



内嵌可满足求解的演化优化及其在软件质量保障中的应用

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2025年8月



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广东省优秀青年（青年提升）基金获得者，兼任中国运筹学会模糊信息与工程分会理事、广东省计算机学会软件工程专委会秘书长，担任国际期刊Mathematics的客座编辑、2025 International Seminar on Theoretical Computer Science的特邀联合主席。

- **主持科研项目：**国家自然科学基金、广东省自然科学基金（青年提升/优青、面上）、广州市科技计划项目、中国博士后基金、企事业委托项目等12余项；
- **发表学术论文：**以第一作者或通讯作者身份在ACM TOSEM、IEEE TSE、IEEE TEVC、IEEE TCYB、ICSE、ISSTA、中国科学：信息科学和软件学报等专业学术期刊和会议上发表论文**50**多篇，代表作入选**ESI**；
- **获得知识产权：**近三年，授权国家发明专利**8**项；
- **制定标准：**以主要完成人制定了全国团体标准T/CI 083-2023《无源码的白盒化测试标准》；
- **获奖情况：**2024和2025年度广东省计算机学会优秀论文一等奖、2018年度ACM中国广州分会的优秀博士学位论文奖、2020年度中国仿真学会智能仿真优化与调度专业委员会优秀博士学位论文奖、2024年度广东省计算机学会教育教学成果奖一等奖和**2023年度广东省科技进步二等奖**；
- **合作企业：**工信部电子五所（中国赛宝实验室）、中国电科旗下的普华基础软件、TCL云创科技有限公司、泰一科技等，**累计经济效益超500万元**



汇报 提纲

01

学术研究篇

02

工程案例篇



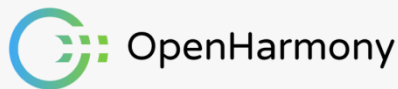
华南理工大学
South China University of Technology

IAIS 智能算法研究中心

学术研究篇

研究背景：基础软件和工业软件（行业应用软件）通常是**可配置软件系统**，其显著特点是具备**高度可配置性**，具有**开发灵活和可复用性强**等优势。

基础软件



操作系统

数据库

编译器



```
145 #
146 # Feature configuration:
147 #
148
149 set(DEAL_II_WITH_CXX11 ON)
150 set(DEAL_II_WITH_CXX14 ON)
151 set(DEAL_II_WITH_CXX17 ON)
152 set(DEAL_II_WITH_CXX20 ${DEAL_II_HAVE_CXX20})
153 set(DEAL_II_WITH_THREADS ON)\n"
154 )
```

Kconfig文件

```
39 config COMPILER_GCC
40     bool "GCC"
41
42 config CROSS_COMPILE
43     string "GCC cross-compile toolchain prefix"
44     depends on COMPILER_GCC
45     default "arm-linux-ohoseabi-" if ARCH_ARM_AARCH32
46
47 config COMPILER_CLANG_LLVM
48     bool "Clang"
49
```



航空航天

汽车

能源交通

工业软件 CAE

中共中央关于制定国民经济和社会发展第十五个五年规划的建议

(2025年10月23日中国共产党第二十届中央委员会第四次全体会议通过)

(11) 加强原始创新和关键核心技术攻关。完善新型举国体制，采取超常规措施，全链条推动集成电路、工业母机、高端仪器、**基础软件**、先进材料、生物制造等重点领域关键核心技术攻关取得决定性突破。突出国家战略需求，部署实施一批

围绕可配置软件系统开发生命周期中的关键核心技术开展系统性研究，对于突破基础软件关键技术瓶颈、提升软件系统自主可控与质量保障能力、加速关键领域**软件国产替代**和**服务国家软件发展战略**具有重要意义。

可配置软件系统中配置选项之间的**复杂约束关系**，可通过**可变性建模工具**（如 Kconfig或Feature Model）进行形式化建模，并进一步编码为合取范式（CNF）形式的逻辑公式（约束条件），从而转化为**可满足性（SAT）问题**的标准求解输入。

可配置软件系统的配置 优化问题

约束条件：CNF形式

优化目标：

- 总费用
- 未选中的模块数
- 之前未使用的模块总数
- 缺陷数



$$\text{Min } F(x) = (f_1(x), f_2(x), f_3(x), f_4(x))$$

Subject to CNF形式的约束条件

$$x = (x_1, x_2, \dots, x_{n_f}) \in \{0, 1\}^{n_f}$$

Principal Engineer
in Chip Design



OptSAT问题 (Nadel 2020)

可满足性(SAT)的通用优化版



在满足CNF约束的前提下，优化一个或者多个目标函数（非线性、黑盒的）

intel.

可配置软件系统的测试 用例生成问题

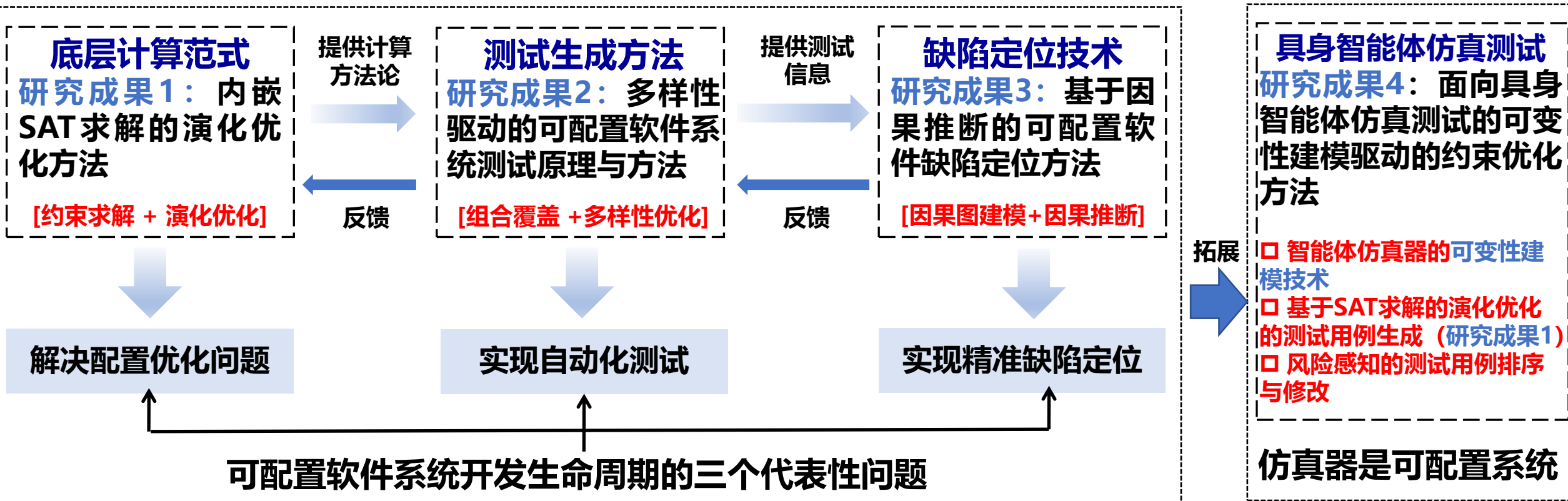
约束条件：CNF形式

优化目标：

- 组合覆盖率
- 测试用例多样性
- 信息熵
- ...



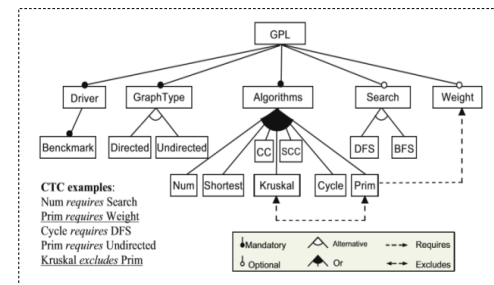
以可配置软件系统为主要研究对象，围绕**配置优化**、**测试生成**和**缺陷定位**等可配置软件系统开发生命周期中的代表性问题，以 OptSAT 问题的**通用求解方法**为突破口，开展系统性研究（研究成果如下图所示）；进一步以**可变量建模技术**为桥梁，将具身智能体仿真器抽象为可配置系统，探索面向具身智能体的质量保障方法。



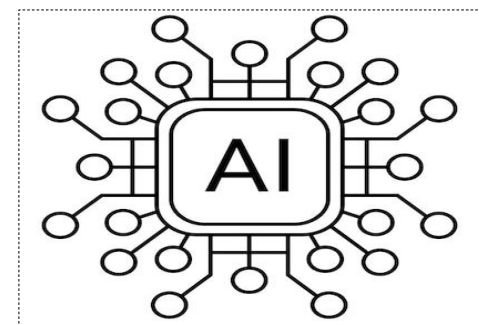
成果简介：针对软件配置优化、芯片设计、软硬件协同及人工智能等领域普遍存在的**可满足最优 (OptSAT) 问题**，构建了SAT求解与演化优化的**内嵌融合框架**，提出了基于SAT求解的自适应演化算子，实现了约束满足与目标优化的**协同演进**，形成了高效的混合优化方法体系。该方法在软件配置优化、作业车间调度、能源资源管理和特征选择等典型场景中得到验证，显著提升了求解效率与解的质量。

OptSAT: 可满足性(SAT)的通用优化版

OptSAT问题的形式化定义：给定一个合取范式 (CNF) 形式的可满足公式 $F(V)$ 以及一个伪布尔 (Pseudo-Boolean, PB) 目标函数 Ψ ，OptSAT 返回一个满足 F 的模型/解 μ ，使得对于所有满足 F 的模型/解 μ' ，都有 $\Psi(\mu) \leq \Psi(\mu')$ 成立。

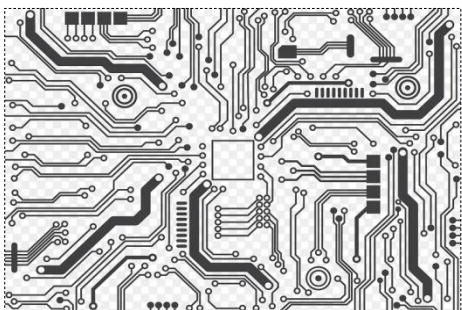


软件配置优化

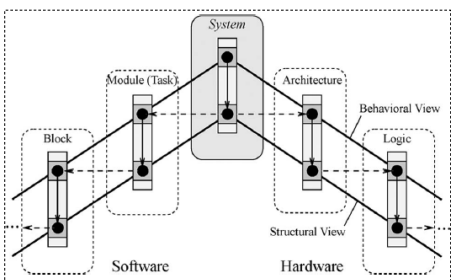


人工智能

芯片设计



软硬件协同设计



- OptSAT求解的是SAT问题的优化变体，其目标是在所有满足约束 F 的解中，找到一个使目标函数 Ψ 最优的解。
- MaxSAT也是SAT问题的优化变体，但是其目标函数局限为线性伪布尔的 (Linear Pseudo-Boolean)。OptSAT则是通用的优化版本。

非线性

黑盒

大规模

约束复杂

多目标

昂贵

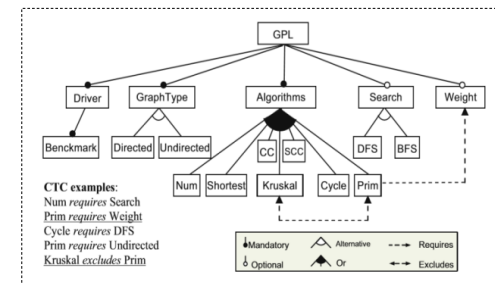
成果简介：针对软件配置优化、芯片设计及软硬件协同等领域普遍存在的**可满足最优 (OptSAT) 问题**，构建了SAT求解与演化优化的内嵌融合框架，提出了基于SAT求解的自适应演化算子，实现了约束满足与目标优化的协同演进，形成了高效的混合优化方法体系。该方法在软件配置优化、作业车间调度、能源资源管理和特征选择等典型场景中得到验证，显著提升了求解效率与解的质量。

OptSAT: 可满足性(SAT)的通用优化版

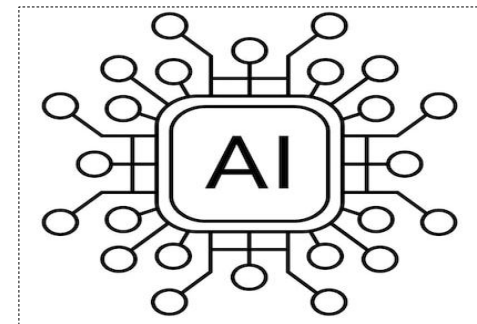
在实际应用中，OptSAT问题（除目标函数外）需要表示为SAT形式。其中，一些问题本身具有SAT形式，而另一些问题则可以通过适当的规约或编码方法转化为SAT形式。

Ref: M. Cadoli and A. Schaerf, "Compiling problem specification into SAT," Artificial Intelligence, vol. 162, no. 1-2, pp. 89-120, 2005.

SAT问题通常采用合取范式 (Conjunctive Normal Form, CNF) 进行表示，其公式由若干子句的合取组成，每个子句为若干文字的析取形式。例如 $(x_1 \vee \neg x_2) \wedge (x_2 \vee x_3 \vee \neg x_4)$ 是一个CNF公式，包含两个子句。

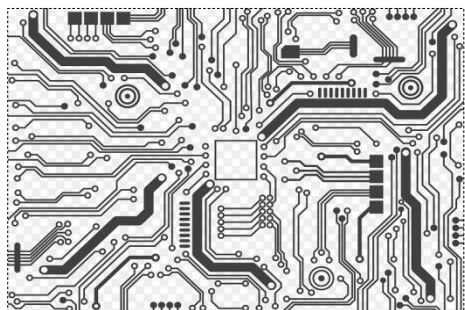


软件配置优化

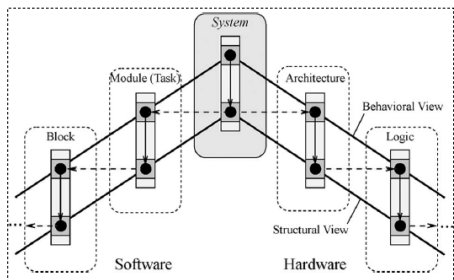


人工智能

芯片设计



软硬件协同设计



关键挑战：“约束满足”和“目标优化”所带来的**双重搜索复杂性**。

□ **约束满足：**每个解都必须满足所有 CNF 约束，这实际上等价于求解一个 SAT 问题，而 SAT 问题是典型的 NP 完全问题——**可行解搜索难**

◆ 演化算法领域的约束处理策略，如惩罚函数法、随机排序、目标-约束分离法等，通常难以奏效，甚至无法保证找到可行解。

□ **目标优化：**在可行解构成的离散、非凸、大规模可行域上搜索最优解面临搜索空间急速增长问题，且目标函数通常是非线性、昂贵的——**可行解优化难**

◆ 不考虑约束的情况下， n 个布尔变量组成的搜索空间规模为 2^n ，随 n 指数式增长。考虑约束的情况下，也仅能有限地缩减搜索空间。

科学问题：如何实现SAT求解与演化优化的**深度融合**，在保证约束满足的同时，实现高效的目标优化，从而突破OptSAT问题的**双重搜索复杂性**。

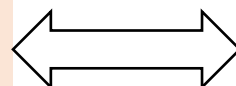
演化优化的优势：

- 适应大规模搜索空间
- 处理非线性与非凸问题
- 适应黑盒场景

演化优化的缺点：

- 对约束处理能力弱，难以直接应对强约束或逻辑约束

优势互补



SAT求解优势：

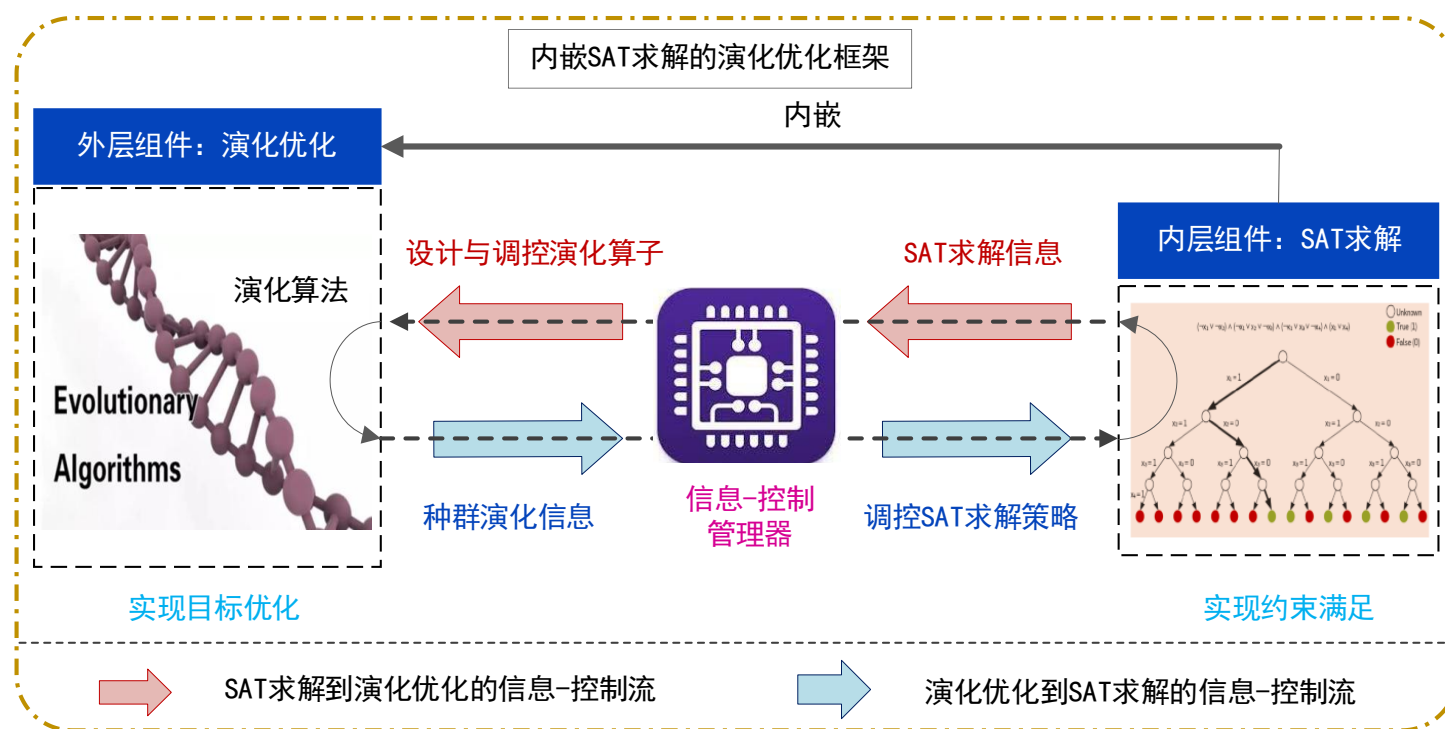
- 对逻辑约束、离散约束和组合约束处理高效，能保证可行性。
- 逻辑推理严谨，可获得精确、确定性的解

SAT求解的缺点：

- 往往只能找到一个可行解，难以保证目标最优性；或者仅能处理线性目标函数（MaxSAT）

针对OptSAT问题，如何充分SAT求解与演化优化的各自优势，实现二者的**深度融合**？

解决思路：采用“**演化优化—SAT求解**”双层协同框架，其中，SAT求解过程被内嵌于演化优化流程之中。通过利用SAT求解所提供的可行性与结构信息，对演化算子进行**设计与自适应调控**；同时，演化过程产生的搜索反馈又用于**动态调整SAT求解策略**，从而实现搜索效率与解多样性的协同提升。



内嵌SAT求解的演化优化框架

代表性工作1：针对 OptSAT 问题（以软件配置优化问题为代表），同时将 **CDCL** 与 **SLS** 两类 SAT 求解器与多目标演化算法 VaEA **深度融合**，提出了一种新的混合优化方法—SATVaEA 算法。

内嵌SAT求解的多目标演化算法SATVaEA

ALGORITHM 1: Framework of the Proposed SATVaEA

Input: FM (a feature model to be configured), N (population size), and θ (a parameter for controlling the frequency of using the two SAT solvers)

Output: Nondominated valid solutions in the final population.

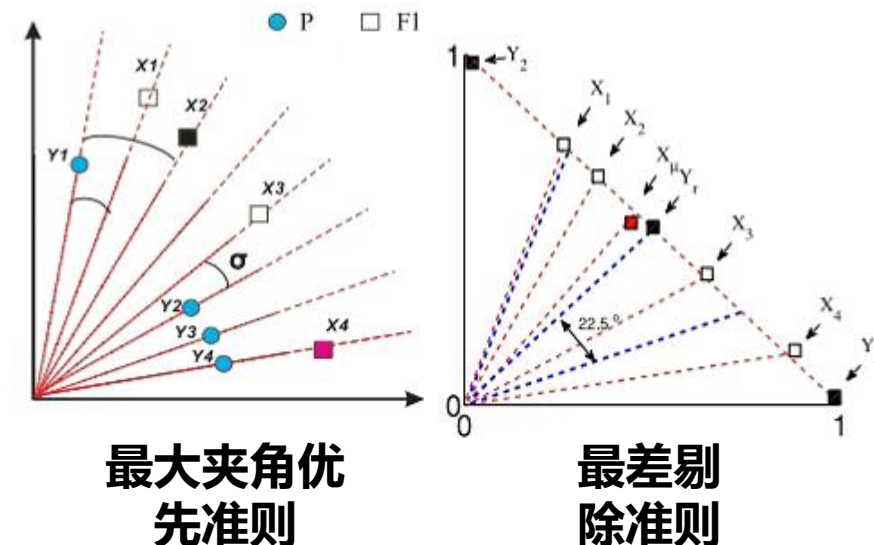
- 1: Simplify the FM
- 2: Initialize population P with N random solutions
- 3: **while** the termination condition is not fulfilled **do**
- 4: Generate an offspring population Q by genetic operators
- 5: $S \leftarrow P \cup Q$ // S is the union of P and Q
- 6: **if** there exist invalid solutions in S **then**
- 7: **if** $rnd < \theta$ **then**
- 8: Apply the SLS-style SAT solver to repair a random invalid solution
- 9: **else**
- 10: Apply the DPLL/CDCL-style SAT solver to generate a valid solution, and use it to replace an invalid one
- 11: **end if**
- 12: **end if**
- 13: Perform the environmental selection to S to select N diversified solutions for the new population P
- 14: **end while**
- 15: **return** Nondominated valid solutions in P

- 基于SLS求解的修复算子
- 基于CDCL求解的替换算子

嵌入



多目标进化算法VaEA [TEVC 2017]



国际审稿人评价：“Furthermore, I suspect that this is *the first time that SLS-style SAT solvers have been used in multi-objective optimization at all.* ...”

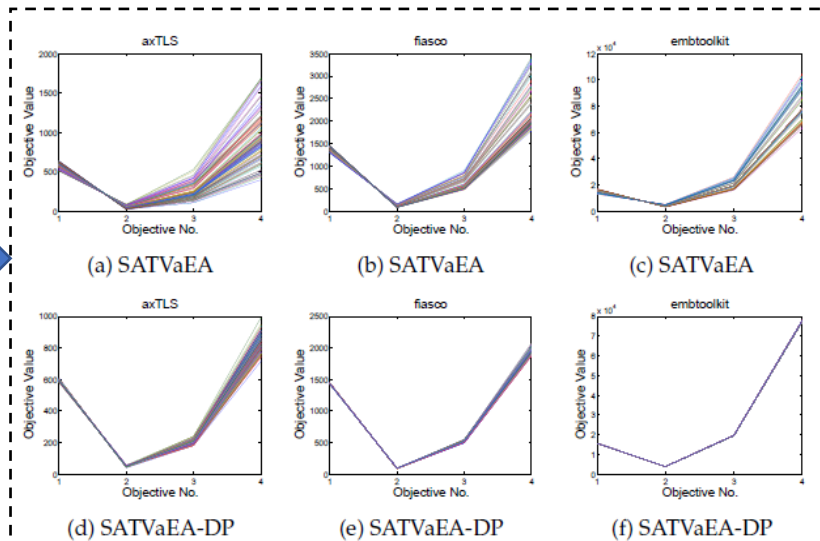
[TOSEM 2018] Yi Xiang, Yuren Zhou*, Zibin Zheng*, Miqing Li. Configuring Software Product Lines by Combining Many-objective Optimization and SAT Solvers, *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 2018, 26 (4): 14.1-14.46

代表性工作1： 同时将 CDCL 与 SLS 两类 SAT 求解器与多目标演化算法 VaEA 深度融合，提出了一种新的混合优化方法—SATVaEA 算法

以配置优化问题为 OptSAT 问题的代表进行性能评估

特征模型	TT50%	TT100%
toybox	582%	577%
axTLS	179%	185%
freebsd-icse11	-3%	-10%
fiasco	35%	59%
uClinux	108%	91%
busybox-1.18.0	N/A	N/A
2.6.28.6-icse11	-14%	-12%
uClinux-config	610%	573%
coreboot	64%	74%
buildroot	77%	70%
embtoolkit	80%	N/A
freetz	313%	N/A
2.6.32-2var	30%	16%
2.6.33.3-2var	24%	18%

移除修复算子 (SLS求解器) 后, 算法获得50% 和100%有效解所增加的时间 (百分比), 最高达 **577%**



移除DPLL/CDCL-类型求解器后, 算法的多样性显著降低

模型	指标	SATVaEA	SATIBEA	SIP+SPEA2+SDE	SIP+NSGA-II
WebPortal	VN (/30)	30	30	30	30
	VR	100%	97%	• 100%	‡ 100%
	IGD	10.6366	16.1697	• 10.7513	‡ 10.5212
	PD	363610.6200	571731.2018	○ 171846.5337	• 151310.5094
	Runtime	3.4810	16.0985	• 27.5430	• 0.6380
E-shop	VN (/30)	30	30	30	30
	VR	100%	97%	• 100%	‡ 100%
	IGD	54.9058	44.8114	○ 239.1933	• 171.2694
	PD	1175298.6980	1011220.8917	• 153724.1969	• 524246.0306
	Runtime	7.3775	19.4395	• 35.2810	• 0.9650
Drupal	VN (/30)	30	30	30	30
	VR	100%	99%	• 100%	‡ 100%
	IGD	14.1677	17.5598	• 18.4402	• 14.9311
	PD	250535.5281	554239.5165	○ 213341.3709	• 159993.2761
	Runtime	4.1250	16.1085	• 27.1520	• 0.6065
Amazon	VN (/30)	30	30	30	30
	VR	100%	7%	• 100%	‡ 100%
	IGD	8.6380	28.0032	• 9.6209	• 10.0130
	PD	54577.8655	184690.1368	○ 22153.5554	• 38384.7146
	Runtime	2.7470	17.4000	• 25.0440	• 0.5890
Random	VN (/30)	30	30	25	25
	VR	100%	99%	• 83%	• 83%
	IGD	657.1179	701.8627	• 22821.3747	• 24091.6980
	PD	1174550.6969	1082824.5819	• 15592.2866	• 15703.5480
	Runtime	118.1385	126.4740	• 80.0140	○ 47.2255
Amazon	VN (/30)	30	24	30	30
	VR	100%	1%	• 100%	‡ 100%

整体性能超越 **Mark Harman** 团队的 SATIBEA 算法, 以及 **Robert M Hierons** 团队的 SIP 方法



同行评价

Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence (IJCAI-19)

Integrating Pseudo-Boolean Constraint Reasoning in Multi-Objective Evolutionary Algorithms

Miguel Terra-Neves^{1,2}, Inês Lynce and Vasco Manquinho¹

¹ INESC-ID / Instituto Superior Técnico, Universidade de Lisboa, Portugal

² OutSystems, Portugal

miguel.neves@outsystems.com, {ines,vmm}@sat.inesc-id.pt

演化优化与约束求解在紧约束多目标组合优化 (MOCO) 问题上的优势互补性, 促使了约束求解与进化优化的融合研究, 而 Xiang et al. (2018) 是这一融合方向的重要代表性工作

[Xiang et al., 2018] Y. Xiang, Y. Zhou, Z. Zheng, and M. Li. Configuring Software Product Lines by Combining Many-Objective Optimization and SAT Solvers. *ACM Transactions on Software Engineering and Methodology*, 26(4):14:1–14:46, 2018.

Xiang等人“演化优化与约束求解相融合”的思想得到了国际同行的广泛认可, 并引发了持续的跟进 (Following) 研究, 体现了上述思想的开创性和引领性

葡萄牙里斯本高等技术学院的I. Lynce教授, 国际知名的SAT与MaxSAT研究学者, SAT4J求解器的核心贡献者之一

Multi-Objective Evolutionary Algorithms (MOEAs) have been at the forefront for solving MOCO problems [Deb et al., 2000; Zhang and Li, 2007; Zheng et al., 2016]. However, in problem instances where it is hard to satisfy all problem constraints, the performance of MOEAs starts to decline. On the other hand, recently proposed constraint-based methods [Soh et al., 2017; Terra-Neves et al., 2018] thrive in solving tightly constrained instances. This duality, between evolutionary algorithms and constraint-based methods, motivated the selective integration of constraint solving in MOEAs [Henard et al., 2015; Xiang et al., 2018].

SBSE的创始人之一 IEEE Fellow

Christopher Henard*, Mike Papadakis*, Mark Harman†, and Yves Le Traon*

Following previous work on using constraint solvers in MOEAs [Henard et al., 2015; Xiang et al., 2018], we propose a generalized smart mutation operator for correcting unfeasible individuals, and a smart improvement operator that uses MCSs to improve already feasible individuals. Experimental results in a large set of VMC instances show that the combination of evolution and constraint solving significantly outperforms pure evolutionary and constraint-based approaches.

同行评价

The Journal of Systems and Software 149 (2019) 382–395



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The Journal of Systems and Software

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New Trends and Ideas

A survey of many-objective optimisation in search-based software engineering

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though no algorithm was clearly superior. Recently, other paper suggested that previous works lack of solution diversity and are still computationally expensive (Xiang et al., 2018). To overcome this, they propose the use of additional SAT solvers to repair infeasible SPL configurations, as well as the application of a new algorithm, named VaEA, to promote particular configurations. SAT-VaEA, which could be catalogued as a diversity-based approach, is compared against SATIBEA and SIP (combined with NSGA-II and SPEA2+SDE) on an extensive collection of FMs, considering four, five and eight objectives. Experiments confirm that SATVaEA is an efficient method, being able to optimise FMs with more than 60,000 features in less than ten minutes. Moreover, it guarantees the return of more diverse solutions than its competitors, meaning that the engineer would have more different alternatives to choose among.

