Intelligent Unmanned System Control Practice

Chapter 1 Introduction

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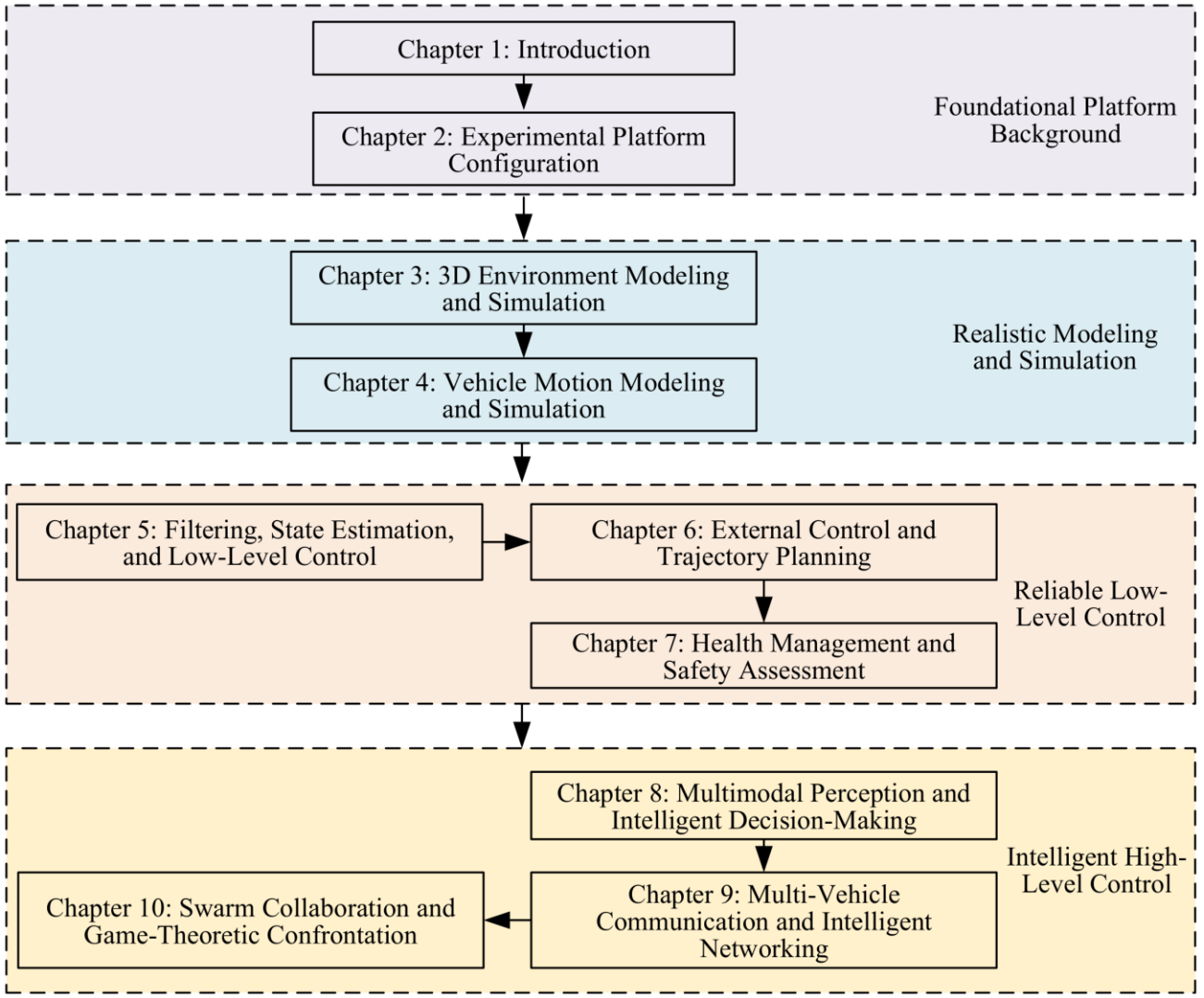
RflySim: http://rflysim.com

Companion Paper



Dai, Xunhua, Jinhu Tu, and Quan Quan. "RflySim ToolChain: a rapid development and validation toolchain for intelligent unmanned swarm systems." Journal of Systems Engineering and Electronics 36.4 (2025): 1077-1093.

Textbook is coming soon...



Chapter Learning Objectives

What You Can Do After Chapter 1

1. Distinguish core concepts, platform types and development trends
2. Explain system architecture, coordinate relationships and vehicle control principles
3. Explain unmanned aerial vehicle (UAV) assembly, calibration, commissioning and staged validation
4. Plan further study and experiments with the RflySim Toolchain and examples

Applying concepts in engineering requires understanding tasks and testing systems in practice.

Chapter Outline

Chapter 1: Concepts, Principles and Experiments

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

4 Units in This Section

1.1.1 Intelligent Unmanned Systems

Textbook: Sec. 1.1.1.1

1.1.2 Classification Methods

Textbook: Sec. 1.1.1.2

1.1.3 Platforms and Examples

Textbook: Sec. 1.1.1.3

1.1.4 Swarm Applications

Textbook: Sec. 1.1.1.4

1.1.1 Intelligent Unmanned Systems

Six Core Concepts

Note: Definitions differ across sources; the wording below fixes their meaning for this course.

- **Unmanned system:** A hardware–software system in which machines perform tasks for people, remotely or autonomously.
- **Unmanned vehicle system:** A system comprising a vehicle without an onboard pilot or driver, plus control, communication and support components.
- **Embodied intelligence:** Adaptive intelligence through bodily perception, action and environmental feedback.
- **Disembodied intelligence:** Intelligence through information processing, without bodily participation in a physical task loop.
- **Intelligent unmanned system:** An unmanned system using artificial intelligence (AI) for autonomous perception, reasoning, decision-making and action.
- **Intelligent unmanned swarm system:** A multi-agent system of intelligent unmanned units cooperating on tasks.

Fully unmanned and automated operation is the ultimate aim of artificial general intelligence (AGI), driving specialization and integration.

1.1.1 Intelligent Unmanned Systems

Intelligent Task Platforms

Note: Fully unmanned means no human intervention during execution. People should still review and issue missions; letting machines decide everything risks loss of control.

- **Components:** A vehicle that can change its own position, with perception, control and communication. Payloads may be cameras, weapons, cargo or passengers. A vehicle need not carry people.
- **Control modes:** Remote control uses human commands. Automatic control follows given goals and rules. Intelligent control adapts actions to environmental information and task needs.
- **Examples:** A person steering around an obstacle from video uses remote control. Following a preset route is automatic control. Detecting a new obstacle and replanning uses intelligent control through perception and autonomous decision-making.
- **Combined modes:** One platform may switch between remote and autonomous control. No onboard driver does not mean no human involvement. Autonomy also depends on who monitors, drives and handles abnormal events or risk.

Human intervention decreases as intelligent control grows, with fully unmanned operation as the ultimate goal.

1.1.1 Intelligent Unmanned Systems

Driving Automation Levels

Note: Human–machine roles in driving can inform other unmanned systems. Assess each task, its operating conditions, and the monitoring and takeover duties.

GB/T 40429: L0–L2 assist the driver; L3–L5 automate driving.

Level and Name	Function When Enabled
L0 Emergency Assistance	Warnings or brief emergency braking. The human continues driving.
L1 Partial Assistance	Sustained steering OR speed assistance, e.g. adaptive cruise control.
L2 Combined Assistance	Assists steering AND speed. The driver continuously monitors.
L3 Conditional Automation	Drives within defined conditions; requests takeover when needed.
L4 High Automation	Drives and handles risk within defined conditions; no human takeover.
L5 Full Automation	Drives and handles risk under all drivable conditions.

Roles: At L2, the human monitors. At L3, the system drives and the human must take over on request.

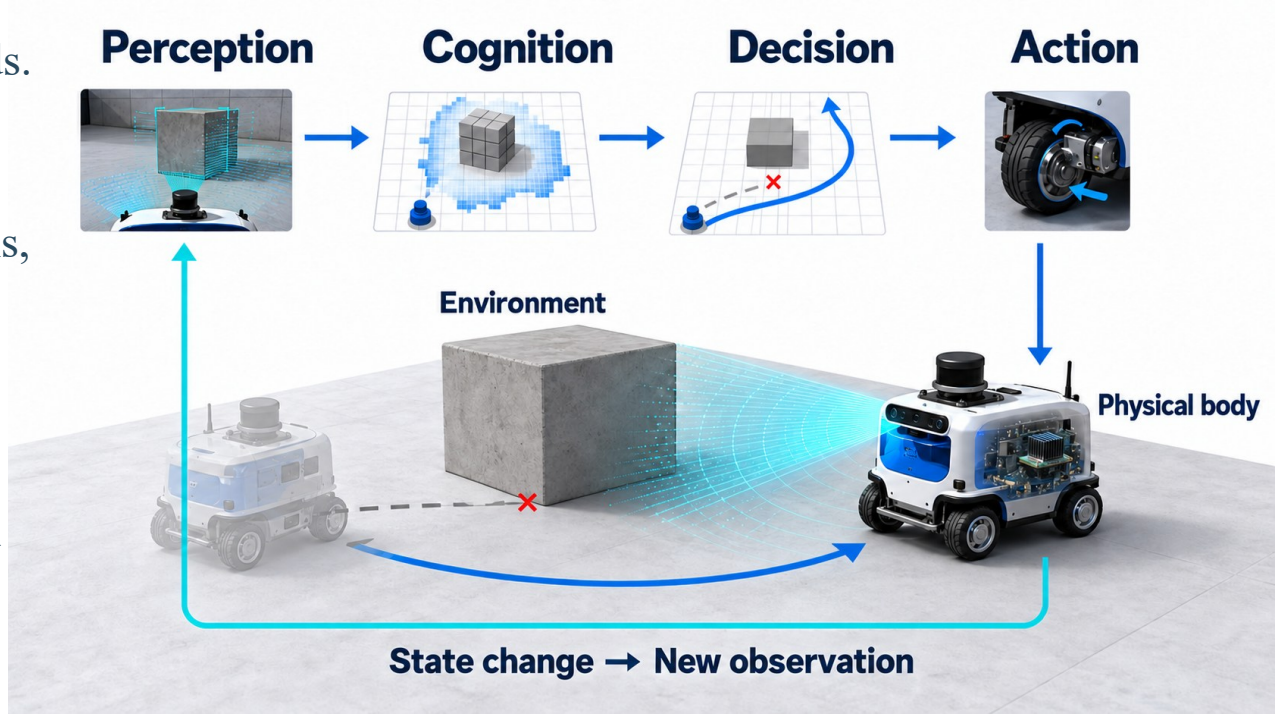
Standards: GB/T 40429-2021, Taxonomy of Driving Automation for Vehicles; SAE J3016
https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=4754CB1B7AD798F288C52D916BFECA34

Unmanned vehicles aim to replace drivers. Embodied intelligence aims to perform general human tasks.

