Keep Critical Systems Working

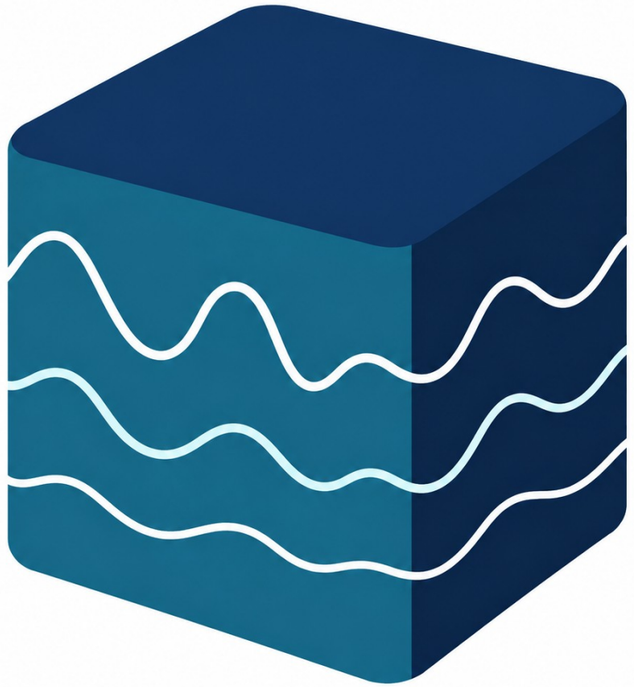
让关键系统可靠运行

Critical AIOps
基于本地 AI 的关键系统智能运行维护

清华大学 裴丹

Dan Pei, Tsinghua University

Local AI for critical systems



TimeSeries Code

Critical Systems and Time-series Intelligence

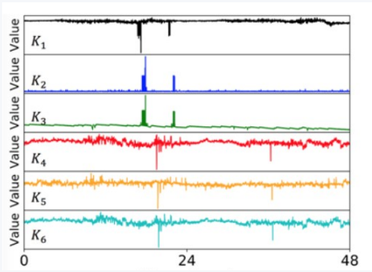
关键系统：关键基础设施及重大生产科研装置

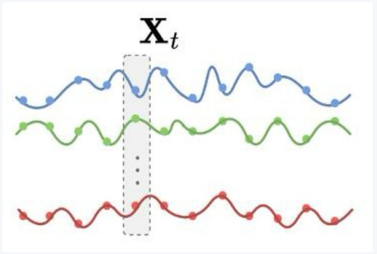
时序：按时间顺序记录的指标值

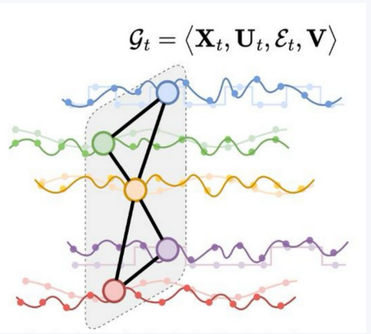
Time series: metric values recorded over time

温度、振动、功率与运行指标，
反映系统的运行状态。结合本地数据与
系统知识，支持故障调查、维护安排。

Temperature, vibration, power and operational metrics record how systems change. Local data and system knowledge guide fault investigation and maintenance.







已有大量时序算法与模型

预测、异常检测、因果分析、时空分析等

Forecasting, detection, causal and spatiotemporal methods...