Xiang, Y.I., Zhou, Y., Zheng, Z., Li, M., 2018. Configuring software product lines by combining many-objective optimization and SAT solvers. ACM Trans. Softw. Eng. Methodol. 26 (4), 14:1–14:46.

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tional cost. Our findings seem to reflect this trend, since just a few works solving problems with more than six objectives consider HV in their experimentation. Finally, only a recent paper (Xiang et al., 2018) reports values for a quality indicator specifically designed for many-objective optimisation, called pure diversity (Wang et al., 2017). The rest of indicators referred in Section 2.2 have not been

仅Xiang等人的论文采用了many-objective optimisation的定制化性能指标，其工作对推动基于多目标优化搜索的软件工程方向实验评估体系的发展起到重要作用

Xiang等人的算法有效克服了既往方法解多样性不足和计算代价过高的关键瓶颈。该引文对该算法进行了大篇幅报道，并从算法效率和决策支持两个维度明确肯定了其优势。

同行评价

英国伦敦大学国王学院
Steffen Zschaler教授
(TSE 2023)

ON SOFTWARE ENGINEERING, VOL. 49, NO. 3, MARCH 2023

We're Not Going to Break It! Consistency-Preserving Operators for Efficient Product Line Configuration

Jose-Miguel Horcas¹, Daniel Strüber¹, Alexandru Burdusel, Jabier Martinez¹, and Steffen Zschaler¹

Automated Optimal Configuration. Ochoa *et al.* [4] present a systematic literature review on automated configuration. The seminal approaches in the field relied on constraint-satisfaction problem (CSP) solvers [3], [40] and custom heuristics [41]. Examples of the now predominant search-based [10], SATIBEA [11], and Clafer-constraints, these works rely computed during the search. from “fix” operator, whereas SATIBEA uses a SAT solver within a “smart” mutation operator whose purpose is to remove violations introduced in previous mutations. Xiang *et al.* vary SATIBEA by studying the impact of different SAT solving techniques and configurations during repair [20], [33]. We discuss the positioning of our work in this line of research in Section 1.

[33] Y. Xiang, Y. Zhou, Z. Zheng, and M. Li, “Configuring software product lines by combining many-objective optimization and SAT solvers,” *ACM Trans. Softw. Eng. Methodol.*, vol. 26, no. 4, pp. 1–46, 2018.

Xiang等人的工作是软件配置优化领域中具有代表性的研究成果之一

Software and Systems Modeling (2023) 22:377–414
<https://doi.org/10.1007/s10270-022-01011-2>

REGULAR PAPER

Empirical analysis of the tool support for software product lines

José Miguel Horcas¹ · Mónica Pinto¹ · Lidia Fuentes¹

tions (e.g., analysis of NFPs). The extension mechanism of **FeatureIDE**, based on plugins, and the provided API allow applying specific optimization techniques (e.g., evolutionary algorithms), additional formalizations of the FMs such as CNF [106], or the use of advanced SAT solvers [107,108]. Most of these applications have been developed as part of a research work and are available as evaluation or proof of concept artifacts. They still require to be properly integrated in a main release of a tool like **FeatureIDE** to make them widely available to the SPL community.

Xiang等人的工作被同行视为FeatureIDE插件化扩展中采用先进SAT求解技术的典型研究工作。

107. Xiang, Y., Zhou, Y., Zheng, Z., Li, M.: Configuring software product lines by combining many-objective optimization and sat solvers. *ACM Trans. Softw. Eng. Methodol.* 26(4), 14:1-14:46 (2018). <https://doi.org/10.1145/3176644>

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代表性工作2：在SATVaEA算法中，**分析并比较**了两类SAT求解器不同实现策略对算法**性能的影响**，为算法在实际应用中的求解器选择与配置提供了**可操作的指导**。



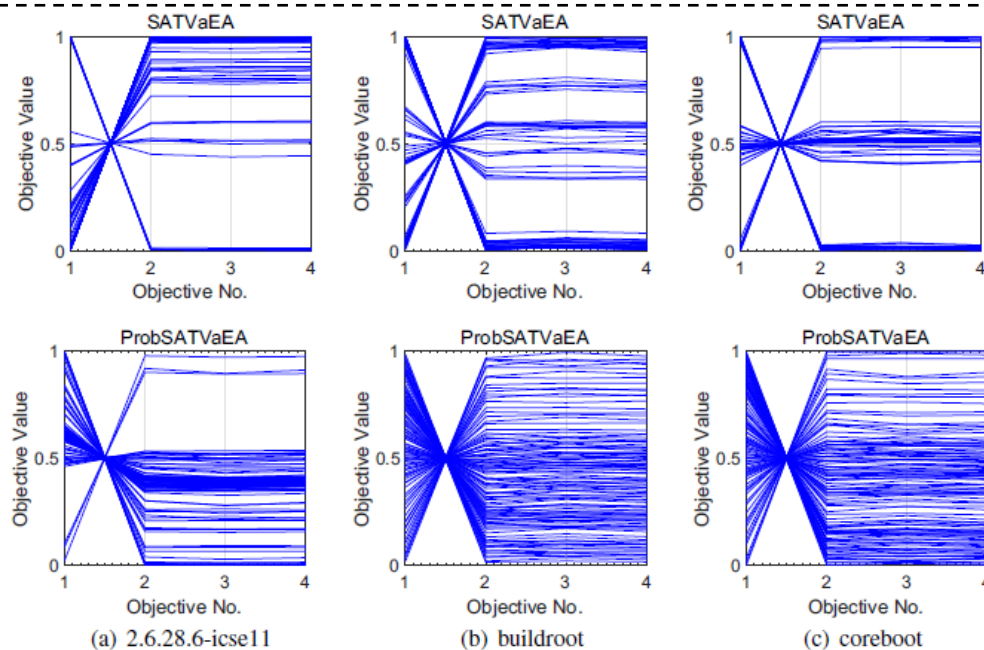
Table 3 Average HV values for different CDCL-SAT solvers

	SAT4J	MiniSat	Plingeling	Glucose
WebPortal	7.144E-01	7.167E-01	7.140E-01	7.168E-01
E-shop	4.445E-01	4.436E-01	4.890E-01	4.496E-01
Drupal	7.222E-01	7.195E-01	7.172E-01	7.215E-01
Amazon	7.151E-01	7.300E-01	7.167E-01	7.433E-01
Random-10000	1.610E-01	1.521E-01	3.060E-01	1.508E-01
RealAmazon	3.514E-01	3.640E-01	4.090E-01	3.823E-01
RealDrupal	3.605E-01	3.595E-01	3.573E-01	3.608E-01
toybox	4.893E-01	4.870E-01	3.786E-01	4.893E-01
axTLS	3.951E-01	3.640E-01	3.583E-01	3.594E-01
frebsd-icse11	3.822E-01	3.808E-01	2.943E-01	3.908E-01
fiasco	1.275E-01	1.207E-01	2.450E-01	1.212E-01
uClinux	5.052E-01	5.033E-01	2.422E-01	5.076E-01
busybox-1.18.0	4.548E-01	4.075E-01	2.771E-01	4.246E-01
2.6.28.6-icse11	1.772E-01	2.026E-01	2.438E-01	1.877E-01
uClinux-config	4.221E-01	1.791E-01	1.071E-01	1.827E-01
buildroot	2.800E-01	2.335E-01	2.399E-01	2.298E-01
freetz	2.519E-01	1.858E-01	1.692E-01	1.847E-01
coreboot	2.322E-01	2.211E-01	9.098E-02	2.180E-01
embtoolkit	3.262E-01	1.994E-01	2.221E-01	2.014E-01
2.6.32-2var	2.773E-01	2.356E-01	2.197E-01	2.318E-01
2.6.33.3-2var	2.562E-01	2.307E-01	2.227E-01	2.311E-01
Summary	16	7	7	12

SAT4J

probSAT

PbSATVaEA 算法



代表性工作3：针对OptSAT问题，设计了融合SAT求解驱动的智能修复算子与分布估计更新算子的算法无关型求解机制，内嵌于NSGA-III、MOEA/D等代表性多目标演化算法。

基于SAT求解的智能修复算子

Algorithm 4 Repair Operator for the OSPS Problem

Input: y // An infeasible solutions violating HCs

Output: y // The solution after repairing

- 1: if $\text{rand}() < \tau$ then
- 2: Repair y using the probSAT solver [52]
- 3: else
- 4: Repair y using the SAT4J solver [53]
- 5: end if
- 6: return y

例子：The solution $y = \{0, 0, 1, 1, 0\}$ is infeasible since it violates two constraints ($x1 \vee x5$) and ($x2 \vee x5$), involving three variables $x1, x2$, and $x5$. We remove their assignments and make $y = \{_, _, 1, 1, _\}$ **partially feasible**. Then y is given to the SAT4J solver, which will complete it and return a feasible solution

基于分布估计的更新算子

Algorithm 1 EoD_update_operator (x, i, u_p)

Input: x (the solution to be updated), i (the i -th subproblem) and u_p (the update probability)

Output: x (the updated solution)

- 1: Construct p_i according to (14)
- 2: for $k \leftarrow 1$ to n do
- 3: $r_1 \leftarrow \text{rand}(0, 1)$
- 4: if $r_1 < u_p$ then
- 5: $r_2 \leftarrow \text{rand}(0, 1)$
- 6: if $r_2 < p_{ik}$ then
- 7: $x_k \leftarrow 1$
- 8: else
- 9: $x_k \leftarrow 0$
- 10: end if
- 11: end if
- 12: end for
- 13: return x

$$p_{ik} = \alpha \cdot 0.5 + (1 - \alpha) \cdot \frac{T_{ik}}{S_i} \quad (14)$$

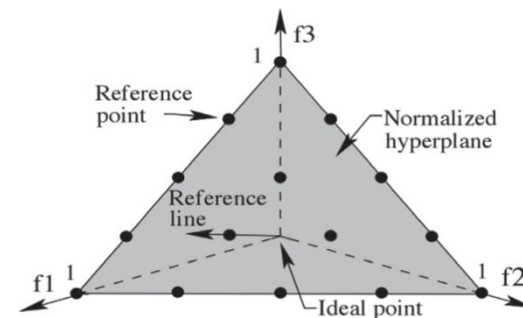
融合



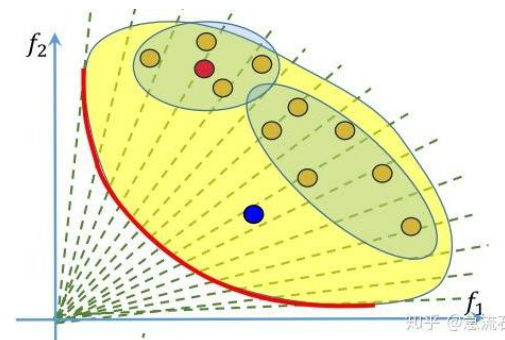
嵌入



多目标演化算法



NSGA-III



MOEA/D

代表性工作3：针对OptSAT问题，设计了融合SAT求解驱动的智能修复算子与分布估计更新算子的算法无关型求解机制，内嵌于NSGA-III、MOEA/D等代表性多目标演化算法。

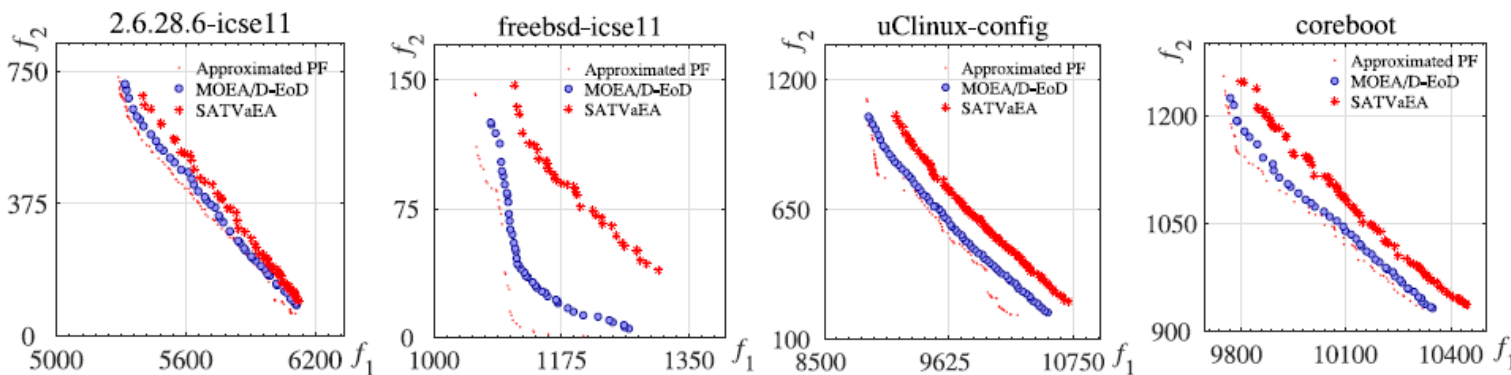
$m=2$

FM	HV		IGD+	
	MOEA/D-EoD	SATVaEA	MOEA/D-EoD	SATVaEA
2.6.28.6-icse11	7.215E-01	4.189E-01	3.120E-02	9.647E-02
freebsd-icse11	8.291E-01	1.797E-01	1.165E-01	5.100E-01
uClinux-config	7.204E-01	3.519E-01	6.689E-02	1.981E-01
buildroot	7.207E-01	4.273E-01	3.733E-02	1.012E-01
freetz	7.070E-01	4.712E-01	2.118E-02	4.390E-02
coreboot	7.711E-01	4.011E-01	5.884E-02	1.800E-01
2.6.32-2var	6.932E-01	3.222E-01	2.035E-02	9.943E-02
2.6.33.3-2var	6.784E-01	3.128E-01	2.480E-02	8.708E-02

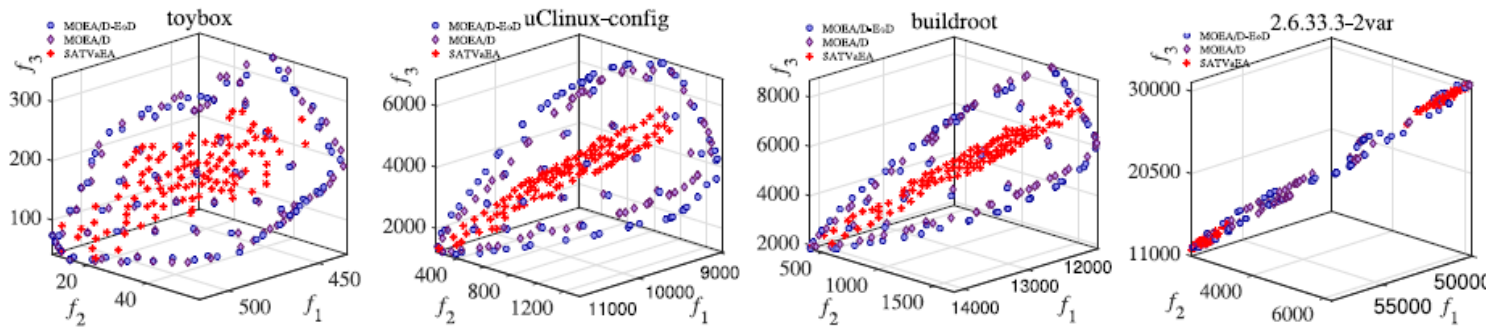
$m=3$

FM	MOEA/D-EoD	MOEA/D	SATVaEA
toybox	8.259E-01	8.281E-01‡	6.930E-01●
axTLS	7.840E-01	7.818E-01‡	6.516E-01●
fiasco	7.026E-01	7.053E-01‡	6.440E-01●
uClinux	8.797E-01	8.764E-01●	7.027E-01●
busybox-1.18.0	6.656E-01	6.533E-01●	5.509E-01●
2.6.28.6-icse11	6.593E-01	6.529E-01●	5.913E-01●
freebsd-icse11	8.231E-01	7.847E-01●	6.523E-01●
uClinux-config	7.357E-01	7.112E-01●	5.995E-01●
buildroot	6.970E-01	6.839E-01●	6.042E-01●
freetz	5.973E-01	5.907E-01‡	5.535E-01●
coreboot	7.684E-01	6.953E-01●	6.612E-01●
2.6.32-2var	5.488E-01	5.448E-01‡	3.923E-01●
2.6.33.3-2var	5.415E-01	5.429E-01‡	3.803E-01●

对目标数 $m=2$ 和 $m=3$ 的软件配置优化问题，MOEA/D-EoD在超体积（HV）和IGD+等性能指标上全面（统计上显著）优于SATVaEA算法。



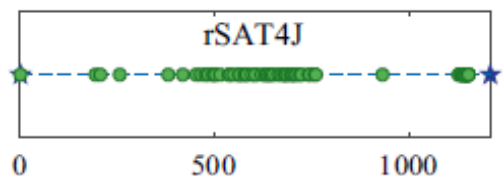
MOEA/D-EoD vs SATVaEA ($m=2$)



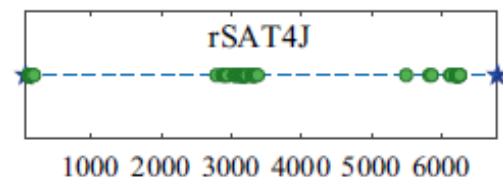
MOEA/D-EoD vs SATVaEA ($m=3$)

MOEA/D-EoD 在收敛性和多样性方面均显著优于 SATVaEA，尤其在边界解的发现能力上表现更为突出。

代表性工作4：针对现有 SAT 求解器**多样性不足**的问题，提出融入**概率感知多样化机制**的增强型SAT求解方法，并将其嵌入演化优化框架，从而提升软件配置优化下游任务中演化算法的性能表现



(a) ecos-icse11



(b) 2.6.28.6-icse11

```
Algorithm 2  $x \leftarrow PaD(n)$ 
Require:  $n$  (number of variables)
Ensure:  $x$  (a candidate)
1:  $x \leftarrow []$  // An unassigned configuration  $x$ 
2:  $p \leftarrow rand[0,1]$  // Generate a random number between 0 and 1 (inclusively)
3: for  $i \leftarrow 1$  to  $n$  do
4:   if  $f_i$  is mandatory then
5:      $x_i \leftarrow true$ 
6:   else if  $f_i$  is dead then
7:      $x_i \leftarrow false$ 
8:   else
9:     if  $rand() < p$  then
10:       $x_i \leftarrow true$ 
11:    else
12:       $x_i \leftarrow false$ 
13:    end if
14:  end if
15: end for
16: return  $x$ 
```

概率感知多样化机制PaD：初始化每个解 x 时，首先生成随机数 p ，然后以概率 p 为 x 的每个变量 x 赋真值。

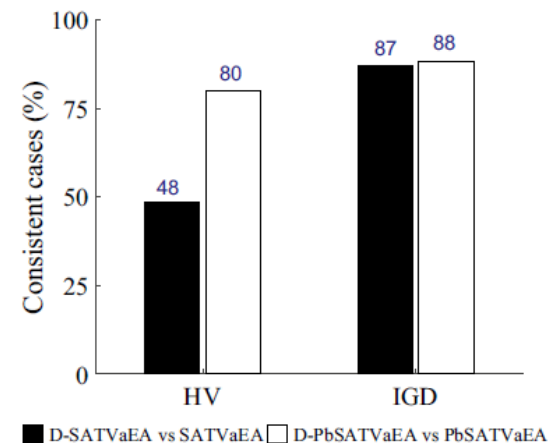
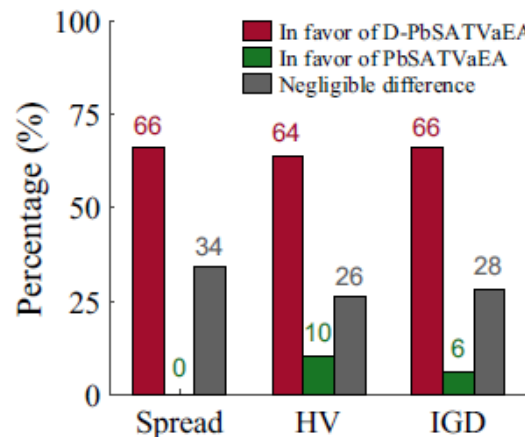
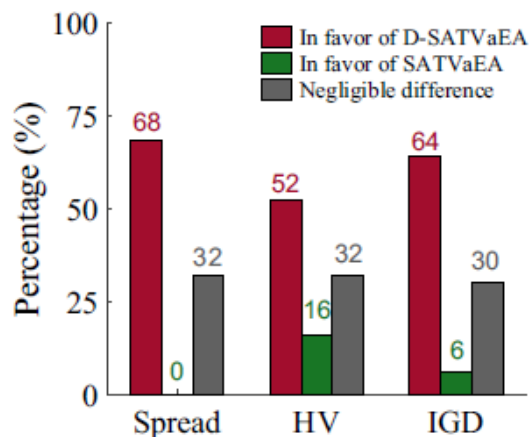
```
Algorithm 5 Search-based framework with PaD
Require:  $\phi$  (propositional formula),  $N$  (population size)
Ensure:  $S$  (final population)
1: Initialize the population  $S$  with  $N$  valid configurations generated by  $PaD$  (Algorithm 2) and  $SAT\_solving$ 
2: while termination condition is not met do
3:    $Q \leftarrow \emptyset$ 
4:   for  $i \leftarrow 1$  to  $N$  do
5:      $\{p_1, p_2\} \leftarrow matingSelection(S)$ 
6:      $\{c_1, c_2\} \leftarrow crossover(p_1, p_2)$ 
7:      $c \leftarrow$  random selection between  $c_1$  and  $c_2$ 
8:      $c \leftarrow mutation(c)$ 
9:     if  $rand() < 0.5$  then
10:       $c \leftarrow PaD\_reassign(c)$ 
11:    end if
12:     $c' \leftarrow SAT\_solving(c, \phi)$ 
13:    Evaluate  $c'$  based on one or more objective/fitness functions
14:     $Q \leftarrow Q \cup \{c'\}$ 
15:  end for
16:   $S \leftarrow environmentalSelection(S \cup Q)$ 
17: end while
18: return  $S$ 
```

实现融入概率感知多样化机制的增强型SAT求解，并将其作为核心模块嵌入演化优化框架

代表性工作4：针对现有 SAT 求解器多样性不足的问题，提出融入概率感知多样化机制的增强型SAT求解方法，并将其嵌入演化优化框架，从而提升软件配置优化下游任务中演化算法的性能表现

Table 6 Medians of Spread, HV and IGD for SATVaEA and D-SATVaEA over 30 runs

SPL	Spread		HV		IGD	
	SATVaEA	D-SATVaEA	SATVaEA	D-SATVaEA	SATVaEA	D-SATVaEA
CounterStrike	1.765e-01	1.176e-01	6.509e-01	6.510e-01	5.008e-02	4.925e-02
HiPAcc	7.143e-02	7.143e-02	6.758e-01	6.780e-01	8.918e-02	8.857e-02
SPLSSimuelESPnP	0.000e+00	0.000e+00	5.812e-01	5.807e-01	2.262e-02	2.329e-02
JavaGC	0.000e+00	0.000e+00	6.942e-01	6.945e-01	3.505e-02	3.525e-02
Poly	0.000e+00	0.000e+00	5.726e-01	5.726e-01	6.449e-03	6.449e-03
VP9	0.000e+00	0.000e+00	5.945e-01	5.944e-01	1.039e-02	1.031e-02
WebPortal	2.222e-01	2.222e-01	6.160e-01	6.174e-01	5.354e-02	5.348e-02
JHPster	0.000e+00	0.000e+00	5.823e-01	5.827e-01	6.642e-02	6.600e-02
Drupal	4.146e-01	4.146e-01	6.638e-01	6.623e-01	6.802e-02	6.815e-02
SmartHomev2.2	3.558e-01	3.566e-01	6.250e-01	6.239e-01	7.195e-02	7.236e-02
VideoPlayer	4.216e-01	3.725e-01	5.969e-01	5.955e-01	7.372e-02	7.348e-02
Amazon	0.000e+00	0.000e+00	6.912e-01	6.899e-01	7.022e-02	7.144e-02
ModelTransformation	3.396e-01	3.491e-01	6.393e-01	6.404e-01	7.388e-02	7.415e-02
CocheEcologico	5.000e-02	5.000e-02	5.933e-01	5.958e-01	8.407e-02	8.329e-02
Printers	5.625e-01	5.625e-01	5.117e-01	5.132e-01	7.180e-02	7.155e-02
fiasco.17.10	5.109e-01	3.043e-01	5.541e-01	5.700e-01	8.011e-02	7.580e-02
uClibo-ng.1.0.29	2.837e+00	1.090e+00	8.232e-01	5.160e-01	5.887e-02	5.689e-02
E-shop	1.475e+00	1.494e+00	4.404e-01	5.428e-01	4.388e-02	4.350e-02
toybox	8.878e-01	8.316e-01	4.141e-01	5.179e-01	6.048e-02	6.124e-02
axTLS	9.388e-01	8.237e-01	9.967e-01	4.964e-01	5.227e-02	5.328e-02
financial	1.171e+00	4.342e-01	6.19e-01	5.070e-01	6.989e-02	5.253e-02
bushybox.1.28.0	1.104e+01	5.068e+00	6.65e-01	5.020e-01	2.924e-02	2.446e-02
mpc50	7.485e+00	5.733e+00	5.070e-01	5.054e-01	2.286e-02	2.162e-02
ref4955	7.223e+00	5.623e+00	9.98e-01	4.995e-01	2.217e-02	2.094e-02
linux	7.853e+00	5.728e+00	9.99e-01	5.006e-01	2.313e-02	2.135e-02
csb281	8.124e+00	5.857e+00	9.042e-01	5.051e-01	2.302e-02	2.096e-02
ecos-icse11	6.163e+00	5.612e+00	9.155e-01	5.166e-01	2.602e-02	2.539e-02
cbas285	7.586e+00	5.963e+00	9.002e-01	5.024e-01	2.369e-02	2.202e-02
vrc4373	7.071e+00	5.828e+00	9.980e-01	4.978e-01	2.339e-02	2.219e-02
pati	7.159e+00	5.813e+00	9.033e-01	5.030e-01	2.154e-02	2.052e-02
dreamcast	7.420e+00	5.973e+00	9.057e-01	5.047e-01	2.200e-02	2.102e-02
pc_i82544	7.560e+00	6.033e+00	9.022e-01	5.030e-01	2.342e-02	2.203e-02
XSEngine	7.042e+00	6.063e+00	9.002e-01	4.998e-01	2.211e-02	2.118e-02
reelit334	7.599e+00	6.072e+00	9.054e-01	5.042e-01	2.310e-02	2.198e-02
occolid	7.265e+00	5.966e+00	9.017e-01	5.025e-01	2.309e-02	2.169e-02
integrator_arm9	7.334e+00	5.332e+00	9.006e-01	5.027e-01	2.312e-02	2.013e-02
olpci2294	8.055e+00	6.041e+00	9.002e-01	5.008e-01	2.322e-02	2.182e-02
olpci2294	7.853e+00	5.941e+00	9.048e-01	5.050e-01	2.189e-02	2.082e-02
phycore	7.686e+00	6.064e+00	9.013e-01	4.990e-01	2.229e-02	2.164e-02
hs7729pci	7.735e+00	5.862e+00	9.987e-01	4.993e-01	2.138e-02	1.954e-02
freebsd-icse11	1.243e+01	6.405e+00	9.789e-01	5.036e-01	2.831e-02	2.302e-02
fiasco	9.305e+00	8.596e+00	9.007e-01	5.094e-01	4.344e-02	4.366e-02
uClinux	3.498e+00	3.158e+00	9.462e-01	5.480e-01	3.828e-02	3.796e-02
Automotive01	6.043e+00	5.328e+00	9.890e-01	4.946e-01	2.506e-02	2.406e-02
SPLIT-FM-5000	1.297e+01	1.265e+01	9.834e-01	4.811e-01	2.168e-02	2.230e-02
bushybox-1.18.0	7.120e+00	6.789e+00	9.042e-01	5.029e-01	2.819e-02	2.793e-02
2.6.28.6-icse11	1.203e+02	2.838e+01	9.634e-01	4.893e-01	3.520e-02	1.294e-02
uClinux-config	2.375e+00	2.297e+01	9.802e-01	4.735e-01	2.556e-02	2.701e-02
buildroot	1.009e+02	6.632e+01	9.402e-01	4.619e-01	3.903e-02	2.835e-02
freetz	2.257e+02	1.494e+02	9.351e-01	4.569e-01	4.082e-02	2.829e-02



(a) SATVaEA v.s. D-SATVaEA (b) PbSATVaEA v.s. D-PbSATVaEA

在大量问题实例最高达**68%**上，D-SATVaEA (TOSEM 2018)和D-PbSATVaEA (EMSE 2020)在Spread、HV和IGD三项性能指标上整体优于对应算法，且即便在HV和IGD指标上存在少量未占优情形，其比例也始终较低（不超过**16%**）；进一步分析表明，Spread的显著提升往往伴随HV和IGD的同步改进：在所有D-SATVaEA相较SATVaEA在Spread上取得显著优势的实例中，分别有**48%**和**87%**的实例在HV和IGD指标上也表现出显著一致的性能提升。

在所有中等规模和大规模实例上，引入PaD增强SAT求解机制的D-SATVaEA在Spread指标上的表现均优于SATVaEA，即多样性显著提升。

软件配置优化问题的实验结果表明，提升SAT求解多样性对于显著改善下游任务性能具有积极且关键的作用！

代表性工作5：针对现有SAT求解器**多样性不足**的问题，提出基于**概率向量对抗机制**的SAT求解方法，并将其嵌入一类特殊的演化算法，即**新颖性搜索**（Novelty Search, NS）

概率向量 P $P_j = \frac{\sum_{i=1}^N tc_{ij}}{N}$ ← **第j个变量在种群中取真的比例**

算法 2. $c \leftarrow \text{DiverseSATsolving}(p)$.