1.1.1 Intelligent Unmanned Systems: Embodied Architecture

Adaptive Intelligence Through Bodily Perception, Action and Feedback

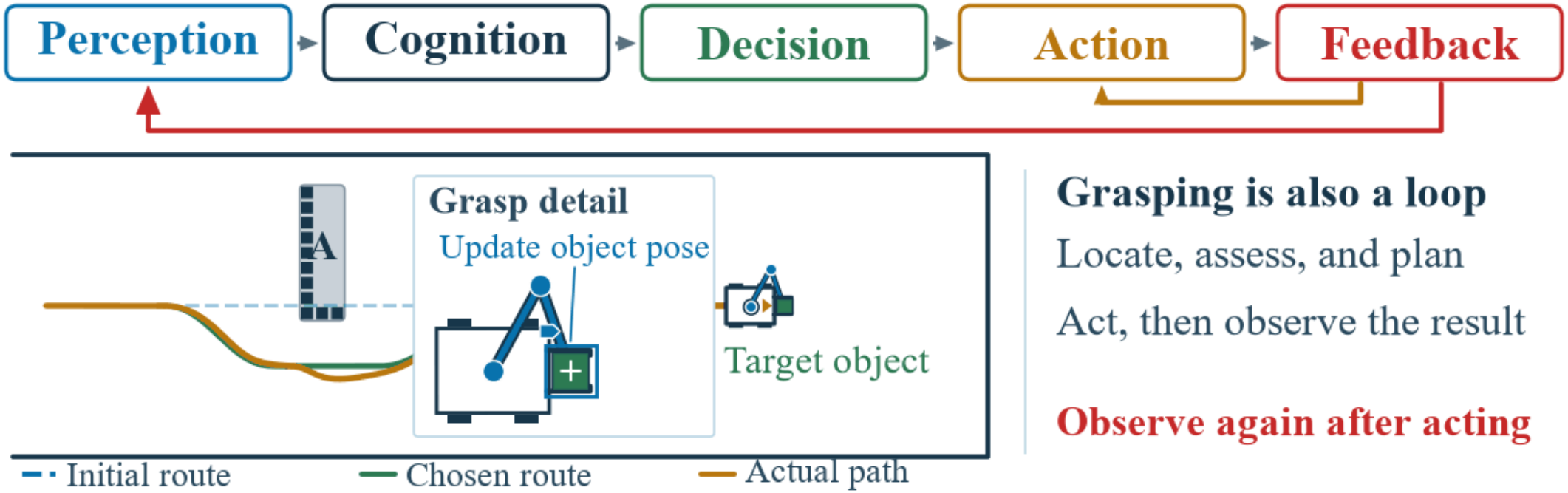
- **Perception and cognition:** Sense the body and surroundings; identify location, obstacles and task needs.
- **Decision and action:** Select a plan; controllers and actuators move the body.
- **Environmental feedback:** Action changes observations, which revise judgments. The body constrains possible actions.
- **Relationship:** Driving combines road perception and vehicle control. Manipulation also coordinates joints, end effectors and contact forces. Both can be embodied intelligence; joint count is not the criterion.



Embodied intelligence turns judgment into bodily action, showing its abilities through environmental interaction.

1.1.1 Intelligent Unmanned Systems: Avoidance and Grasping

Obstacle Avoidance, Then Grasping: Two Task Loops



Grasping is also a loop

Locate, assess, and plan

Act, then observe the result

Observe again after acting

Avoidance and grasping each close the perception–cognition–decision–action–feedback loop.

To handle change, machines must correct actions and revise plans when needed.

1.1.1 Intelligent Unmanned Systems: Task Priorities

Vehicle Mobility and Embodied Manipulation



- **Motion tasks:** Cruising, search and transport stress position, trajectory and attitude. Perception supports navigation and avoidance.
- **Contact tasks:** Grasping, assembly and wall probing stress end-effector position, contact force and task results.
- **Coordination:** Prioritize mobility in transit, then coordinate position and force in contact. Autonomous navigation can also be embodied intelligence. In some typical settings, vehicle systems stress motion > perception > manipulation, while embodied intelligence stresses manipulation > perception > motion.

Motion stresses trajectory and attitude. Manipulation stresses joints, end effectors and contact force. Tasks set priorities.

1.1.1 Intelligent Unmanned Systems

Vehicles and Embodied Intelligence

Key point: Embodied intelligence extends beyond humanoids. Human-like bodies suit everyday human environments; specialized tasks and industries can use purpose-built forms.

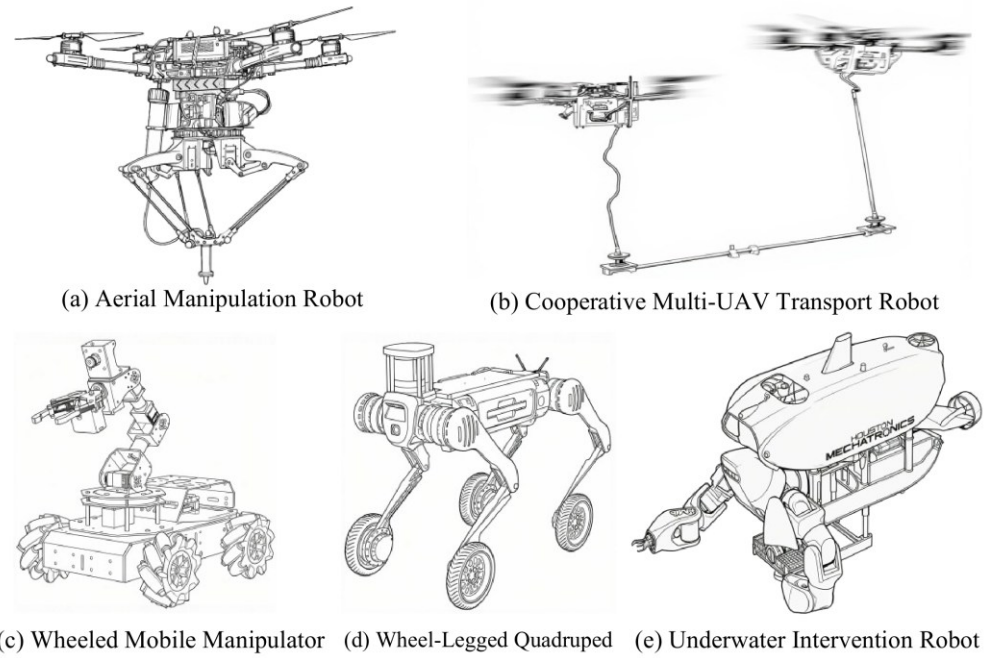


Fig. 1.2 Embodied Unmanned Systems

Unmanned vehicles and embodied intelligent systems converge on mobility plus physical interaction:

- **Aerial work:** Drone-mounted arms combine flight and grasping. Cooperative lifting coordinates vehicles and payloads—an example of aerial embodied intelligence.
- **Ground and underwater work:** Wheeled, wheeled-legged and underwater intervention robots combine mobility with manipulation.
- **Shared mechanism:** Perception interprets the environment; decision coordinates motion and manipulation; execution feedback corrects later actions.

Combining mobility and manipulation lets machines reach a site and do the work there.

1.1.1 Intelligent Unmanned Systems

Shared Development Framework

Note: Drones, autonomous driving and robotics increasingly share methods and tools, accelerating the evolution of unmanned systems.

- **Common functions:** Organize different vehicles by perception, understanding, decision, control and execution. Connect modules through explicit data and action interfaces.
- **Shared methods and data:** Reuse recognition, map representations, path planning and simulation training. Share data and training experience when tasks and sensing conditions match.
- **Body differences:** Aircraft, ground vehicles and robotic arms differ in action spaces, dynamics and contact conditions. Adapt execution interfaces and low-level control to reduce repeated high-level development.
- **Inspection example:** Drones and ground robots can share crack recognition. To reach the same inspection point, one plans a flight path and the other a traversable ground route.

Sharing perception and decision experience may reduce repeated development across robots.

1.1.1 Intelligent Unmanned Systems

Understanding Problems and Organizing Tasks

Note: Embodied intelligence coordinates body, cognition and environment. Disembodied intelligence emphasizes information processing; the two can be integrated.

- **Definition:** Disembodied intelligence processes information to reason and generate outputs without a body in a physical task loop. Embodied intelligence includes bodily action and environmental feedback.
- **Model capabilities:** Language models process text and code. Multimodal models also use images and other inputs, e.g. ChatGPT analyzing inspection photos and writing a report.
- **Task agents:** Agents use models and tools toward a goal, continuing from tool results, e.g. Codex reading code, editing programs and running tests.
- **Models and execution:** Models supply capabilities. Agents organize tasks. Physical execution also needs control and feedback. Reports and software test results are information outputs, not robot actions.

Information processing helps people understand problems and can support physical action within an embodied loop.

1.1.1 Intelligent Unmanned Systems

Inspection: Analysis and Physical Action

Task: Identify facility defects and complete an inspection

Note: Large disembodied models may respond too slowly for real-time embodied perception and decision. Their integration requires a suitable architecture.

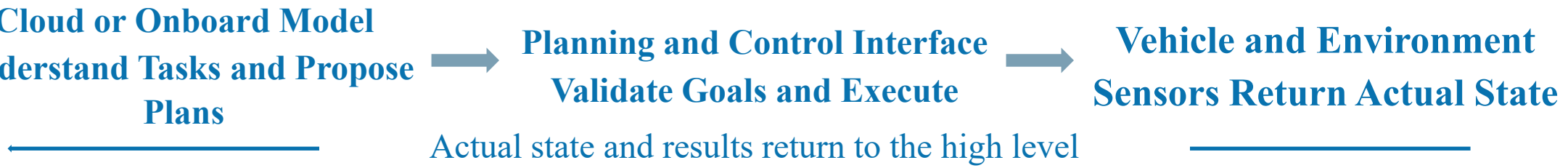
Comparison	Disembodied: Inspection Analysis	Embodied: Autonomous Inspection
Input	Photos, descriptions and records	Updated observations and the robot's own state
Output	Defect report or inspection plan	Physical action via planning and control
Feedback	Retrieval and software tool results	Motion and manipulation change observations
Assessment scope	Standalone information assistant or model application	Body–algorithm–environment interaction

Embodiment concerns physical interaction; cloud and onboard describe computation location.

For large AI models to act on their advice, reasoning must connect to physical action.

1.1.1 Intelligent Unmanned Systems: Model Interfaces

Cloud and Onboard Models in One Physical Task Loop



- **Cloud calls:** Access remote models and centralized computing. Networks affect data transfer and response time.
- **Onboard operation:** Less reliance on external networks suits local perception and interaction, but computing, memory and power are limited.
- **Layered roles:** The model turns "inspect this wall" into subgoals such as inspection points. Planning and control turn them into feasible motion. Sensor feedback checks results. Interfaces limit actions and retain stop and takeover options.

Turning model plans into physical action requires sensing, execution and feedback on results.

1.1.1 Intelligent Unmanned Systems

Tool Calls and Device Operation

Note: Desktop agents such as Claude Code, Codex and Workbuddy already automate most software tasks. The trend is toward physical-world execution.