感知状态 → 形成证据 → 推理与预测 → 支持运行决策

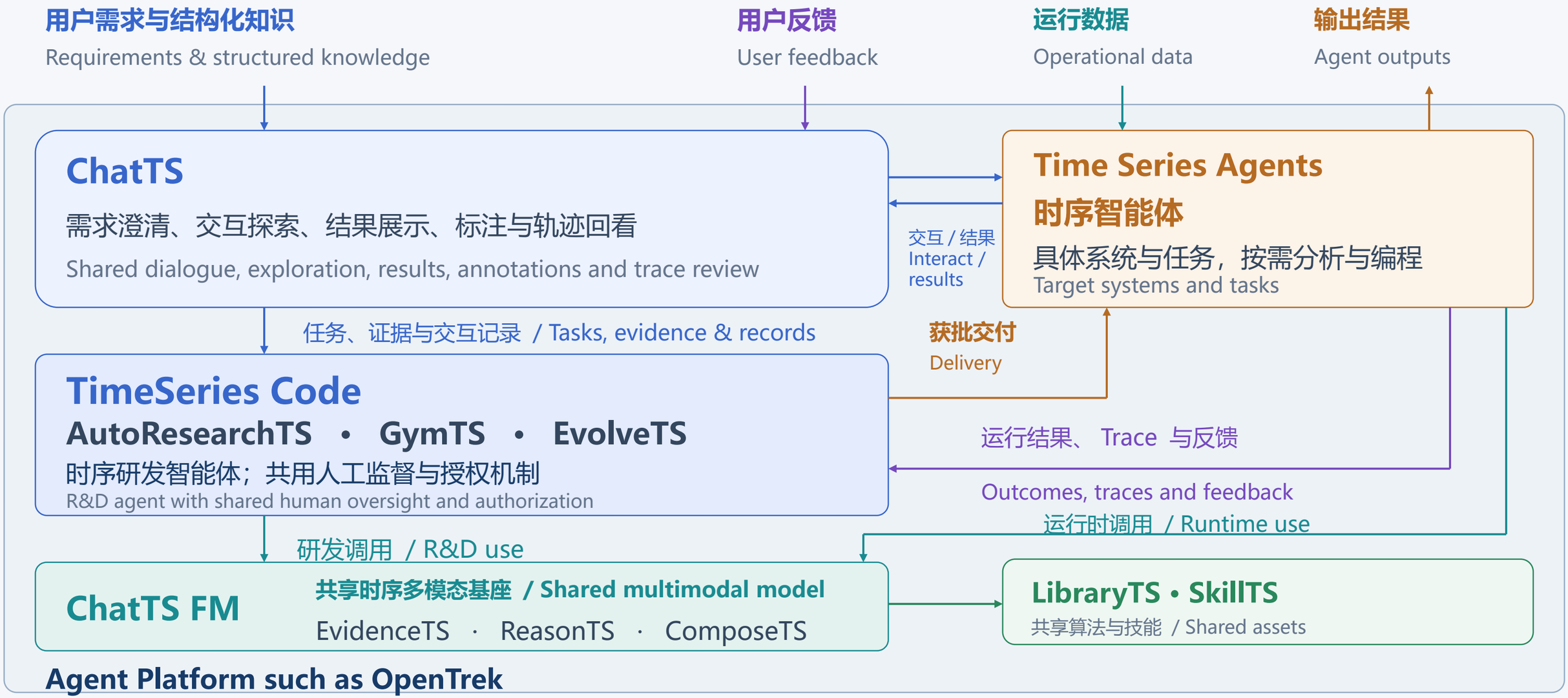
Perceive state → Form evidence → Reason and predict → Support decisions

数据、工况和需求持续变化，研制验证还需遵守本地权限、时延与资源约束

Changing data and requirements call for local development and validation under access and resource constraints.

TimeSeries Code

用户本地环境：时序智能体的研制、验证、运行与改进



信息基础设施

Information Infrastructure

数据中心与算力网络：云与智算集群、服务器、存储及运行软件

Data centers & compute networks: Cloud / AI clusters, servers, storage, runtime software

通信设施与网络：基站、骨干网络、卫星通信与星地链路

Communication facilities & networks: Base stations, backbone and satellite links

导航与授时设施及网络：导航地面站、授时台站及星地设施

Navigation & timing: Ground stations, time-service stations and space-ground facilities



运行中的时序问题

软件变更与负载波动交织，需要联合指标、日志与轨迹定位性能退化。

Correlate metrics, logs and traces to distinguish workload changes from software-related performance degradation.

配图为设施类型示意，不表示已交付项目。

能源系统

Energy Systems

电力系统：发电、储能、输配电、用电及运行控制

Power systems: Generation, storage, transmission, distribution, use & control

火电、水电、核电、风电、光伏、电池储能、抽水蓄能

Thermal, hydro, nuclear, wind, solar, battery and pumped storage



运行中的时序问题：跨工况比较设备状态，结合负载与环境区分正常波动和性能退化。

Compare equipment across operating conditions and separate normal variation from degradation.

