hydraulic Atlas

- **Quadruped load carrying:** Foot contact and joint motion support outdoor loads; body posture adapts to terrain and changing forces.
- **Humanoid motion:** Hydraulic Atlas coordinates joints during stepping, flight and landing to link different support phases.
- **Dynamic balance:** Continuous posture measurements guide foot placement and joint torque during motion, beyond a static stance. Payload, energy and terrain limit sustained operation.

Legged platforms adapt to terrain through measurement and joint coordination. Payload and energy also constrain sustained operation.

1.2.1 Robotics: Embodied Intelligence

From Dynamic Balance to Embodied Intelligence

Around 2005
Boston Dynamics: BigDog; Cheetah and Atlas follow

➡

2021
Tesla announces its Optimus project

➡

Recent Years
Unitree, AgiBot, Tiangong: industrialization in China

- **Bottleneck:** Low-level perception and control limit stable walking, jumping and load carrying.
- **Dynamic control:** Boston Dynamics advanced balance, jumps and flips; Optimus and Chinese brands pursue humanoid motion control and dexterous grasping.
- **Embodied intelligence:** Real-time body−environment interaction (Deck 1.1). Maturing autonomous control and fast-evolving large AI models drive research and industry interest.
- **Prospects:** Robots can approach or exceed humans on specific tasks and may serve complex, high-risk settings.

Advances in motion control and large AI models are driving robotics toward embodied intelligence.

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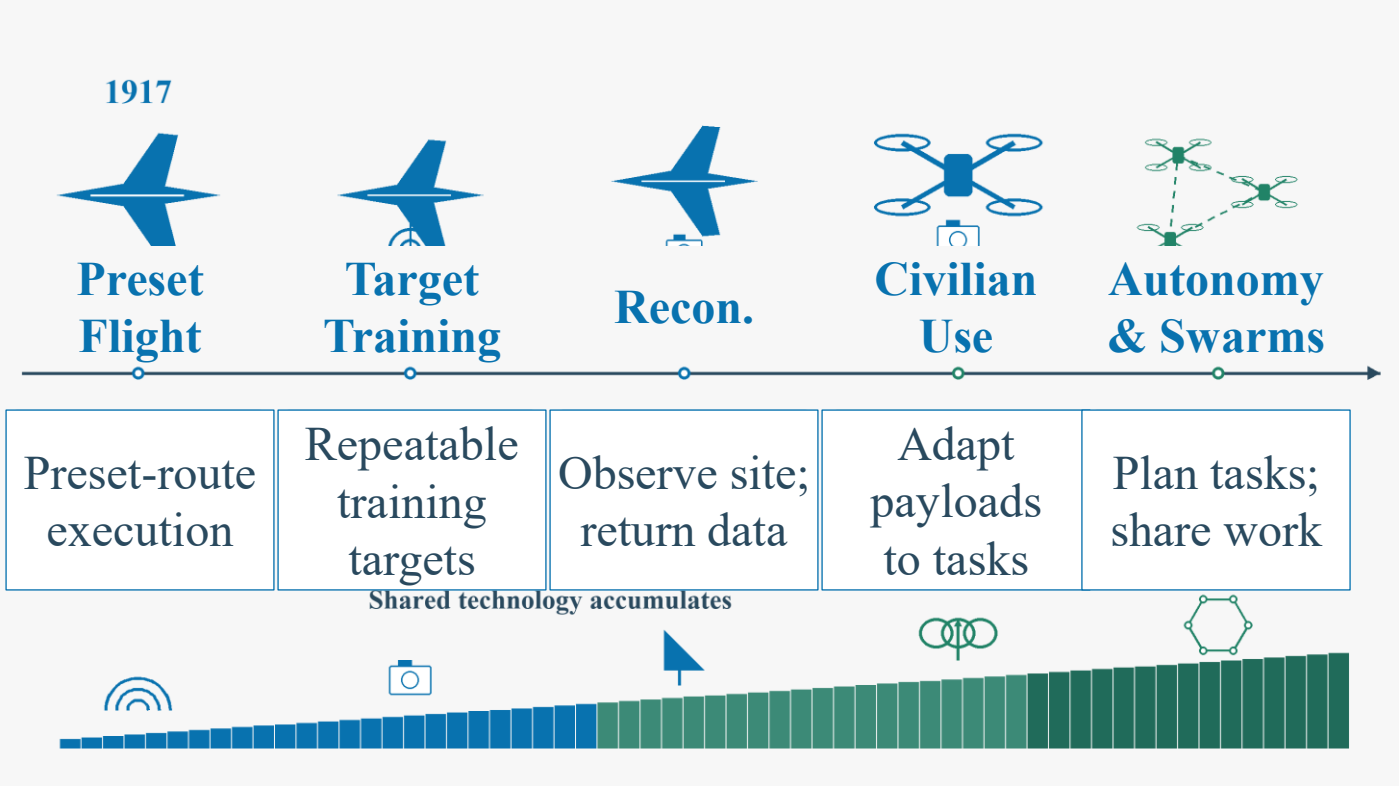
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1.2.4 Convergence and Distinctions
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1.2.2 UAVs: Capability Development

Task Needs Drive Parallel UAV Development



Parallel mission routes. The steps below show accumulated technology, not mission ranks.

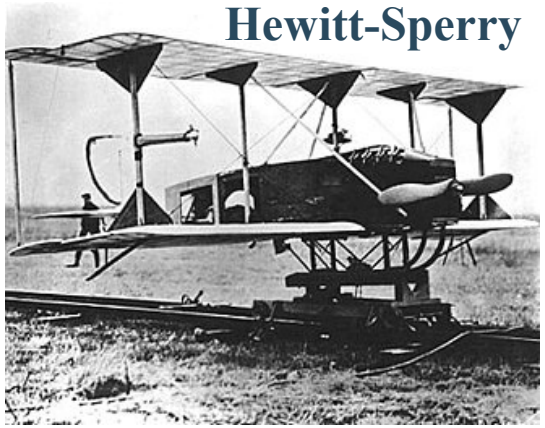
- **Remote execution:** Preset control follows a specified heading and range. Target drones provide repeatable targets for training and testing.
- **Mission branches:** Persistent coverage drives high-altitude, long-endurance platforms. Field deployment drives miniaturization. Both routes coexist.
- **Wider use:** Lower costs and easier operation support civilian missions. Environmental perception and plan updates support mission autonomy.