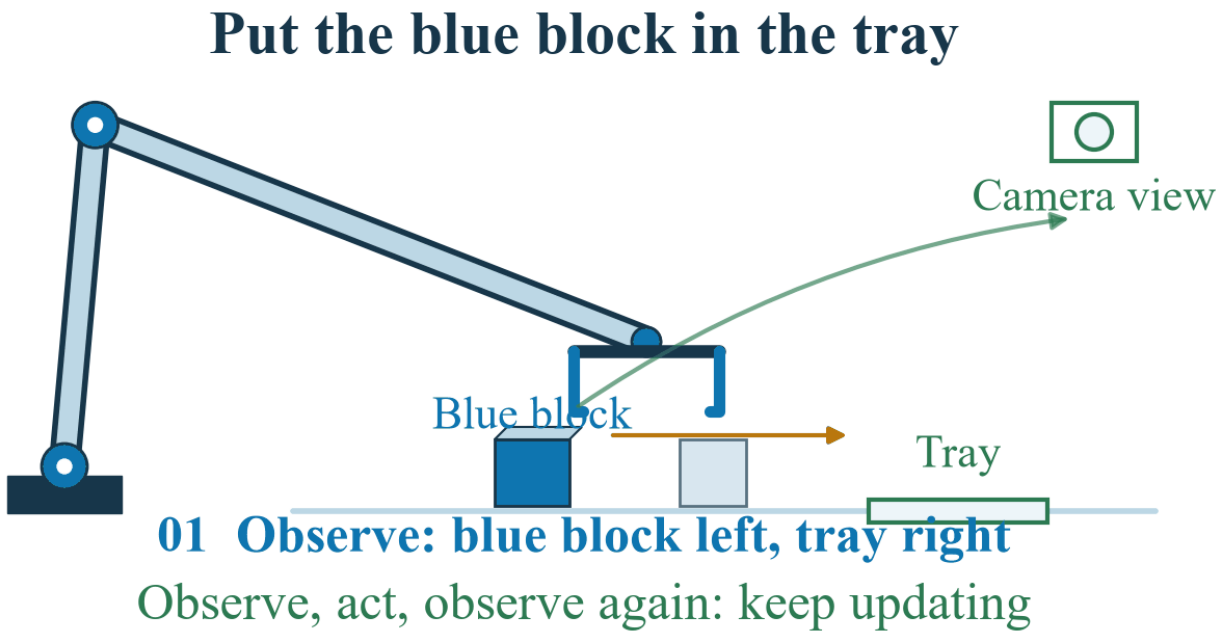
- **Trend:** Large AI models are expanding from answers and content generation to tool calls, device-state reading and physical task coordination, using real feedback to adjust later tasks.
- **Interfaces:** Expose device capabilities, readable states and available actions through a common interface. Agents organize tasks. Drivers and controllers convert commands into physical action.
- **Example:** Anthropic's Model Hardware Standard (MHS) protocol connects pipettes, robot arms and plate readers. Agents coordinate devices and adjust experimental parameters from measurements.
- **Layered execution:** Models handle slower task orchestration. Local deterministic programs handle fast actions. Device control, permissions and emergency stops remain independent to keep operations controllable.

MHS research preview (2026-08): https://www.modelhardwarestandard.com/

Beyond calling device functions, models can learn to turn human requests into actions.

1.1.1 Intelligent Unmanned Systems: Vision–Language–Action (VLA) Models

Instructions and Actions in a Perception–Action Loop



- **V, Vision:** Locate the blue block and tray.
- **L, Language:** Specify "put the blue block in the tray."
- **A, Action:** Output position and gripper opening/closing targets.
- **Loop:** The controller executes a short action segment. New observations update later actions.

VLA architecture and action sequences (paper, Sec. III): https://arxiv.org/abs/2604.15483

Understanding instructions is only a start. Robots must learn task execution from manipulation experience.

1.1.1 Intelligent Unmanned Systems: VLA Training and Transfer

Learning Actions from Vision-Language Knowledge and Robot Demonstrations

Vision-Language Model
Understand the Scene and Task → **Action Generation Module**
Incorporate Robot State → **Numerical Action Commands**
Joints / End Effector / Gripper

- **Training:** Pretraining links objects and language. Robot demonstrations record images, instructions and actions. Updating model parameters teaches action selection from observations.
- **Action representation:** Encode actions as discrete tokens and decode them into numbers, or generate continuous sequences with an action network. Controllers track joint or end-effector targets. Post-action observations become the next input.
- **Benefits and limits:** Shared semantics and manipulation experience help transfer to new objects or instructions. Transfer across robots still depends on training data, action interfaces and workspace limits. Retrain or adapt when needed.

VLA training, action encoding and transfer: https://openvla.github.io/

After learning how to act, predicting consequences can further support autonomous decisions.

1.1.1 Intelligent Unmanned Systems: World Models · Predicting Action Outcomes

Predict What Happens Next from State and Action

Current observation or state

Candidate action

→ **World model** **Predict action outcomes** →

Next state or observation
For policies and planning

- **Compared with VLA:** VLA generates actions; a world model represents environment dynamics and predicts next states from observations and candidate actions, helping planners compare outcomes.
- **Working together:** language or multimodal models interpret tasks; world models predict spatial and dynamic changes; planners compare actions; controllers execute the chosen action.
- **Relation to embodiment:** an optional prediction module for offline reasoning or physical feedback loops. It may use images, states or latent features, beyond explicit 3D scenes.

World models: principles and experiments: https://worldmodels.github.io/

Model trials before real tests may cut the cost of robot trial and error.

1.1.1 Intelligent Unmanned Systems: World Models · Inspection

Compare Routes; Correct Predictions with Observations

- **Compare before acting:** near an occlusion, an inspection vehicle predicts views and collision risks along different routes, then selects an action suited to its task.
- **Learning and testing:** try policies in a predicted environment to reduce physical exploration; then test adaptation to the target environment with independent simulation and real data.
- **Prediction errors:** missed obstacles or incorrect contact predictions can make dangerous actions look feasible. Long rollouts accumulate error and drift from reality.
- **Correct during execution:** use short horizons and update the state with new observations. Keep independent collision constraints, emergency stops and human takeover; generated images are not measurements.

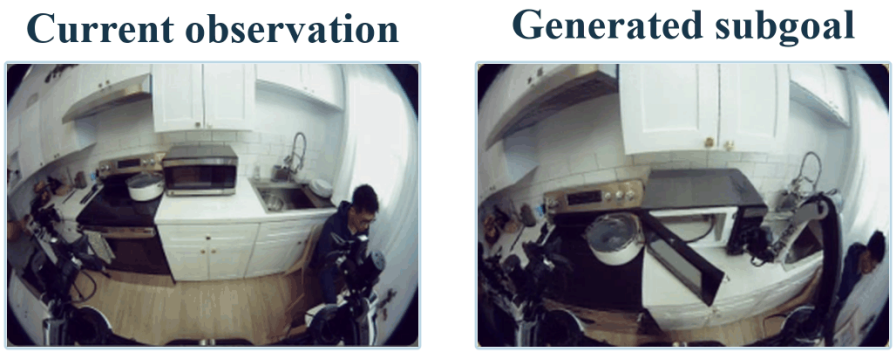
Interactive world model example: https://deepmind.google/models/genie/

Predictions help compare actions; real feedback corrects errors. Both guide decisions.

1.1.1 Intelligent Unmanned Systems: VLA and World Models

VLA Actions and World-Model Subgoals

Press the microwave open button



Physical Intelligence, Fig. 3 (cropped and translated), CC BY 4.0.

- **Demonstrated capability:** π0.7 (2026-04) folded clothes and made coffee in reported evaluations, showing cross-task skill reuse.
- **Mechanism shown:** a world model generates a desired near-future view to guide VLA actions. A goal image does not guarantee the result.
- **Transfer conditions:** No folding-task training data came from the target UR5e setup; data from other robots and related experience were used.

π0.7 task demos and research: https://www.pi.website/blog/pi07

Single-agent trend: VLA actions and world-model goal images can share a physical feedback loop.

1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · Beyond One Agent

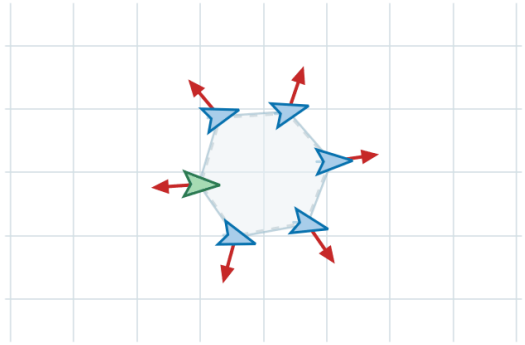
One Agent Has Limits; Task Sharing Extends Coverage

- **Broader scope:** earlier examples focused on one robot interacting with its environment. Larger inspection areas, more targets or parallel tasks shift attention to coordination among agents.
- **Task benefits:** dividing inspection areas expands simultaneous coverage. Air-ground teams combine aerial views with close inspection; spare capacity can cover tasks left by departing nodes.
- **Coordination costs:** concurrent operation brings overlap, route contention and collision risks. State exchange, task allocation and motion coordination also consume communication, computing and support resources.
- **Making cooperation work:** shared goals need clear task allocation and conflict handling. Multiple agents are worthwhile when task benefits offset coordination overhead, not simply because there are more devices.

Multi-agent cooperation can accomplish tasks beyond a single agent's capacity.

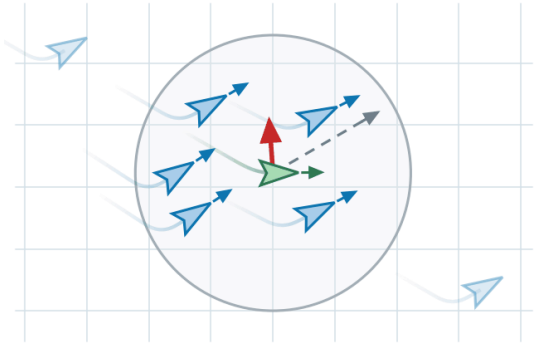
1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · Swarm Intelligence

How Local Interactions Create Collective Behavior



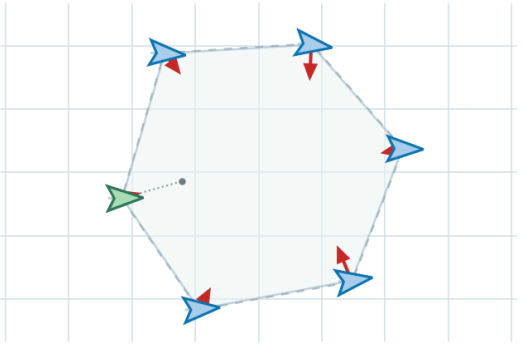
Separation

Avoid close approaches



Alignment

Match neighbors' mean velocity



Cohesion

Move toward the local centroid

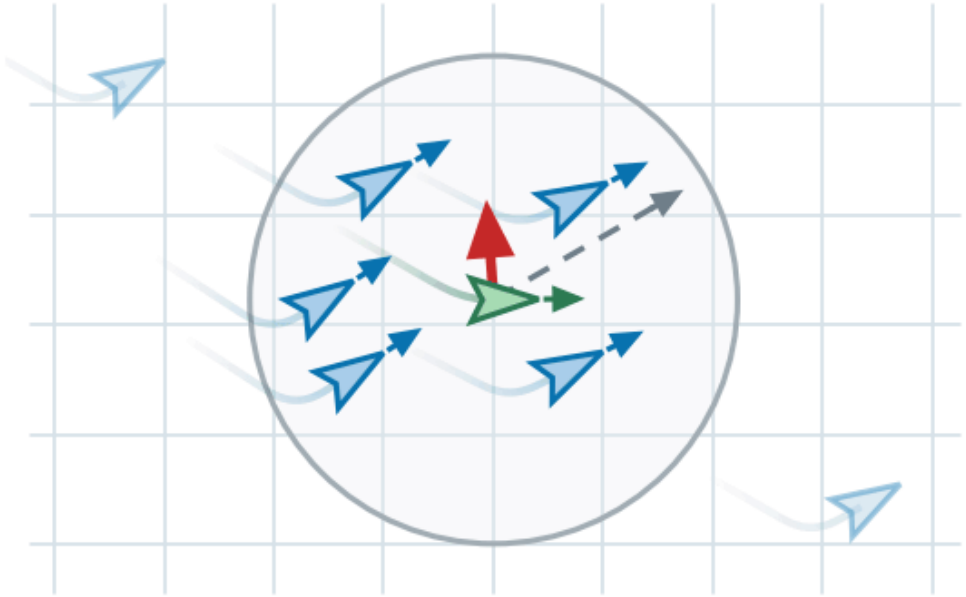
Swarm intelligence studies collective behavior arising from local interactions and self-organization. Boids uses three local rules to model group motion, inspiring coordinated control. Think of cooperation in bee colonies, ant colonies and wolf packs.

Original Boids model and demos: https://www.red3d.com/cwr/boids/

Local rules can create collective behavior; engineering also needs tasks and constraints.