油气设施与网络：生产装置、储罐、输送管网及关键机组

Oil & gas: Production facilities, storage tanks, pipelines and critical machinery

热力系统：热源、换热站、循环泵与供热管网

Heat systems: Heat sources, heat-exchange stations, pumps and networks

煤炭采选与储运设施：
矿井、选煤厂、提升与通风、输煤设施

Coal: Mines, preparation plants, hoisting, ventilation and coal handling

氢能制储输设施：
电解制氢成套装置、储氢与压缩输送装备

Hydrogen: Electrolysis systems, storage, compression and transmission

配图为设施类型示意，不表示已交付项目。

交通运输与航空航天系统

Transport & Aerospace Systems

陆地载具与轨道交通：车辆、高铁、地铁及关键子系统

Land vehicles & rail transport: Vehicles, high-speed trains, metros and subsystems

船舶与水下载具：大中小型船舶、潜艇及船载运行系统

Ships & underwater vehicles: Vessels of all sizes, submarines and onboard systems

航空器与航空动力：飞机、小型无人机、航空发动机

Aircraft & aero propulsion: Airplanes, small UAVs and aircraft engines

航天器与保障设施：飞船、卫星平台、测控与地面保障

Spacecraft & support: Space vehicles, satellite platforms, tracking and ground support

交通物流设施与网络：路桥隧、港站机场、仓储及信号调度

Transport & logistics: Roads, bridges, tunnels, hubs, warehousing and traffic control



运行中的时序问题

把任务阶段与运行工况纳入分析，识别关键子系统的状态变化与关联异常。

Interpret subsystem signals in the context of mission phases and operating conditions.

配图为设施类型示意，不表示已交付项目。

重大工业装备与生产设施

Major Industrial Equipment & Production Facilities

重大制造装备：光刻机、高端工业母机（五轴机床、精密加工中心）

Manufacturing equipment: Lithography systems, five-axis machine tools, machining centers

制造验证与生产试验装备：高端装备整机试验台、在线质量检测装备

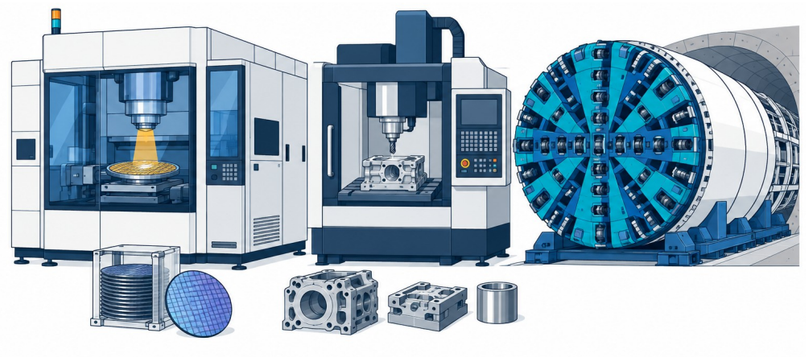
Validation & production tests: High-end equipment test benches and quality inspection

重大工程作业装备：盾构机、硬岩隧道掘进机（ TBM ）

Engineering work equipment: Shield tunnelling machines and hard-rock TBMs

关键工业生产设施：冶金装置、化工装置、选矿系统与关键产线

Industrial production: Metallurgical and chemical plants, mineral processing and key lines



运行中的时序问题

设备、控制软件与工艺状态相互影响，需要结合运行模式判断异常与性能变化。

Relate equipment signals to control software, process conditions and operating modes.