1. $r \leftarrow \text{rand}(0, 1)$ // r 是位于 $[0, 1]$ 区间的随机数
2. **if** $r < 1 - P_r$ **do** // P_r 为控制参数
3. $c \leftarrow \text{rSAT4J}()$ // 随机化的 SAT4J 求解器 (CDCL 类型)
4. **else**
5. $c \leftarrow \text{dProbSAT}(p)$ // 多样性 ProbSAT 求解器 (SLS 类型)
6. **end if**
7. **return** c

多样性SAT求解：以概率 r 调用两类SAT求解器，其中，SAT4J（CDCL 类型）通过对决策启发式中的随机化相关控制参数进行扰动以提升搜索多样性，而ProbSAT（SLS类型）则通过引入**基于概率向量的“对抗”机制**来增强解的多样性。

算法 3. $c \leftarrow \text{dProbSAT}(p)$.

1. $c \leftarrow \text{null}$
2. **for** $i \leftarrow 1$ **to** n **do**
3. **if** 第 i 个特征是强制的
4. $c_i \leftarrow 1$
5. **elseif** 第 i 个特征是废弃的
6. $c_i \leftarrow 0$
7. **else**
8. **if** $\text{rand}(0, 1) < 1 - p_i$
9. $c_i \leftarrow 1$
10. **else**
11. $c_i \leftarrow 0$
12. **end if**
13. **end if**
14. **end for**
15. 若 c 不可行，则运用 ProbSAT 求解器修复 c
16. **return** c

对抗机制：以概率 $1 - p_i$ （而非 p_i ）为变量赋真值

Algorithm 1 NS algorithm for SPL sampling

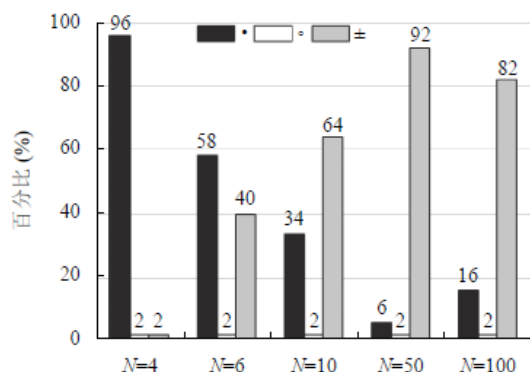
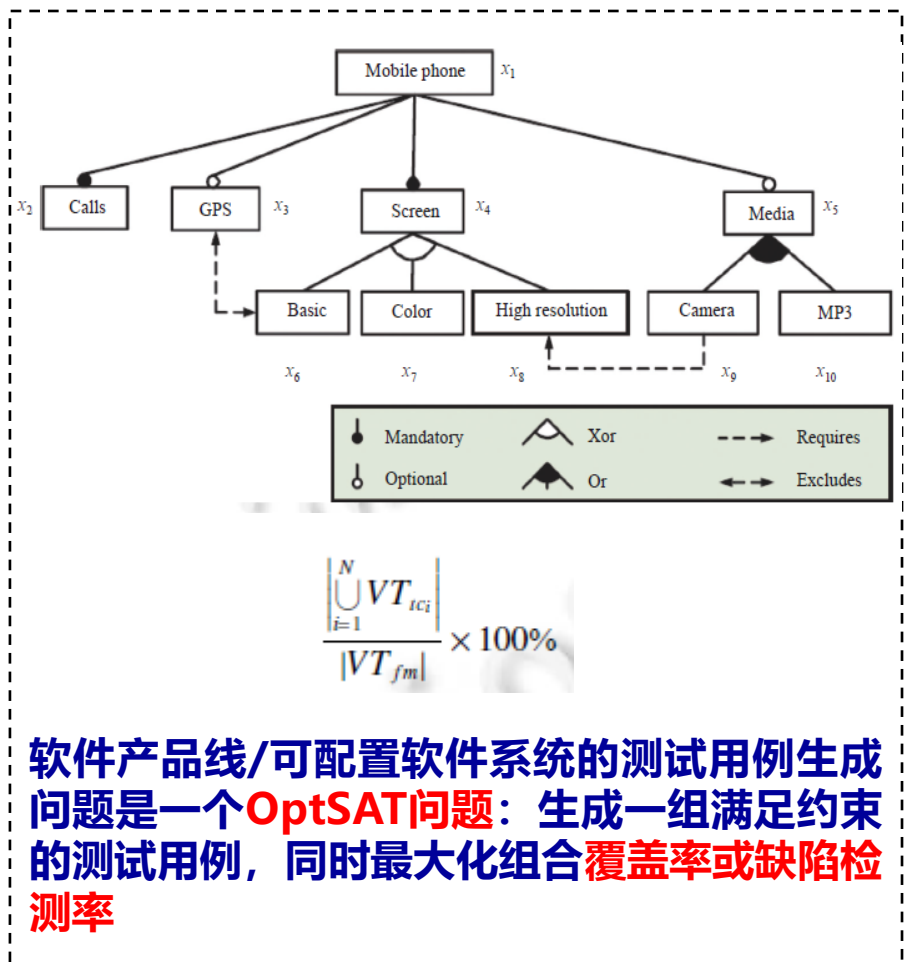
Input: archive size (N), execution time (max_t), repair probability (P_r) and neighbor size (N_b)

Output: archive \mathcal{A}

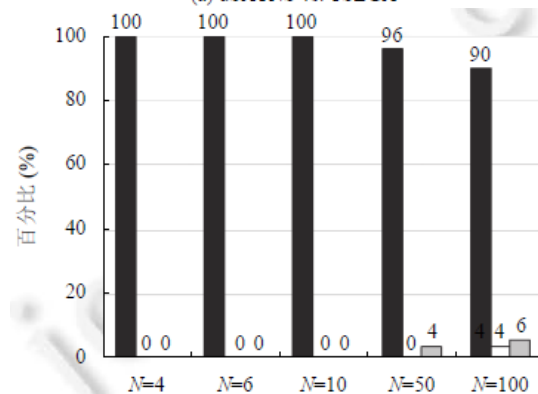
- 1: Initialize the archive \mathcal{A} by generating N configurations in an unpredictable way as in [4]
- 2: **while** the elapsed time is less than max_t **do**
- 3: Generate a random configuration c
- 4: **if** c is not valid **then**
- 5: **if** $\text{rand}(0, 1) < P_r$ **then**
- 6: Repair c using the probSAT solver [52]
- 7: **else**
- 8: Replace c by an unpredictable configuration got from the randomized SAT4J solver
- 9: **end if**
- 10: **end if**
- 11: **for each** $x \in \mathcal{A} \cup \{c\}$ **do**
- 12: Calculate the novelty score $\rho(x)$ by Eq. (2)
- 13: **end for**
- 14: $c_{worst} \leftarrow$ the worst member in \mathcal{A} concerning the novelty score // c_{worst} has the minimum novelty score
- 15: **if** $\rho(c) > \rho(c_{worst})$ **then**
- 16: $c_{worst} \leftarrow c$ // Replace the worst archived member by c
- 17: **end if**
- 18: **end while**
- 19: **return** \mathcal{A}

嵌入NS算法，属于质量-多样性（Quality-Diversity, QD）优化算法（演化算法的一个分支）

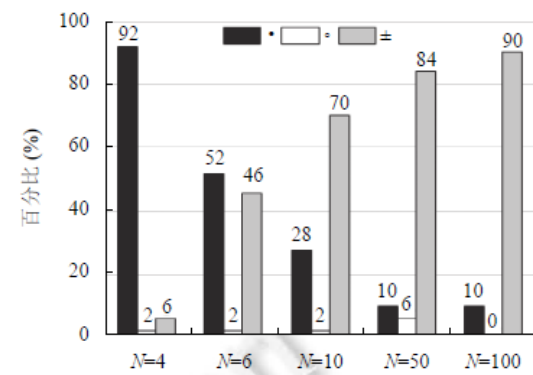
代表性工作5：针对现有SAT求解器多样性不足的问题，提出基于概率向量对抗机制的SAT求解方法，并将其嵌入一类特殊的演化算法，即新颖性搜索（Novelty Search, NS）



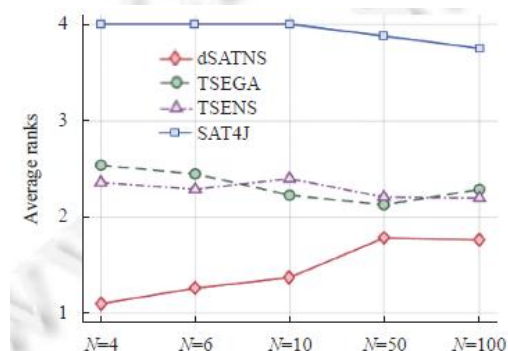
(a) dSATNS vs. TSEGA



(c) dSATNS vs. SAT4J



(b) dSATNS vs. TSENS



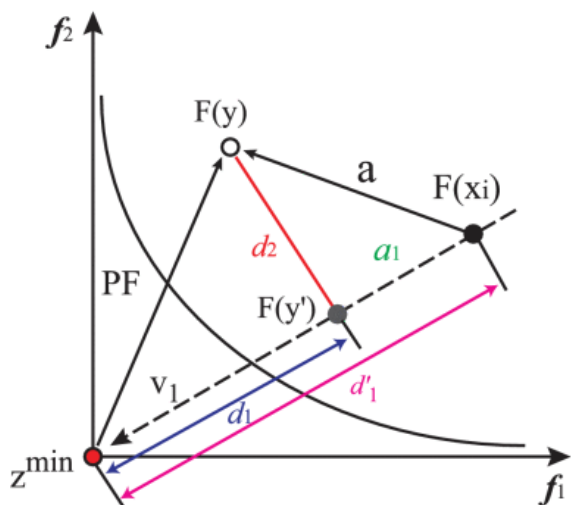
Friedman 检验得到的各算法的平均排名 (average ranks)

与先进算法相比，dSATNS 整体排名第一；相较 SAT4J，其在90%以上实例上取得统计显著的性能提升。

内嵌基于概率向量对抗机制的SAT求解方法，有助于NS算法提升测试覆盖率和缺陷检测率！

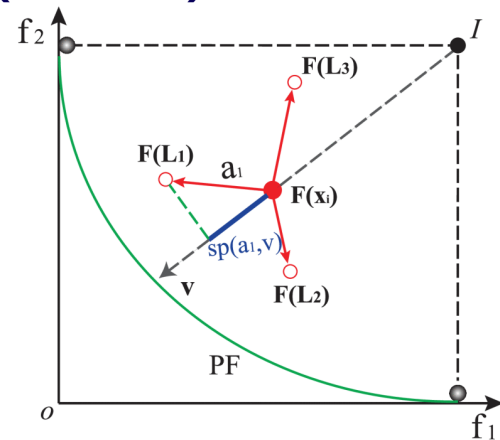
代表性工作6：针对演化优化，提出融合**夹角**和**标量投影**的自适应**多目标演化算法**及**约束处理机制**。

基于**夹角**和**标量投影**的多目标进化算法 (PAEA)



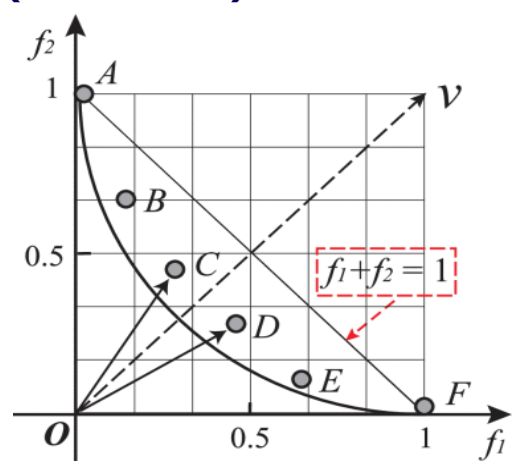
TCYB 2019*

基于**标量投影**选择领导者的多目标粒子群优化算法 (MaPSO)



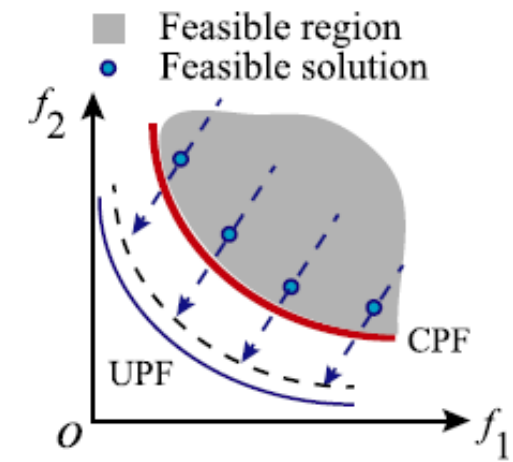
TCYB 2020

基于Pareto**自适应参考点**的多目标进化算法 (PaRP/EA)



TEVC 2020a

面向多目标演化优化的**自适应约束处理机制**ToM



TCYB 2023

[TCYB 2019*] Yuren Zhou, **Yi Xiang***, Zefeng Chen, Jun He, Jiahai Wang. A Scalar Projection and Angle based Evolutionary Algorithm for Many-objective Optimization Problems, *IEEE Transactions on Cybernetics (TCYB)*, 2019, 49(6): 2073-2084

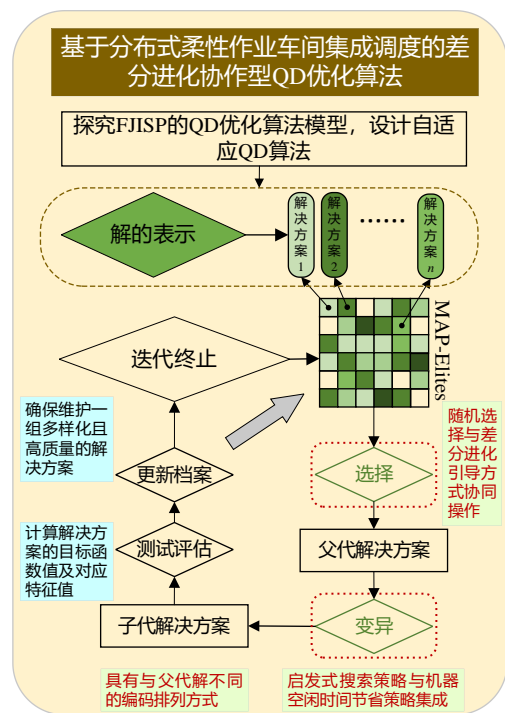
[TCYB 2020] **Yi Xiang**, Yuren Zhou*, Zefeng Chen, Jun Zhang. A Many-objective Particle Swarm Optimizer with Leaders Selected from Historical Solutions by Using Scalar Projections, *IEEE Transactions on Cybernetics (TCYB)*, 2020, 50(5):2209-2222

[TEVC 2020a] **Yi Xiang**, Yuren Zhou*, Xiaowei Yang, Han Huang. A Many-objective Evolutionary Algorithm With Pareto-adaptive Reference Points. *IEEE Transactions on Evolutionary Computation (TEVC)*, 2020, 24(1): 99-113

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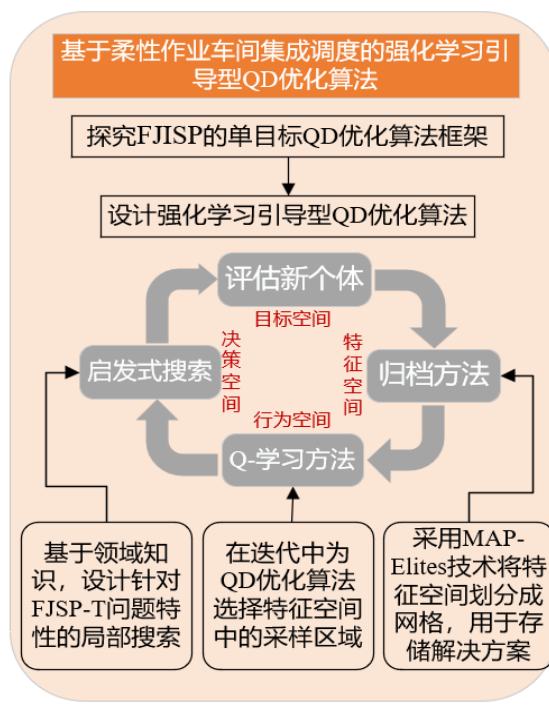
代表性工作7：针对演化优化，提出强化学习增强的质量-多样性（QD）优化算法求解车间调度问题。

QD优化与差分进化的融合机制



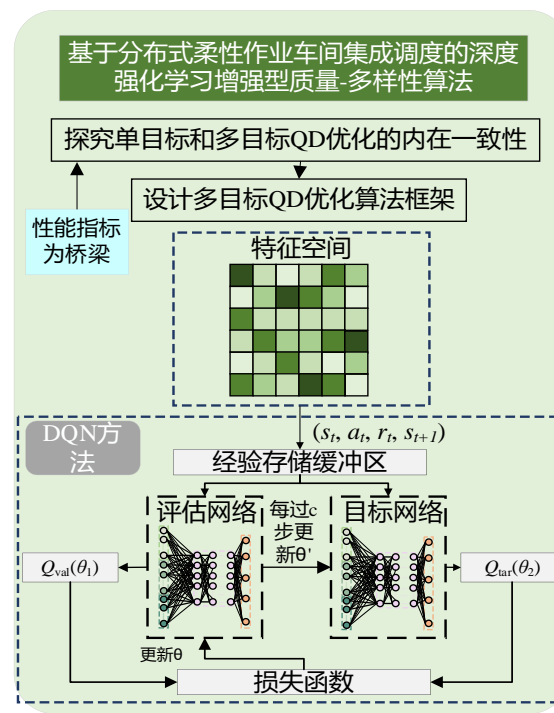
TEVC 2024*

强化学习引导的QD优化算法



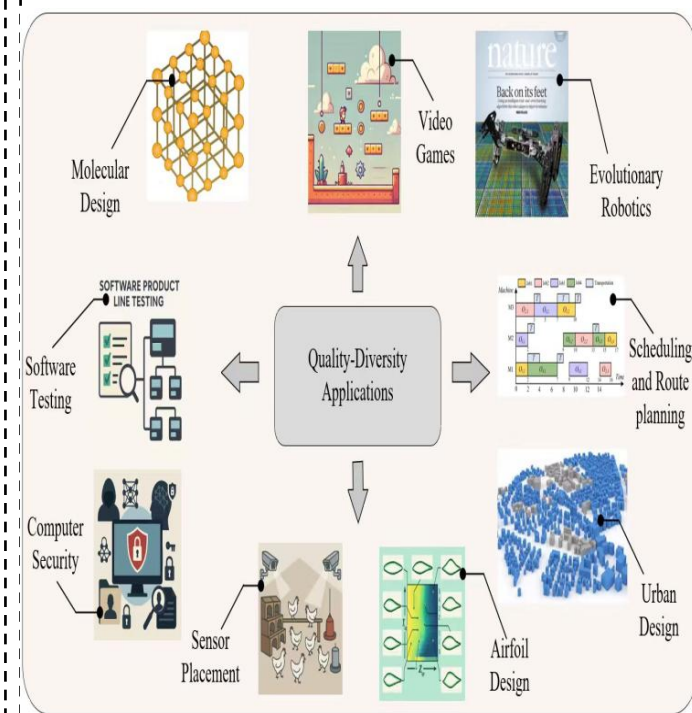
EAAI 2026*

深度强化学习增强的QD优化算法



中国科学：信息科学 2025*

QD优化最新综述



SWEVO 2026*

[TEVC 2024*] Haoxiang Qin, Wenlei Bai, **Yi Xiang***, Fangqing Liu, Yuyan Han, and Ling Wang. A Self-adaptive Collaborative Differential Evolution Algorithm for Solving Energy Resource Management Problems in Smart Grids, *IEEE Transactions on Evolutionary Computation*, vol. 28, no. 5, pp. 1427-1441, Oct. 2024, doi: 10.1109/TEVC.2023.3312769

[EAAI 2026*] Haoxiang Qin, **Yi Xiang***, Yuyan Han, Yuting Wang, Junqing Li, and Quanke Pan. A knowledge region selection enhanced quality-diversity algorithm for real-world flexible job shop scheduling with Automated Guided Vehicles transportation. *Engineering Applications of Artificial Intelligence*, vol. 164, pp. 113352, Nov. 2026. DOI: doi.org/10.1016/j.engappai.2025.113352

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相关论文:共16篇, 其中TEVC*5, TOSEM*1, TCYB*4, 中国科学: 信息科学*1, 软件学报*1, 其他JCR一区/CCF-B*4

[1] **Yi Xiang**, Xiaowei Yang*, Yuren Zhou, Han Huang. Enhancing Decomposition-Based Algorithms by Estimation of Distribution for Constrained Optimal Software Product Selection. *IEEE Transactions on Evolutionary Computation (TEVC)*, 2020, 24(2): 245-259 (JCR一区期刊)

[2] **Yi Xiang**, Yuren Zhou*, Miqing Li, Zefeng Chen. A Vector Angle based Evolutionary Algorithm for Unconstrained Many-Objective Optimization, *IEEE Transactions on Evolutionary Computation (TEVC)*, 2017, 21(1): 131-152 (JCR一区期刊; **ESI高被引论文**)

[3] **Yi Xiang**, Yuren Zhou*, Xiaowei Yang, Han Huang. A Many-objective Evolutionary Algorithm With Pareto-adaptive Reference Points. *IEEE Transactions on Evolutionary Computation (TEVC)*, 2020, 24(1): 99-113 (JCR一区期刊)

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- [10] Yuren Zhou, Yi Xiang *(**通讯**), Zefeng Chen, Jun He, Jiahai Wang. A Scalar Projection and Angle based Evolutionary Algorithm for Many-objective Optimization Problems, *IEEE Transactions on Cybernetics (TCYB)*, 2019, 49(6): 2073-2084 (JCR一区期刊)
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- [14] Yi Xiang, Xiaowei Yang*, Han Huang, Zhengxin Huang, Miqing Li. Sampling Configurations From Software Product Lines Via Probability-aware Diversification and SAT Solving. *Automated Software Engineering (AUSE)*, 2022, 29(2): 54.1-54.45 (CCF-B类期刊)
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相关专利

- [1] 向毅;徐书凝;黄翰;曹捷;崔书中, 一种基于多目标MAP-Elites的机器人损伤恢复方法, 发明专利 (授权号: ZL 2024 1 0612668.5) , 2024年07月16日
- [2] 向毅;秦浩翔;韩玉艳;王玉亭, 一种分布式柔性作业车间的调度方法及装置, 发明专利 (授权号ZL 2023 1 1831353.1) , 2025年10月17日
- [3] 秦浩翔;向毅;韩玉艳;王玉亭, 带自动导引车的分布式柔性作业车间的调度方法及装置, 发明专利 (授权号ZL 2024 1 0670337.7) , 2025年10月10日

竞赛获奖



Evolutionary Computation in the Energy Domain: Optimal PV System Allocation

Organised by João Soares, Fernando Lezama, José Almeida, Bruno Canizes, Zita Vale, Wenlei Bai, and Kwang Y. Lee

2nd

Genetic and Evolutionary Computation Conference

July 14-18, 2024
Melbourne, Australia (hybrid)

Tianyu Gao, Yi Xiang, Haoxiang Qin
South China University of Technology



J.R. Singh



CIS Prize: USD 300

Xiao Zhang

Evolutionary Computation in the Energy Domain: Operation and Planning Applications Global classification (average of track 1 and track 2)

3rd

Genetic and Evolutionary Computation Conference

July 15-19, 2023
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Haoxiang Qin, Wenlei Bai, Yi Xiang, Fangqing Liu, Yuyan Han, Ling Wang, and Kwang Y. Lee

School of Software Engineering, South China University of Technology, China; Oracle Energy and Water, Oracle America Inc., Austin, TX, USA; School of Computer Science, Liaocheng University, China; Department of Automation, Tsinghua University, China; Department of Electrical and Computer Engineering, Baylor University, Waco, TX

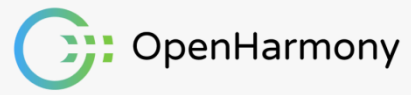


William La Cava
William La Cava
Competitions Chair

Sara Silva
Sara Silva
General Chair

成果简介：面向基础软件与工业软件等可配置软件系统的质量保障需求，针对现有测试方法理论可解释性不足与测试效率偏低的挑战，从统计学视角系统揭示了测试用例多样性与交互组合覆盖率之间的显著正相关关系，为多样性驱动测试方法提供了坚实的**理论支撑与可解释依据**。在此基础上，构建了以测试用例**多样性**为核心优化目标的数学模型，设计了基于内嵌SAT求解的演化优化范式（**研究成果1**）的模型求解方法，显著提升了测试用例的多样性与缺陷检测能力。

基础软件



 操作系统	 数据库	 编译器
----------	---------	---------

 航空航天	 汽车	 能源交通
----------	--------	----------



```
145 #
146 # Feature configuration:
147 #
148
149 set(DEAL_II_WITH_CXX11 ON)
150 set(DEAL_II_WITH_CXX14 ON)
151 set(DEAL_II_WITH_CXX17 ON)
152 set(DEAL_II_WITH_CXX20 ${DEAL_II_HAVE_CXX20})
153 set(DEAL_II_WITH_THREADS ON)\n"
154 )
```

```
39 config COMPILER_GCC
40     bool "GCC"
41
42 config CROSS_COMPILE
43     string "GCC cross-compile toolchain prefix"
44     depends on COMPILER_GCC
45     default "arm-linux-ohoseabi-" if ARCH_ARM_AARCH32
46
47 config COMPILER_CLANG_LLVM
48     bool "Clang"
```

工业软件 CAE

核心挑战

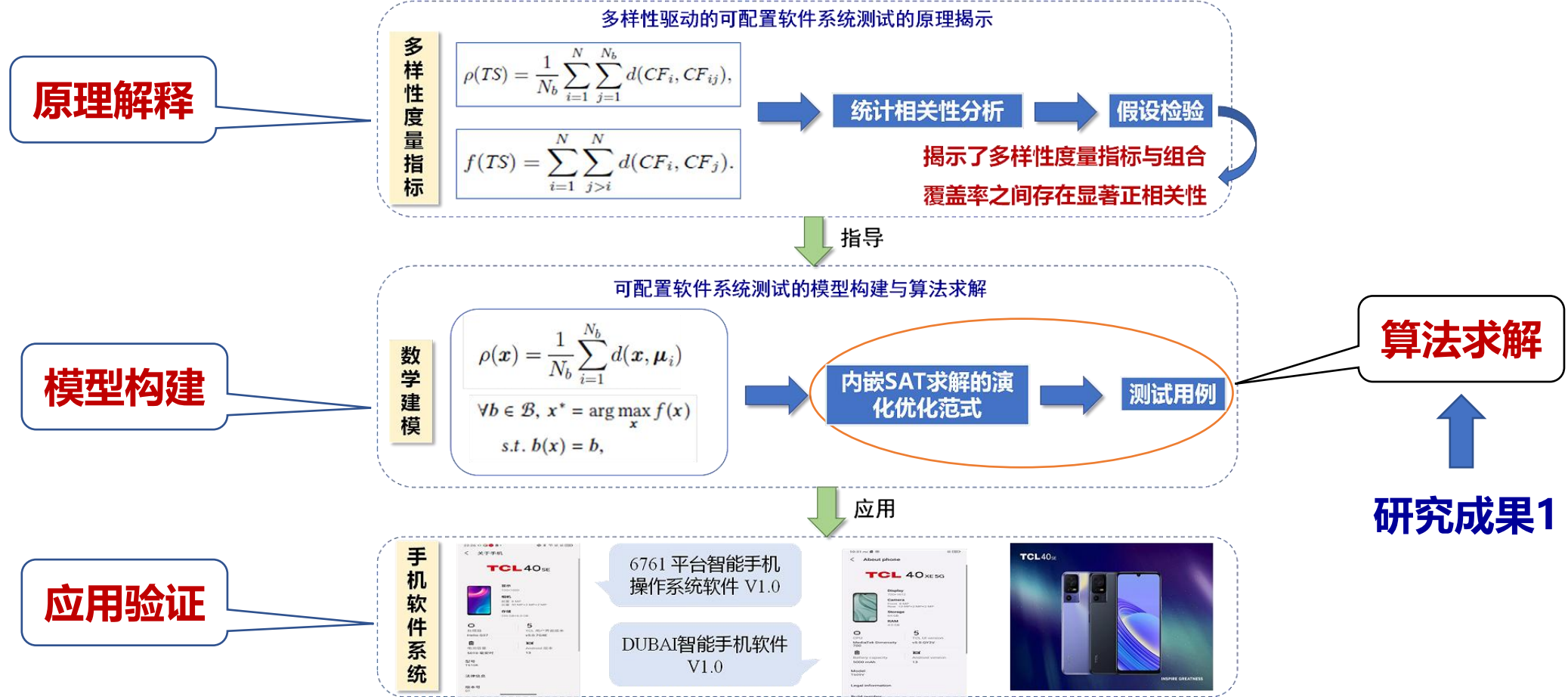
- 配置空间的规模随着配置选项数量呈**指数式增长**，如此庞大的配置空间使得对所有配置进行穷举测试在**计算上不可行**。
- t -组合测试作为实际中广泛应用的测试方法，旨在覆盖所有 t -阶配置选项或特征的交互。然而，随着系统规模和交互强度 t 的增加，潜在交互数量呈**指数式膨胀**，从而需要生成大量的系统级测试用例，这在测试用例的**生成与执行效率**方面带来了严峻挑战。
- 多样性驱动测试方法是 t -组合测试的高效替代，但**缺乏可解释性**。

假设任选两个特征 f_1 和 f_2 ，则它们组成的2-阶特征交互（或2元组）是：
(f_1, f_2)、 ($f_1, \sim f_2$)、 ($\sim f_1, \sim f_2$)、 ($\sim f_1, f_2$)

特征交互的数量为： $C_n^t \cdot 2^t$  随着 t （交互强度）指数式增长

- Linux kernel (6888 个配置选项)，实现完全2-阶覆盖需要**480**个测试用例。
- 若 t 增大，现有方法甚至**无法**在有限时间内**生成**实现完全 t -阶覆盖的测试用例

解决方案：从统计学视角出发，揭示测试用例多样性与交互组合覆盖率的显著正相关关系，进而构建以“多样性最大化”为目标的测试优化模型，并设计内嵌SAT求解器的质量-多样性（Quality-Diversity, QD）优化范式进行求解。通过在实际手机软件操作系统中的应用，验证了该方法的有效性，为可配置软件系统的自动化测试提供了可推广的技术路径。



代表性工作1：从统计学角度出发揭示了测试用例多样性与t-组合覆盖率之间的**统计正相关性**，为多样性驱动测试方法提供了可解释的依据——**科学发现**

多样性度量指标

新颖得分

$$\rho(TS) = \frac{1}{N_b} \sum_{i=1}^N \sum_{j=1}^{N_b} d(CF_i, CF_{ij}),$$

相似性度量

$$f(TS) = \sum_{i=1}^N \sum_{j>i}^N d(CF_i, CF_j).$$

随机生成若干测试集，通过执行相关性分析来观察多样性度量指标与t-组合覆盖率之间的相关性和相关程度的大小

假设检验

- 测试集规模 $N=50, 100, 500$
- $t = 2, \dots, 6$ (5个取值)
- $N_b = 2, 15, N/4, N/2, 3N/4$ (5个取值)

国际同行评价：Correlations between t-wise coverage and similarity-based sampling seem to be natural and intuitive but **no in-depth investigation has been conducted so far confirming this intuition** (迄今尚无深入研究证实这一直觉). Hence, the insights presented by the authors of the manuscript **are relevant and valuable** (切题且有价值) for the research community on sample-based SPL testing.