1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · Boids Rules

From Neighbor Velocities to Individual Steering



Average nearby velocities

Gray dashed arrow:
mean velocity direction

Red: steering acceleration

Heading error: 29.3 deg

Outside agents are excluded

Fig.: Neighborhood velocity averaging and individual steering in alignment (teaching simulation)

Local alignment builds a shared direction, a basic mechanism of collective coordination.

1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · System Components

Shared Tasks, Information Exchange and Joint Decisions

- **Intelligent agents:** each node perceives itself and its environment, makes local judgments within its task scope, and acts to complete its assigned work.
- **Communication and coordination:** nodes exchange states and task information. Coordination algorithms allocate targets and adjust routes so local actions serve the shared task with less overlap and conflict.
- **Inspection example:** a UAV shares the location of a suspected defect; a ground robot inspects the site at close range. The result updates the task list, and other nodes adjust their assignments.
- **Organization:** self-organizing swarms emphasize distributed control without a single central node. Multi-vehicle systems may also use centralized or hybrid scheduling, depending on tasks, communication and node capabilities.

Intelligent swarms share information and coordinate action for common tasks; running together is not enough.

1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · Capabilities

Intelligence, Autonomy and Reassignment Enable Adaptation

- **Intelligence:** recognize task objects, interpret the environment and choose actions; use shared images to identify facilities needing reinspection instead of repeating every scan.
- **Autonomy:** navigate and make local decisions within the assigned task without continuous human control. Report tasks beyond the node's capabilities and follow a predefined response.
- **Flexibility:** reassign work when new targets appear or nodes leave, using members with spare capacity. Continuity depends on resources, connectivity and reassignment mechanisms.
- **Heterogeneous complementarity:** UAVs observe large areas; ground or underwater robots perform close-range work. Common information interfaces and task allocation combine their different strengths.

Greater swarm autonomy may shift people from individual piloting to overall task management.

1.1.1 Intelligent Unmanned Systems: Intelligent Swarms · Operation and Oversight

Swarm Coordination and Human Oversight

- **Distributed control and cooperation:** nodes control motion using local and neighboring information. Shared goals constrain task allocation; state and intent updates reduce conflicts and coordinate timing.
- **Reliability:** allocate tasks with battery and fault states in mind. Available members take over when nodes leave, maintaining task execution under specified conditions.
- **Safety and security:** collision avoidance, speed limits and emergency stops reduce harm to people and equipment. Authentication, access control and message validation prevent unauthorized access and manipulation.
- **Serving people and oversight:** people set goals, update priorities and monitor operation. When anomalies occur, they can stop, reassign tasks or take control, with clear responsibility and access to controls.

People supervise swarms through tasking, goal updates and emergency intervention, taking control when needed.

1.1.1 Intelligent Unmanned Systems

Physical Interaction, Reasoning and Swarms

Goal: Artificial General Intelligence (AGI)
Embodiment, swarms and unmanned operation: distinct dimensions

- **Physical interaction:** Vehicles and robots combine mobility with manipulation.
- **Information processing:** Disembodied models add understanding and reasoning when connected to feedback.
- **Cooperation:** Coordinated agents form swarms. Ovals indicate relationships, not strict containment.

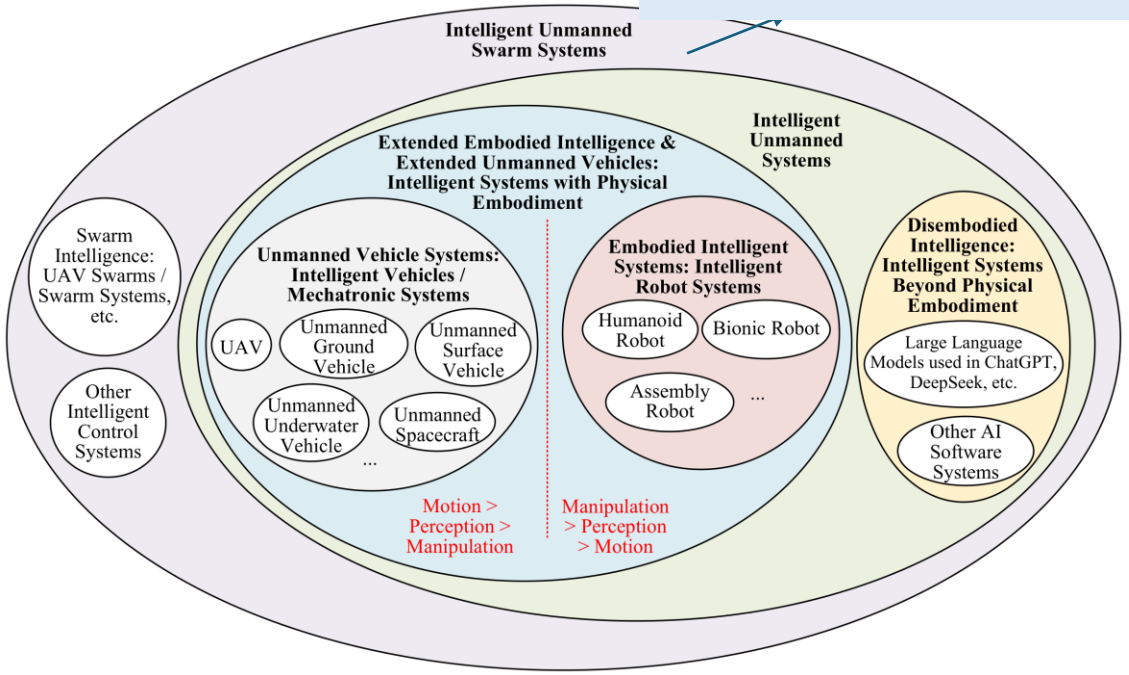


Fig. 1.1 Concepts of intelligent unmanned systems

Unmanned operation, physical interaction and swarm cooperation combine to expand work machines can do for us.

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Textbook: Sec. 1.1.1.2

1.1.3 Platforms and Examples

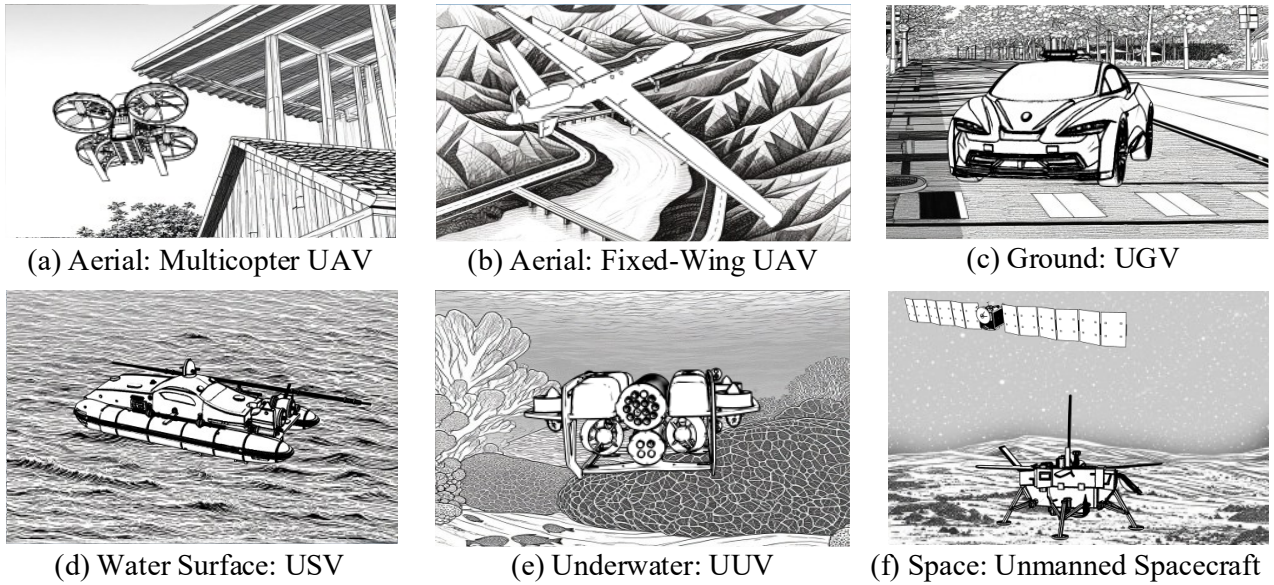
Textbook: Sec. 1.1.1.3

1.1.4 Swarm Applications

Textbook: Sec. 1.1.1.4

1.1.2 Classification Methods: Operating Environment and Vehicle Type

Classify by Operating Domain and Platform Configuration



(a) Aerial: Multicopter UAV (b) Aerial: Fixed-Wing UAV (c) Ground: UGV

(d) Water Surface: USV (e) Underwater: UUV (f) Space: Unmanned Spacecraft

Fig. 1.3 Vehicles by Operating Domain

UGV: unmanned ground vehicle

USV: unmanned surface vehicle; UUV: unmanned underwater vehicle

- **Operating environment:** where it works. Underwater, land and air impose different sensing, communication and motion constraints.
- **Platform configuration:** how it moves. Fixed-wing aircraft need forward flight; rotors permit hovering; airships use buoyancy.
- **Task matching:** environment and configuration limit reach. Then consider payload, work method and deployment.

Classification helps match a platform to a task, beyond simply labeling machines.

1.1.2 Classification Methods: Operating Domains · Common Environments

Constraints Underwater, on Water, on Land and in Air

- **Underwater:** satellite positioning is hard to use directly; water quality limits visibility. Navigation often combines inertial and acoustic data; links may be tethered or acoustic.
- **On water:** wind and waves disturb attitude and track; salt spray corrodes equipment. Hull design, attitude control, sealing and corrosion resistance set sea-state limits.
- **On land:** passage width, slopes and steps limit access. Wheel, track or foot contacts affect traversability; perception guides route choice.
- **In air:** gravity requires continuous support; wind disturbs attitude and position. Aerodynamics, energy and feedback control support flight and payload operation.

A change of environment changes a task's main perception, communication and motion challenges.

1.1.2 Classification Methods: Operating Domains · Special Environments

Special Conditions in Near Space, Space and Beyond Earth

- **Near space (about 20–100 km above ground):** thin air changes aerodynamic support and propulsion. Long stays require day/night energy and thermal management; aerostats and solar aircraft take different approaches.
- **Space:** orbital motion is governed mainly by gravity and inertia, without sustained wing lift. Heat rejection in vacuum, radiation protection and energy management become key design tasks.
- **Beyond Earth:** after landing, local gravity, terrain and lighting shape operation. Long-distance communication is delayed, so rovers need some onboard navigation and obstacle avoidance.
- **Overlapping classes:** extraterrestrial describes the mission location, not a motion type. One planetary mission can include spaceflight, landing and surface exploration.

Environment labels may overlap; the medium, energy and communication conditions set design limits.

1.1.2 Classification Methods: Vehicle Types and Platforms

Support and Propulsion Determine How Platforms Move

- **Wings and rotors:** fixed wings need relative airflow for lift and suit sustained forward flight. Rotors actively move air to hover, requiring continuous power.
- **Buoyant support:** airships use air buoyancy; boats use water buoyancy. Displaced fluid provides most support, but station keeping must still counter wind or current.
- **Wheels, tracks and legs:** wheels roll continuously; tracks spread ground contact. Legs choose discrete footholds, adding balance, contact-control and mechanical complexity.
- **Underwater propulsion:** thrusters produce thrust; control surfaces use relative water flow to change motion. Submersibles also control depth and attitude; buoyancy and thruster layout affect maneuvering.

How a platform moves determines which kinds of work it can do for people.