配图为设施类型示意，不表示已交付项目。

重大科技基础设施

Major Scientific Facilities

重大科研试验与计量装置：大型研究风洞、动力试验与标定设施

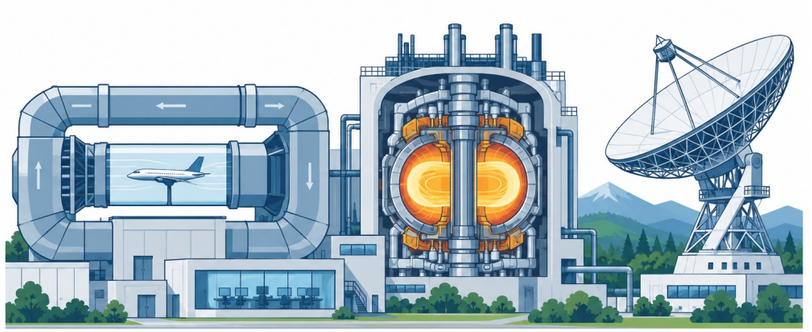
Research tests & metrology: Large research wind tunnels, propulsion tests and calibration

大型科学实验与模拟装置： EAST 、 BEST 、光源、加速器与中子源

Scientific experiments & simulation: EAST, BEST, light sources, accelerators, neutron sources

重大科学观测设施：天文望远镜、科学遥感与科研观测台网

Scientific observation: Astronomical telescopes, scientific remote sensing and observatories



运行中的时序问题

试验条件和仪器状态会影响观测结果，需要区分装置运行变化与实验本身的变化。

Distinguish changes in the facility or instruments from changes in the experiment itself.

配图为设施类型示意，不表示已交付项目。

环境感知与监测系统

Environmental Sensing & Monitoring Systems

机器人感知：射频、振动与触觉
Robot sensing: RF, vibration and touch

环境观测雷达及其组网：天气雷达、雷达观测站
Environmental radar & networks: Weather radar and radar stations

环境观测声呐与水声感知装置：观测声呐、水声阵列
Environmental sonar & acoustics: Observation sonar and underwater arrays

气象观测网络（气象台站）与海洋监测网络（观测站、浮标）
Weather networks: Meteorological stations / Ocean networks: Stations and buoys

地震监测网络（地震台站）与空气质量监测网络（自动监测站）
Seismic networks: Seismic stations / Air-quality networks: Automatic stations

水环境监测网络（河湖水质站）与地质安全监测网络（沉降观测站）
Water-quality networks: River / lake stations / Geological safety: Subsidence stations



运行中的时序问题

核对观测质量、校准状态与传感器漂移，避免把设备异常误判为环境变化。

Separate changes in the observed environment from sensor drift, calibration issues and equipment faults.

配图为设施类型示意，不表示已交付项目。

水利与城市管网

Water Infrastructure & Urban Utility Networks

水利工程与水网：水库、堤坝、泵站、闸门与输调水网络

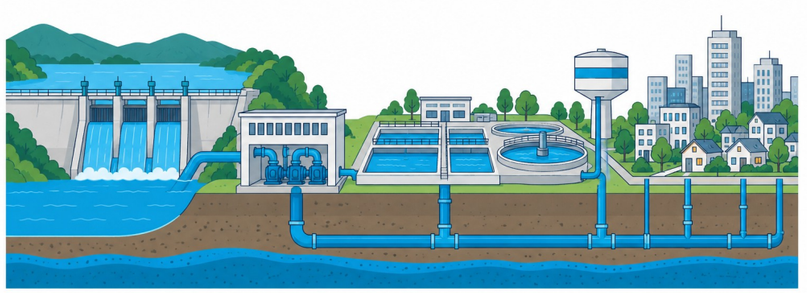
Water engineering & networks: Reservoirs, dams, pumps, gates and water transfer

城市供排水与处理设施：水厂、排水泵站、处理设施与防洪排涝

Urban water supply, drainage & treatment: Waterworks, pumping, treatment and flood drainage

城市地下管网与综合管廊：市政管线、廊体、通风与排水设备

Underground networks & utility tunnels: Utility lines, tunnel structures, ventilation and drainage



运行中的时序问题

设施相互联动，需结合水位、压力、流量与设备状态，判断异常来自哪里。

Combine level, pressure, flow and equipment records to locate anomalies across connected facilities.