1.2.2 UAVs: Preset Flight

Two Preset-Flight Projects During World War I

- **Navy project:** The U.S. Navy launched the Hewitt-Sperry Automatic Airplane project in 1917. It achieved a stable pilotless test flight on March 6, 1918.
- **Army project:** The Kettering Bug belonged to the U.S. Army Air Service. Its first flight test was on October 2, 1918. It saw no combat before the Armistice.
- **Shared concept:** Both were aerial torpedoes, carrying explosives along a preset heading and range under onboard control.
- **Limits:** Range estimates used preset quantities such as engine revolutions. The aircraft could neither sense nor correct for changing winds en route, limiting impact accuracy and reliability.

Hewitt-Sperry



Kettering Bug



Early unmanned aircraft used preset control. Limited accuracy and reliability constrained practical use.

1.2.2 UAVs: Origins of Reconnaissance

From Target Training to Reconnaissance Information



AQM-34 Lightning Bug Reconnaissance variant (1962)



BQM-34F Firebee II Target drone (1968)

- **Target training:** Introduced in the 1950s, Firebee provided aerial targets for firing practice and weapons-system qualification, emphasizing stable and repeatable flight.
- **Reconnaissance:** The Lightning Bug reconnaissance variant followed in the 1960s, carrying cameras into mission areas to gather and return intelligence.
- **System changes:** New missions required changes to payloads, energy, recovery and data links. Information could return with the recovered aircraft or through communication.

Reconnaissance variants expanded the mission from providing aerial targets to gathering and returning useful information.

1.2.2 UAVs: Reconnaissance Variants

AQM-34L: Reconnaissance, Recovery and Reuse



AQM-34L Firebee (1969)

- **Air launch:** A DC-130 delivers the aircraft to mission airspace; after release it flies the reconnaissance route.
- **Mission payload:** The route and photo timing affect coverage; image quality determines whether target information can be interpreted.
- **Midair recovery:** A helicopter catches the parachute, recovering the aircraft and information for inspection and possible reuse.

Unmanned reconnaissance delivers value through timely information delivery as well as flight over the target.

1.2.2 UAVs: Persistent Surveillance

Persistent Coverage: Altitude, Endurance and Data



RQ-4 Global Hawk reconnaissance UAV

- **Coverage:** First flown in February 1998. Altitude widens the view; endurance extends time on station.
- **RQ-4B:** Ceiling about 18.3 km; endurance over 34 h supports wide-area surveillance.
- **Payloads:** Radar, electro-optical and infrared sensors; configuration varies by production Block.
- **Data links:** Return information; ground processing and operational support sustain continuous missions.

Global Hawk combines altitude, endurance and mission payloads. Persistent surveillance depends on reliable information gathering and transmission.

1.2.2 UAVs: Miniaturization

Field Deployment: Scout and Miniaturization Tradeoffs

- **Milestone:** Developed by Israel Aerospace Industries (IAI), Scout entered Israeli Air Force service in 1979, representing a route toward small reconnaissance platforms for field deployment.
- **Motivation:** After the 1973 Yom Kippur War, Israel developed small UAVs including Tadiran's Mastiff and IAI's Scout. They demonstrated strategic value in the 1982 Lebanon War.
- **Field deployment:** The platform carries sensors to the mission site. A ground station monitors the mission and processes information. Launch and recovery sites, transport preparation and communication affect deployment efficiency.
- **Tradeoffs:** A smaller airframe eases transport and deployment but limits equipment and energy capacity. Large, long-endurance platforms emphasize persistent coverage and require suitable launch, recovery and support facilities.

Small platforms favor field deployment. Long-endurance platforms favor persistent coverage. Payloads and support determine suitable missions.

1.2.2 UAVs: Information Links

Reconnaissance in the Information Chain



IAI Scout reconnaissance UAV (foreground)
Exhibition photograph, 2008

- **Sensing:** Onboard payloads gather images and other site data. Platform position, observation area and sensing conditions affect quality.
- **Transmission and judgment:** Data links return information for ground personnel or systems to analyze; communication quality and timeliness affect usability.
- **Execution:** Useful results also need suitable decisions and execution conditions. A break anywhere in the chain can prevent useful results despite obtaining images.

Reconnaissance carries the system's eyes farther. Timely information delivery and use in decisions turn this sensing advantage into mission value.

1.2.2 UAVs: Progress in China

Two Parallel UAV Development Routes in China



Wing Loong-2 (2017)



Rainbow-4 (2011)



Rainbow-5 (2015)

- **Development routes:** Wing Loong: Chengdu institute, Aviation Industry Corporation of China (AVIC); first model flown in 2007, China's first reconnaissance-strike UAV. Rainbow: 11th Academy, China Aerospace Science and Technology Corporation (CASC).
- **Reconnaissance and strike:** Electro-optical payloads detect/track a target; onboard weapons strike it, shortening detection-to-action time. These long-endurance UAVs also conduct long-range surveillance and electronic warfare.

1.2.2 UAVs: Low-Altitude Applications

Consumer UAVs: Changing Cost and Ease of Use



Parrot AR.Drone consumer UAV

- **Product integration:** Around 2010, consumer products combined stabilization, which automatically maintains attitude, with live video to a phone and phone-based control.
- **Wider applications:** Lower costs and easier learning made aerial photography, environmental monitoring and research more accessible. The payload determines what information can be gathered.
- **Operating conditions:** Endurance, payload and reliability limit use. Easier operation does not remove airspace or safety constraints.