实验验证：31个真实或者构造的特征模型（特征数最多18,434）

- 在绝大多数情形下，Pearson相关系数 r 显著大于0。
- 正相关性**
- 图中蓝色数字表示显著正相关个数。显然，绝大多数正相关关系是统计显著的($p < 0.05$) **显著正相关性**
- 与 N_b 的其他取值相比，在几乎所有情形下， $N_b = N$ 的相关性强度最弱。即，基于相似性的适应值 ($N_b = N$) 不如一般性的新颖得分有效。

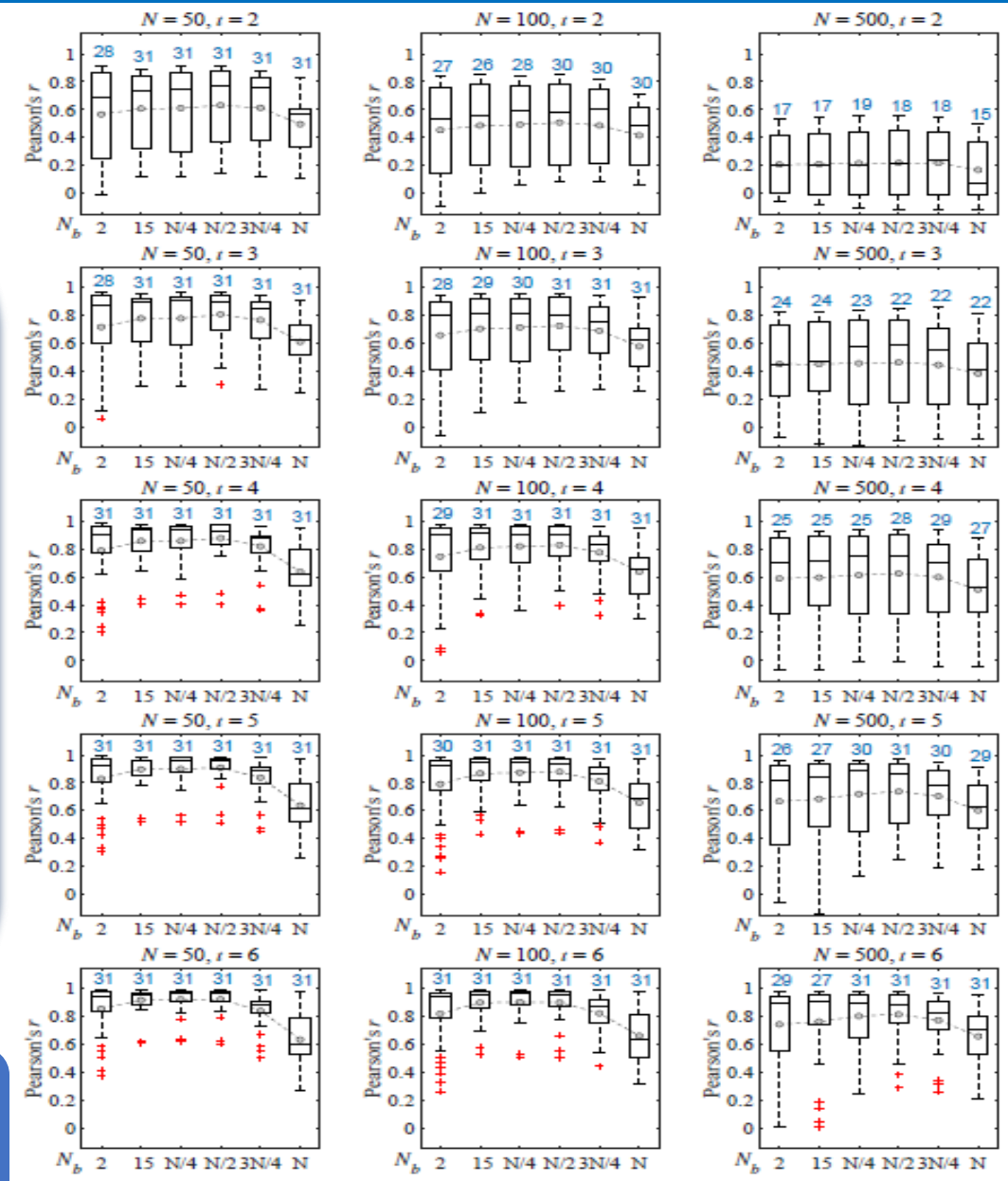


图 5-1 相关性分析结果（箱线图），其中每个子图中的虚线连接相邻的两个平均值。

从统计学角度，解释了多样性驱动可配置软件系统测试的基本原理，使得该测试方法具有了理论保障。

代表性工作2: 引入新颖性搜索 (Novelty Search, NS) 演化算法, 通过奖励差异化测试用例来提升多样性。NS以新颖性为驱动的演化机制, 与可配置系统测试中生成差异化配置以提高覆盖率和缺陷检测能力的目标高度契合。

$$\rho(\mathbf{x}) = \frac{1}{N_b} \sum_{i=1}^{N_b} d(\mathbf{x}, \mu_i), \quad (2)$$

某个体的新颖得分定义为该个体与其最近Nb个个体的平均距离。距离的计算可采用以下几种方式:

$$d^{Jaccard}(\mathbf{x}, \mu_i) = 1 - \frac{|\mathbf{x} \cap \mu_i|}{|\mathbf{x} \cup \mu_i|}, \quad d^{Dice}(\mathbf{x}, \mu_i) = 1 - \frac{2|\mathbf{x} \cap \mu_i|}{|\mathbf{x} \cup \mu_i| + |\mathbf{x} \cap \mu_i|}.$$

$$d^{Hamming}(\mathbf{x}, \mu_i) = 1 - \frac{|\mathbf{x} \cap \mu_i|}{|\mathcal{F}|}, \quad d^{Antidice}(\mathbf{x}, \mu_i) = 1 - \frac{|\mathbf{x} \cap \mu_i|}{2|\mathbf{x} \cup \mu_i| - |\mathbf{x} \cap \mu_i|}.$$

Algorithm 1. NS Algorithm for SPL Sampling

Input: archive size (N), execution time (max_t), repair probability (P_r) and neighbor size (N_b)
 Output: archive \mathcal{A}

- 1: Initialize the archive \mathcal{A} by generating N configurations in an unpredictable way as in [4]
- 2: while the elapsed time is less than max_t do
- 3: Generate a random configuration c
- 4: if c is not valid then
- 5: if $rand(0, 1) < P_r$ then
- 6: Repair c using the probSAT solver [52]
- 7: else
- 8: Replace c by an unpredictable configuration got from the randomized SAT4J solver
- 9: end if
- 10: end if
- 11: for each $\mathbf{x} \in \mathcal{A} \cup \{c\}$ do
- 12: Calculate the novelty score $\rho(\mathbf{x})$ by Eq. (2)
- 13: end for
- 14: $c_{worst} \leftarrow$ the worst member in \mathcal{A} concerning the novelty score // c_{worst} has the minimum novelty score
- 15: if $\rho(c) > \rho(c_{worst})$ then
- 16: $c_{worst} \leftarrow c$ // Replace the worst archived member by c
- 17: end if
- 18: end while
- 19: return \mathcal{A}

实验验证：31个真实或者构造的特征模型（特征数最多18,434）

TABLE 3

Average Rankings of the Algorithms Obtained by the Friedman Test

Algorithm	Ranking
NS	1.1935
GA	2.1935
SamplingDown	2.6677
Unpredictable	3.9452

TABLE 4

Summary of \widehat{A}_{12} Comparisons for Each Magnitude of the Effect Size

	NS vs	GA	SamplingDown	Unpredictable
Large	$ES > 0.5$	123	130	148
	$ES < 0.5$	6	5	0
Medium	$ES > 0.5$	4	6	0
	$ES < 0.5$	2	3	0
Small	$ES > 0.5$	2	3	0
	$ES < 0.5$	6	1	3
Negligible	/	12	7	4

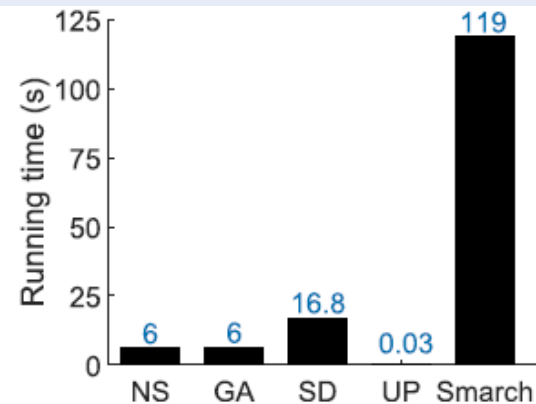


Fig. 6. Average running time on small-scale FMs. 'SD' and 'UP' stand for SamplingDown and Unpredictable, respectively.

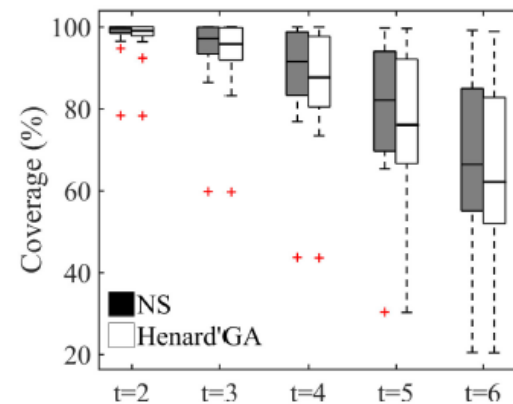


Fig. 7. T -wise coverage obtained by NS and Henard's GA, shown in boxplots.

NS获得最优的整体性能，分别在79%、84%和95%的情形下较GA、SamplingDown和Unpredictable等主流算法有大幅度改进（效应值大于0.5）。同时，NS的运行时间仅为工具Smarch的5%。

同行评价

北京航空航天大学、新加坡国立大学、德国慕尼黑工业大学和重庆大学的联合研究团队 (TOSEM 2024)

Solving the t -Wise Coverage Maximum Problem via Effective and Efficient Local Search-Based Sampling

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challenge [110]) for evaluating the scalability of *LS-Sampling-Plus*. Furthermore, we carry out empirical evaluations on the benchmark collection (which is collected by Xiang et al. [125] and specifically designed for measuring the fault detection capability) for exploring the fault detection capability of *LS-Sampling-Plus*.

its state-of-the-art competitors. Also, our experiments on the benchmark collection, which is originally prepared by Xiang et al. [125] and is designed for evaluating the fault detection capability, demonstrate that *LS-Sampling-Plus* achieve considerably better fault detection capability than all its competitors.

774,148. Furthermore, in order to assess the fault detection capability of *LS-Sampling-Plus*, we adopt a benchmark collection that is originally collected by Xiang et al. [125]. This benchmark collection

[125] Yi Xiang, Han Huang, Miqing Li, Sizhe Li, and Xiaowei Yang. 2022a. Looking for novelty in search-based software product line testing. *IEEE Transactions on Software Engineering* 48, 7 (2022), 2317–2338.

全文中多处 (至少7处) 引用并评价了TSE 2022

detection capability than its state-of-the-art competitors. In fact, Xiang et al. [125] have already prepared a benchmark collection for assessing the fault detection capability of *NS*, and *NS* is adopted as a main competitor in this work. Hence, we employ such benchmark collection in this experiment.

experiment, a t -option fault is expressed as a valid t -wise option combination. For each benchmark, Xiang et al. [125] have provided a set of t -option faults ($2 \leq t \leq 6$). According to the literature [125], these t -option faults are generated by a commonly used fault simulator [2, 6], which has

introduced by the literature [125]. Because our experiments show that both uniform sampling and *Baital* fail to generate test suite on the majority of the target benchmarks (i.e., the benchmarks collected by Xiang et al. [125]), in Table 14 we do not present the results of uniform sampling and

Xiang 等人所构建的测试集在数据层面奠定了引文 TOSEM 2024 实验研究的基础, 是其实验评估的重要依托。

Baranov et al. [9] proposed an adaptive weighted sampling method called *Baital*, and Xiang et al. [125] presented a novelty search-based method named *NS*. *Baital*, *NS*, and *PLEDGE* represent the current state of the art in solving the t -wise CovMax problem. The evaluation results reported

Xiang 等人提出的NS方法与Baital、PLEDGE等欧美研究团队提出的方法一道, 被公认为解决 t -wise 最大化问题的最先进 (state-of-the-art) 方法之一

IEEE Fellow

同行评价

英国谢菲尔德大学
Robert M. Hierons教授

Software Testing, Verification and Reliability

WILEY

SURVEY ARTICLE OPEN ACCESS

A Systematic Mapping Study of the Metrics, Uses and Subjects of Diversity-Based Testing Techniques

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Received: 25 January 2024 | Revised: 30 September 2024 | Accepted: 17 December 2024

Keywords: diversity artefacts | diversity-based testing | diversity-based tools | fault localization | similarity-based testing | similarity metrics | test data generation | test case prioritization | test case selection | test suite reduction



5.17 | SPLs Configuration

SPL configuration refers to the process of selecting and combining specific features or components from a SPL to create a customized software product that meets specific requirements or user preferences. It involves choosing the desired features, their variations and their configurations to create a tailored software solution. Diversity between SPL configurations is used in many papers [32, 141, 148].

Xiang等人的工作是SPL配置问题研究中采用配置多样性指标的代表性工作之一

148. Y. Xiang, H. Huang, M. Li, S. Li, and X. Yang, "Looking for Novelty in Search-Based Software Product Line Testing," *IEEE Transactions on Software Engineering* 1, no. 1 (2021): 1-1, <https://doi.org/10.1109/TSE.2021.3057853>.

代表性工作3: 提出定制化的距离度量以及多样化的SAT求解器, 结合新颖性搜索算法, 以增量方式生成多样化样本, 从而为大规模可配置系统实现可扩展的测试用例生成方法

定制化的距离度量

$$d_{ij} = d(x_i, x_j) = \frac{1}{2} \cdot \left(\frac{\text{abs}(\mathcal{T}(x_i) - \mathcal{T}(x_j))}{n} \right) + \frac{1}{2} \cdot \left(1 - \frac{|x_i \cap x_j|}{n} \right) \cdot \delta$$

其中,

$$\delta = \begin{cases} \frac{1}{\max\{\mathcal{T}(x_i), \mathcal{T}(x_j)\}} & \mathcal{T}(x_i) + \mathcal{T}(x_j) \leq n, \\ \frac{1}{n - \min\{\mathcal{T}(x_i), \mathcal{T}(x_j)\}} & \text{otherwise.} \end{cases}$$

多样化的SAT求解器

```

算法 2.  $c \leftarrow \text{DiverseSATsolving}(p)$ .


---


1.  $r \leftarrow \text{rand}(0, 1)$  //  $r$  是位于  $[0, 1]$  区间的随机数
2. if  $r < 1 - P$ , do //  $P$ , 为控制参数
3.    $c \leftarrow \text{rSAT4J0}$  // 随机化的 SAT4J 求解器 (CDCL 类型)


---


4. else
5.    $c \leftarrow \text{dProbSAT}(p)$  // 多样性 ProbSAT 求解器 (SLS 类型)
6. end if
7. return  $c$ 
    
```



Algorithm 1: NSbS algorithm

```

Input:  $\phi$  (propositional formula),  $N$  (sample size)
Output:  $\mathcal{A}$  (archived samples)
1 Initialize the archive  $\mathcal{A}$  by generating  $N$  solutions to  $\phi$  using the randomized SAT4J solver [25];
2 Initialize the distance matrix  $\mathbf{D} = (d_{ij})_{(N+1) \times (N+1)}$ , where  $d_{ij}$  ( $i, j = 1, \dots, N$ ), as given in Eq. (3), is the distance between  $x_i \in \mathcal{A}$  and  $x_j \in \mathcal{A}$ ;
3 For each  $x \in \mathcal{A}$ , calculate its novelty score  $\rho(x)$  based on Eq. (1);
4 while the termination condition is not met do
5    $\{p_1, p_2\} \leftarrow \text{matingSelection}(\mathcal{A})$ ;
6    $\{c_1, c_2\} \leftarrow \text{crossover}(p_1, p_2)$ ;
7   for  $i \in \{1, 2\}$  do
8      $c_i \leftarrow \text{mutation}(c_i)$ ;
9     if  $c_i$  is invalid then
10      Repair  $c_i$  using the probSAT solver [5];
11     end
12      $\mathcal{A} \leftarrow \text{updateArchive}(\mathcal{A}, c_i)$ ;
13   end
14 end
15 return  $\mathcal{A}$ 
    
```

[ICSE 2022] Yi Xiang, Han Huang*, Yuren Zhou, Sizhe Li, Chuan Luo, Qingwei Lin, Miqing Li, Xiaowei Yang*. Search-based Diverse Sampling from Real-world Software Product Lines. In 44th *International Conference on Software Engineering (ICSE'22)*, 2022, 1945-1957.

[软件学报2024] 向毅, 黄翰*, 罗川, 杨晓伟. 基于多样性SAT求解器和新颖性搜索的软件产品线测试, *软件学报*, 2024, DOI:10.13328/j.cnki.jos.006906

实验验证

Table 2: Time taken to sample a configuration (in milliseconds). *timeout* = one hour

FM	NSbs	SAT-based	DDbs	Unigen3	Smarch
lrzip	2	1	18	<1	185
LLVM	2	<1	5	<1	110
X264	87	<1	10	<1	151
Dune	2	<1	14	<1	163
BerkeleyDBC	148	<1	14	<1	165
HiPAcc	2	<1	99	5	329
JHipster	10	<1	161	1	388
Polly	92	<1	400	1	373
7z	120	<1	1299	3	467
JavaGC	9	<1	780	1	381
VP9	6	<1	2412	2	396
fiasco_17_10	12	<1	timeout	15	3260
axTLS_2.1.4	6	<1	timeout	12	895
fiasco	93	1	timeout	20	58003
toybox	13	<1	timeout	7	7123
axtls	14	1	timeout	34	13515
uClibc-ng_1.0.29	7	<1	timeout	4681	4239
toybox_0.7.5	7	<1	timeout	231	3492
uCLinux	61	2	timeout	258	39713
ref4955	46	1	timeout	timeout	37299
adderII	49	1	timeout	timeout	48508
ecos-icse11	40	1	timeout	timeout	timeout
m5272c3	45	1	timeout	timeout	43946
pati	46	1	timeout	timeout	38404
olpce2294	51	1	timeout	timeout	53946
integrator_arm9	65	2	timeout	timeout	377666
at91sam7sek	49	1	timeout	timeout	45776
se77x9	70	2	timeout	timeout	timeout
phycore229x	49	1	timeout	timeout	56323
busybox-1.18.0	202	3	timeout	timeout	timeout
busybox_1.28.0	37	<1	timeout	timeout	18087
embtoolkit	2306	35	timeout	timeout	timeout
freebsd-icse11	201	7	timeout	timeout	timeout
uCLinux-config	296	7	timeout	timeout	timeout
buildroot	6916	21	timeout	timeout	timeout
freetz	16540	35	timeout	timeout	timeout
2.6.28.6-icse11	558	29	timeout	timeout	timeout
2.6.32.2var	36000	256	timeout	timeout	timeout
2.6.33.3-2var	36000	289	timeout	timeout	timeout

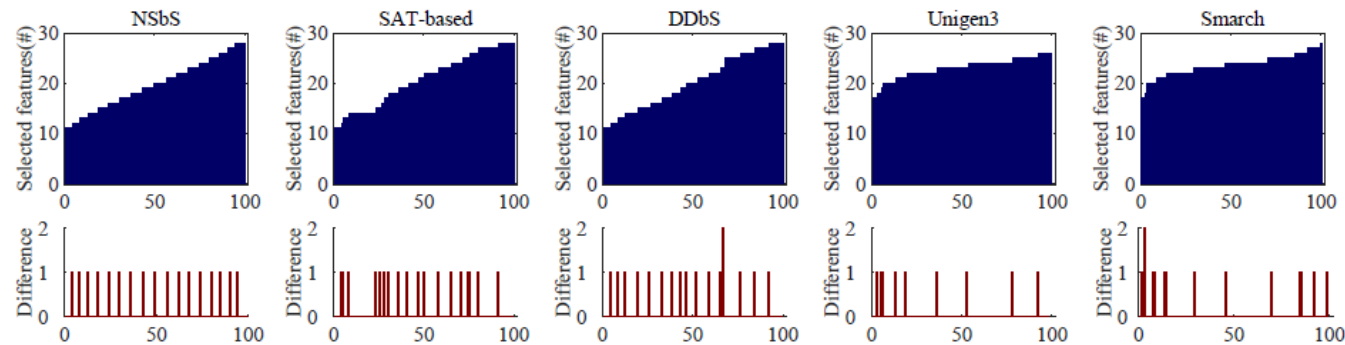
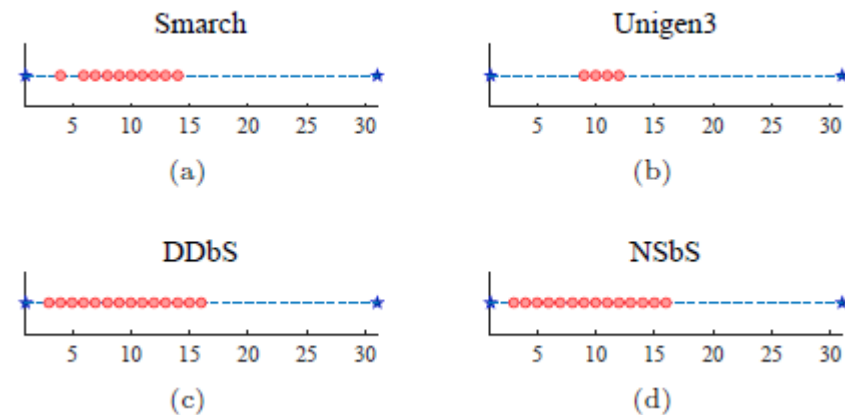


Figure 3: For configurations generated by each sampler on JHipster, the number of selected features and the difference of this number between two successive configurations are shown in histograms.



实验结果表明, 在所有五种被评估的方法中, 只有我们所提出的方法实现了可扩展的多样性采样, 且生成效率提高了488倍。

[ICSE 2022] Yi Xiang, Han Huang*, Yuren Zhou, Sizhe Li, Chuan Luo, Qingwei Lin, Miqing Li, Xiaowei Yang*. Search-based Diverse Sampling from Real-world Software Product Lines. In 44th *International Conference on Software Engineering (ICSE'22)*, 2022, 1945-1957.

[软件学报2024] 向毅, 黄翰*, 罗川, 杨晓伟. 基于多样性SAT求解器和新颖性搜索的软件产品线测试, *软件学报*, 2024, DOI:10.13328/j.cnki.jos.006906

同行评价

Proceedings of the Workshop on the Algorithmic Foundations of Robotics (WAFR), 2023. WAFR为机器人算法领域的顶级学术工作坊.

Xiang 等人提出的采样方法在方法设计上具有新颖性 (novel), 其方法论价值已开始向软件工程以外的研究领域扩展, 并被机器人学领域学者借鉴用于运动规划程序的设计空间探索等问题的研究.

Design Space Exploration for Sampling-Based Motion Planning Programs with Combinatory Logic Synthesis

Tristan Schäfer^(✉), Jan Bessai, Constantin Chaumet, Jakob Rehof,
and Christian Riest

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suitable programs. Xiang et al. provide a novel approach to sample algorithm configurations for large software product lines [34]. They use SAT solvers to find an initial set of valid sample points (i.e., algorithm configurations) and a search procedure that uses a distance metric to build a uniform sampling set incrementally. The resulting samples are a reduced representation of the software product line, enabling the application of techniques such as optimization procedures or performance prediction. Jamshidi et al. proposed a concept to explore the space

34. Xiang, Y., Huang, H., Zhou, Y., Li, S., Luo, C., Lin, Q., Li, M., Yang, X.: Search-based diverse sampling from real-world software product lines. In: 2022 IEEE/ACM 43rd International Conference on Software Engineering (ICSE). International Conference on Software Engineering. Proceedings, IEEE (2022), not yet published as of 04/02/2022



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同行评价

Empirical Software Engineering (2024) 29:146
<https://doi.org/10.1007/s10664-024-10516-x>

Software product line testing: a systematic literature review

Halimeh Agh¹ · Aidin Azamnouri¹ · **Stefan Wagner^{1,2}**

Accepted: 19 June 2024 / Published online: 2 September 2024
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Additionally, several studies proposed tool support for their specific approaches. They used SAT solvers to generate configurations to satisfy the feature model constraints which, in turn, reduces the configuration space to be tested (Henard et al. 2013, 2014a, b; Galindo et al. 2016; Hervieu et al. 2016; Souto and d'Amorim 2016; Fragal et al. 2019; Luthmann et al. 2019a; Krieter et al. 2020; Xiang et al. 2022). Using or implementing a tool or toolkit to produce valid configurations has been proposed by Ensan et al. (2012), Al-Hajjaji et al. (2016), Arrieta et al. (2016), Al-Hajjaji et al. (2019) and Arrieta et al. (2019). For example, FeatureIDE has been used in studies by Al-Hajjaji et al. (2016), Arrieta et al. (2016), Al-Hajjaji et al. (2019), and Arrieta et al. (2019); this tool can generate valid configurations manually and automatically.

德国慕尼黑工业大学
Stefan Wagner 全职教授



Xiang 等人2022) 的工作与David Benavides等国际SPL领域权威学者的相关研究一道, 被归纳为利用SAT求解器生成满足特征模型约束配置的代表性方法。

Xiang Y, Huang H, Zhou Y, Li S, Luo C, Lin Q, Yang X (2022) Search-based diverse sampling from real-world software product lines. In: ICSE'22, pp 1945–1957. <https://doi.org/10.1145/3510003.3510053>

代表性工作4: 提出一种基于质量-多样性演化优化的可配置软件系统测试方法, 用于生成兼具特征多样性和高质量的测试集

数学模型

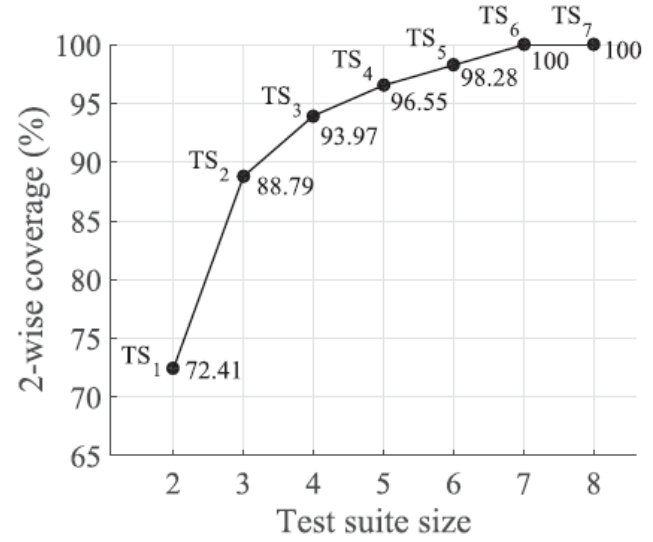
$$\forall b \in \mathcal{B}, x^* = \arg \max_x f(x)$$

$$s.t. b(x) = b,$$

f: 目标函数
 —覆盖率、多样性等
b: 特征/行为向量
 —测试集规模

特征多样性

覆盖率



- TS₁ = {tc₆, tc₇}
- TS₂ = {tc₂, tc₅, tc₇}
- TS₃ = {tc₁, tc₆, tc₇, tc₈}
- TS₄ = {tc₁, tc₅, tc₆, tc₇, tc₈}
- TS₅ = {tc₁, tc₂, tc₅, tc₆, tc₇, tc₈}
- TS₆ = {tc₁, tc₂, tc₄, tc₅, tc₆, tc₇, tc₈}
- TS₇ = {tc₁, tc₂, tc₃, tc₄, tc₅, tc₆, tc₇, tc₈}

测试集规模

MAP-Elites 算法

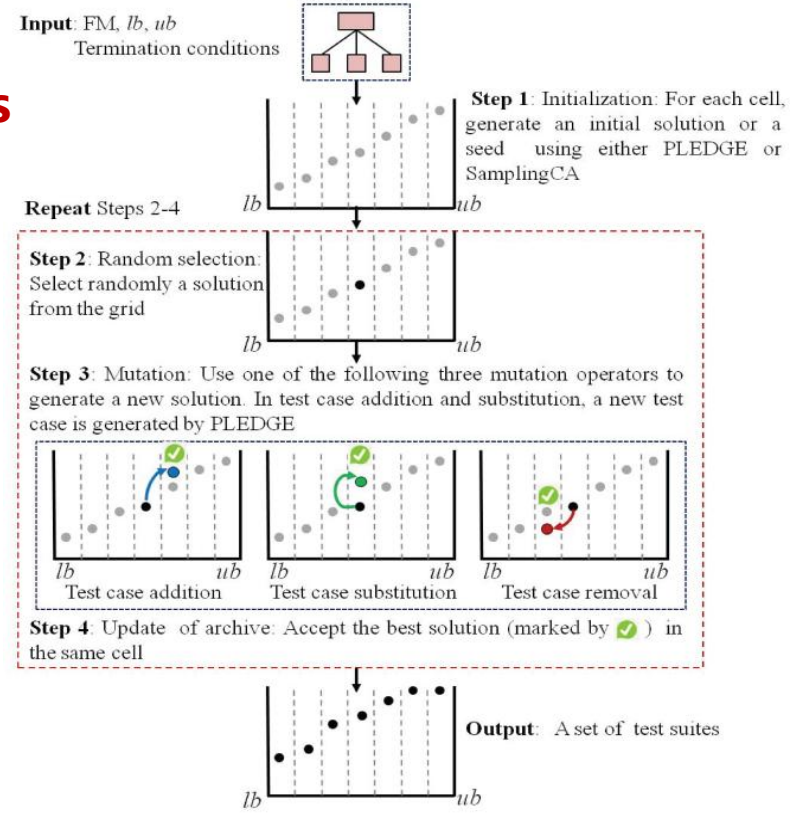


Fig. 3. Overview of MAP-Elites for automated test suite generation.