配图为设施类型示意，不表示已交付项目。

ChatTS and ChatTS FM

统一交互工作区与共享时序多模态基座

ChatTS

对话澄清、交互探索、结果展示、标注与轨迹回看

Dialogue and exploration; results, annotations and trace review; on-demand views

ChatTS FM

以时序为核心，支持语言、视觉、音频与结构化知识

Time-series multimodal foundation model: language, vision, audio and structured knowledge

Representation → Evidence → Reasoning → Decision

EvidenceTS

Derive, check and organize findings
Sources, uncertainty and admissibility

形成、核查并组织发现；主张支持与反证
来源与不确定性；发生 / 观测 / 可用时间
可采纳性、冲突与互证

ReasonTS

Evidence-based reasoning
Diagnosis, prediction and decisions

因果与反事实推理
按需请求新观测或实验

ComposeTS

Coding and workflow construction
Using LibraryTS and SkillTS

编写、测试和调试；按需辅助视图
工具与代码由 Agent Platform 执行

两类智能体共享模型能力； ChatTS 提供交互入口

The R&D agent and time series agents share the model; ChatTS provides the interaction workspace.

AutoResearchTS: Autonomous R&D

多路线研制与实验迭代，比较方案及资源成本

输入：本地任务与约束、获授权的数据、标注及结构化知识

Inputs: local goals and constraints, authorized data, annotations and structured knowledge

AutoResearchTS

提出不同方案，比较实验结果并继续修订

探索与组合表征、证据、推理和决策方法
记录方案改动、实验结果、版本与资源成本
在预算内比较路线，组织评审与获批交付

Develop and compare alternative solutions, recording changes, results and costs

ComposeTS
Implementation, testing and debugging

GymTS
Experiments and evaluation evidence

人工监督贯穿 TimeSeries Code：可审查、可干预，候选版本不自行批准上线

Human oversight spans the R&D process. Candidate versions require review and authorization.

GymTS: Local Experimentation and Evaluation

提供可复现实验与独立评测，接入本地数据及领域仿真 / 测试环境

GymTS

本地历史数据、运行轨迹与标注；任务要求、工况和验收标准

Local history, traces and annotations; task requirements, operating conditions and acceptance criteria

EnvironmentTS

接入领域仿真、试验台与本地回放
保存实验状态，提供交互与奖励接口
在可比条件下复现，记录结果与轨迹

Integrate domain simulators, testbeds and replay
Save experiment state, support interaction and rewards
Compare under controlled conditions, retain results and traces

AutoBenchTS

自动复现与基准维护
分级测试、独立验收与回归
检查各环节、整体效果与安全

Reproduce methods and maintain benchmarks
Staged tests, independent acceptance and regression
Check components, whole-task results and safety

实验与评测证据支持 AutoResearchTS 研制和 EvolveTS 改进

Experiment and test evidence support development and improvement of delivered agents.

接入已有领域环境；不要求从零建设各行业的全部仿真器和试验台

EvolveTS: Recursive Self-Improvement (RSI)

根据历次反馈改进交付的智能体，复用经验并跟踪效果

输入 / Inputs

运行与实验结果、 Trace 、交互标注、用户反馈；当前技能、策略及版本

Outcomes, traces, annotations and feedback; current skills, policy and versions

AutoResearchTS 返回评测结论与版本状态 / Review conclusions and version status

技能级改进 / Skill improvement

经 AutoResearchTS 研制，复用 ChatTS FM
由 GymTS 验证技能、代码和工作流
记录验证依据与适用条件，供后续任务复用

不依赖本地模型训练

No local model training required

Agentic RL （可选 / Optional ）

仅在模型、数据与奖励、资源和授权齐备时
利用轨迹与奖励优化目标智能体策略
输出待评测的模型或适配器

不是每个现场都需要或具备训练条件

Requires a suitable model, data/rewards, resources and authorization

运行经验 → 改进候选 → 实验与评测 → 人工批准 → 更新目标智能体

Across runs: operational evidence → Candidates → Testing → Approval → Targeted update

Time Series Agents

面向具体系统与任务，运行中复用共享模型、算法和技能

运行观测与上下文
Observations and context

目标、约束与授权
Goals, constraints and authorization

Time Series Agents

已验证流程及按需分析、推理与编程；依据证据、目标与约束决策

Validated workflows and on-demand analysis; decisions under evidence, goals and constraints