Integrating stabilization, video links and mobile control made UAVs easier to use and brought them to a wider public.

1.2.2 UAVs: Low-Altitude Applications

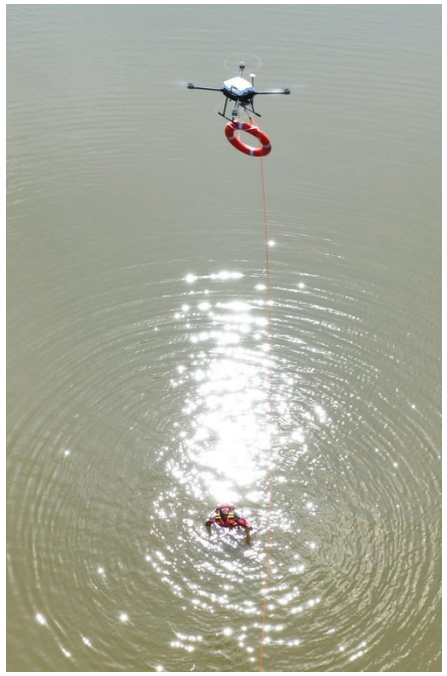
Industry UAVs: Tasks Shape Payloads and Systems



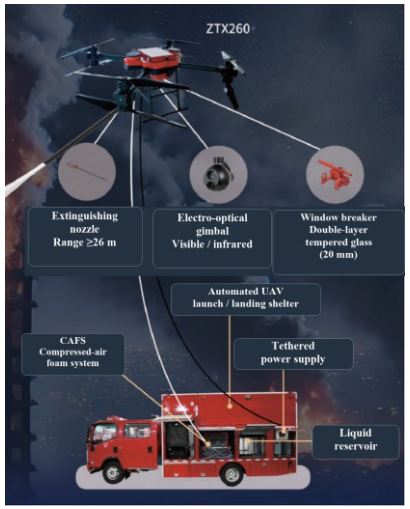
Crop protection: match spray rate to flight path



Logistics: payload affects endurance



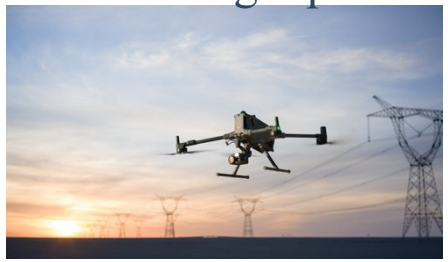
Rescue: positioning guides delivery



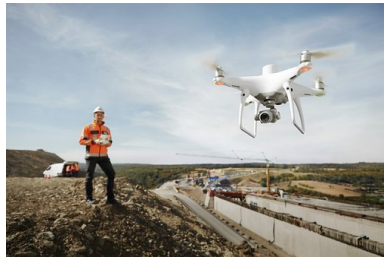
Spraying
Break glass
Launch/land

Observation
Liquid supply
Power supply

Ground-supported firefighting



Inspection: distance affects imaging

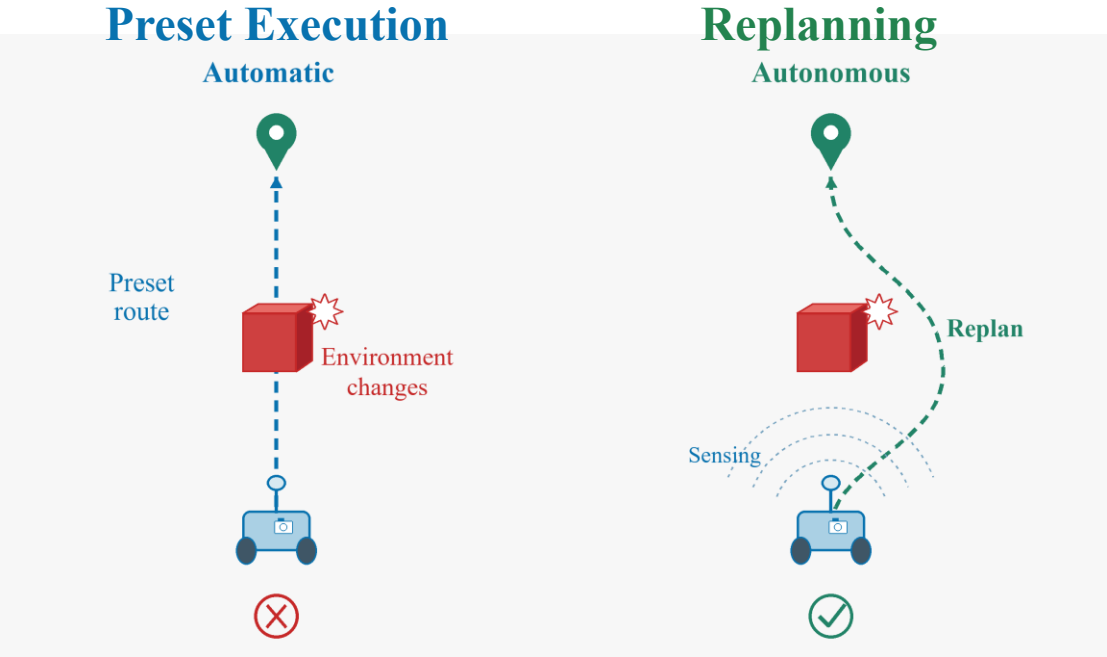


Mapping: combine imagery and positioning

Industry capability comes from the flight platform, mission payload and ground support working together.