实验验证

Table 5. QD-Score for Pairwise Coverage Obtained by MAP-Elites, YASA, InclLing, and SamplingCA

	MAP-Elites	YASA	\hat{A}_{12}	MAP-Elites	InclLing	\hat{A}_{12}	MAP-Elites	SamplingCA	\hat{A}_{12}
ZipMe	5.306e+02	4.682e+02	↑ l	7.306e+02	7.071e+02	↑ l	6.218e+02	6.106e+02	↑ l
BerkeleyDBFootprint	5.035e+02	4.867e+02	↑ l	6.063e+02	5.844e+02	↑ l	5.926e+02	5.844e+02	↑ l
Apache	6.145e+02	5.862e+02	↑ l	6.172e+02	5.979e+02	↑ l	6.093e+02	5.979e+02	↑ l
argo-uml-spl	5.248e+02	4.926e+02	↑ l	6.248e+02	6.092e+02	↑ l	6.172e+02	6.092e+02	↑ l
LLVM	7.088e+02	6.516e+02	↑ l	7.102e+02	6.869e+02	↑ l	6.984e+02	6.873e+02	↑ m
PKJab	5.395e+02	5.136e+02	↑ l	5.395e+02	5.305e+02	↑ l	6.325e+02	6.316e+02	↑ s
Curl	9.764e+02	9.482e+02	↑ l	1.476e+03	1.454e+03	↑ l	9.632e+02	9.691e+02	↓ m
Wget	9.677e+02	9.229e+02	↑ l	1.269e+03	1.254e+03	↑ l	9.579e+02	9.644e+02	↓ m
x264	1.444e+03	1.342e+03	↑ l	1.845e+03	1.821e+03	↑ l	1.327e+03	1.347e+03	↓ l
BerkeleyDBC	1.813e+03	1.753e+03	↑ l	2.013e+03	1.994e+03	↑ l	1.686e+03	1.723e+03	↓ m
gpl	1.006e+03	9.299e+02	↑ l	1.108e+03	1.101e+03	↑ l	1.079e+03	1.097e+03	↓ m
BerkeleyDBMemory	2.624e+03	2.550e+03	↑ l	2.828e+03	2.805e+03	↑ l	2.584e+03	2.654e+03	↓ l
fame_dbms_fm	9.947e+02	9.180e+02	↑ l	1.593e+03	1.581e+03	↑ l	1.180e+03	1.190e+03	↓ m
DesktopSearcher	8.175e+02	7.408e+02	↑ l	9.177e+02	9.110e+02	↑ l	8.073e+02	8.182e+02	↓ l
CounterStrikeSFM	8.008e+02	7.938e+02	↑ l	8.999e+02	8.904e+02	↑ l	8.877e+02	9.048e+02	↓ l
BerkeleyDBP	8.092e+02	7.567e+02	↑ l	1.010e+03	9.957e+02	↑ l	9.022e+02	9.088e+02	↓ m
LinkedList	1.377e+03	1.301e+03	↑ l	1.875e+03	1.878e+03	↓ l	1.354e+03	1.388e+03	↓ m
SensorNetwork	1.073e+03	1.011e+03	↑ l	1.375e+03	1.359e+03	↑ l	9.581e+02	9.792e+02	↓ m
HIPAcc	3.109e+03	3.067e+03	↑ l	3.715e+03	3.711e+03	↑ m	2.951e+03	3.043e+03	↓ m
SPLSSimuelESPnP	8.049e+02	7.525e+02	↑ l	1.604e+03	1.603e+03	↑ s	9.878e+02	1.003e+03	↓ m
TankWar	1.367e+03	1.302e+03	↑ l	1.568e+03	1.568e+03	~ n	1.260e+03	1.283e+03	↓ m
JavaGC	4.144e+03	4.090e+03	↑ l	5.050e+03	5.074e+03	↓ l	4.014e+03	4.115e+03	↓ s
Polly	3.334e+03	3.256e+03	↑ l	3.539e+03	3.550e+03	↓ l	3.009e+03	3.076e+03	↓ s
DVSSample	8.632e+03	8.723e+03	↓ l	9.457e+03	9.613e+03	↓ l	8.508e+03	8.869e+03	↓ l
VP9	3.238e+03	3.191e+03	↑ l	3.544e+03	3.545e+03	↓ s	2.973e+03	3.028e+03	↓ s
WebPortal	1.821e+03	1.729e+03	↑ l	2.421e+03	2.430e+03	↓ l	1.615e+03	1.660e+03	↓ m
JHipster	3.332e+03	3.161e+03	↑ l	4.627e+03	4.653e+03	↓ l	3.312e+03	3.397e+03	↓ l
Drupal	1.162e+03	1.116e+03	↑ l	1.266e+03	1.268e+03	↓ l	1.275e+03	1.275e+03	↓ l
SmartHomev2.2	1.544e+03	1.460e+03	↑ l	1.745e+03	1.755e+03	↓ l	1.433e+03	1.466e+03	↓ m
VideoPlayer	1.081e+03	9.969e+02	↑ l	1.282e+03	1.289e+03	↓ l	1.269e+03	1.289e+03	↓ m
Amazon	9.674e+03	9.842e+03	↓ l	9.814e+03	9.946e+03	↓ l	9.674e+03	9.927e+03	↓ l
ModelTransformation	2.983e+03	2.844e+03	↑ l	3.190e+03	3.214e+03	↓ l	2.623e+03	2.674e+03	↓ m
CocheEcologico	8.507e+03	8.479e+03	↑ l	9.132e+03	9.220e+03	↓ l	8.629e+03	8.760e+03	↓ l
n30Model1	1.094e+03	9.976e+02	↑ l	1.296e+03	1.276e+03	↑ l	1.083e+03	1.101e+03	↓ m
n30Model2	1.398e+03	1.315e+03	↑ l	1.701e+03	1.684e+03	↑ l	1.276e+03	1.301e+03	↓ m
n30Model3	1.387e+03	1.324e+03	↑ l	1.589e+03	1.577e+03	↑ l	1.176e+03	1.199e+03	↓ m
n30Model4	1.482e+03	1.413e+03	↑ l	2.180e+03	2.171e+03	↑ l	1.553e+03	1.590e+03	↓ m
n30Model5	1.004e+03	9.513e+02	↑ l	1.305e+03	1.284e+03	↑ l	9.844e+02	1.014e+03	↓ m
n30Model6	1.115e+03	1.085e+03	↑ l	1.514e+03	1.508e+03	↑ l	1.196e+03	1.219e+03	↓ m
n30Model7	1.558e+03	1.488e+03	↑ l	2.060e+03	2.067e+03	↓ l	1.439e+03	1.484e+03	↓ s
n30Model8	1.003e+03	9.014e+02	↑ l	1.304e+03	1.287e+03	↑ l	1.022e+03	1.056e+03	↓ m
n30Model9	1.376e+03	1.337e+03	↑ l	1.678e+03	1.674e+03	↑ m	1.241e+03	1.293e+03	↓ m
n30Model10	1.367e+03	1.275e+03	↑ l	1.771e+03	1.758e+03	↑ l	1.286e+03	1.334e+03	↓ m
n50Model1	9.301e+02	8.752e+02	↑ l	9.311e+02	9.289e+02	↑ l	1.022e+03	1.035e+03	↓ l
n50Model2	1.455e+03	1.344e+03	↑ l	1.953e+03	1.962e+03	↓ l	1.527e+03	1.571e+03	↓ s
n50Model3	1.454e+03	1.344e+03	↑ l	1.954e+03	1.962e+03	↓ l	1.534e+03	1.571e+03	↓ s
n50Model4	1.830e+03	1.744e+03	↑ l	2.531e+03	2.543e+03	↓ l	1.803e+03	1.867e+03	↓ s
n50Model5	1.760e+03	1.575e+03	↑ l	2.557e+03	2.563e+03	↓ l	1.637e+03	1.679e+03	↓ m
n50Model6	2.057e+03	1.959e+03	↑ l	2.260e+03	2.264e+03	↓ s	1.840e+03	1.884e+03	↓ m
n50Model7	2.435e+03	2.255e+03	↑ l	2.642e+03	2.613e+03	↓ l	2.355e+03	2.421e+03	↓ s
n50Model8	1.666e+03	1.632e+03	↑ l	2.263e+03	2.276e+03	↓ l	1.746e+03	1.792e+03	↓ m
n50Model9	1.473e+03	1.417e+03	↑ l	1.676e+03	1.679e+03	↓ m	1.353e+03	1.392e+03	↓ m
n50Model10	1.482e+03	1.335e+03	↑ l	1.583e+03	1.578e+03	↑ l	1.372e+03	1.399e+03	↓ s

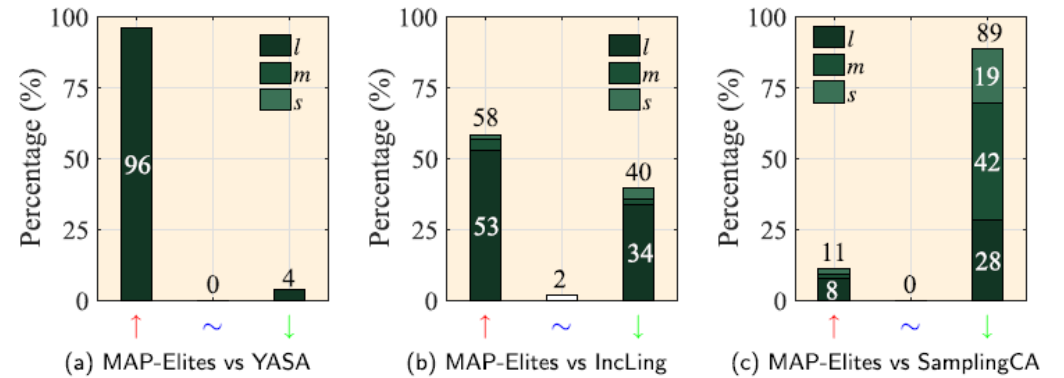


Fig. 14. \hat{A}_{12} comparisons between MAP-Elites and three state-of-the-art t -wise testing tools.

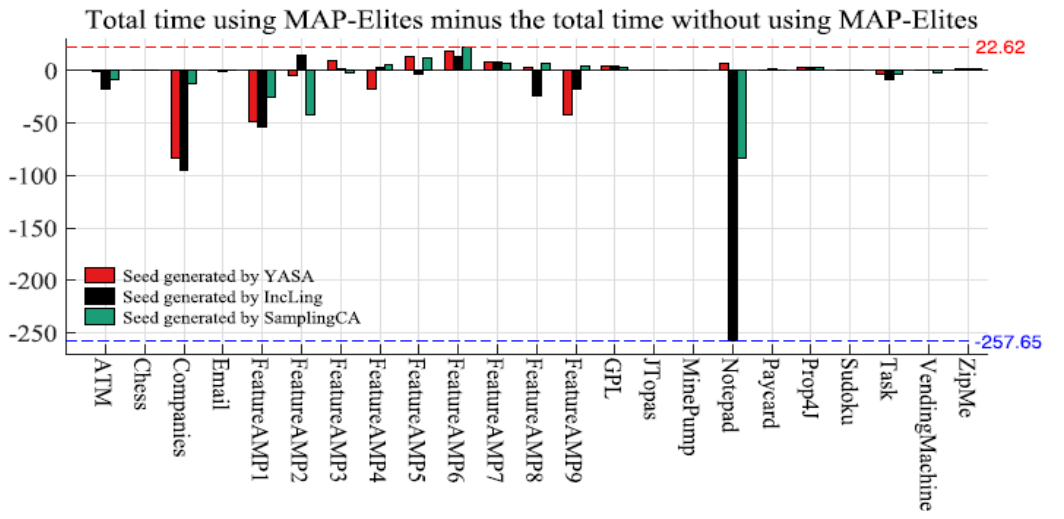


Fig. 20. The differences between the total time with and without using MAP-Elites.

特征多样性的提升使得测试执行时间最多节省192.5个小时

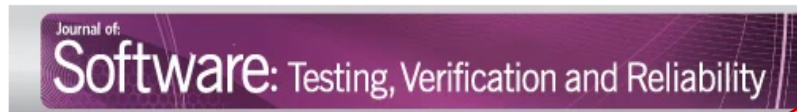
[TOSEM 2023] Yi Xiang, Han Huang*, Sizhe Li, Miqing Li, Chuan Luo, Xiaowei Yang*. Automated Test Suite Generation for Software Product Lines Based on Quality-Diversity Optimization, *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 2023,33(2):46.1-46.52

[AUSE 2022] Yi Xiang, Xiaowei Yang*, Han Huang, Zhengxin Huang, Miqing Li. Sampling Configurations From Software Product Lines Via Probability-aware Diversification and SAT Solving. *Automated Software Engineering (AUSE)*, 2022, 29(2):54.1-54.45

同行评价

英国谢菲尔德大学
Robert M. Hierons教授

澳门科技大学 **Rubing Huang**教授 (TR 2025)



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A Systematic Mapping Study of the Metrics, Uses and Subjects of Diversity-Based Testing Techniques

Islam T. Elgendy, **Robert M. Hierons**, Phil McMinn

them in terms of average percentage fault detection. In another study, Xiang et al. [181] developed a model for test suite generation of SPLs using quality-diversity optimization. Each test case is represented a binary sequence of n -features, and the fitness function for test generation is guided by feature diversity that is calculated using antdice distance.

Xiang 等人将Quality-Diversity优化引入测试用例生成的研究工作, 已获得国际软件测试领域权威学者的关注与详细引述

181. Y. Xiang, H. Huang, S. Li, M. Li, C. Luo, and X. Yang, "Automated Test Suite Generation for Software Product Lines Based on Quality-Diversity Optimization," *ACM Transactions on Software Engineering and Methodology* 33, no. 2 (2023): 1–52, <https://doi.org/10.1145/3628158>.

3326

IEEE TRANSACTIONS ON RELIABILITY, VOL. 74, NO. 3, SEPTEMBER 2025

Applying Lexicographic Ordering to Software Product Line Testing

Tao Li, Chenhui Cui, Yinyin Xu, and **Rubing Huang**, Senior Member, IEEE

in the black-box testing environment, LO-TCP may fail. For example, SPL testing [12] is to test a family of related software products that share a common set of features and functionalities. It is generally available to access the feature set rather than the white-box code information. Motivated by these facts, in this article, we transfer LO-TCP to SPL testing, which mainly leverages test configuration coverage instead of code coverage. Given a test suite, the test configuration coverage is relatively easy to collect, because it is a static metric to measure test cases that does not require to execute the test cases. This approach is

该引文以Xiang的工作为例, 阐明了软件产品线测试(SPL testing)中白盒代码信息难以获取的基本特性, 并为将LO-TCP方法迁移至SPL testing场景提供了重要启发 (Motivated)。

[12] Y. Xiang, H. Huang, S. Li, M. Li, C. Luo, and X. Yang, "Automated test suite generation for software product lines based on quality-diversity optimization," *ACM Trans. Softw. Eng. Methodol.*, vol. 33, no. 2, pp. 1–52, 2023.

相关论文、专利、标准和获奖

- [1] **Yi Xiang**, Han Huang*, Miqing Li, Sizhe Li, Xiaowei Yang*. Looking For Novelty in Search-based Software Product Line Testing. *IEEE Transactions on Software Engineering (TSE)*, 2022, 48(7): 2317-2338 (CCF-A类期刊, 2024年广东省计算机学会论文奖一等奖)
- [2] **Yi Xiang**, Han Huang*, Sizhe Li, Miqing Li, Chuan Luo, Xiaowei Yang*. Automated Test Suite Generation for Software Product Lines Based on Quality-Diversity Optimization, *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 2023,33(2):46.1-46.52 (CCF-A类期刊)
- [3] **Yi Xiang**, Han Huang*, Yuren Zhou, Sizhe Li, Chuan Luo, Qingwei Lin, Miqing Li, Xiaowei Yang*. Search-based Diverse Sampling from Real-world Software Product Lines. In 44th International Conference on Software Engineering (**ICSE'22**), 2022: 1945-1957 (CCF-A类会议)
- [4] **向毅**, 黄翰*, 罗川, 杨晓伟. 基于多样性SAT求解器和新颖性搜索的软件产品线测试, **软件学报**, 2024, 35(6), 2821-2843.
- [5] **向毅**, 周士璇, 黄翰, 曹捷, 黄沛, 一种自动驾驶仿真测试特征选择方法, **发明专利** (ZL 2025 1 0497546.0), 授权 2025.07.
- [6] **向毅**, 王悦琪, 黄翰, 曹捷, 一种基于主动学习的可配置软件系统的性能预测方法 **发明专利** (ZL 2024 1 1175764.4), 授权, 2024.11.
- [7] 黄翰;袁中锦;**向毅**;曹捷;雷丰强, 一种基于用例增强的自动化软件产品线特征模型生成方法, **发明专利** (ZL 2025 1 0715849.5), 授权, 2025.09
- [8] 黄翰, 曹捷, 刘方青, **向毅**, 徐杨, 陶然, 郝志峰, 蔡瑞初, 黄山, 无源码的白盒化测试标准, 中国国际科技促进会标准化工作委员会, 2023-6-26, T/CI 083-2023 (**全国团体标准**)
- [9] 黄翰; 应华江; 刘方青; **向毅**; 杨忠明; 曹捷; 杨晓伟; 颜学明; 钟国威; 李双燕, 智能化软件工程关键技术及应用, 广东省人民政府, 科技进步二等奖, 2023 (**广东省科技进步奖**)
- [10] 向毅 (主要撰写人), 汽车基础软件测试指南, 2025, 发布单位: 中国汽车工业协会软件分会、中国汽车基础软件生态标委会 (AUTOSEMO) (**汽车行业指南**)

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团体标准

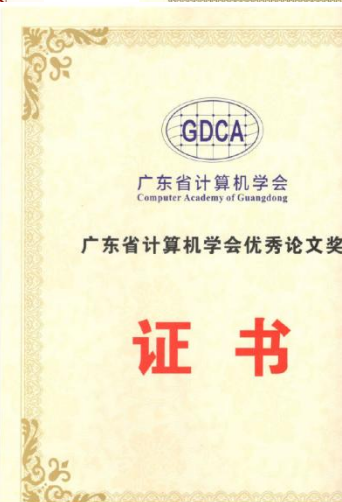
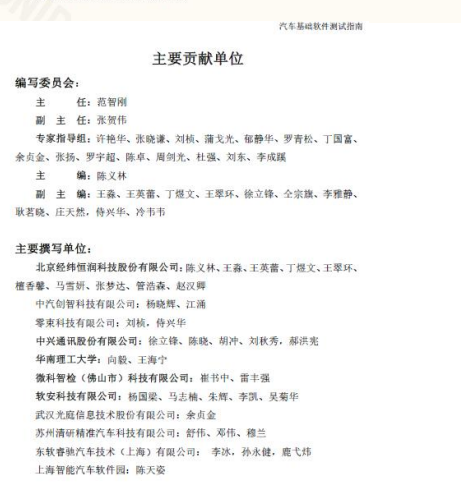
1:1 083-2023

无源码的白盒化测试标准

Standard for glass-box testing without source code

2023-6-26 发布 2023-6-26 实施

中国国际科技促进会 发布

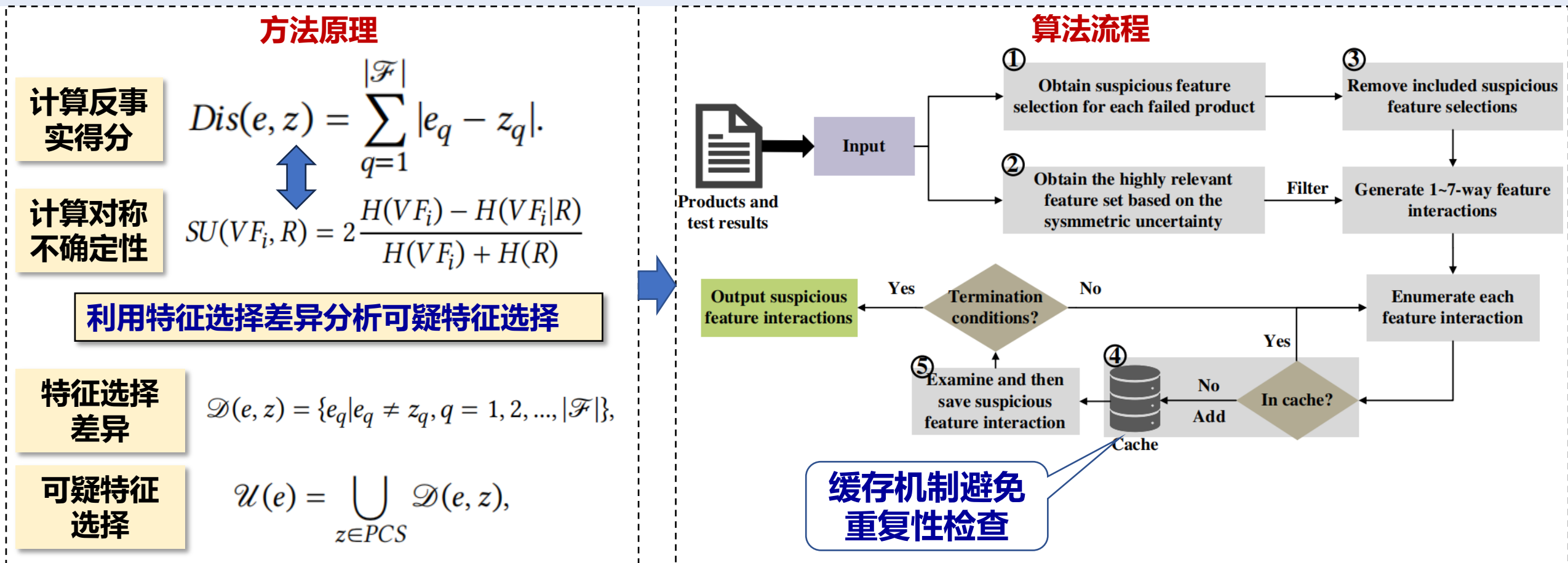


成果简介：针对可配置软件系统中的**可变缺陷**定位问题，现有方法在特征层面因搜索空间庞大且存在冗余搜索而导致定位效率低，而在语句层面又因忽略缺陷交互与故障之间的因果关系而存在定位准确性不足的局限。本研究提出了一种融合因果推断的低成本缺陷定位方法。

□ 该方法在特征层面引入**反事实因果推理**和**对称不确定性理论**，结合包含关系与重复检测策略，有效压缩搜索空间、减少冗余计算，显著提升**特征级定位效率**；

□ 在语句层面构建引入中介变量的**约简因果模型**，将因果效应分析与频谱信息有机融合，实现了从特征交互到语句根因的高精度定位。该成果为可配置软件系统的智能调试提供了高效、可扩展的新思路。

代表性工作1：引入**反事实因果推理**和**对称不确定性**理论，结合缓存机制避免重复性检查，有效压缩搜索空间、减少冗余计算，显著提升定位缺陷特征交互效率



实验验证

Systems	<i>n</i> -way	VarCop	CRFL	Rate (%)	Systems	<i>n</i> -way	VarCop	CRFL	Rate (%)
BankAccountTP	1-way	55.97	2.42	95.7	ExamDB	1-way	7.61	4.69	38.4
	2-way	141.42	17.41	87.7		2-way	20.18	10.90	46.0
	3-way	208.68	52.25	75.0		3-way	32.02	15.31	52.2
	4-way	187.66	75.36	59.8		4-way	31.41	14.29	57.8
	5-way	102.26	52.88	48.3		5-way	18.67	8.39	54.5
	6-way	31.18	19.03	39.0		6-way	6.18	2.76	55.3
	7-way	4.10	2.73	33.4		7-way	0.88	0.39	55.7
BerkeleyDB	1-way	856.00	183.00	78.6	GPL	1-way	432.50	9.10	97.9
	2-way	40310.00	12364.00	69.3		2-way	4492.66	241.52	94.6
	3-way	1252994.50	410817.00	67.2		3-way	30989.59	2897.80	90.6
	4-way	28919106.00	8833702.00	69.5		4-way	156563.35	21091.91	86.5
	5-way	-	-	-		5-way	612209.61	101700.66	83.4
	6-way	-	-	-		6-way	1917635.11	368773.49	80.8
	7-way	-	-	-		7-way	4923805.55	1027440.15	79.1
Elevator	1-way	18.60	1.40	92.5	TankWar	1-way	186.00	34.00	81.7
	2-way	25.20	4.60	81.7		2-way	1692.40	461.60	72.7
	3-way	19.75	5.90	70.1		3-way	9786.80	3136.40	68.0
	4-way	8.05	3.40	57.8		4-way	40254.40	12796.00	68.2
	5-way	1.35	0.75	44.4		5-way	125001.40	36024.40	71.2
	6-way	0.00	0.00	-		6-way	303782.00	78203.00	74.3
	7-way	0.00	0.00	-		7-way	591282.40	135145.80	77.1
Email	1-way	64.86	3.67	94.3	ZipMe	1-way	66.20	3.71	94.4
	2-way	165.28	20.64	87.5		2-way	195.04	23.29	88.1
	3-way	266.61	57.33	78.5		3-way	403.49	69.36	82.8
	4-way	285.31	86.39	69.7		4-way	622.65	121.45	80.5
	5-way	203.19	74.86	63.2		5-way	727.91	143.36	80.3
	6-way	92.94	38.25	58.8		6-way	642.78	122.29	81.0
	7-way	24.75	10.81	56.3		7-way	421.20	76.75	81.8

与主流的特征级定位方法相比，特征交互检查数至少减少50%-98%

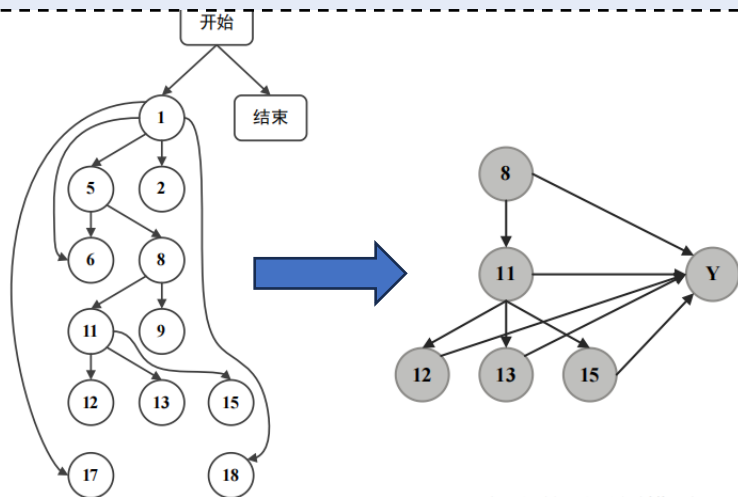
Systems	VarCop		CRFL		Ratio
	Average	STD	Average	STD	
BankAccountTP	3.17	1.61	0.18	0.07	17.6
BerkeleyDB	179425.64	8095.63	21551.35	16359.10	8.3
Email	16.34	8.79	0.89	0.42	18.4
ExamDB	2.83	0.97	0.09	0.03	31.4
Elevator	40.28	18.74	1.88	0.76	21.4
GPL	3590.49	3127.89	649.20	433.52	5.5
TankWar	96.95	63.81	15.91	10.35	6.1
ZipMe	1150.00	706.35	72.94	41.89	15.8

提出定位方法的效率在小型系统平均提升22.2倍，在大型系统平均提升9倍

代表性工作2：在得到可疑特征交互的基础上，利用程序切片隔离出可疑语句；引入一种**约简的因果图模型**来提升因果推理效率；并验证了**因果效应与频谱效应融合的融合**的必要性