确认执行，并以新观测验证效果 / Confirm execution; verify effects with new observations

输出：状态与风险判断、预测、建议及授权行动 / Assessments, predictions, advice and authorized actions

ChatTS FM

EvidenceTS · ReasonTS · ComposeTS

LibraryTS / SkillTS

共享算法与技能

ChatTS

按需对话、展示结果与收集反馈

临时分析不自动成为持久更新；运行结果、 Trace 与反馈进入 EvolveTS

Ad hoc analysis does not silently persist. Outcomes, traces and feedback inform EvolveTS.

LibraryTS and SkillTS

共享资产支持研制与运行；发布新版本后，按目标选择启用

LibraryTS

可信算法与时序模型实现

预处理、特征工程、相似度与距离
聚类、变点与漂移、分类
预测、异常检测、时空分析
因果发现、因果推断、时序模型实现
ARIMA 、 OmniAnomaly 、 TimesFM 等…
接口、版本、来源、验证依据与限制

Preprocessing, features, distance and clustering
Change points, classification, forecasting and detection
Spatiotemporal, causal analysis and time-series models…
APIs, versions, provenance and validation

SkillTS

可复用技能、代码与工作流

技能指令与工具绑定
适用条件、输入输出约定
版本、验证依据、批准记录与已知限制

Reusable skills, tool bindings, code and workflows
Applicability and input/output contracts
Versions, validation, approvals and known limitations

ComposeTS 调用两库； EvolveTS 使用当前技能与版本组织改进

ComposeTS invokes both repositories; EvolveTS uses current skills and versions.

资产发布与运行采用分开：新版本不自动覆盖所有智能体 / Release does not force adoption by every agent

Agent Platform such as OpenTrek

共同承载 TimeSeries Code 与 Time Series Agents

TimeSeries Code

时序研发智能体
研制、实验、验证与交付

R&D agent for the development process

获准版本

Approved

Time Series Agents

时序智能体
执行具体系统的时序任务

Runtime agent for a target system and task

模型、工具与执行调度
Models, tools, execution and scheduling

发布、权限与隔离
Release, permissions and isolation

运行观测与轨迹采集
Observability and execution traces

审计、恢复与回滚
Audit, recovery and rollback

共同平台不要求同一实例、模型或权限； OpenTrek 是平台实例之一

Shared hosting does not imply shared instances or permissions. OpenTrek is an example platform.

Human Oversight and Authorized Updates

TimeSeries Code 三个模块共用监督机制，现场数据默认留在现场

AutoResearchTS • GymTS • EvolveTS

过程可审查、可干预

Inspect evidence and intervene during the process

明确可修改范围、数据权限、预算与停止条件，记录依据与版本

候选版本经评测与批准

Evaluate and approve candidates before release or use

基准、资产与版本更新需审核批准；按约定标准独立验收，获批后按目标启用

本地技能改进无需模型训练； Agentic RL 仅在条件与授权齐备时可选

不默认回传现场数据；目标模型候选默认不覆盖共享 ChatTS FM

Local data stay local by default. Target-agent candidates leave the shared foundation unchanged by default.

Case 1. Development Request

案例一：应用单位提出在线异常检测系统的研发需求

示意案例 / Illustrative case

用户需求与已有知识

Requirements and available knowledge

请根据 KPI 数据，研发一套在线异常检测系统。

Develop an online anomaly detector for KPI monitoring.

数据与授权、拓扑、测点语义、运行约束
已有知识先提供，之后逐步澄清核实

Data access, topology, sensor semantics and constraints
Provide what is known; clarify and verify over time