1.2.2 UAVs: Mission Expansion

Preset Routes and Autonomous Replanning



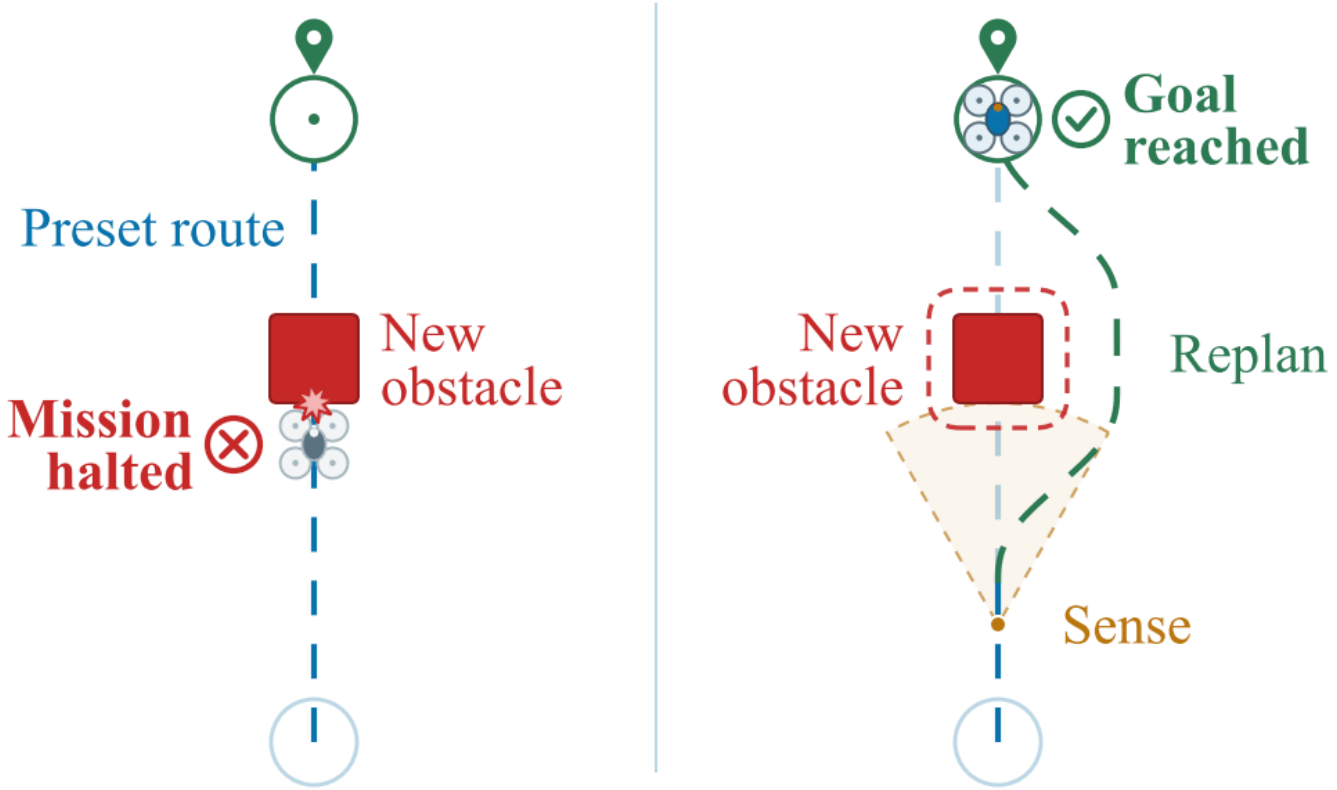
Preset execution versus environmental replanning

- **Preset execution:** A fixed route may be interrupted by environmental changes if no mechanism handles new obstacles.
- **Environmental replanning:** Obstacle information enables a new path toward the goal within motion and safety constraints.
- **Scope of autonomy:** Human roles in sensing, plan updates and execution set its degree. Beyond its capabilities, the system stops or transfers control to a person.

Environmental perception and plan updates enable adaptation. Responses to abnormal conditions keep execution within the authorized scope.

1.2.2 UAVs: Mission Expansion

After Conditions Change: Preset Execution or Replanning



Two outcomes when a new obstacle appears on the same route (conceptual illustration)

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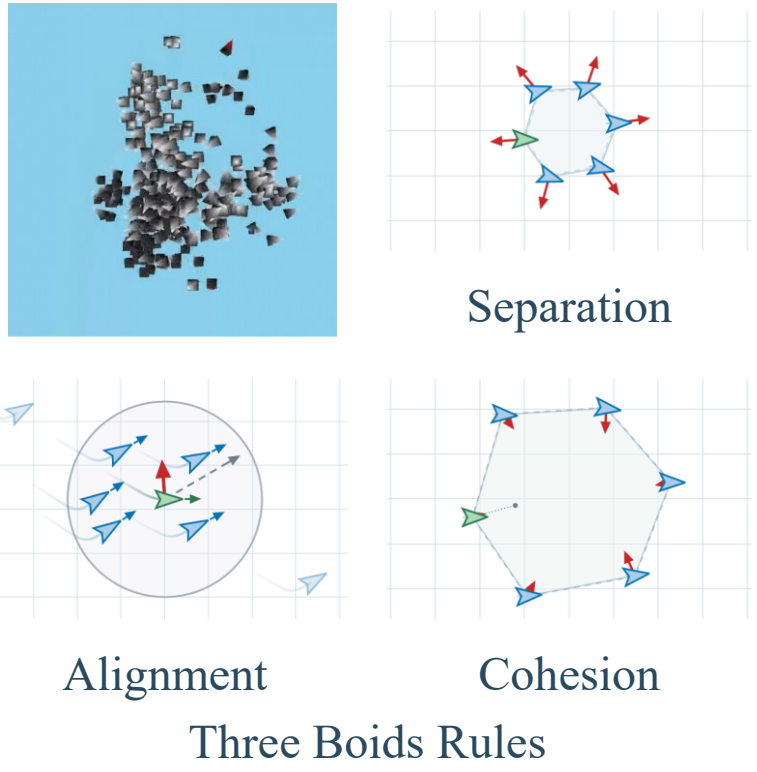
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Textbook: Sec. 1.1.2 Introduction

1.2.3 Unmanned Swarms: Collective Behavior

Boids: Local Rules and Collective Motion

- **Model origin:** Reynolds introduced Boids (1987): organized group motion from local interactions.
- **Separation:** Adjust motion to avoid collisions with nearby neighbors.
- **Alignment:** Match neighbors' velocity vectors: direction and speed, beyond heading alone.
- **Cohesion:** Move toward the local group's position to stay connected, using nearby members without global knowledge.
- **Engineering limits:** Real swarms need state estimation, task allocation and task continuity after failures, under communication, dynamics and collision-avoidance constraints.