方法原理

构建约简因果图模型



$$\tau = E[E[Y | T = 1, X] - E[Y | T = 0, X]]$$

$$Y = \alpha + \tau T + \beta X + \nu R + \varepsilon$$

$$suspiciousness(s) = \mu \times E'(s) + (1 - \mu) \times H(s)$$

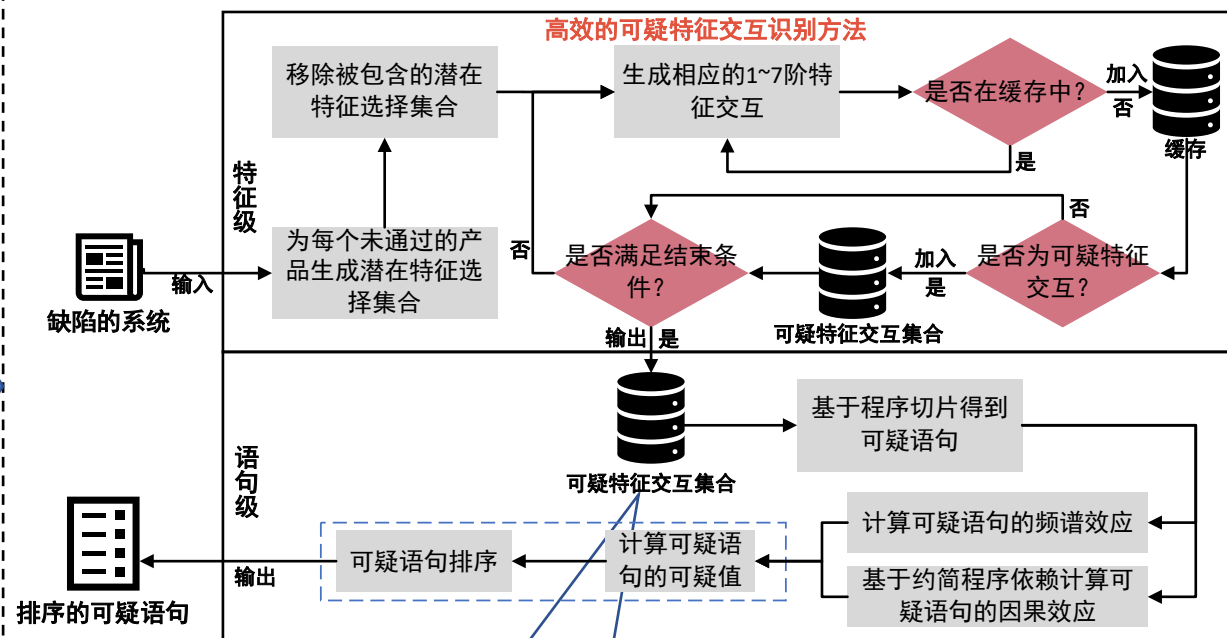
因果效应

频谱效应

计算因果效应

计算语句可疑性

算法流程



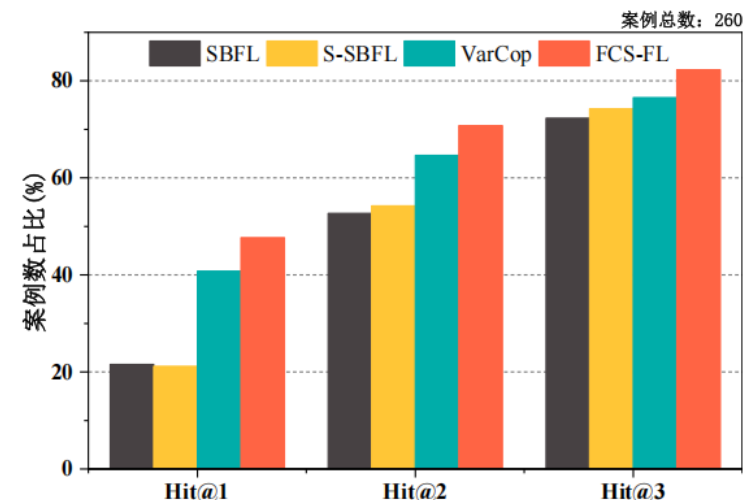
特征级到语句级的递进式定位

实验验证

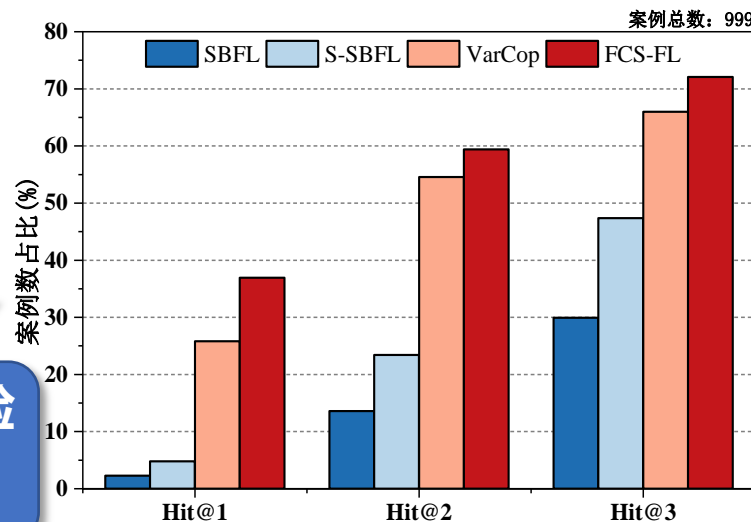
单缺陷的案例情形

SBFL 指标	FCS-FL	VarCop	S-SBFL	SBFL	FB
Tarantula	5.65	5.97	7.79	12.27	104.56
Ochiai	4.85	5.07	6.89	7.95	90.19
Op2	4.17	4.26	5.24	5.33	77.93
Barinel	6.71	7.11	9.73	12.27	104.56
Dstar	4.63	4.83	6.54	7.89	87.94

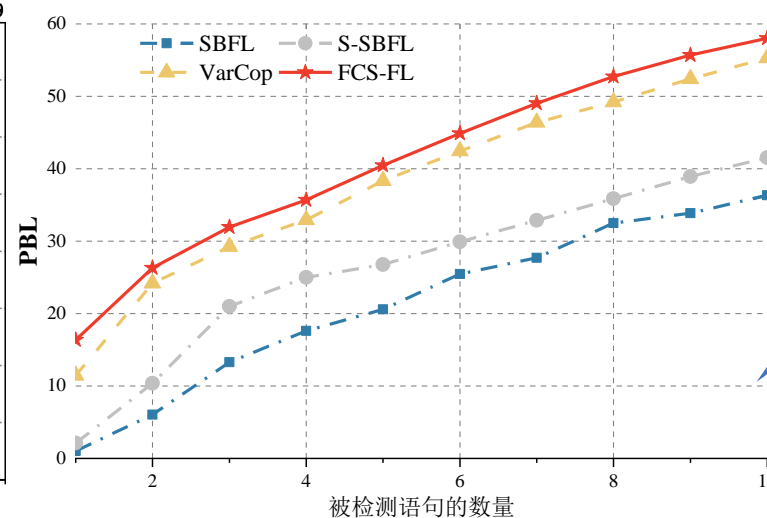
提出方法的根因定位效果明显提升，测试人员在**第一次**检查即可检查出**超50%**的缺陷语句



多缺陷共存的案例情形



超**70%**的案例中在**前三次**检查中即可定位到缺陷语句



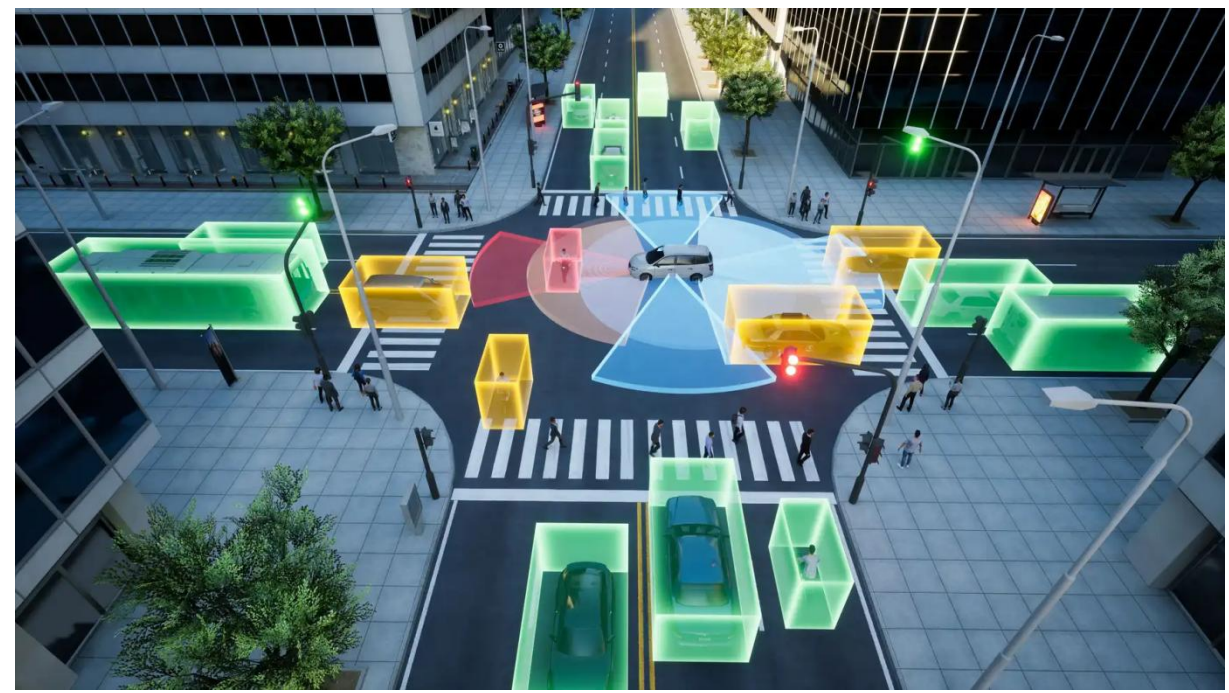
基于约简因果图模型对根因定位性能提升

相关论文、专利

- [1] Haining Wang (博士生), **Yi Xiang*** (通讯), Han Huang, Jie Cao, Kaichen Chen, and Xiaowei Yang. A Low-Cost Feature Interaction Fault Localization Approach for Software Product Lines, 2025, Proc. ACM Softw. Eng. 2, ISSTA, Article ISSTA042 (July 2025), 23 pages. <https://doi.org/10.1145/3728917>
- [2] 王海宁, **向毅*** (通讯), 黄翰*, 吴春国, 冯夫健, 杨晓伟. 一种融合因果效应的高效软件产品线缺陷定位方法. **软件学报**, 2025, 已录用
- [3] 袁中锦, 黄翰*, **向毅*** (通讯), 刘方青, 郝志峰. 融合中文需求本语义特征的UML活动图自生成方法. **软件学报**, 2025, 已录用
- [4] **向毅**, 王海宁, 黄翰, 曹捷, 崔书中, 赵元波, 一种软件产品线的自动化功能型缺陷定位方法, 发明专利 (ZL 2024 1 0931424.3), 授权, 2024.10.
- [5] 王海宁 (博士生), **向毅**, 黄翰, 曹捷, 崔书中, 一种可配置软件系统的可变性自动分析方法, 发明专利 (CN 2025109654502), 已受理, 2025.10

研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

问题背景：具身智能体（如自动驾驶、无人机等）的仿真测试是确保其安全性与可靠性的关键手段。其中，关键测试场景的生成及其排序是提升测试效能、加速风险暴露的核心任务。



高维强约束场景空间下高风险仿真场景的高效生成，是具身智能体仿真测试的关键科学问题

研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

基本思路：将具身智能体的仿真场景空间通过可变性建模技术进行形式化描述，从而将测试用例生成过程转化为特征模型上的采样问题。

select a set of representative test scenarios, and (2) how to assess the effectiveness of a test scenario suite. In this paper, we leverage variability modelling techniques to select scenarios from a scenario space and assess the resulting scenario suites with a mutation score as metric. We capture the scenario space in a feature model and generate representative subsets with feature-interaction coverage sampling. The mutation score assesses the failure-finding effec-

- We apply variability modelling and management techniques to scenario-based ADAS testing:
 - We show that an FM is a suitable modelling formalism for configuration spaces of simulation tools.
 - We show that FM sampling is suitable to scenario-based ADAS testing by comparing coverage-based and random sampling with expert strategies.



可变性建模

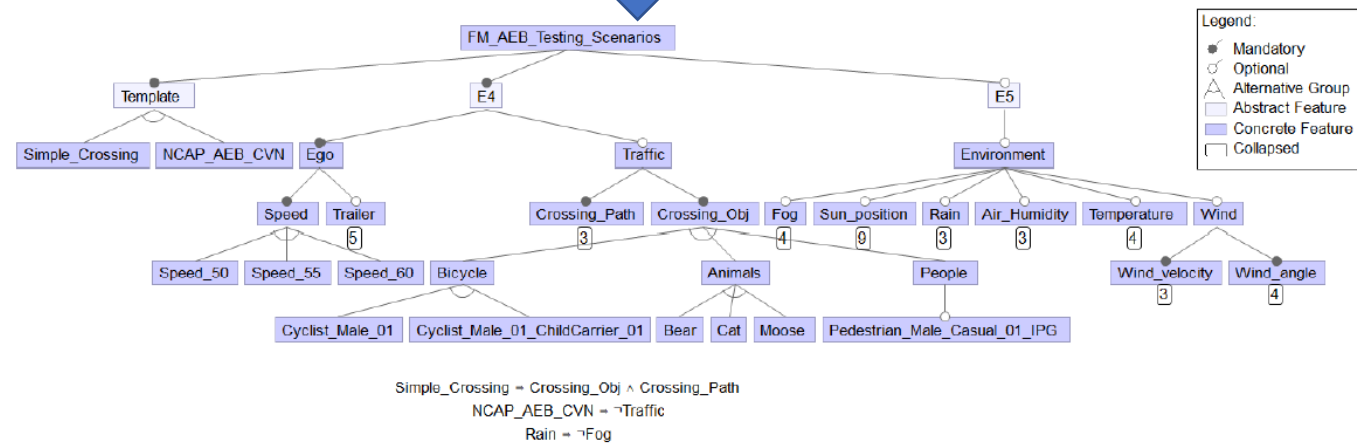


Figure 3: Example FM for scenario generation for AEB-system

研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

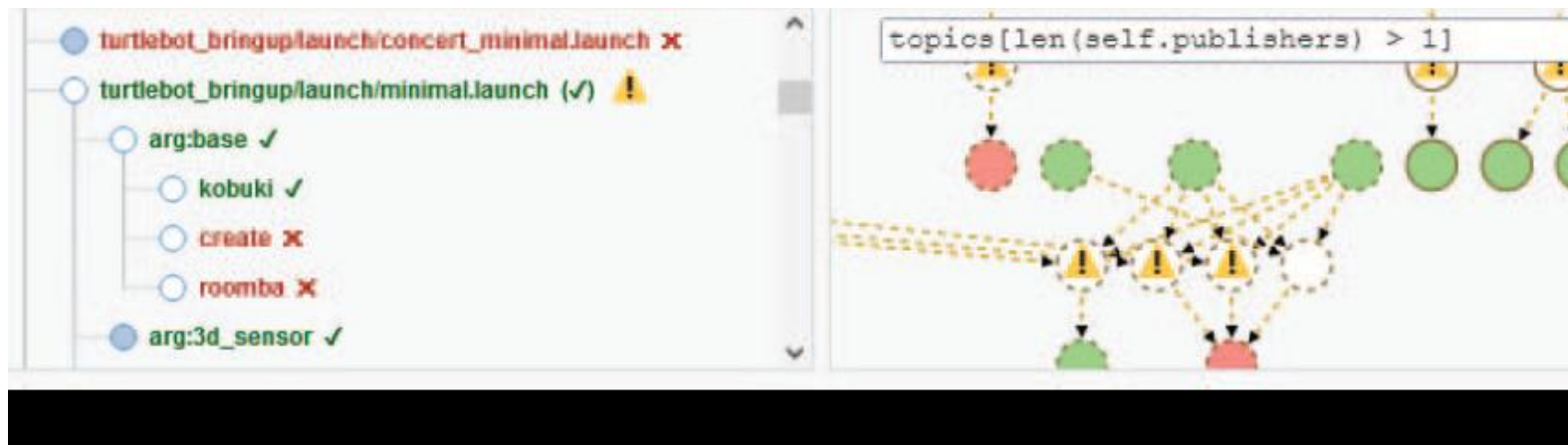
基本思路：将具身智能体的仿真场景空间通过可变性建模技术进行形式化描述，从而将测试用例生成过程转化为特征模型上的采样问题。

Abstract—Robotic applications are often designed to be reusable and configurable. Sometimes, due to the different supported software and hardware components, as well as the different implemented robot capabilities, the total number of possible configurations for a single system can be extremely large. In these scenarios, understanding how different configurations coexist and which components and capabilities are compatible with each other is a significant time sink both for developers and end users alike. In this paper, we present a static analysis tool, specifically designed for robotic software developed for the Robot Operating System (ROS), that is capable of presenting a graphical and interactive overview of the system's runtime variability, with the goal of simplifying the deployment of the desired robot configuration.

ROS application and how it is often expressed. We found out that variability management is a mostly manual and error-prone process, both for developers and (perhaps more so) for users. This served as motivation for us to develop a methodology and tool where ROS applications are interpreted as SPLs.

```
1 <launch>
2   <arg name="vel_topic" default="vel_cmd" />
3   <arg name="use_teleop" default="false" />
4   <param name="max_vel" type="double" value="0.8" />
5   <include file="$(find example)/launch/diagnostics.launch" />
6   <node name="controller" pkg="robot_teleop" type="kb_teleop"
7     if="$(arg use_teleop)">
8     <remap from="vel_cmd" to="$(arg vel_topic)" />
9   </node>
10  <node name="controller" pkg="robot_planner"
11    type="laser_planner" unless="$(arg use_teleop)">
12    <remap from="vel_cmd" to="$(arg vel_topic)" />
13 </node>
14 </launch>
```

Fig. 1. Example ROS launch file.



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

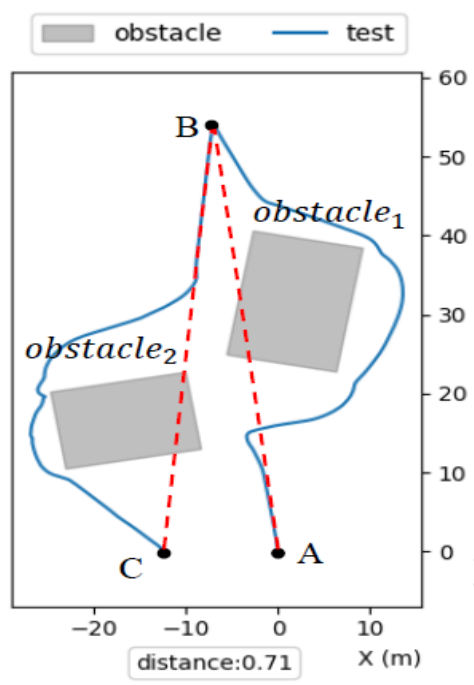
代表性工作1：随着无人机在复杂自主任务中的广泛部署，系统化安全测试对保障其可靠运行愈发关键。尽管仿真测试提供了安全且高效的验证途径，但其有效性高度依赖于在有限计算资源下生成多样且易诱发故障的测试场景。

关键挑战1：定向搜索结构多样化的测试场景

结构多样化的测试场景能够激发无人机产生不同行为，从而从多角度暴露潜在缺陷；然而，在连续场景空间中高效生成此类多样且有效的场景仍面临显著挑战。

关键挑战2：有限资源下测试场景的高效生成

在高保真仿真中运行一次无人机场景往往耗时且计算开销巨大，导致难以进行大规模场景探索与迭代优化。因此，如何在有限计算预算下优先生成最具测试价值的场景成为一项关键挑战。



无人机仿真测试



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

解决方案：将无人机测试场景生成建模为质量-多样性（QD）优化问题，同时兼顾场景多样性与故障触发潜力，并提出 TLQD 两级框架：首先在行为空间中实现广泛行为覆盖，其后通过基于行为的扰动算子和基于排斥的修复算子对潜在高价值区域进行细化，以保证场景的多样性与结构可行性。

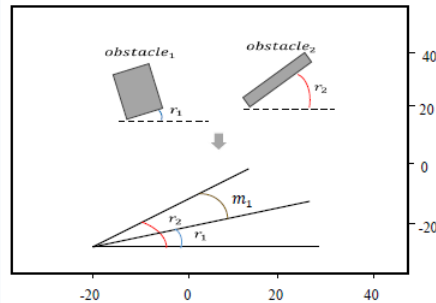
QD优化模型

$$\forall b \in \mathcal{B}, \quad x^* = \arg \min_{x \in \Omega} f(x) \quad \text{s.t.} \quad b(x) = b,$$

目标函数

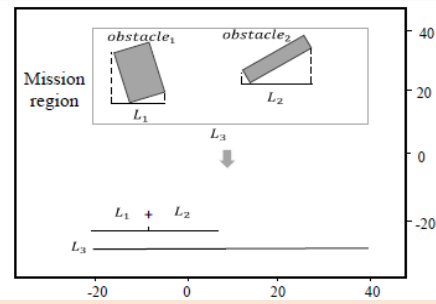
$$f(x) = \min Dis(x | SM, E).$$

与障碍物的最小距离



行为特征1

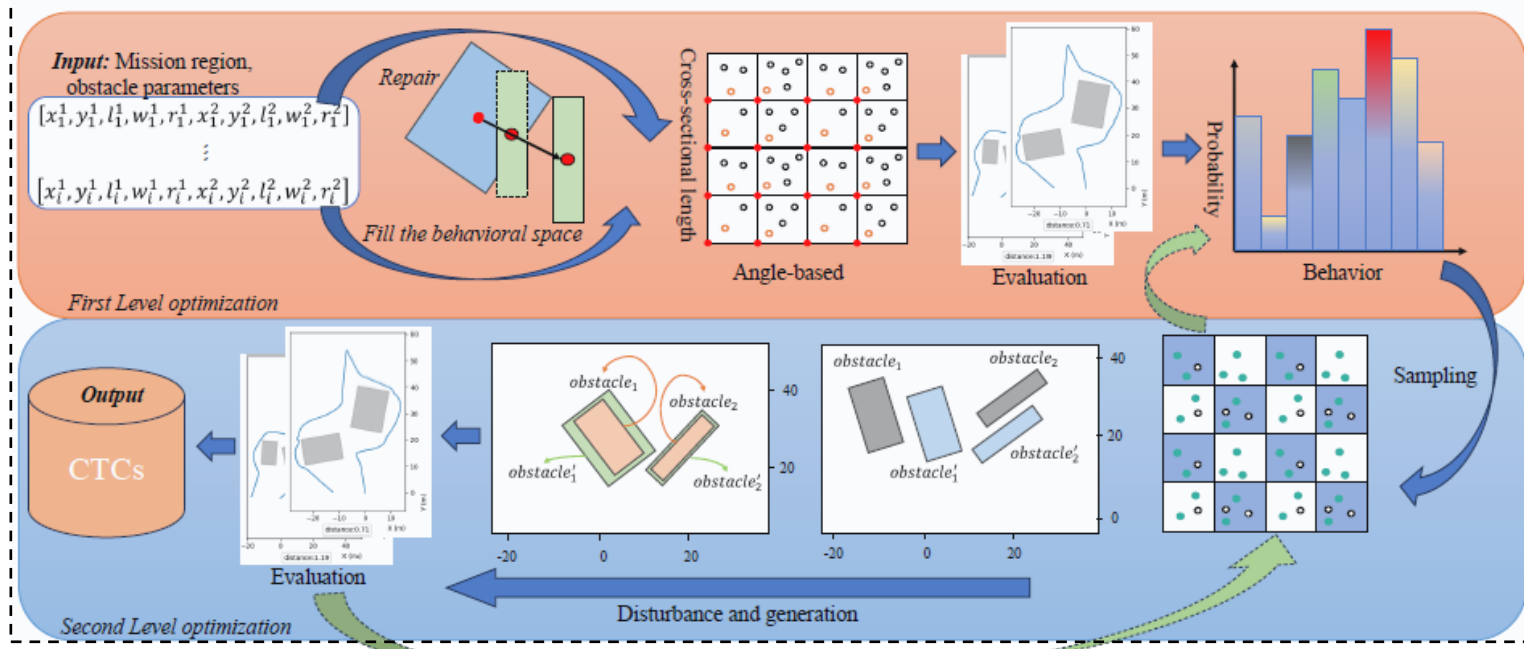
障碍物的夹角



行为特征2

障碍面长区域的比例

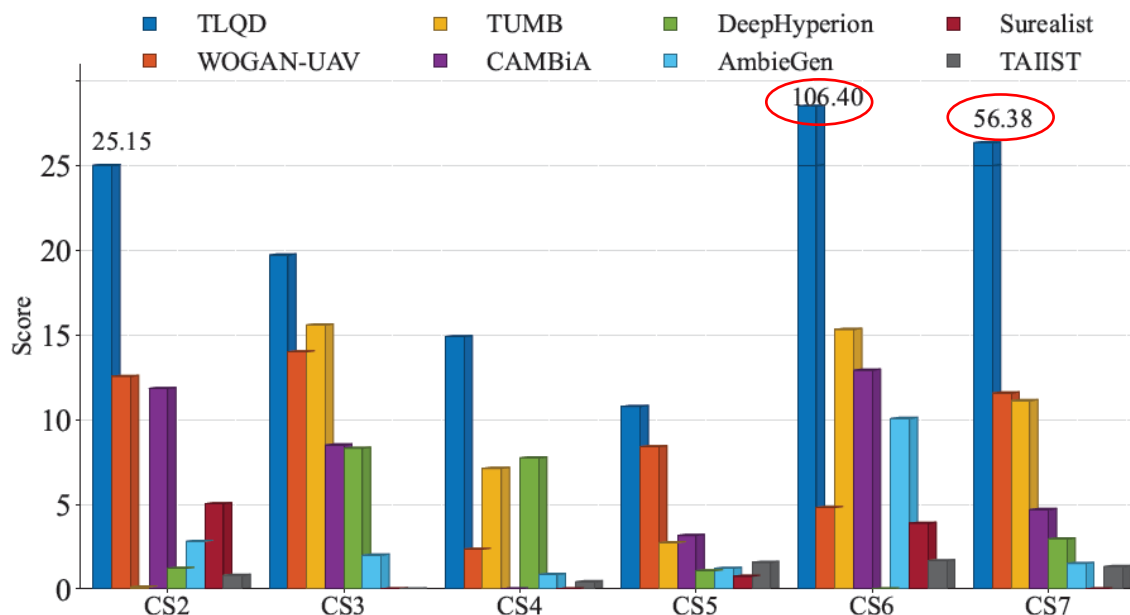
所提出的 TLQD 框架的整体架构。上半部分展示第一层优化过程，用于行为空间的探索；下半部分展示第二层优化过程，用于局部细化与关键测试场景（CTC）的生成。



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

实验验证

Algorithm	#Obst.	CS2		CS3		CS4		CS5		CS6		CS7		Rank Sum	Score Sum	Final Rank
		#	score	#	score	#	score	#	score	#	score	#	score			
TLQD	2	54	25.15	38	19.72	27	14.90	34	10.77	97	106.40	51	56.38	6	233.32	1
WOGAN-UAV	3	61	12.55	72	14.00	81	2.35	39	8.40	71	4.81	90	11.57	18	53.69	2
TUMB	[1-4]	69	0.12	113	15.59	135	7.12	114	2.73	151	15.32	125	11.12	22	52.00	3
CAMBA	2	36	11.84	30	8.50	33	0	11	3.16	102	12.92	22	4.69	24	41.11	4
DeepHyperion	2	2	1.22	28	8.31	10	7.74	22	1.08	7	0	14	2.96	34	21.31	5
AmbieGen	[1-4]	30	2.82	46	2.00	36	0.86	65	1.22	151	10.07	30	1.51	32	18.47	6
Surrealist	2	10	5.03	1	0	10	0	1	0.75	19	3.88	2	0	40	9.67	7
TAIiST	[2-4]	7	0.81	13	0	6	0.43	11	1.57	29	1.67	22	1.33	39	5.81	8
SUM		269	59.54	341	68.12	338	33.40	297	29.68	627	155.07	356	89.56			

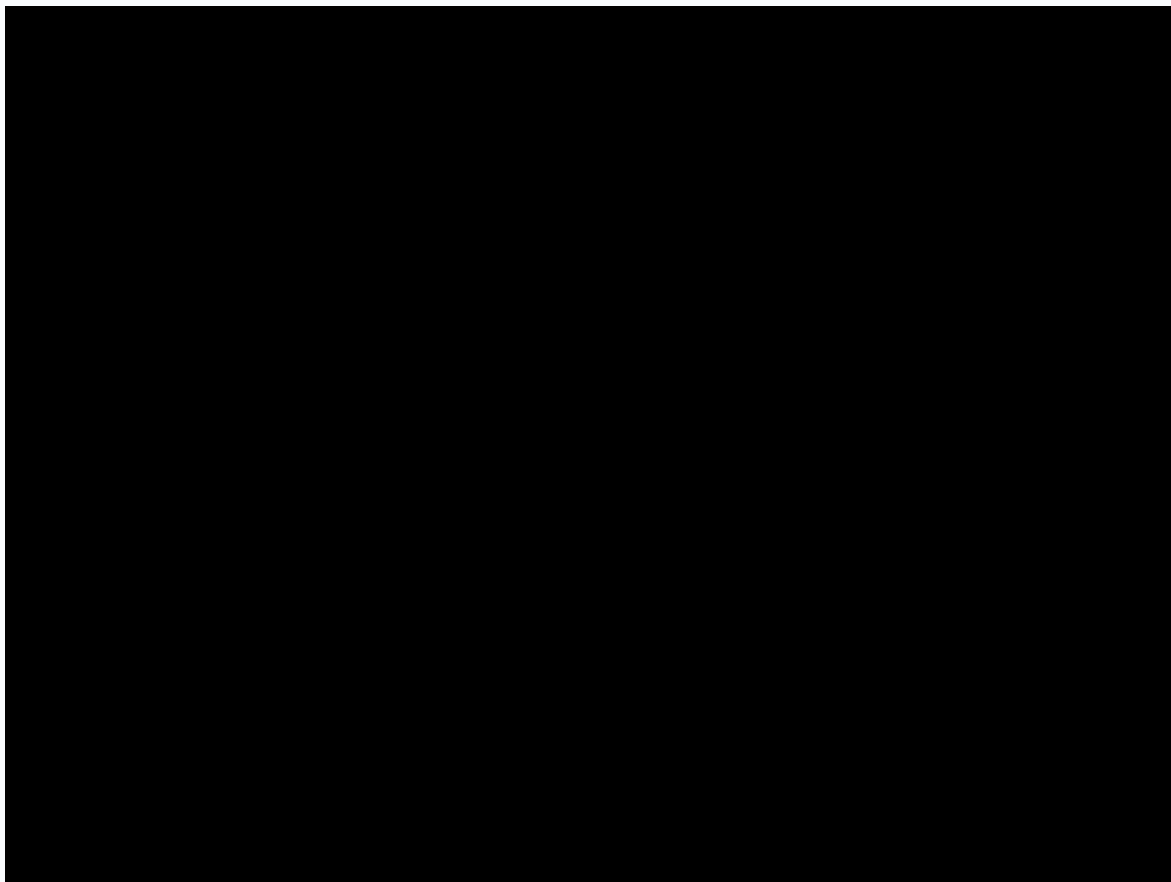


所提出的TLQD算法整体性能最优（得分排名第一）。在复杂任务 CS6 和 CS7 中表现尤为突出，其得分约为第二名算法的5倍，并在较简单的 CS2-CS5 任务中依然保持领先，展现出跨任务复杂度的稳健优势。