ChatTS

澄清任务、评测口径与验收要求

Clarify the task and acceptance criteria

需求版本一 / Requirements v1

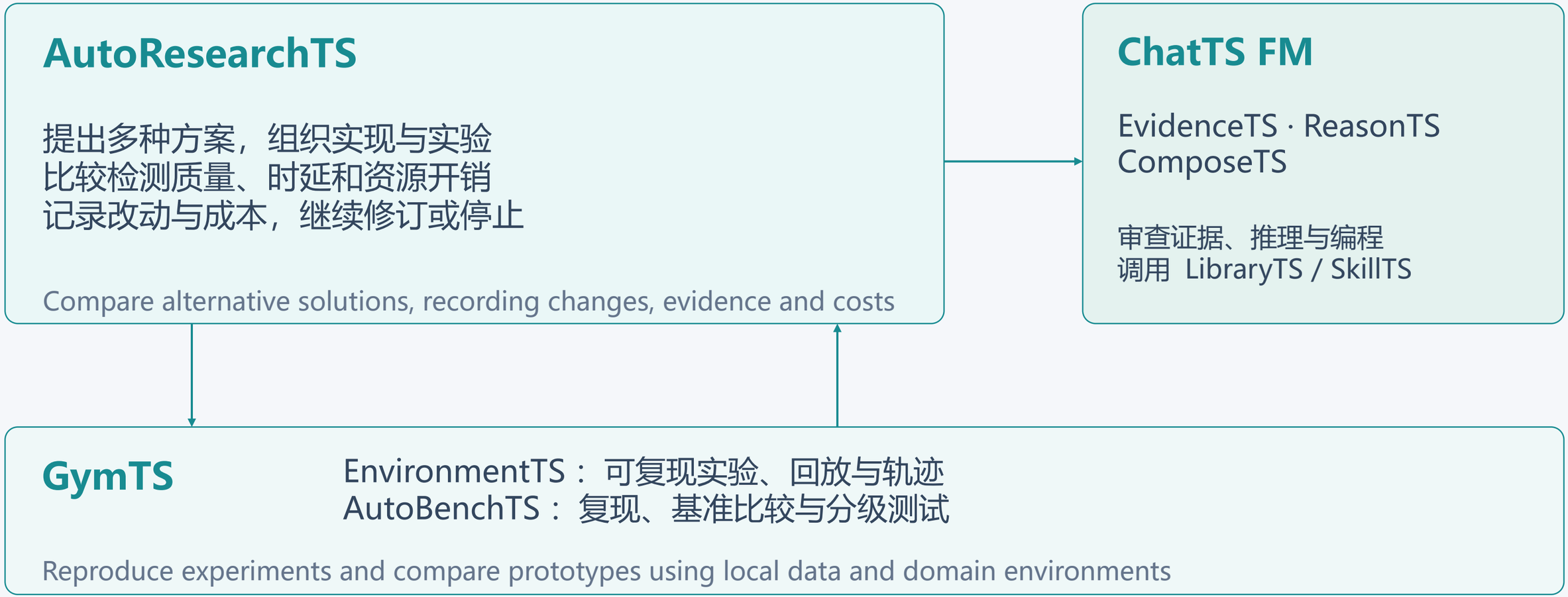
本地硬件：由用户单位指定
示例目标：延迟 < 2 s， F1 ≥ 0.80
输入输出、评测划分、权限与运行条件

Illustrative targets; actual performance requires evaluation
User-specified hardware and authorized data

Case 2. Workflow and Prototype

案例二：共享模型和资产支撑自主研制，实验结果用于修订方案

示意案例 / Illustrative case



交互探索与按需视图通过 ChatTS 完成 / Inspect data, annotate findings and compare results in ChatTS

Case 3. Validation and Independent Acceptance

案例三：开发验证与独立验收分别进行

示意案例 / Illustrative case

开发验证
Development validation

有需要时拟合任务检测模型
验证数据用于选择算法、阈值与流程
AutoResearchTS 调用 ComposeTS 实现
EnvironmentTS 保存结果、轨迹和版本

Fit a task detector when needed
Use validation data to choose methods and settings
Retain implementation versions and experiment evidence

冻结

Freeze

独立验收
Independent acceptance

冻结代码、模型和配置
AutoBenchTS 开展独立测试
使用未参与开发的数据
评估质量、时延、资源与安全

Freeze the candidate version
Use held-out acceptance data
Evaluate quality, latency, resources and safety

测试数据不用于反复挑选版本；按约定标准独立验收，再评审批准

Keep held-out tests independent. Apply agreed acceptance criteria and review the evidence before approval.