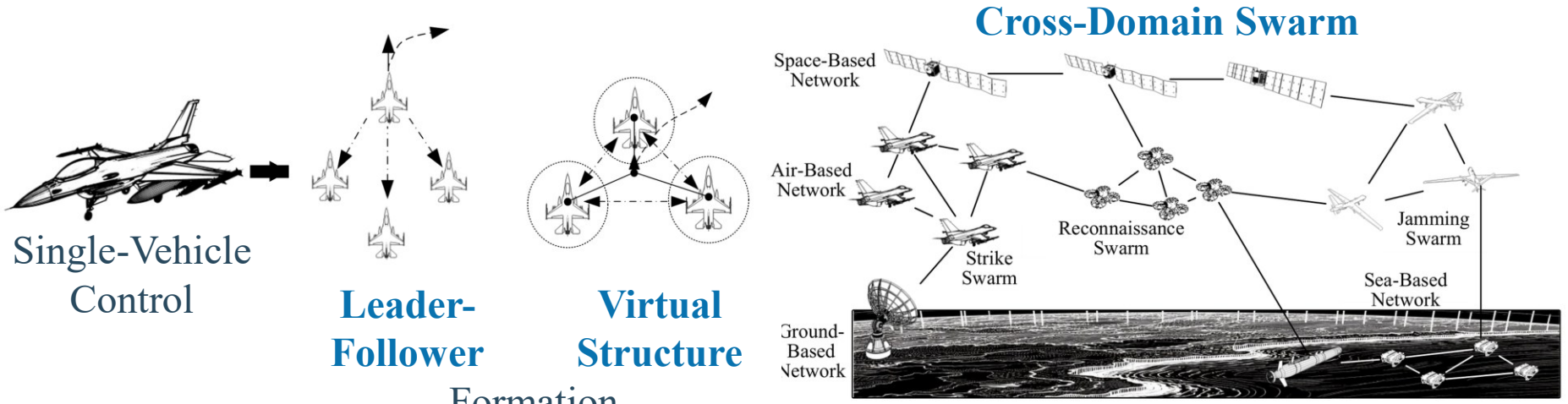
Three Boids Rules

Local rules can produce collective motion. Real swarms must also meet engineering constraints.

1.2.3 Unmanned Swarms: Organization

From Formation Constraints to Cross-Domain Roles

Fig. 1.4 Unmanned Systems from Single Unit to Swarm



- **Formation:** Add relative-position constraints to single-vehicle target tracking.
- **Methods:** Leader-follower uses a leader reference; virtual structure assigns each vehicle a point in the formation.
- **Cross-domain roles:** Reconnaissance, strike and jamming groups exchange information via space-, air-, ground- and sea-based networks.

1.2.3 Unmanned Swarms: Collaboration at Scale

The Perdix UAV Trial: Scale and Collective Behavior

- **Trial conditions:** U.S. Department of Defense materials report 103 Perdix micro-UAVs released from three F/A-18 aircraft in October 2016.
- **Collective decisions:** Shared information coordinates behavior so individual actions serve the group mission, beyond simultaneous flight.
- **Adaptation and self-healing:** The public demonstration showed adaptive formation flight and self-healing: reorganization and task continuation after node changes.
- **Limits:** Collaboration was shown under specific conditions. Communication quality, environment and node failures affect actual effectiveness.



Perdix UAV in testing

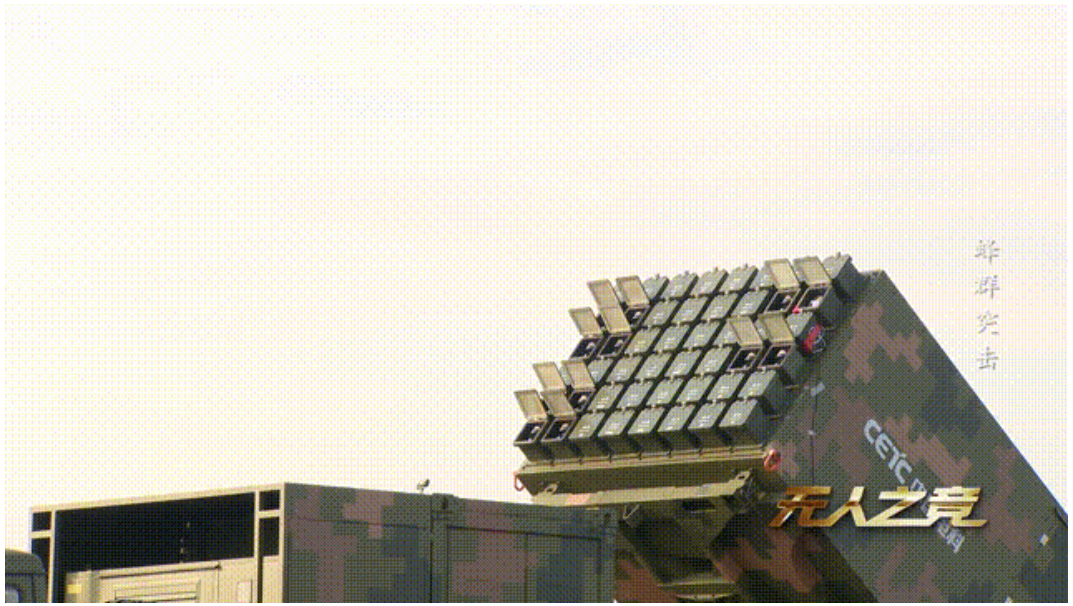


Perdix demonstrated collective decisions and organizational adaptation. Practical use still requires communication, collision avoidance and mission continuity.