1.1.2 Classification Methods: Applying the Classification

Power-link Inspection Across the Sea: Task, Then Domain

Inspection target	Domain and key conditions	Candidate platforms and limits
Overhead lines, tower tops	Aerial views: cover the line and approach local defects	Fixed-wing aircraft cover large areas; multicopters hover for close checks
Subsea cables, foundations	Underwater: water quality and currents affect visibility, positioning and work	AUVs: survey lines; ROVs: close checks AUV: autonomous underwater vehicle; ROV: remotely operated vehicle
Shore stations, ground routes	On land: surfaces, steps and narrow spaces limit access	Wheeled, tracked or legged; select by route and work needs

Teaching scenario: one power project includes overhead lines, subsea cables and shore stations.

One project can span domains; each segment's access and work needs determine candidate configurations.

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1.1.2 Classification Methods

Textbook: Sec. 1.1.1.2

1.1.3 Platforms and Examples

Textbook: Sec. 1.1.1.3

1.1.4 Swarm Applications

Textbook: Sec. 1.1.1.4

1.1.3 Platforms and Examples: Vehicle Overview

Five Platform Classes: Typical Forms and Task Constraints

Class	Typical platforms	Tasks and main limits
Unmanned aircraft systems	Fixed-wing, multicopter, VTOL fixed-wing Helicopter, airship, micro rotorcraft, flapping-wing	Imaging, mapping, inspection Endurance; takeoff/landing
Unmanned ground systems	Wheeled, tracked, multi-legged robots Humanoid robots	Transport, inspect, manipulate Terrain and access limits
Unmanned surface vehicles	Unmanned boats and ships Motor or sail propulsion	Surface patrol and mapping Wind, waves and endurance
Unmanned underwater vehicles	Remotely operated and autonomous vehicles Hybrid platforms, large unmanned submarines	Underwater sensing, close work Pressure; communication
Unmanned space systems	Satellites, uncrewed spacecraft, deep-space probes Related launch platforms: reusable rockets	Comms, sensing, exploration Energy and communication delay

VTOL: vertical takeoff and landing — a capability shared by several aircraft configurations.

We next examine each vehicle class's features and strengths, with representative models.

1.1.3 Platforms and Examples: Unmanned Aircraft Systems

Aircraft, Ground Station and Data Link: Distinct Roles

- **System and aircraft:** An unmanned aircraft system (UAS) includes an unmanned aerial vehicle (UAV), ground station and data link. The aircraft carries mission equipment and flies.
- **Autopilot and flight controller:** This book uses autopilot for the general control device. On a UAV, the flight controller estimates state from sensor data and continuously adjusts control outputs.
- **Ground station and link:** The station plans missions, monitors status and enables takeover. The data link connects ground and onboard systems, carrying commands, status and payload data.
- **Operating roles:** The ground plans and supervises; onboard systems control flight. On link loss, onboard capabilities and preset policies determine return, mission continuation or other protective modes.

Unmanned flight needs a full system and a configuration suited to its mission.

1.1.3 Platforms and Examples: UAS / Aerial Configurations

Lift and Hovering in Four Aerial Configurations

> Hybrid VTOL fixed-wing layouts include lift-and-cruise, tail-sitter and tiltrotor designs.

Configuration	Lift source	Hover capability	Tradeoff
Conventional fixed-wing	Wing in forward airflow	Cannot hover	Must keep flying forward
Multicopter	Rotors push air downward	Hovers in place	High continuous power use
Hybrid VTOL fixed-wing	Lift mode varies by layout	Hovers in vertical mode	More complex transitions
Unmanned helicopter	Main-rotor aerodynamic lift	Can hover	More drivetrain upkeep

Hover and long range serve different needs, sustaining multiple flight configurations.

1.1.3 Platforms and Examples: UAS / Conventional Fixed-wing UAVs

How Propulsion and Payload Shape Endurance



CH-4 Rainbow



Wing Loong II

- **Propulsion:** CH-4 (piston) and Wing Loong II (turboprop) are two of China's most representative reconnaissance/strike UAVs, with different weight classes, payloads and customization options.
- **Endurance:** Forward airflow over the wings generates lift, enabling efficient long-range cruise. Fuel adds available energy; mission payloads add weight and drag.
- **Mission choice:** Wide-area mapping and persistent observation favor range and endurance. Fixed-wing UAVs cannot hover, but can circle a target area and aim an electro-optical gimbal for continuous observation and target lock.

Efficient cruise supports endurance; payload and fuel allocation set time aloft.

1.1.3 Platforms and Examples: UAS / Conventional Fixed-wing UAVs

High-altitude Coverage or Medium-altitude Versatility



RQ-4 Global Hawk



MQ-9 Reaper

- **High-altitude coverage:** RQ-4 and WZ-7 emphasize wide-area observation. Altitude expands the view; sensors determine visible detail.
- **Medium-altitude missions:** MQ-9 uses turboprop power. Pay mass affect range and mission capability.
- **Selection criteria:** Coverage and identification accuracy guid aircraft carries sensors; the link returns observations.



WZ-7 (China)

High-altitude reconnaissance favors coverage; medium-altitude roles balance mission and payload.

1.1.3 Platforms and Examples: UAS / Multicopter UAVs

System Integration Makes Hovering a Practical Tool



DJI Mavic 4 Pro



AR.Drone

- **Integrated functions:** AR.Drone and Mavic 4 Pro represent different stages of consumer UAV development. Stabilization, video links and simple controls let users focus on imaging and observation.
- **Inspection value:** Hover and low-speed motion help maintain viewing angles and recheck details. Stable images and easy operation turn configuration capabilities into work efficiency.
- **Development tradeoffs:** Ready-made functions favor ease of use and image quality. Controller changes or added sensors also require open interfaces, power and payload margins; the next platform emphasizes modification.

Integration eases use; research modifications need open interfaces and modifiable systems.

1.1.3 Platforms and Examples: UAS / Multicopter UAVs

Open Systems for Control and Coordination Tests



Crazyflie 2.1: propeller guards



Crazyflie 2.1: bare platform



Size reference

- **Modifiability:** Crazyflie 2.1 provides open firmware and hardware documentation. Developers can modify control code, read states and add modules to study localization and multi-UAV coordination.
- **Repeatable tests:** Propeller guards, the bare platform and a handheld view show its structure and scale. A small platform enables repeated indoor tests under controlled conditions to compare motion before and after changes.
- **Test setup:** Added modules add mass and consume energy and interface resources. List the variables the algorithm must access, the sensors it needs and how the platform will be stopped.

Open micro platforms make control and coordination tests easy to modify and repeat.

1.1.3 Platforms and Examples: UAS / Hybrid VTOL Fixed-wing

Lift Transfer in Lift-and-cruise and Tail-sitter Designs



Zhuoyi ZV15E



V-BAT

- **Lift-and-cruise:** ZV15E adds takeoff/landing rotors to a fixed wing. Rotors provide most lift in takeoff/landing, wings in cruise; idle rotors still add weight and drag.
- **Tail-sitter:** V-BAT stands vertically for takeoff/landing and flies horizontally in cruise. Airframe, payload and controls must suit both attitudes and the transition.
- **Control tradeoff:** Fewer tilting mechanisms simplify the mechanical structure. Lift transfer and changing payload orientation still constrain control and mission support.

Runway independence and efficient cruise drive the exploration of diverse VTOL designs.

1.1.3 Platforms and Examples: UAS / Hybrid VTOL Fixed-wing

Tiltrotor Flight and Transition Constraints



Bell Eagle Eye

- **Power transmission:** Bell Eagle Eye's engine stays in the mid-fuselage. Shafts drive both rotors; the engine does not tilt with the nacelles.
- **Lift transfer:** Rotors provide most lift in hover. Tilting rotors provide forward thrust as the wings take over lift. Speed, attitude and nacelle angle must be coordinated.
- **Mechanics and aerodynamics:** Tilt mechanisms and transmission add complexity. In hover, rotor downwash hits the wings, creating a downward force that requires extra rotor thrust.

Tiltrotors combine hover and cruise; transferring lift is the main transition challenge.

1.1.3 Platforms and Examples: UAS / Unmanned Helicopters

Main-rotor Lift and Tail-rotor Torque Balance



AR500C

- **Main rotor:** Blade pitch (blade mounting angle) adjusts total thrust. Tilting the rotor disk redirects thrust to move forward, backward or sideways.
- **Tail rotor:** Counters main-rotor reaction torque; changing its thrust controls heading.
- **Structural tradeoff:** A large rotor and drivetrain support missions but add stowage, inspection and maintenance demands.

Main-rotor lift enables hover and forward flight; tail rotor and drivetrain affect control and upkeep.

1.1.3 Platforms and Examples: UAS / Unmanned Helicopters

Coordinating Shipboard Takeoff, Stowage and Upkeep



MQ-8C Fire Scout

- **System scope:** MQ-8C's main and tail rotors enable flight. Shipboard missions also need deck guidance, stowage, maintenance and maritime support.
- **Moving deck:** Wind, waves and ship motion keep the deck moving. Approach, takeoff, landing and recovery depend on relative aircraft/deck motion and changing conditions.
- **Support:** Rotor folding saves stowage space; unfolding and maintenance prepare the next flight. Communications, weather, sea state and support capacity limit operations.

Shipboard flight needs reliable takeoff/landing on a moving deck, stowage and maintenance.

1.1.3 Platforms and Examples: UAS / Airships and Aerostats

Buoyancy, Persistence and Environmental Limits



S4000 airborne wind power system



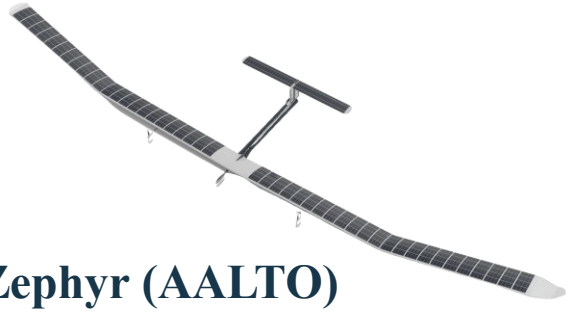
HiSentinel series

- **Buoyancy:** Lighter-than-air platforms stay aloft through envelope buoyancy, unlike aerodynamic wing or rotor lift. Air density affects the required volume.
- **Tethered and free flight:** S4000 uses cables to constrain position, requiring load-bearing tethers and ground support. Airships use onboard propulsion; station keeping depends on wind tolerance and energy.
- **Mission tradeoffs:** High-altitude platforms such as HiSentinel aim for persistent coverage. Envelope volume, wind tolerance, relocation and ground support limit deployment.

Buoyancy supports persistence; tethering, volume, wind and support determine its uses.