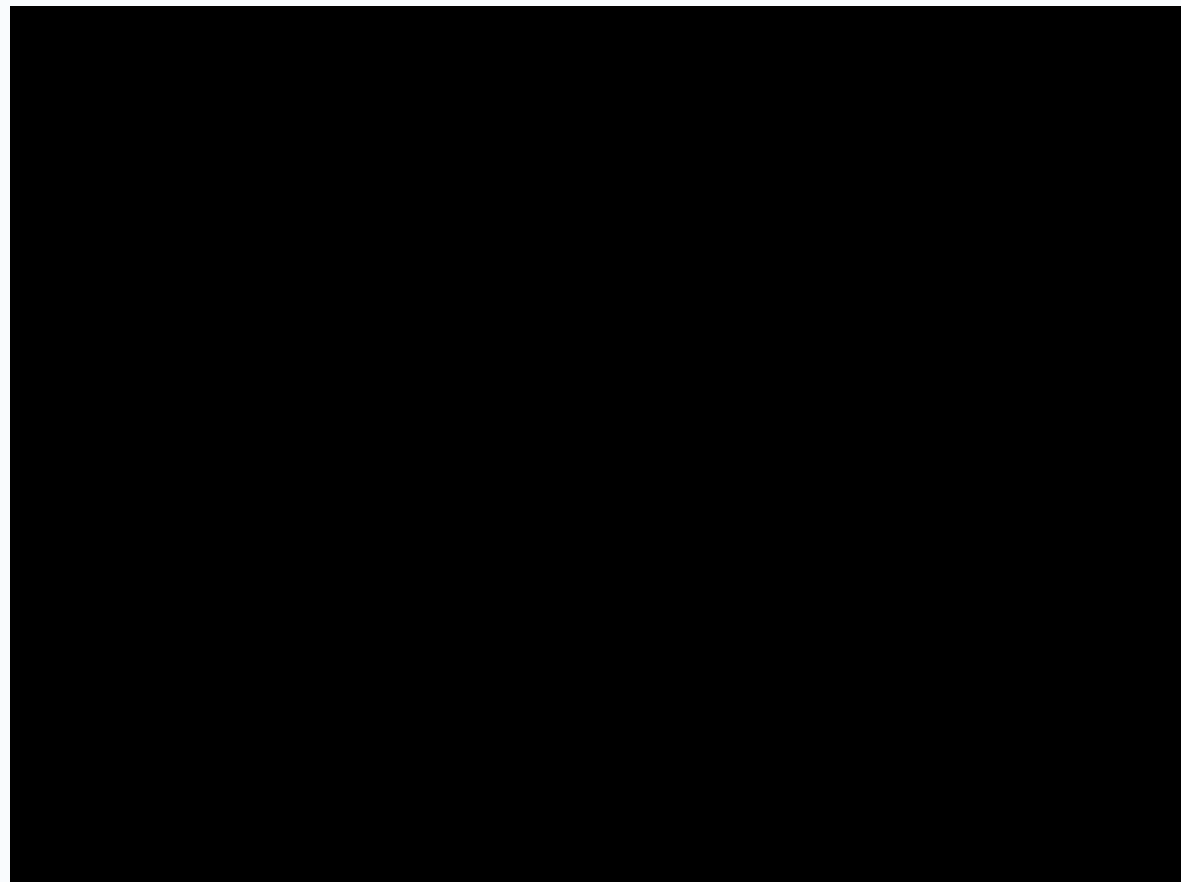
研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

演示系统

自动驾驶仿真测试



无人机仿真测试



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

代表性工作2：在自动驾驶中，测试用例即测试场景。由于仿真测试代价较高，如何对场景进行高效排序（即测试用例排序TCP），使关键风险尽早暴露，成为提升测试效率的重要问题。

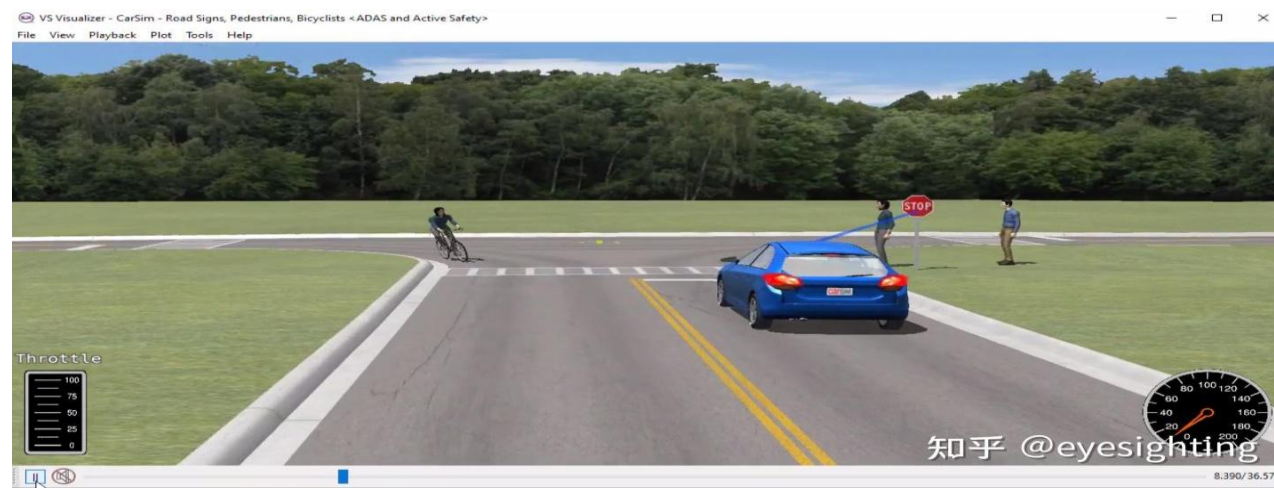
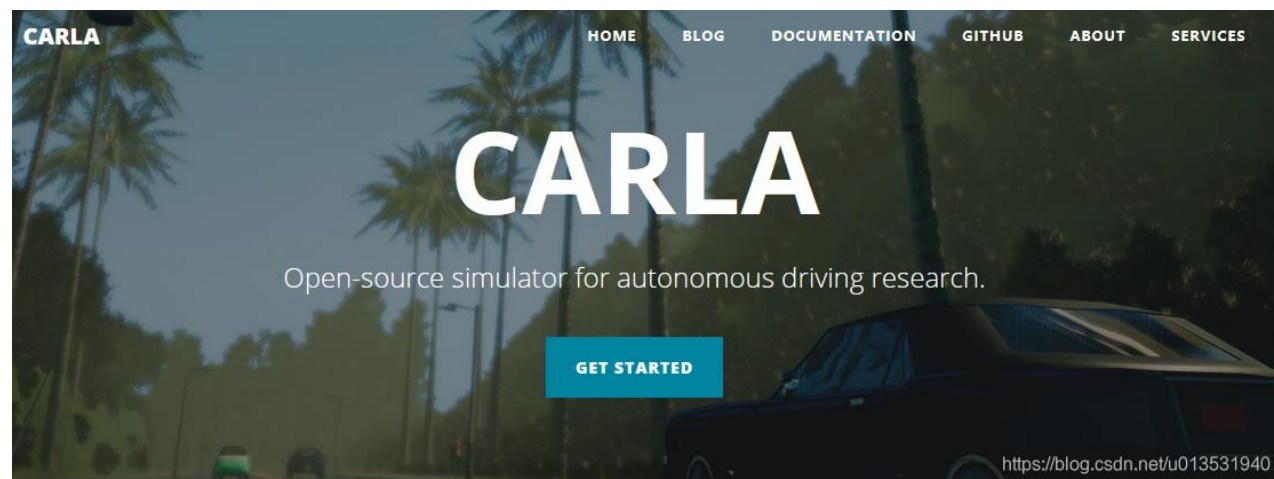
自动驾驶仿真测试

关键挑战1：表示鸿沟问题

原始特征空间缺乏**风险语义**且通用降维技术无法弥合这一鸿沟，传统 TCP 方法在**失真表示**上搜索，难以有效识别高风险场景

关键挑战2：搜索短视性问题

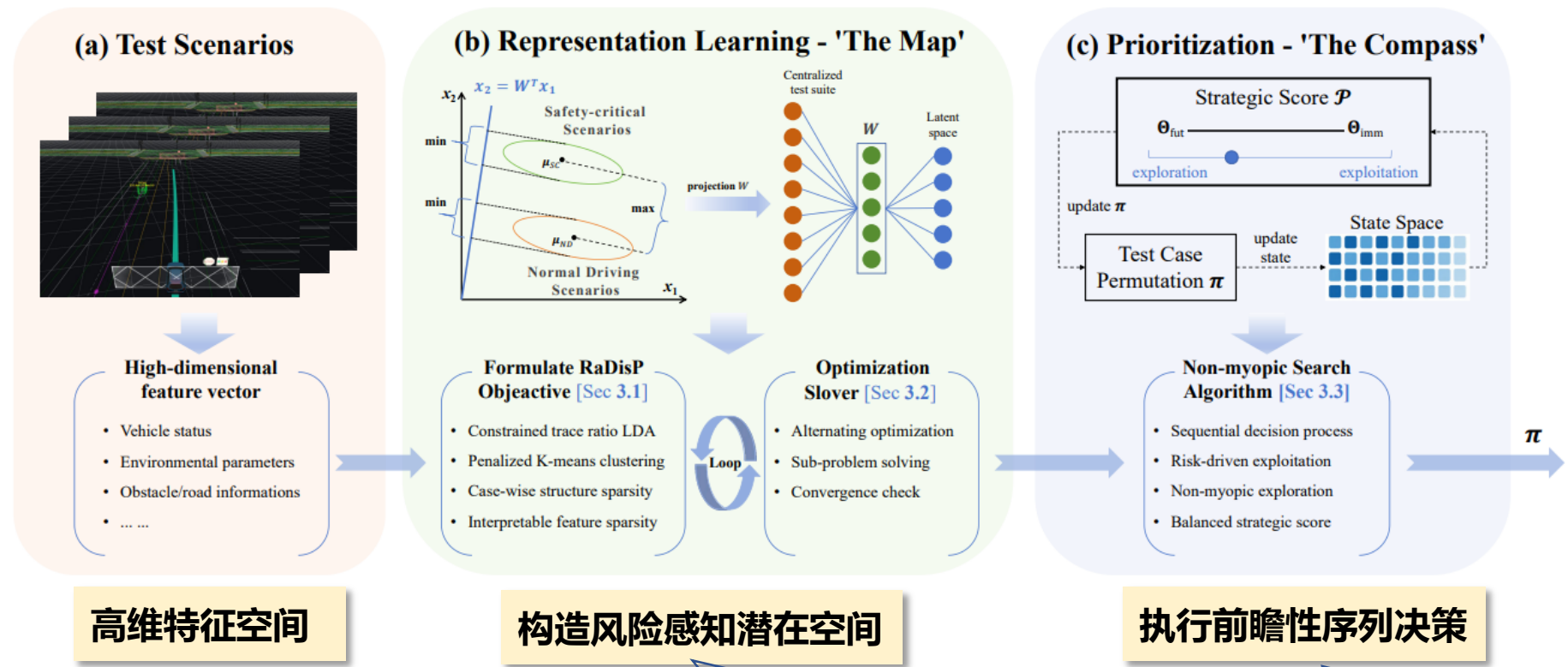
现有方法缺乏对测试空间**全局结构的理解**，难以兼顾开发与探索，从而限制了对多样化故障模式的发现能力。



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

解决方案：提出一种两阶段协同优化框架，从根本上解决表示学习与序列决策的双重挑战。核心思想是从“在糟糕的地图上优化导航”转向“先绘制一张高质量的地图，再用更高效的策略导航”

TCP新范式：
在风险感知潜空间中
进行前瞻性搜索



向毅, 周士璇, 黄翰, 曹捷, 黄沛, 一种自动驾驶仿真测试特征选择方法, 发明专利 (ZL 2025 1 0497546.0), 授权 2025.07.

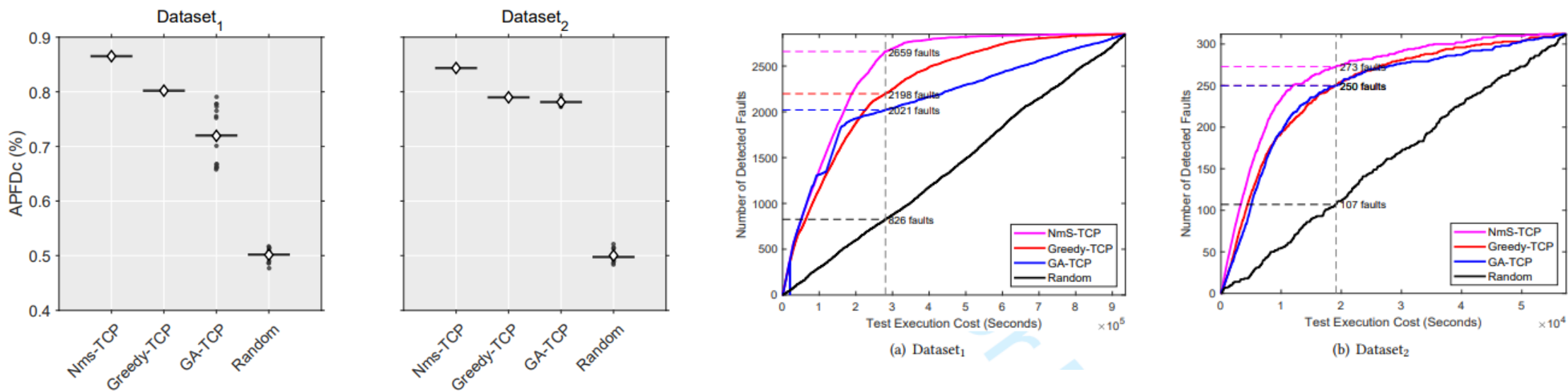
技术支持

高维的原始测试用例数据投影到一个低维、结构化的潜在空间, 几何结构直接反映风险分布

TCP问题建模为确定性序列决策过程, 在风险感知空间中执行全局最优化搜索

研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

实验验证

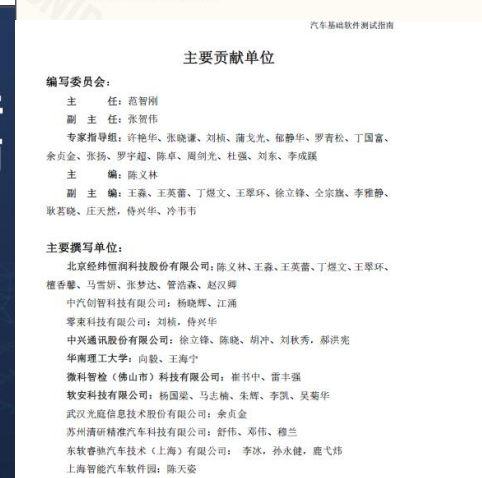


Dataset	Approach	Prioritization	Test Execution	Total Time	
		Time (s)	Time (s)	seconds	hours
Dataset ₁ (Large-scale) (Target: 2659 faults)	NmS-TCP	2,858.0	280,399.9	283,257.9	78.7
	Greedy-TCP	1,882.4	528,851.0	530,733.4	147.4
	GA-TCP	752.6	772,127.9	772,880.5	214.7
	Random	≈0.0	881,514.3	881,514.3	244.9
Dataset ₂ (Small-scale) (Target: 273 faults)	NmS-TCP	4.2	19,044.7	19,048.9	5.3
	Greedy-TCP	2.8	26,273.1	26,275.9	7.3
	GA-TCP	162.3	27,569.6	27,731.9	7.7
	Random	≈0.0	49,653.5	49,653.5	13.8

在相同测试成本下，NmS-TCP在Dataset1以30%的执行代价发现了**93%** (2659/2849) 的故障、显著优于Greedy-TCP的77.2%，并在Dataset2中检测到273个故障，超过GA-TCP与Greedy-TCP的**250**个，充分体现了其在测试早期快速暴露系统漏洞的卓越效率。同时，NmS-TCP的运行时间在Dataset1和Dataset2上分别平均仅为其它方法的**40.7%**和**59.9%**。

研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法

相关论文、专利、标准和获奖



研究成果4：面向具身智能体仿真测试的可变性建模驱动的约束优化方法



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研究成果5 (未来) : 基于多智能体协作的可配置软件缺陷自动修复方法





华南理工大学
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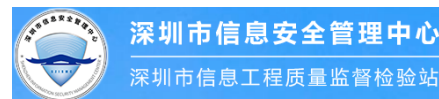
智能算法研究中心

工程案例篇

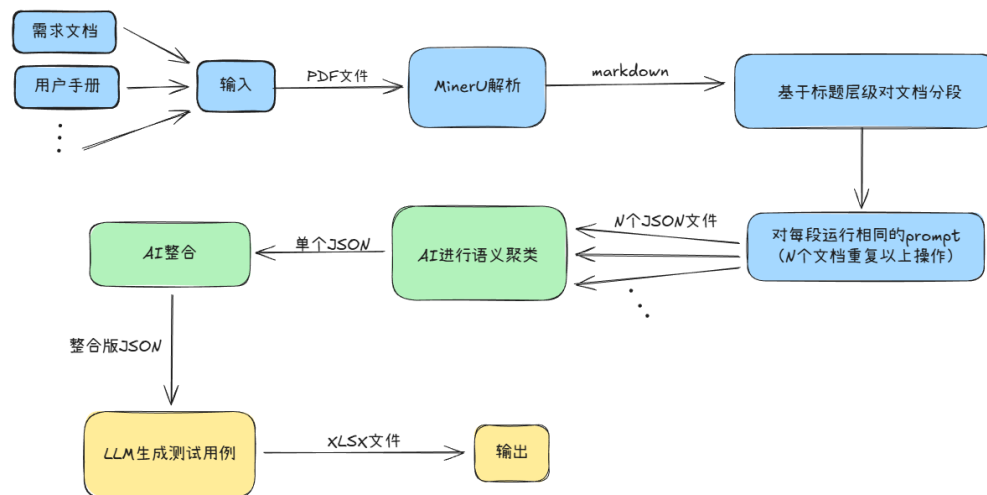
工程案例1：AI大模型驱动的需求到测试用例自动生成系统

与微科智检合作

系统简介：本系统基于 **AI 大模型**，对合同、需求文档、用户手册等多源文档进行**智能解析**，自动生成可直接落地的测试用例，有效降低**人工设计成本**，减少因需求不清和经验差异导致的**覆盖不足与冗余问题**，帮助企业实现测试过程的自动化、标准化和高质量交付。



演示视频



需求ID	系统模块	功能点	测试需求
TC-FT-0001	一网通移动端-实有法人管理模块	实有法人信息录入	验证支持同时录入消防批文、环保批文编号，并能正确添加相关附件。
TC-FT-0002	一网通移动端-实有法人管理模块	实有法人信息暂存/注销	验证网格员能够对未完成的法人信息进行暂存，暂存的信息能在暂存列表中正确显示，并支持后续完善及上报；验证系统在网络中断恢复后，能自动缓存之前录入的信息，确保信息完整性；验证网格员能通过移动端正确执行实有法人的注销操作。

功能点	前置条件	测试点	测试内容
实有法人信息录入	已登录一网通移动端并进入实有法人管理模块；用户具备录入实有法人信息的权限。	录入消防批文编号	在实有法人信息录入页面，点击“消防批文编号”输入框
实有法人信息录入	已登录一网通移动端并进入实有法人管理模块；用户具备录入实有法人信息的权限。	录入环保批文编号	在实有法人信息录入页面，点击“环保批文编号”输入框

对应需求	操作步骤	预期结果
TC-FT-0001	1. 点击“消防批文编号”输入框。 2. 输入正确的消防批文编号。	1. 输入框显示正确输入的消防批文编号。 2. 页面提示“消防批文编号录入成功”。
TC-FT-0001	1. 点击“环保批文编号”输入框。 2. 输入正确的环保批文编号。	1. 输入框显示正确输入的环保批文编号。 2. 页面提示“环保批文编号录入成功”。

工程案例2：基于AI的无人机任务智能排班系统

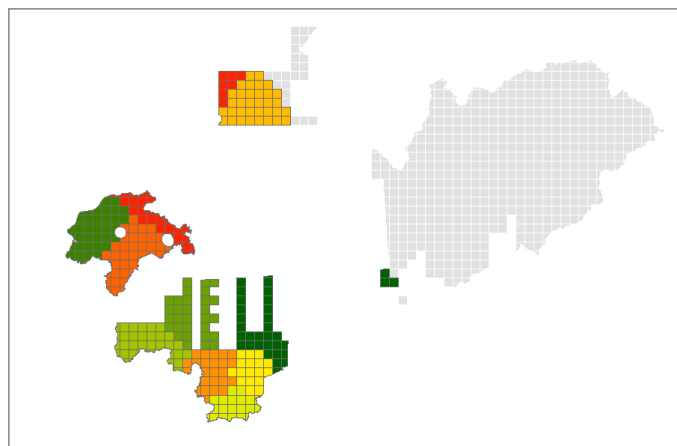
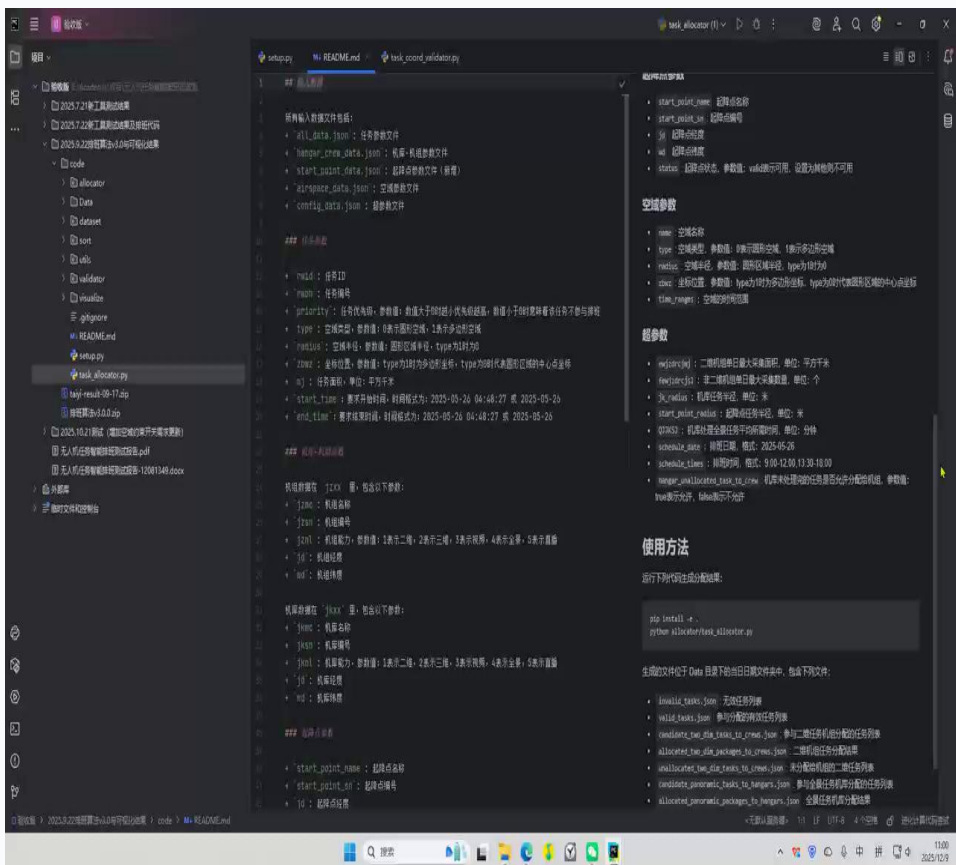


与微科智检合作

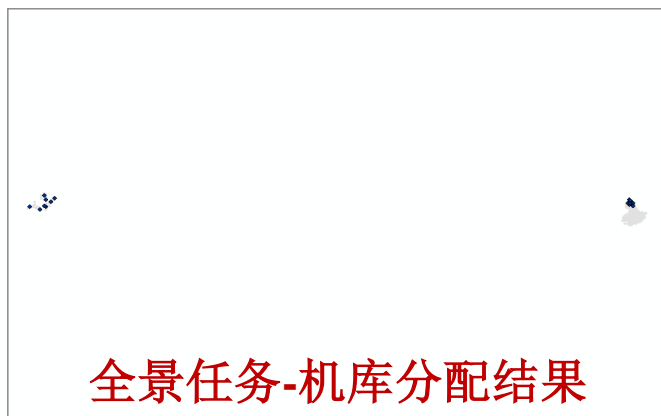
系统简介：面向无人机企业多任务、多约束场景下人工排班**效率低、稳定性差**的问题，本系统基于定制化**聚类与智能优化**算法，在综合空域、任务优先级、时间窗口及机组资源约束的条件下，实现无人机任务的**自动化、高效调度(几分钟)**，显著减少人工干预，提升资源利用率和任务执行效率。



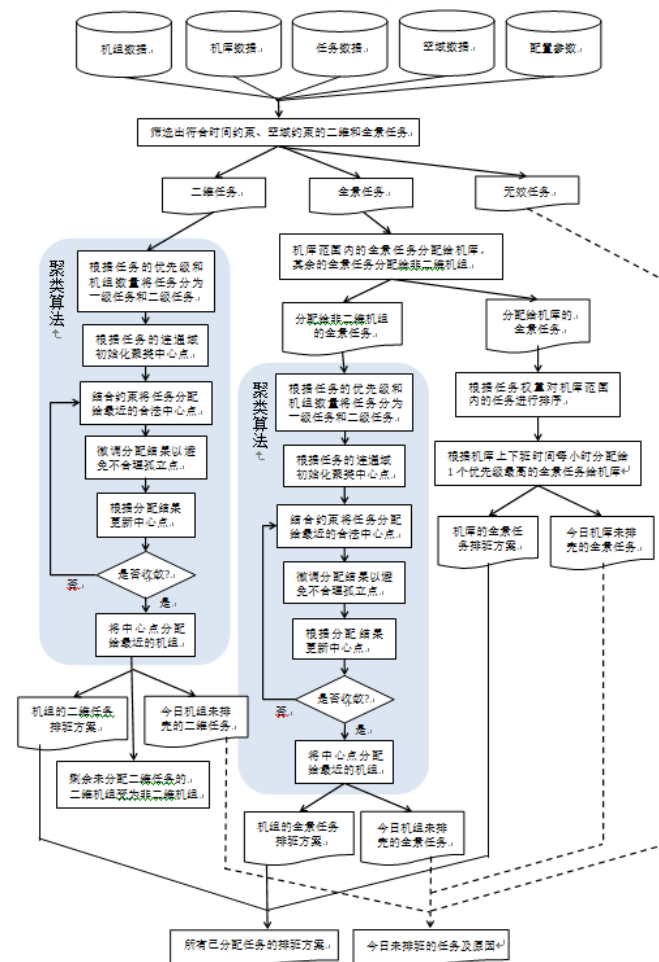
演示视频



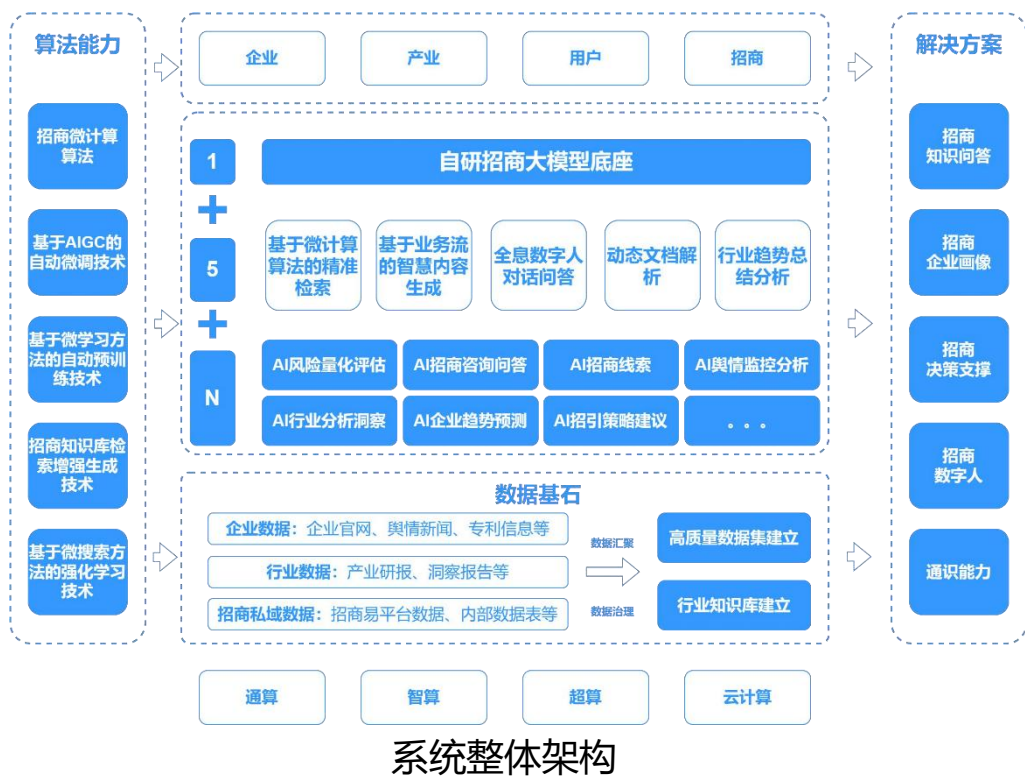
二维任务-机组分配结果



全景任务-机库分配结果

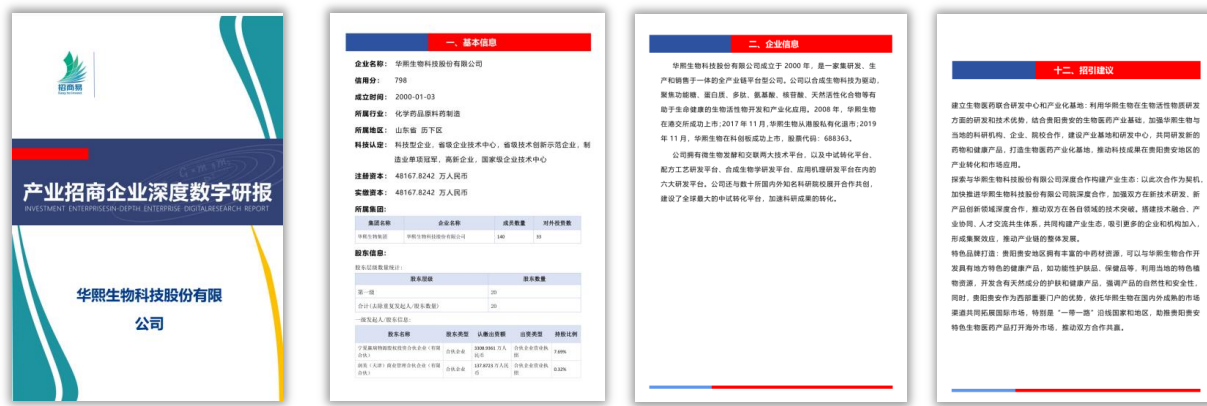


系统简介：基于自研招商大模型底座，融合AIGC自动微调等算法技术，旨在通过**自动化处理海量招商研报与深度行业洞察**解决招商信息呈指数级增长导致的筛选压力过大等问题。有效降低了信息处理时长与人工成本，最终实现了招商决策的**精准化、智能化与实时化**。