1.2.3 Unmanned Swarms: Collaboration at Scale

Atlas: China's UAV Swarm Combat System



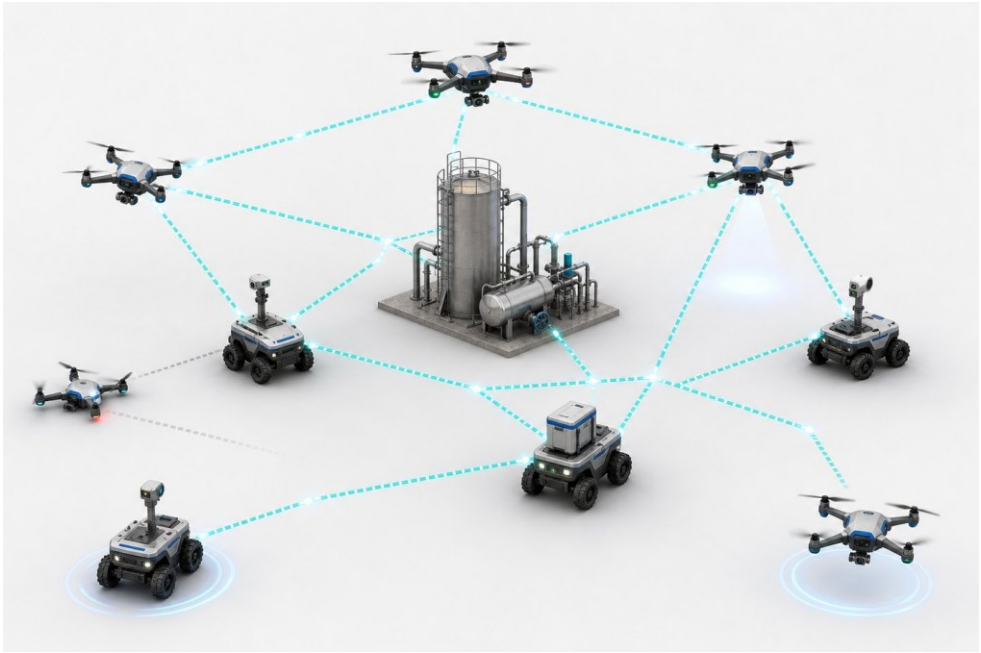


China Electronics Technology Group Corporation UAV swarm launch vehicle and launcher (2024)

- **Launch platform:** 48 UAVs per vehicle; two vehicles can launch 96 in rapid succession.
- **Command and support:** A command vehicle assigns tasks and supervises the swarm; a support vehicle sustains operations. UAVs share information to coordinate.

1.2.3 Unmanned Swarms: Decentralization

Why Share Decisions as a Swarm Grows?



Mesh linking nodes without one command center

- **Scaling pressure:** More nodes increase the central computing and communication load for collecting states and issuing actions. Center failure interrupts new commands, creating a single point of failure.
- **Local cooperation:** Nodes help make decisions using local and neighboring information, moving part of the computation to the field.
- **Added cost:** Nodes have inconsistent information. Delays and packet loss can cause duplicate task assignments, requiring coordination rules.

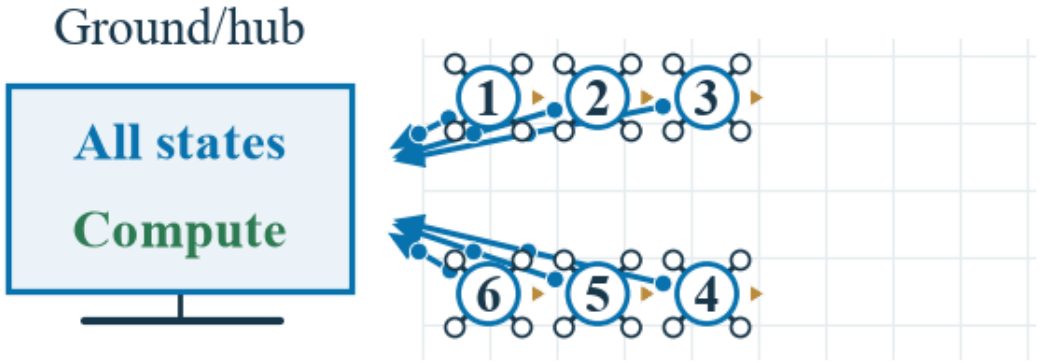
Decentralization shares decision-making through local cooperation. Maintaining consistency adds communication and coordination costs.