1.1.3 Platforms and Examples: UAS / High-altitude Pseudo-satellites

Daytime Power for Flight and the Night Ahead



Zephyr (AALTO)



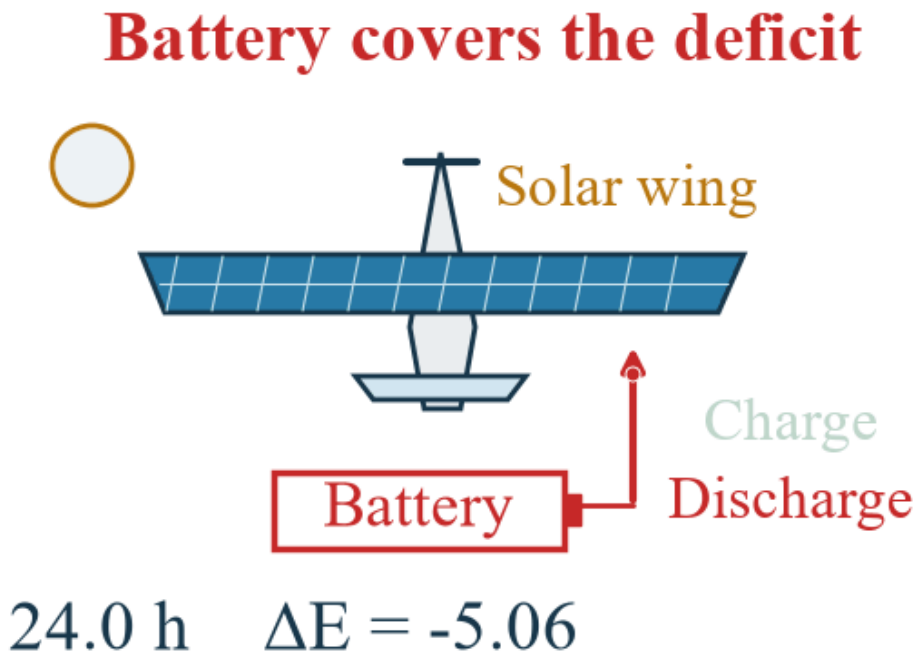
PHASA-35

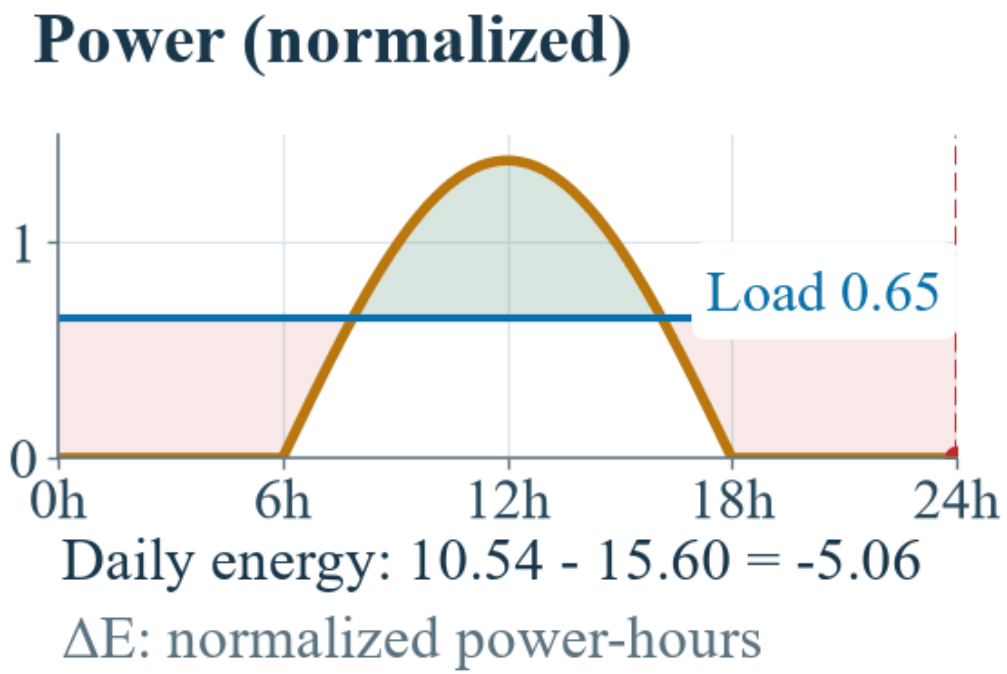
- **Platforms:** High-altitude pseudo-satellites fly persistently in the stratosphere, giving satellite-like coverage within the atmosphere. Zephyr and PHASA-35 are lightweight solar-powered fixed-wing UAVs.
- **Day-night balance:** Daytime generation powers flight and payloads while charging batteries. Stored energy powers night flight; battery mass raises flight energy use, creating a coupled tradeoff.
- **Persistent coverage:** Winds affect the speed and power needed to stay over an area; payloads also consume energy. Energy harvesting, storage and use must sustain the full day-night cycle.

Persistent coverage rests on day-night energy balance, within payload and environmental limits.

1.1.3 Platforms and Examples: UAS / Solar-powered Flight

A 24-hour Energy Budget: When to Charge or Discharge





Day-night charging/discharge: net daily deficit with these parameters (simplified model)

Sustained flight needs a daily energy balance; daytime charging alone is insufficient.

1.1.3 Platforms and Examples: UAS / Micro Air Vehicles

Micro Rotors and Flapping Wings: Mechanisms and Uses



Black Hornet Nano



BionicSwift

- **Micro rotors:** Platforms such as Black Hornet use rotor lift to hover and observe in confined spaces. Small size limits endurance, payload capacity and wind tolerance.
- **Flapping wings:** BionicSwift's moving wings generate both lift and propulsion. Capability depends on endurance, payload and wind tolerance under the mission conditions.
- **Scale tradeoffs:** Micro platforms have limited energy and payload margins. Wind disturbances, sensing errors and manufacturing deviations jointly affect flight control and mission performance.

Small size opens confined spaces but cuts endurance, payload and wind margins.

1.1.3 Platforms and Examples: UAS / Micro Air Vehicles

Tailless Flapping-wing Dynamics and Control



DelFly Nimble

- **Control:** Left/right wingbeat-frequency differences produce roll. Servos change dihedral to shift wings fore/aft for pitch and adjust wing roots for yaw. Wings provide lift and propulsion.
- **Scale and tests:** About 29 g, 33 cm span and 17 Hz wingbeats; over 5 min hovering and about 4 g payload were measured under separate test conditions.
- **Dynamics:** Reynolds number is the ratio of inertial to viscous forces. At low Reynolds numbers, viscosity matters more; wing motion and body response are strongly coupled.

Flapping wings couple lift, propulsion and attitude control; coordination is key.

1.1.3 Platforms and Examples: UAS / Configuration Selection

Hover, Range and Configuration Choice

> Hover, range and launch-site needs call for different configurations and support.

Configuration	Endurance / efficiency	Typical missions	Main limits
Conventional fixed-wing	Usually efficient cruise	Reconnaissance, mapping, surveillance	No stationary hover
Multicopter	Often energy/payload limited	Close-up imaging, inspection	Limited endurance and coverage
Hybrid VTOL fixed-wing	Balances endurance and site access	Medium/long-range mapping, no runway	Airframe and transition-control costs
Unmanned helicopter	Depends on size and powerplant	Rough terrain, shipboard takeoff/landing	Drivetrain and upkeep costs

Close work favors hover, wide areas favor cruise; combining both adds structural and control tradeoffs.

1.1.3 Platforms and Examples: Unmanned Ground Systems (UGS) / Platform Types

Ground Platforms: Roads, Terrain and Manipulation

- **Continuous surfaces:** Wheels roll efficiently for road transport. Wheel size, traction, slope and turning space limit access.
- **Soft or broken terrain:** Tracks spread contact over a larger area, reducing average ground pressure. Turning slip, energy use and track wear add costs.
- **Discrete footholds:** Multi-legged robots choose footholds and adjust posture to cross some obstacles. Better traversability requires contact sensing, balance control and joint actuation.
- **Human environments:** Humanoid robots combine bipedal motion and hand manipulation to use human passages and tools, adding balance, load and human-robot safety demands.

Choosing wheels, tracks or legs balances efficiency, obstacle crossing and manipulation.

1.1.3 Platforms and Examples: UGS / Wheeled Unmanned Ground Vehicles

Rolling Efficiency and Terrain Limits Shape Use



Tesla Cybercab

Rys Pro



- **Wheeled mobility:** Roads, campuses and factory sites favor speed and motion efficiency; soft soil, deep mud and high steps restrict access.
- **Urban missions:** Passenger mobility represented by Cybercab relies on perception and decision-making. Operations cover traffic rules, fallback in abnormal conditions and remote operation.
- **Different settings:** Rys Pro serves battlefield surveillance and support, emphasizing links, payloads and environmental tolerance. Evaluation criteria change with mission and environment, even for a wheeled chassis.

Wheels are efficient on regular surfaces; public roads add rules and abnormal situations.

1.1.3 Platforms and Examples: Ground / Tracked UGVs

Chassis Mobility, Payloads and Communication



Sharp Claw 1



Uran-9

- **Tracks:** More ground contact aids travel through some mud and rubble, at a cost in speed, energy and maintenance.
- **Platforms:** Sharp Claw 1 and Uran-9 differ in weight and mission equipment, so payloads, support needs and uses differ.
- **System limits:** Link quality and interference affect remote control and data return. Autonomy sets the need for real-time human input.

Chassis set access, payloads set tasks, and links and autonomy limit sustained use.

1.1.3 Platforms and Examples: Ground / Electric Quadrupeds

Foot Placement, Posture and Deployment Needs



Unitree Go2



ANYmal

- **Contact and control:** Quadrupeds coordinate footholds, contact and body posture. Series springs in ANYmal's joints cushion landings and aid torque control.
- **Development:** Go2 EDU exposes low-level interfaces. Environmental protection affects field suitability, while interface access determines development scope.
- **Limits:** Slopes, payload and endurance set mission scope. Rain/dust protection and fall recovery affect sustained use. The value of legs depends on terrain.

Quadrupeds adapt to terrain through foot placement, stable contact and body coordination.

1.1.3 Platforms and Examples: Ground / Hydraulic Quadrupeds

Heavy Loads and Dynamic Motion: System Costs



Quadruped Robot

- **Hydraulics and force control:** Two-stage servo valves can regulate cylinders for closed-loop joint force control, supporting heavy-load and dynamic-motion research.
- **Disturbance recovery:** After a side push or slip, the robot restores balance by reselecting footholds and adjusting contact and posture, beyond applying more force.
- **System costs:** Noise, energy use and upkeep limit daily use. Payload, slope and wading capability depend on conditions. Energy replenishment, fault recovery and maintenance time limit sustained operation.

Hydraulics support heavy loads and dynamic motion, at a cost in noise, energy and upkeep.

1.1.3 Platforms and Examples: Ground / Humanoids

Human Workspaces and Development Needs



Unitree G1



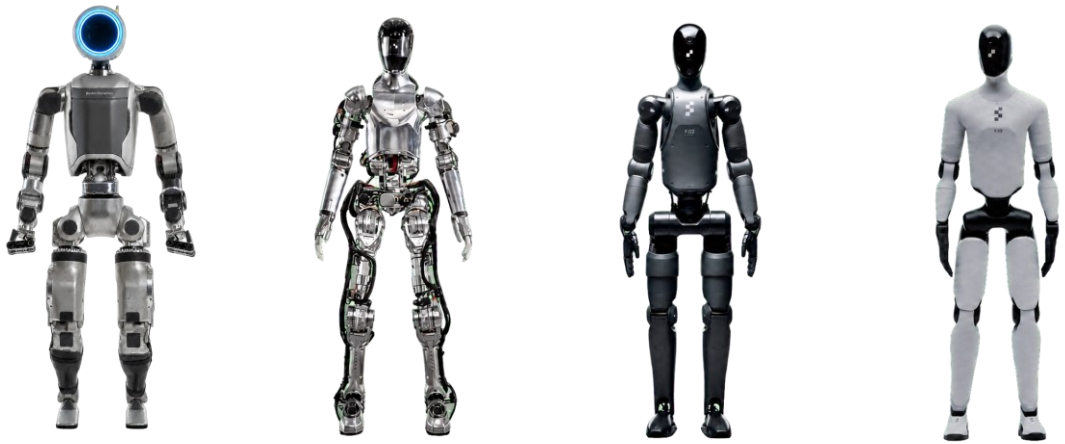
Tesla Optimus

- **Environment:** Stairs, handles, shelves and tools are usually sized for people. Humanoids can use them, but operation still needs balance, motion control and load capacity.
- **Development:** Unitree G1 and Optimus address different development and task needs. Available functions depend on model, generation and interface access.
- **Task metrics:** Carrying needs load capacity, precision work needs motion accuracy. Sustained operation depends on working time, repeated task completion and disturbance recovery.