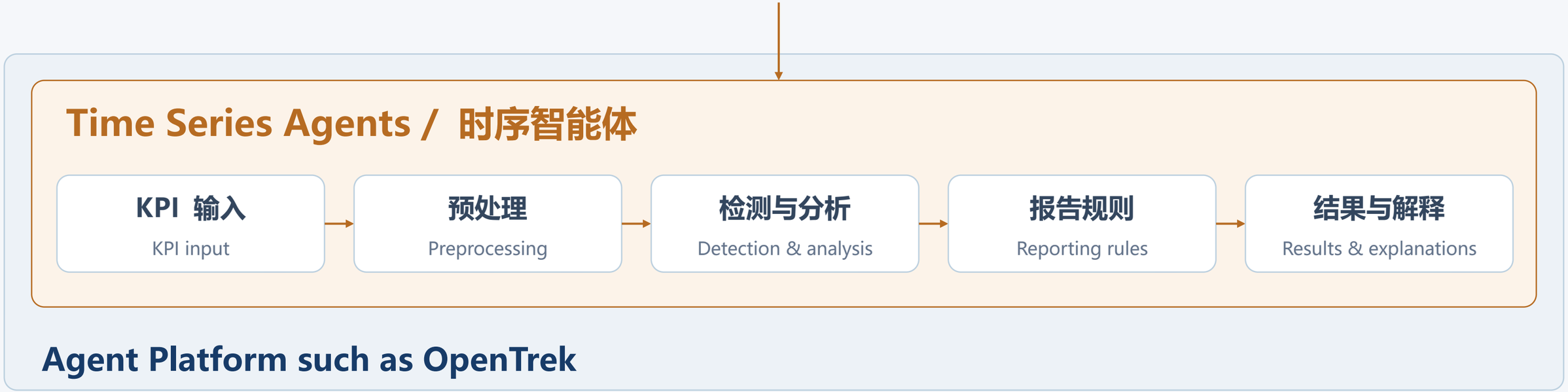
Case 4. First Production Release

案例四：交付第一版时序智能体，观察真实运行表现

示意案例 / Illustrative case

AutoResearchTS 组织交付，版本经过评测与人工批准

Deliver the approved version after evaluation and human review



小范围上线，观察接口、时延与检测质量，保留运行轨迹和恢复路径

Start with a limited rollout. Observe results and traces, and retain a recovery path.

Case 5. Feedback Reveals New Requirements

案例五：上线之后，用户补充真实需求

示意案例 / Illustrative case

“夜间不报异常，白天减少误报，尤其关注上午九点到十点。”

“Do not report anomalies at night. Reduce daytime false positives, especially from 9 to 10 AM.”



一种待用户确认的解释：保留夜间检测记录，调整报告策略，单独检查重点时段的漏报

One interpretation to confirm: retain nighttime detection logs, revise reporting rules, and check missed events during priority periods. Reporting volume and detection quality require separate evaluation.

Case 6. A Full Second Development Cycle

案例六： EvolveTS 组织改进，重新研制、验证并批准目标版本

示意案例 / Illustrative case



核对重点时段改善，也检查其他时段与已有能力

Check gains in priority periods and regressions elsewhere before approval

评测批准后，更新目标 Time Series Agents

Deliver version 2 after approval; its operation provides evidence for the next improvement cycle.

Critical AIOps Summary

让关键系统可靠运行 / Keep Critical Systems Working

结合本地 AI 、连续观测与系统知识，研制、验证并持续改进时序智能体

Use local AI, observations and system knowledge to develop, validate and improve time series agents

ChatTS 统一交互：需求、知识、探索、结果与反馈

TimeSeries Code

AutoResearchTS · GymTS · EvolveTS

获批交付 / Update

Time Series Agents

具体系统与任务 / Systems & tasks

共享 ChatTS FM 、 LibraryTS 与 SkillTS ； 共同运行于 Agent Platform such as OpenTrek

复用经验证的运行经验，独立验收并批准每次持久更新

Reuse validated operational experience. Require independent acceptance and approval for persistent updates.