1.2.3 Unmanned Swarms: Decentralization

Costs of Centralized and Distributed Coordination

Centralized: hub computes

Same task: fly right in formation

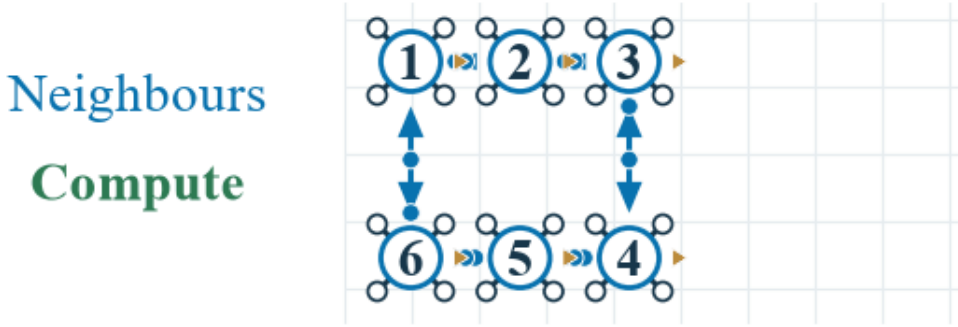


1 Report all agent states

All states → hub → individual commands

Distributed: each agent computes

Same task: fly right in formation



1 Get relative neighbour positions

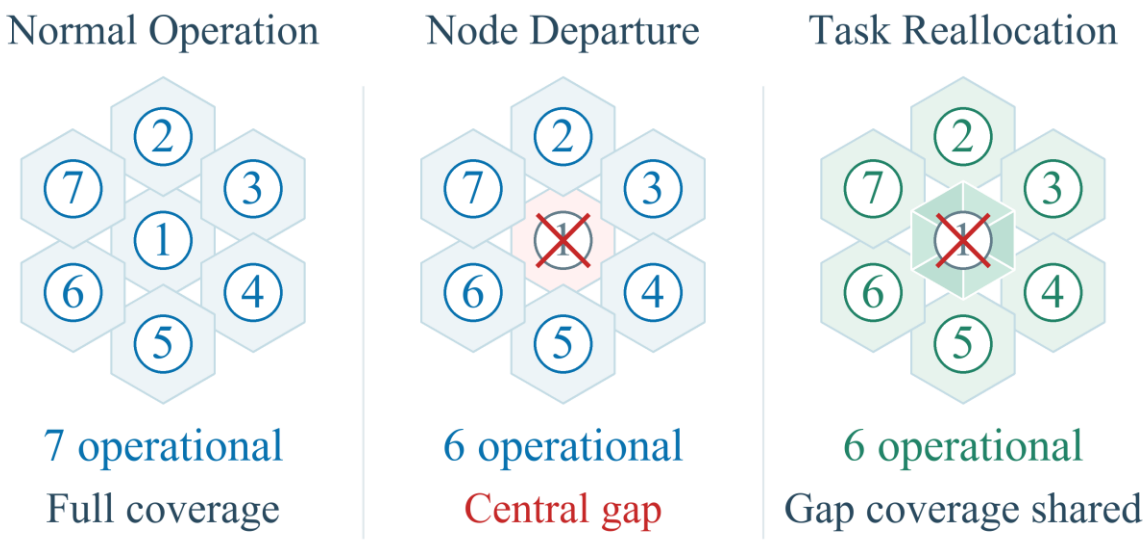
Neighbour data → local computation

Blue: state data Green: computation / commands Amber: flight path / direction

Same formation task: different data sources and command-computation sites (numerical example)

1.2.3 Unmanned Swarms: Reconfiguration After Failure

From Demos to Mission Continuity



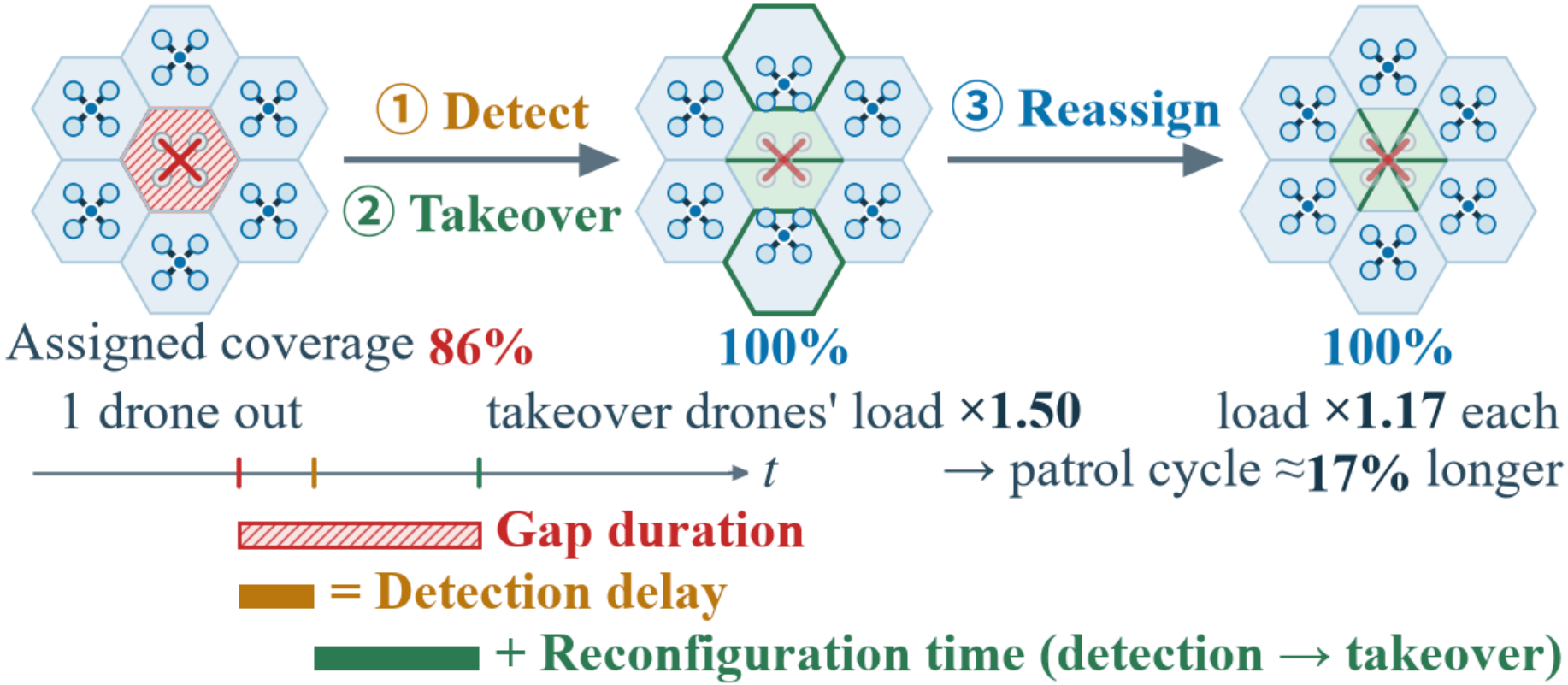
Detection, takeover and task reallocation after a node leaves (schematic)

- **Detect change:** Nodes or monitors detect anomalies from state updates. Delays can look like node departure; late detection delays task continuation.
- **Take over:** Remaining nodes accept unassigned tasks within their capability and resources; added work also consumes resources for existing tasks.
- **Reallocate:** Task changes alter formation and coverage. Slow reconfiguration prolongs gaps; remaining resources limit recoverable mission scope.