A key value of humanoids is compatibility with existing human workspaces.

1.1.3 Platforms and Examples: Ground / Humanoids

From Demonstrations to Daily Production



Boston Dynamics Electric Atlas

Figure 01–03

- **Platforms:** Atlas and Figure span different generations. Actuation, configuration and capability depend on the version.
- **Workstation coordination:** Perception identifies objects. Grasping and movement perform the work. Matching these steps to the workstation cycle supports continuous, repeated execution.
- **Operational support:** Protective stops and fall recovery handle faults around people. Energy replenishment and maintenance affect downtime. Together they determine sustained workstation operation.

Production needs reliable daily work, beyond a single demonstration.

1.1.3 Platforms and Examples: USVs / Propulsion and Payloads

Propulsion, Payload and Sea State Set Endurance



JARI-USV-A



Sea Hunter

- **Surface operations:** USVs support surveying, monitoring, patrol and transport assistance. Wind, waves, salt spray, collisions and recovery support limit missions.
- **Mission fit:** JARI-USV-A Orca and Sea Hunter use different energy and mission configurations. Propulsion and equipment both use energy. Payload mass and power demand affect time on station.
- **Tradeoffs:** Speed, endurance, payload and seakeeping define capability. Rapid arrival favors speed, long monitoring favors time on station. Stored energy limits both.

USVs balance response speed and time on station. Payload and sea state affect endurance.

1.1.3 Platforms and Examples: USVs / Sail Propulsion

Wind for Propulsion, Solar for Equipment



Saildrone Family Illustration

- **Energy roles:** Wind provides propulsion. Solar power supports sensing, navigation and communication, suiting long ocean observations with low-power equipment.
- **Wing and weather:** A rigid wing sail uses a tail trim tab to set angle of attack. Storm missions need a shorter, stronger wing, trading thrust against environmental resilience.
- **Mission record:** Explorer ran continuously for 370 days on a specific observation mission. Time on station depends on wind, route, payload power and maintenance.

Wind and solar support long sampling missions, within environmental and payload limits.

1.1.3 Platforms and Examples: UUVs / ROVs and AUVs

Tethered Work or Autonomous Survey

Comparison	Remotely Operated Vehicle (ROV)	Autonomous Underwater Vehicle (AUV)
Information and Control	Operators receive observations by cable and send piloting or work commands	Onboard systems execute missions Subsea links limit real-time intervention
Power and Mobility	Onboard batteries or tether power Tether and handling limit movement	Usually carries its own energy Range: energy, navigation and recovery
Typical Tasks	Close observation, inspection and work Humans can judge details in real time	Survey lines, inspection and sampling Onboard systems decide how to navigate

Tethers extend human subsea operation. Autonomy shifts more local decisions onboard.

1.1.3 Platforms and Examples: UUVs / ROVs

Tethers Carry Control and Data, Power Varies



BlueROV2



Jason

- **Links and power:** The tether carries surface commands and return video. ROVs can use onboard batteries or tether power. Data and power are separate configurations.
- **Observation class:** BlueROV2 uses onboard batteries by default. Six thrusters control five degrees of freedom except pitch. Eight add pitch, controlling all three translations and rotations.
- **Work class:** Jason uses a relay vehicle to isolate ship heave, with power and launch/recovery support. Sustained seafloor work needs vehicle, tether and support vessel together.

ROV endurance depends on power, tethers and recovery support for remote subsea work.

1.1.3 Platforms and Examples: UUVs / Full-Ocean-Depth ROVs

At 10,000 m: Pressure, Tethers and Recovery



KAIKO ROV

- **Architecture:** A ship lowers KAIKO's launcher (relay platform) on a main cable, then deploys the vehicle on a secondary cable. KAIKO reached 10,911 m in 1995.
- **Deep-sea limits:** Pressure is about 110 MPa at 11,000 m. Pressure-resistant structures, cable weight and drag, connector reliability and handling capacity limit depth and working conditions.
- **Failure lesson:** The 2003 vehicle loss involved the 250 m secondary cable, not the 12,000 m main cable. A local connection can affect the entire system.

At 10,000 m, pressure resistance, tethers and ship support enable deployment and return.

1.1.3 Platforms and Examples: UUVs / Deep-Sea AUVs

Untethered Travel Needs Onboard Power and Navigation



Qianlong III



Autosub Long Range

- **Autonomous travel:** Qianlong III and Autosub Long Range carry their own energy and navigate autonomously for the mission. Umbilical length does not directly limit range.
- **Navigation:** Underwater position estimates combine inertial, velocity, depth or acoustic data. Error accumulation and opportunities for position correction set long-range accuracy.
- **Mission limits:** Onboard energy and limited underwater links constrain operation. Return energy, lost-link handling and recovery conditions limit range and duration.

Untethered range shifts more energy, positioning and recovery responsibility onboard.

1.1.3 Platforms and Examples: UUVs / Hybrid AUV/ROV

Hybrid Modes Combine Autonomy and Human Input



Sabertooth Hybrid AUV/ROV

- **Autonomous phase:** The vehicle navigates and inspects for the mission, reducing continuous manual piloting.
- **Intervention:** Fiber-optic tether or underwater optical links allow manual approach and intervention.
- **Resident setup:** A docking station recharges and exchanges data. Navigation, docking and energy support continued work.

Modes and options: https://www.saab.com/products/sabertooth

One platform can switch between autonomous travel and real-time work as the task changes.

1.1.3 Platforms and Examples: UUVs / Portable AUVs

Portability, Payload and Deployment Support



REMUS 100

- **Portability:** REMUS 100's small hull eases transport, launch and recovery, supporting rapid deployment and repeat missions in shallow water.
- **Space:** A small hull diameter limits room for batteries, thrusters and sensors. Energy and payload limits constrain range and mission duration.
- **Module fit:** Payload changes can alter weight, buoyancy distribution and power use. Interfaces, positioning accuracy and recovery conditions set suitability.

Portable AUVs deploy quickly; longer missions or heavier payloads need more energy and space.

1.1.3 Platforms and Examples: UUVs / Large Unmanned Submarines

Larger Hulls Add Capacity and Deployment Demands



HSU-001

- **Space:** A larger hull has more room for energy storage and payloads, supporting different mission configurations.
- **Deployment:** Size and weight raise transport, lifting and launch/recovery needs. Support facilities must match.
- **Sustained missions:** Energy enables operation. Navigation error, communication and recovery plans limit range.

Larger hulls add capacity. Modular designs let one hull serve different missions.

1.1.3 Platforms and Examples: UUVs / Extra-Large Unmanned Submarines

Modular Payloads Reuse Hulls and Need Integration



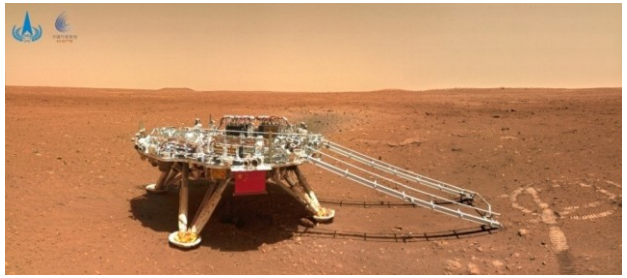
Orca: Extra-Large Unmanned Underwater Vehicle (XLUUV)

- **Mission modules:** Orca swaps modules to reuse its base platform across missions. Modules also change payload and energy needs.
- **Integration:** Swaps may alter weight, center of gravity and buoyancy. Power demand and interfaces affect power supply and control. Stored energy, navigation corrections and recovery support limit mission scope.
- **Scale:** Small platforms ease transport and deployment. Larger ones carry more energy and payload. Wider coverage usually raises launch, recovery and maintenance demands.

Swappable mission equipment reuses the development investment in a proven platform.

1.1.3 Platforms and Examples: Space / Exploration and Launch

Exploration vs. Reusable Launch



Tianwen-1 Probe



Falcon 9

- **Planetary exploration:** Tianwen-1 explores Mars. Entry, descent, landing and roving are interdependent. Successful transitions enable mission completion.
- **Launch and reuse:** Falcon 9 transports payloads and reuses some components. Recoverable parts, reflight count and preparation between launches shape repeated transport capability.
- **Metrics:** Exploration measures mission completion and findings. Reusable launch measures effective delivery, component reuse and turnaround.

Exploration needs linked mission stages. Reusable launch needs repeated transport.

1.1.3 Platforms and Examples: Space / Recovery and Reuse

Recovery Methods and Reflight Preparation

Starship



Long March 10B





- **Recovery scope:** First stages, upper stages or other parts may be recovered, depending on system design.
- **Recovery methods:** Vertical landing, mechanical capture and net recovery describe how, separately from which parts. The lower center image shows Long March 10B net recovery.
- **Repeat transport:** Recovered parts need inspection, repair and reflight. Maintenance effort and turnaround affect cost and transport frequency.

Reuse can cut transport costs only with repeated flights and efficient refurbishment.

1.1.3 Platforms and Examples: Applying Platform Selection

Cross-Sea Inspection: Match Platforms to Tasks

Task Stage	Selection Basis	Platform Role
Line Survey / Detailed Inspection	Wide-area efficiency differs from close-range hovering	Fixed-wing or VTOL for surveys; multirotors inspect suspect sites
Subsea Cables: Survey / Follow-Up Inspection	Survey-line cruising differs from detailed real-time inspection	AUVs survey along planned lines; ROVs verify underwater anomalies
Shore Stations and Support	Surface, steps, tool use, and launch/recovery needs vary	Ground platforms inspect stations; ships or shore stations provide support

Shared output: anomaly records with location, time and quality notes for follow-up inspection.

Each stage needs the right platform; the whole mission needs coordination.

Chapter Outline

Chapter 1: Concepts, Principles and Experiments

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

4 Units in This Section

1.1.1 Intelligent Unmanned Systems

Textbook: Sec. 1.1.1.1

1.1.2 Classification Methods

Textbook: Sec. 1.1.1.2

1.1.3 Platforms and Examples

Textbook: Sec. 1.1.1.3

1.1.4 Swarm Applications

Textbook: Sec. 1.1.1.4

1.1.4 Swarm Applications: Task Decomposition

Cross-Platform Inspection: From Shared Goal to Tasks

- **Shared goal:** cover lines, subsea cables and shore stations as required; record suspect-site checks. Flying or sailing through alone is insufficient.
- **Complementary roles:** aerial observation, underwater cable access and ground access to shore stations. Assign by reach, sensors, energy and deployment site.
- **Task handoffs:** surveys locate suspect sites; follow-up platforms accept jobs and return evidence. Update one task list to reduce gaps and duplication.
- **Shared status:** report progress, position and available resources. If a node leaves, others can take over only with the right capabilities and capacity.

Let each platform use its strengths, then connect the results into a complete job.