Swarms add communication and divided roles. Continuing tasks after node failure is a challenge for reliable collaboration.

1.2.3 Unmanned Swarms: Reconfiguration After Failure

After a Node Leaves: Detection, Takeover and Reallocation



Node departure and task reallocation (conceptual illustration)

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1.2.4 Convergence and Distinctions: Development Trends

How Three Routes Build System Capabilities

- **Vehicle foundations:** Robotics improves motion control and environmental interaction. UAVs combine flight, mission payloads and information transmission to expand mission execution.
- **Intelligence for vehicles:** Onboard perception and AI take over selected judgments in control and decision-making. Aircraft, ground vehicles and vessels can then complete specific authorized tasks without human piloting.
- **Swarm collaboration:** Communication and task allocation organize multiple vehicles. Shared information coordinates node decisions so individual capabilities jointly serve the mission.
- **Directions:** Increase single-vehicle mission autonomy and reduce dependence on one center through distributed decisions. Protection against communication failures, hacking, data breaches and malicious interference becomes essential.

As the three routes converge, machines that can move develop into systems that can complete tasks autonomously.

1.2.4 Convergence and Distinctions: Capability Limits

Capability Layers and Operating Conditions

Layer	Task Capability	Requirements	Limits
Mechanical Execution	Preset actions via mechanical relationships	Fixed transmission: gears, linkages, etc.	No state feedback: hard to auto-correct
Feedback Correction	Continuously measure error and correct motion	Measurement, control computation, drive response	Measurement error; actuator limits
Mission Autonomy	Adapt the mission plan to changing conditions	Perception, planning, mission authorization	Outside operating scope: fallback or human takeover
Multi-Vehicle Coordination	Allocate tasks to nodes; coordinate actions	Share states, communicate, allocate tasks	Link loss / node departure: reconfigure tasks

Execution, correction, autonomy and coordination can coexist. Capability depends on their integration and operating conditions.

Class Discussion

Assessing Claims: Producers, Users and Regulators

- **Mission capability:** For a claim of autonomous task completion, what task and environment are specified? How is success rate measured, where do people assist, and what happens after failure?
- **Costs and benefits:** For a claim of lower cost, what alternative is the baseline? Does the comparison cover purchase cost or life-cycle cost, including personnel, training, maintenance and operational support?
- **Operational safety and security:** For a claim of safety, which risks of harm or communication threats are addressed? Which conditions were tested, and which risks remain uncovered?
- **Multi-vehicle coordination:** For a claim of strong collaboration, how quickly is a departing node detected, and who takes over? How do task completion and coverage completeness change?

Clarifying the needs and evaluation criteria of producers, users and regulators helps improve product design.

Section Summary

Integrating Capabilities Needs a Shared Architecture

- **Development gains:** Mechanisms and feedback provide motion. Payloads and communication expand task scope. Perception and collaboration support adaptation to the environment.
- **Shared challenge:** Capabilities must share state, power and actuation resources within one vehicle. Simply placing modules together cannot complete a task.

From Capabilities to Implementation

Functions: what must be done
Components: which devices implement it
Operation: how information and commands interact

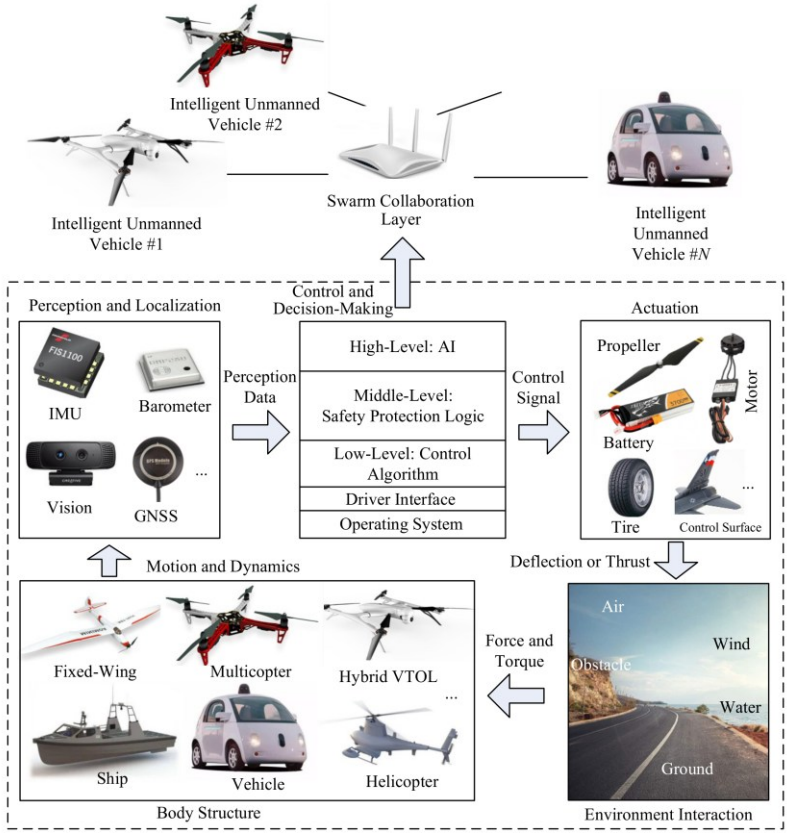


Fig. 1.6 Unified framework