1.1.4 Swarm Applications: Organization

Formations Coordinate Motion; Swarms Organize Tasks

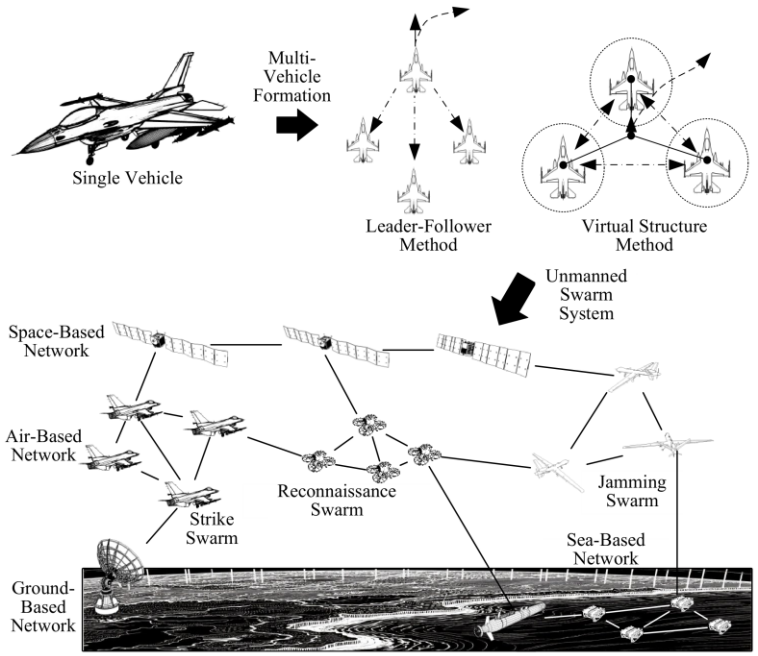


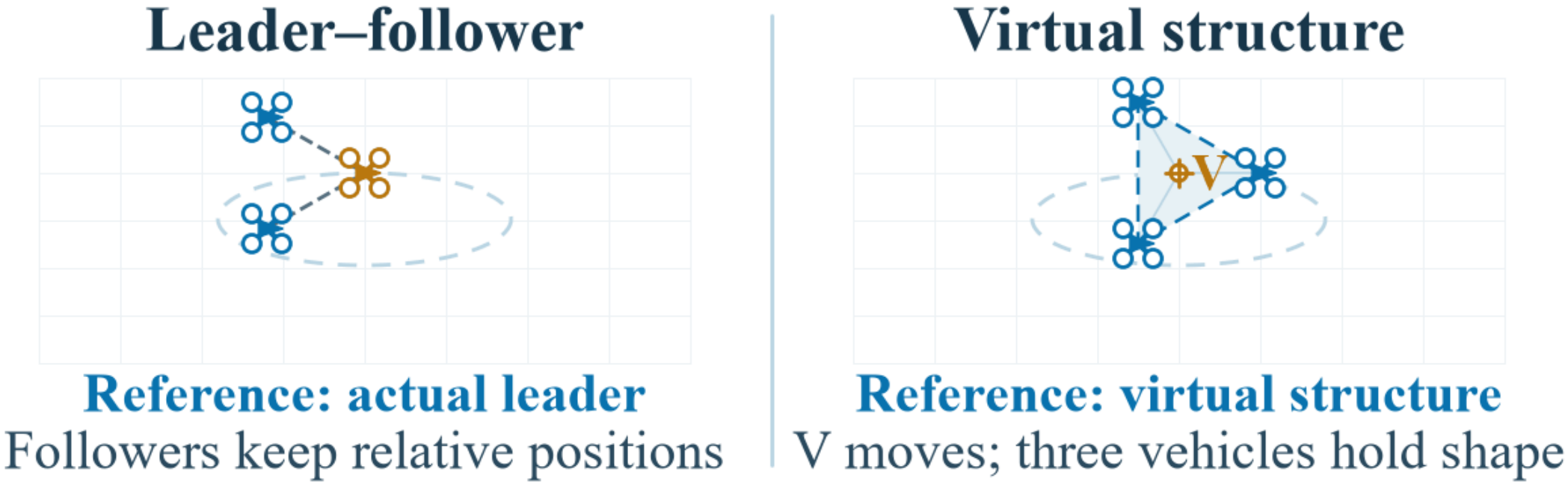
Fig. 1.4 From Single Units to Swarms

- **Formation (top):** holds a set geometry, usually with no more than a few dozen nodes. Leader-follower: maintain positions relative to a leader. Virtual structure: track points on a virtual rigid body.
- **Swarm (bottom):** sea, air, ground and space platforms divide roles for a shared task; scale may reach hundreds or thousands.
- **Inspection:** area surveys, shared suspect sites and follow-up assignments need coordination without a fixed formation.

Formations coordinate motion; swarms organize tasks. Count alone cannot define them.

1.1.4 Swarm Applications: Formation Methods

Leader-Follower and Virtual Structure: References



Reference: actual leader
Followers keep relative positions

Reference: virtual structure
V moves; three vehicles hold shape

Figure: Leader-follower and virtual structure references (simplified kinematics)

Formation control coordinates individual motion into a prescribed spatial pattern.

1.1.4 Swarm Applications: Information and Decisions

Who Decides? Centralized, Distributed and Hybrid Organization

Organization	Information and Task Decisions	Cross-Sea Inspection: Role and Cost
Centralized	Members report status; the center assigns follow-up jobs	Supports global scheduling; depends on the center and uplinks
Distributed	Nodes use local and shared data to negotiate or adapt roles	Responds locally; incomplete data require resolving duplicates and conflicts
Hybrid	Center sets areas and priorities; local nodes coordinate execution	Global planning plus local response; needs clear authority and handoffs

Organization sets information access and task assignments; platforms control their own motion.

1.1.4 Swarm Applications: Information and Task Flow

Close the Loop: Detection, Assignment and Follow-Up

- **Detect and mark:** survey nodes report location, time, observation evidence and quality. Use a shared position reference so follow-up platforms find the same object.
- **Assign and confirm:** the scheduler or coordinating nodes select by capability, distance and capacity. Acceptance prevents unassigned sites and duplicate dispatch.
- **Inspect and report:** approach for detailed evidence; report complete, failed or pending. Different sites can run in parallel; locate each site before inspection.
- **Update tasks:** write results to the shared list; new evidence closes a case, triggers another check or sends it to a human. Use the latest task state, not just position.

Coordination turns one machine's finding into work another can take over.

1.1.4 Swarm Applications: Interfaces and Reconfiguration

Open Interfaces Let Different Platforms Continue the Work

- **Shared meanings:** use consistent coordinates, time, object IDs and task states. Matching field names still mislead if units or reference frames differ.
- **Available capabilities:** report sensors, reach, remaining energy and operating status. Match tasks to capability; nodes are not freely interchangeable.
- **Task handover:** departing nodes release unfinished jobs; replacements inherit location, evidence and progress. Reassignment reduces repeat scans and gaps after interruption.
- **Modular organization:** open interfaces combine functions. Military concepts such as Mosaic Warfare also emphasize modularity and network reconfiguration; capability still depends on interfaces and resources.

Handover of task state lets a swarm keep working as its members change.

1.1.4 Swarm Applications: Faults and Continuity

How Does the Mission Continue After Link or Node Failure?

- **Delayed data:** use timestamps to reduce trust in stale observations and status. Pause coordination needing live data; keep local avoidance and preset protection actions.
- **Node departure:** return unfinished jobs to the unassigned list. Reassign to members with the payload, reach and energy; do not divide them equally by default.
- **Low energy:** recover or return early and release future tasks. Leave margins in replenishment and replacement plans instead of waiting for exhaustion.
- **Too few resources:** reduce coverage or frequency, or seek human help; log unfinished jobs. Test these responses under delays, node departures and energy changes in simulation and field trials.

Swarm reliability also means reorganizing the remaining resources when members leave.

1.1.4 Swarm Applications: Military Uses

Changing Platform Roles and Task Organization

> Small UAVs in the Russia-Ukraine conflict serve varied roles, which alone do not make a swarm.

Operational Stage	UAV Task	Effect on Operations
Reconnaissance	Survey forces and equipment by area	Less need for close-in scouting
Targeting Support	Acquire targets; correct fire	Separate recon and strike roles
Strike	Conduct strikes directly	Switch between recon and strike

Small platforms span recon, targeting support and strike, changing roles and task allocation.

1.1.4 Swarm Applications: Civil Uses—Low-Altitude Airspace

UAS Traffic Management (UTM): Role and Limits

- **Scope:** UAS Traffic Management (UTM) coordinates flight intent and airspace use and supports conflict management; it does not replace individual UAV flight control.
- **Plans and airspace:** routes, times and mission types express flight intent. Available airspace affects operations; permissions follow the applicable rules.
- **Conflict management:** routes and flight intent reveal potential conflicts. Warnings of conflicts or boundary violations guide adjustments and human intervention.
- **Onboard execution:** perception detects local obstacles; flight control executes motion commands. Airspace coordination, onboard control and human intervention jointly support operations.

Scaled UAV operations need stable flight and well-managed shared airspace.

1.1.4 Swarm Applications: Uses and Challenges

Four Key Advances Needed for Practical Swarms

- **Ad hoc networking:** moving nodes change connectivity. Networks must reconfigure automatically and deliver status and task messages with low delay despite intermittent links.
- **Cooperative control:** distributed nodes use local information. Adapt local decisions to changing conditions while keeping them aligned with the overall mission.
- **Hybrid virtual-real training:** high-fidelity simulation recreates outages, node departures and complex settings. Repeatedly train and test policies, then validate on real vehicles.
- **Game theory and adversarial operation:** under jamming, deception or opposition, anticipate opponents, protect nodes and still complete the mission.

Practical swarms must keep cooperating as members and links change.

Class Exercise: Analyze a Complete Mission

Cross-Sea Inspection: Classification, Selection and Coordination

- **Task:** inspect overhead lines, subsea cables and shore stations; examine suspect sites closely. Ships and shore stations support operations; account for actual environmental conditions and endurance limits.
- **Classify and select:** specify domains, approaches and candidate configurations. Explain why survey and follow-up may need different platforms; no model names required.
- **Autonomy and coordination:** assign decisions to people or onboard systems. Show how survey results trigger follow-up and what information both share.
- **Faults and evaluation:** one follow-up unit leaves. Explain how work continues; compare coverage, verification quality, time and resources before and after.

Body ≠ decision-making; joint flight ≠ distributed control; no human on site ≠ autonomy.

Reference Analysis: Classification and Capabilities

Select Platforms, Then Assess Autonomy and Interaction

- **Platforms:** air for overhead assets, underwater for cables, ground for shore stations. Select configurations by coverage, hovering, access and real-time operation.
- **People:** set areas, review suspect sites and take over remotely. Onboard systems may stabilize, navigate and avoid local obstacles within defined conditions.
- **Interaction:** stored-photo analysis processes information. Autonomously approaching a suspect site and adapting to fresh observations maintains ongoing body−environment interaction.
- **Capability limits:** a tethered ROV can hold depth automatically; equipping a UAV with a robotic arm does not ensure autonomy. Judge the actual division of perception, decision, action and feedback.

Human involvement and physical interaction are separate criteria; systems can combine traits.

Reference Analysis: Organization and Evaluation

Evaluate Coordination Through Handoffs and Results

- **Coordination evidence:** survey findings trigger follow-up assignments; status and verification evidence return to the shared list. Observable handoffs require information to change subsequent action.
- **Performance:** for the same area and quality requirements, compare coverage, verification quality, completion time, energy and labor. Adding nodes can also raise organizational costs.
- **Mission continuity:** reassign a departed node's unfinished jobs by capability and resources. Record added time, gaps in inspection coverage and human intervention to assess continued operation.
- **Transfer the method:** analyze marine observation, warehouse logistics and other uses through tasks, capabilities, information, roles and results. Metrics and failure consequences change with the mission.

Judge autonomy by independent action, coordination by joint work, and value by the task.

Class Discussion

Adapt Platforms and Organization When Conditions Change

Change one mission condition; explain why platform choice, roles and evaluation change.

1 Terrain: Roads to Gravel and Steps

Which now: wheels, tracks or legs?
What extra actuation and control costs?

2 Task: Survey to Detailed Follow-Up

Which aerial and underwater types?
Changes in viewing distance and human roles?

3 Resources: 200 Nodes, 30% Offline

What still works; which tasks must shrink?
Judge by connectivity, payloads and reserves.

4 Load: Cargo to Passengers

Extra protection, comfort and support needs?
What do passenger carriage and driverless operation mean?

Our wish for machines to work for us keeps unmanned systems evolving.