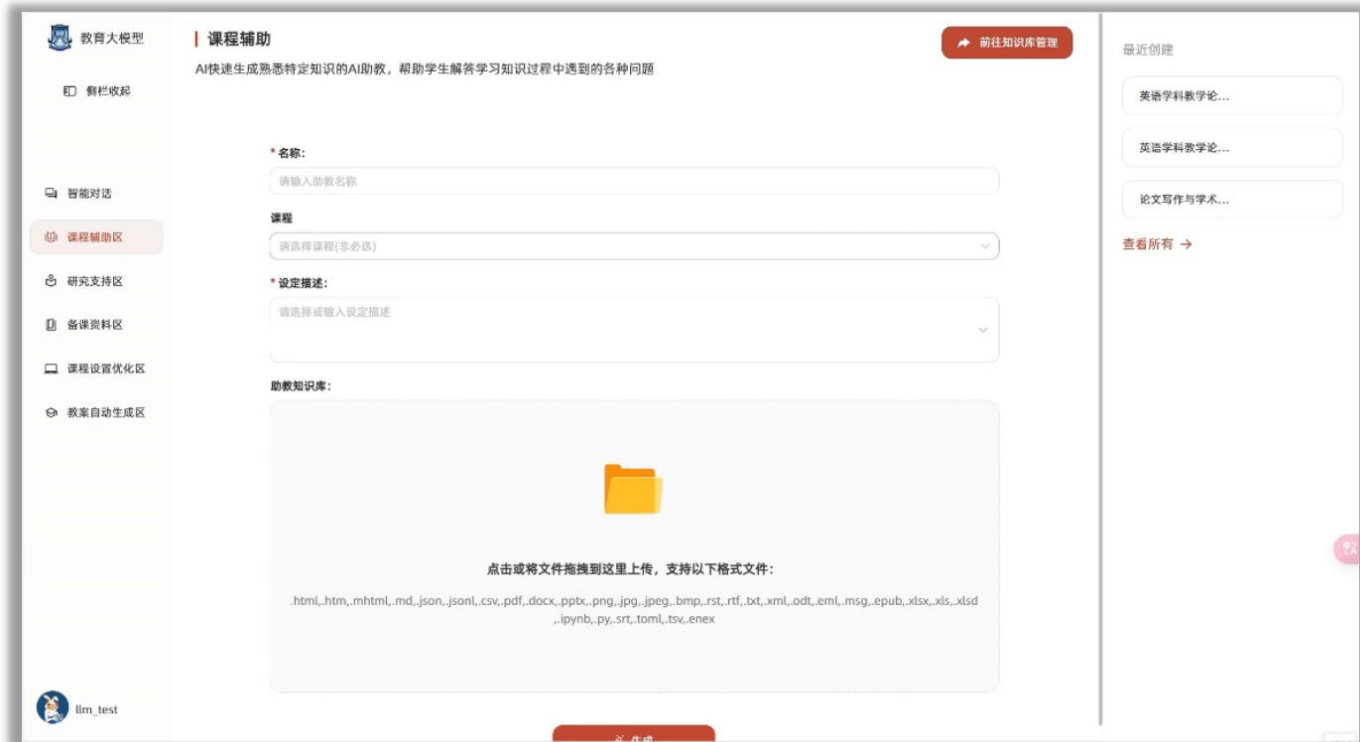


招商系统

应用案例



系统简介：基于国产大模型底座，融合**微搜索路径增强**等垂直领域微调技术，旨在通过构建**外语教师教育专用大模型**解决师范类教育中课程辅助不精准、教研支持不足的问题。有效了降低师生检索专业文献与备课的时间成本，实现教学设计智能化、学情分析数据化与高效化。



系统整体架构

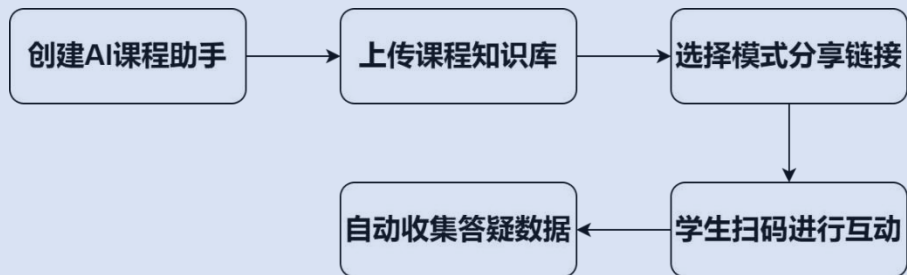
工程案例4：外语教师教育大模型应用系统



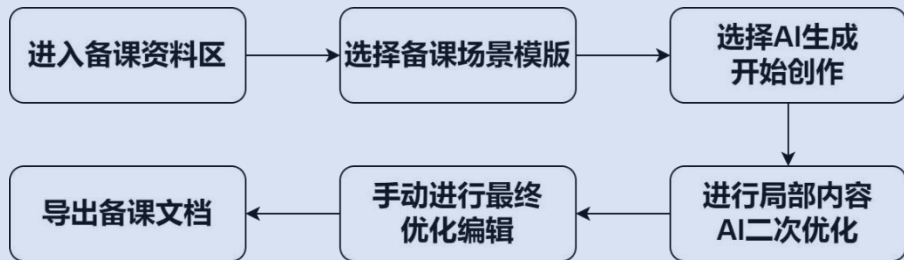
与微科智检合作

功能应用：智能问答、研究支持，教案生成等等

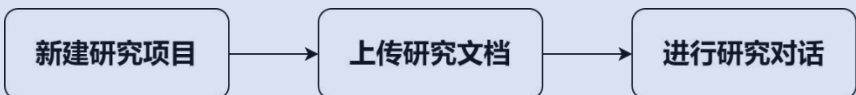
课程辅助



备课资料



研究支持



工程案例5：AI素养教育平台



与微科智检合作

系统简介：基于作文写作专属微调大模型与各类国产模型，深度融合AI智能体技术，旨在通过“助你学AI、AI助你学”双驱动模式提高中小生素养，减轻老师负担；有效降低了青少年学习AI前沿技术的认知难度，帮助实现学生AI素养与学科核心素养的全面进阶。



系统整体架构

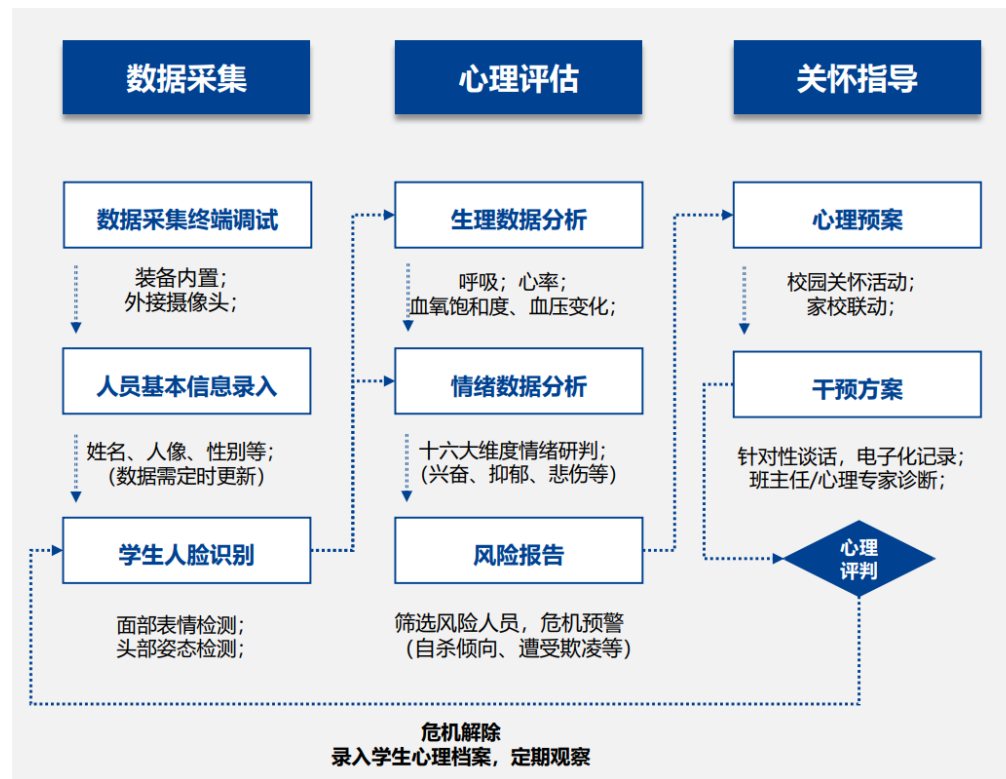


工程案例6：智能心理监护系统(视觉大脑-情绪识别)

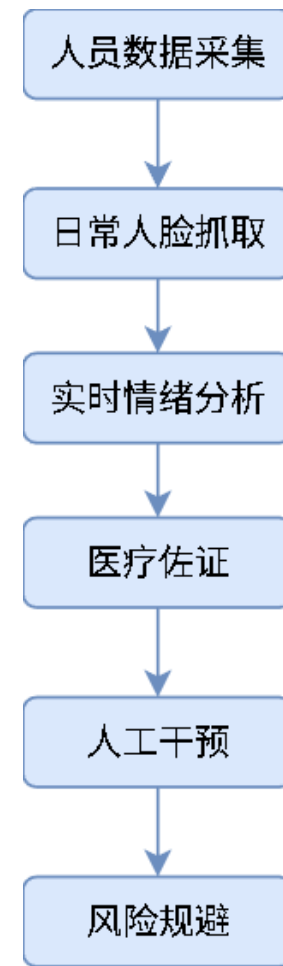


与微科智检合作

系统简介：基于非接触式微表情识别、生理特征分析及大数据预警算法，融合了先进的AI视觉大脑技术。旨在通过**实时情绪监控**与**心理状态评估**解决传统心理测评存在的延迟性高、无法实时捕捉危机信号的问题。有效降低心理危机事件的突发风险与人工筛查成本，实现心理健康管理从“事后干预”向“事前预警、实时监护”的智能化转型。



业务流程



实际流程

核心功能



智能数据分析

智能心理档案



实时风险预警

情绪监护 > 关注对象

关注对象

提供关注对象的人员信息。

关注中 已结束 待关注

姓名: [输入] 部门: [选择] 时间范围: [选择] 开始日期 至 结束日期 查询

姓名	部门	心理监护等级	心理监护值	开始时间	结束时间	来源	操作
[姓名]	[部门]	高度关注	7.2214	2024-02-29 23:11:37	2024-04-01 23:59:59	自动添加	删除 健康记录 心理档案
[姓名]	[部门]	适度关注	5.601	2024-03-15 14:10:07	2024-03-29 23:59:59	自动添加	删除 健康记录 心理档案
[姓名]	[部门]	保持观察	2.7011	2024-03-13 12:10:03	2024-04-01 23:59:59	自动添加	删除 健康记录 心理档案
[姓名]	[部门]	保持观察	2.4142	2024-03-08 11:40:18	2024-03-29 23:59:59	自动添加	删除 健康记录 心理档案
[姓名]	[部门]	保持观察	2.2432	2024-03-01 15:17:21	2024-03-23 23:59:59	自动添加	删除 健康记录 心理档案
[姓名]	[部门]	指标正常	1.6928	2024-03-14 10:10:06	2024-03-28 23:59:59	自动添加	删除 健康记录 心理档案

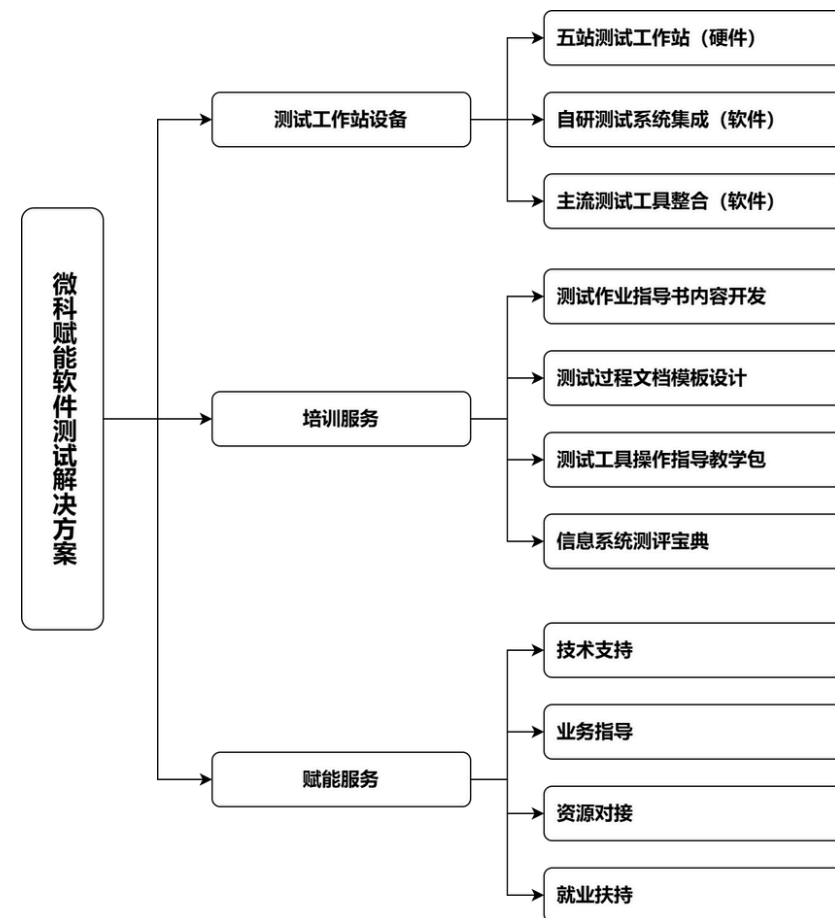
共 6 条 上一页 1 下一页 前往 1 页 10条/页

中度抑郁及轻微妄想症状真实判别案例



由学校老师及医院诊断确认, 该同学存在 **中度抑郁及轻微妄想症状**。出现敌对心理, 情绪上低落, 对大部分事情显得兴趣缺缺。

系统简介：基于**微搜索路径覆盖的测试用例自动生成方法**等核心 AI 技术，旨在通过人工智能驱动的一站式软件体检服务体系解决传统软件测试中对源码依赖度高、人力投入大及测试覆盖率不足的问题。有效了降低测试成本与技术泄露风险，实现测试流程的智能化、自动化、平台化与高效化升级。



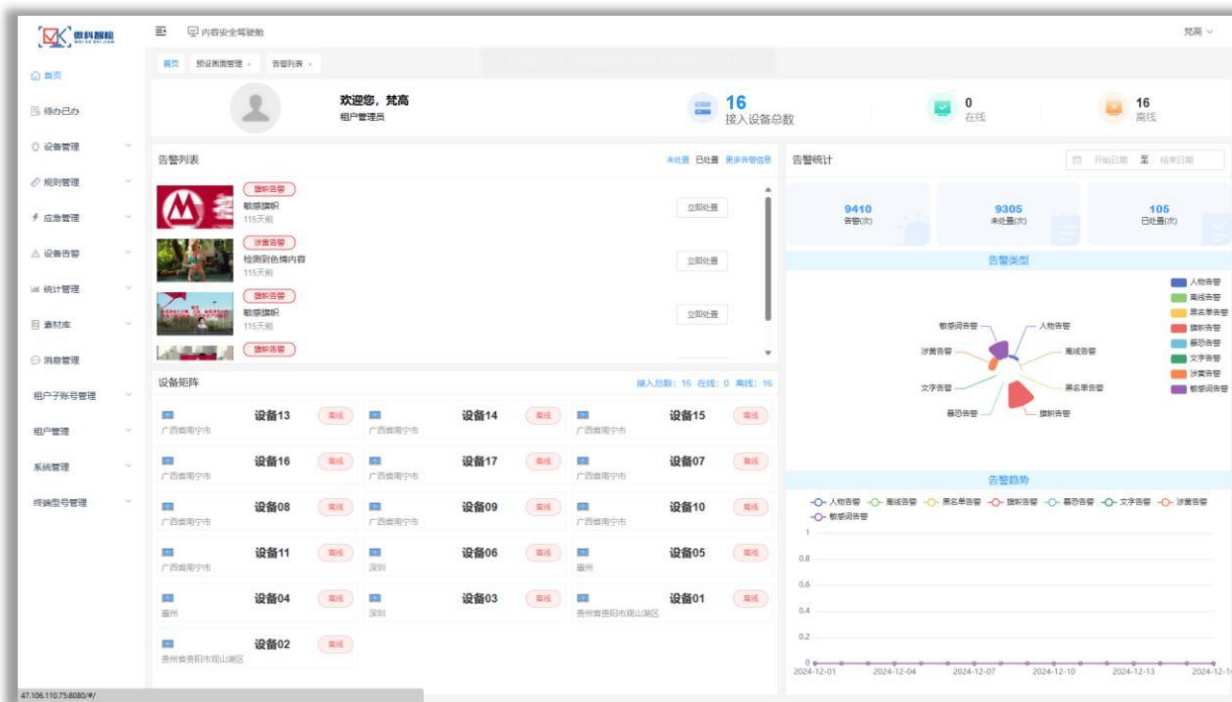
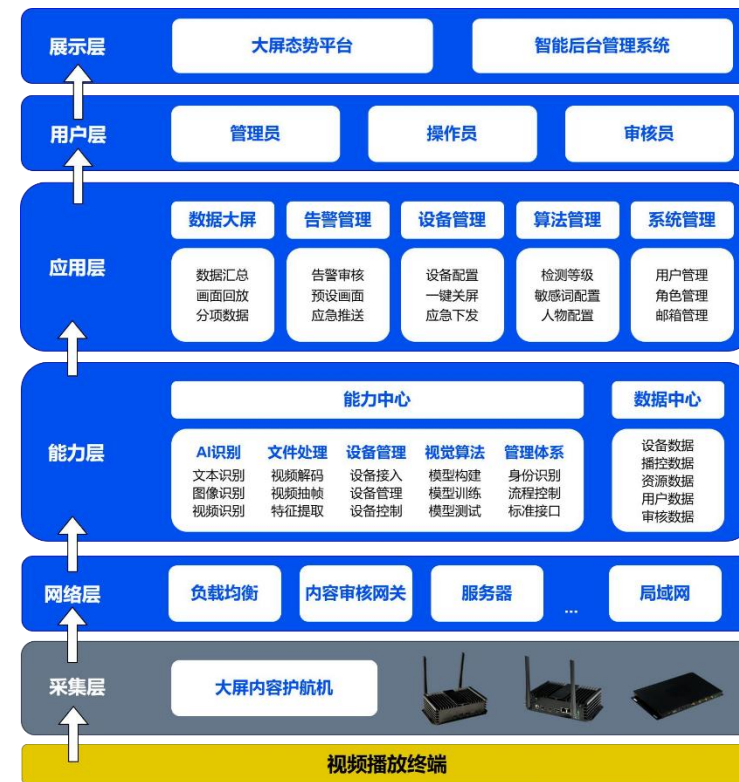
工程案例8：大屏内容安全护盾



与微科智检合作

系统简介：基于微计算、AI视觉识别及多媒体融合处理技术，采用“云、边、端”协同的产品架构。旨在通过嵌入式实时内容监测与自动物理截断机制解决公共显示屏在信息发布过程中面临的种种风险。有效减少了因显示内容违规导致的品牌公信力受损与社会负面影响，实现大屏内容发布的实时监控与秒级阻断。

系统整体架构



大屏态势平台-可视化大屏数据



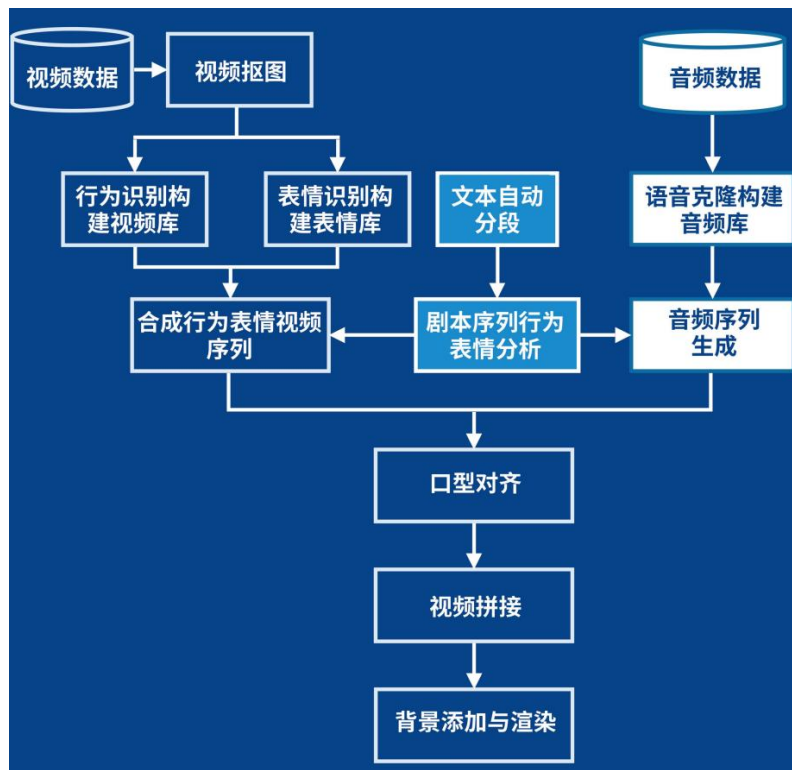
安全护盾样机展示



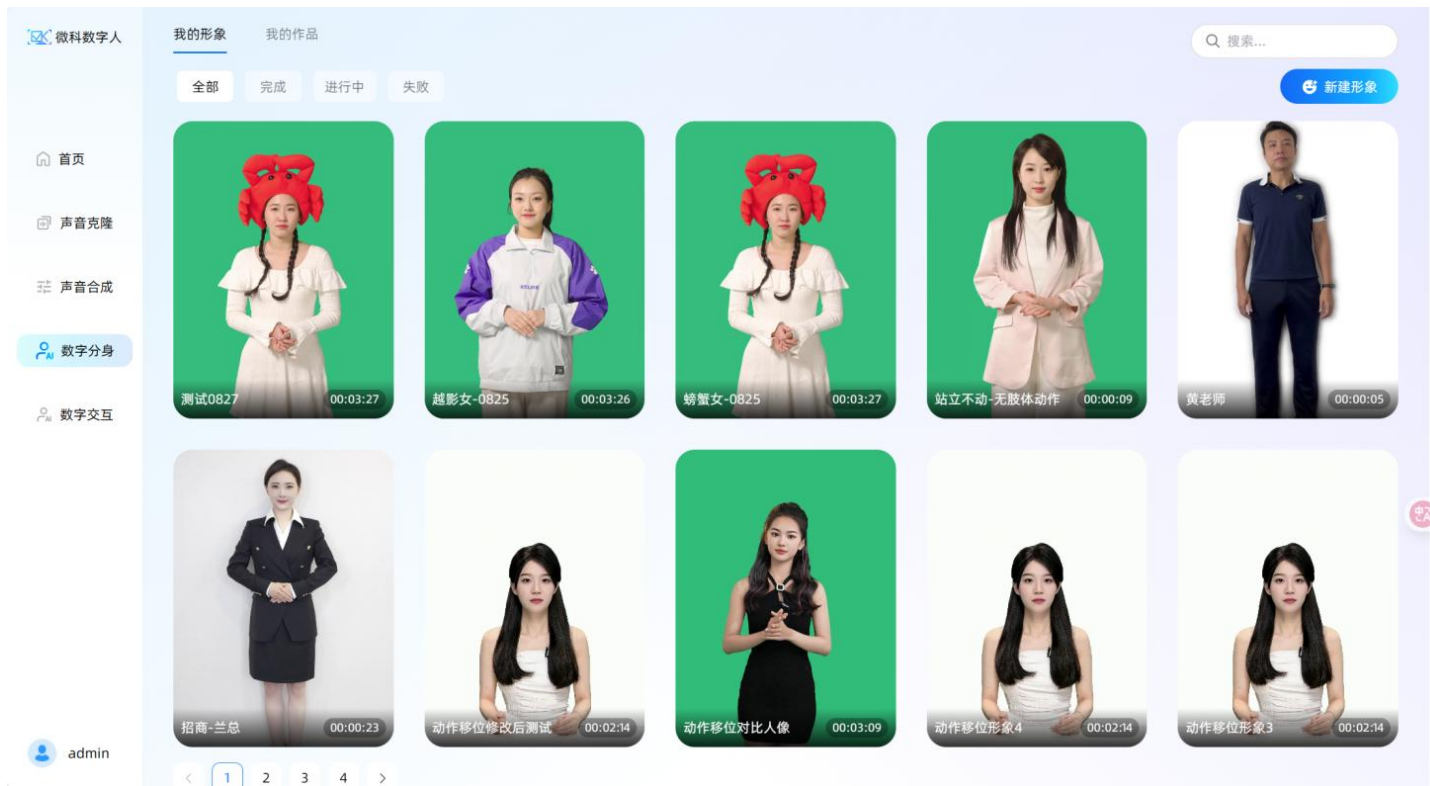
应用场景：
可部署在独立全彩屏、显示器、多屏拼接系统等
多种内容显示载体上



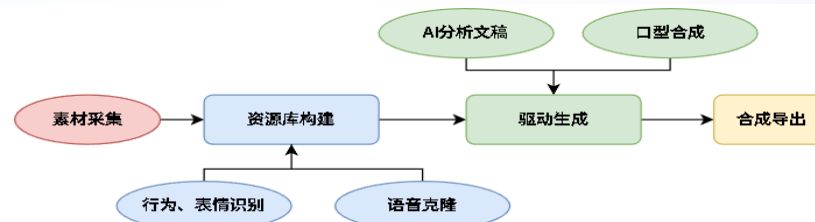
系统简介：基于**微搜索算法**、**神经网络声码器**及**约束优化模型**等核心AI技术，旨在通过高仿真数字分身解决知识与资讯传播中“一对多”模式下反馈沟通困难、理解偏差的问题。有效降低了内容生产成本，减少了传统虚拟人制作中周期过长的技术瓶颈。



数字虚拟人制作技术流程

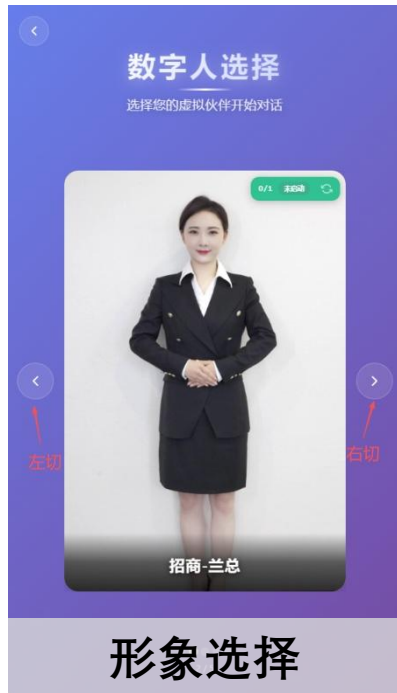


数字人系统

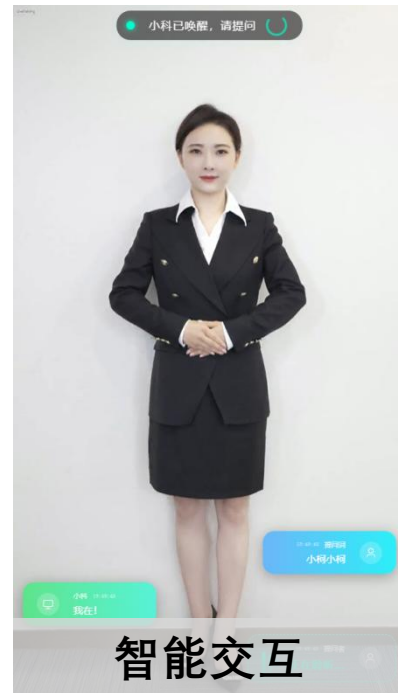


解决行业痛点

- 1.突破瓶颈: 解决了传统数字人制作周期长 (通常需3天-2周)、素材要求高、无法自适应表情动作等缺点。
- 2.成本优化: 全自动化处理极大降低了人工干预成本。
- 3.场景灵活: 支持同人多角度、多人同屏对话等复杂交互场景



形象选择



智能交互

代表性论文成果

代表性论文	微搜索算法效果
[1] Han Huang, Yihui Liang*, Xiaowei Yang, Zhifeng Hao. Pixel-level Discrete Multiobjective Sampling for Image Matting. <i>IEEE Transactions on Image Processing</i> , 2019,27(8):3739-3751.	核心指标Gradient Error优于其他采样抠图算法
[2] Yihui Liang, Han Huang*, Zhifeng Hao, Zhaoquan Cai. Multiobjective Evolutionary Optimization Based on Fuzzy Multicriteria Evaluation and Decomposition for Image Matting. <i>IEEE Transactions on Fuzzy Systems</i> . (2019) 27(5): 1100-1111..	核心指标MSE较其他优化算法降低80%。核心指标SAD、MSE均优于其他采样抠图算法
[3] 冯夫健,黄翰,吴秋霞*,凌霄,梁椅辉,蔡昭权.基于群体协同优化的高清图像前景遮罩提取算法. <i>中国科学:信息科学</i> , 2020, 50(3): 424-437.	在总共27个用例中的16个用例上优于现有先进算法。
[4] Yihui Liang, Han Huang*, Zhifeng Hao, Kay Chan Tan. Deep Infrared Pedestrian Classification Based on Automatic Image Matting. <i>Applied Soft Computing</i> (2019): 484-496.	帮助先进算法提升了3%-7%的分类精度
[5] Fan Zhun, Lu Jiewei, Wei Caimin, Huang Han, Cai Xinye and Chen Xinjian.* A hierarchical image matting model for blood vessel segmentation in fundus images. <i>IEEE Transactions on Image Processing</i> , 2018,28(5): 2367-2377.	核心指标AUC、Acc均优于其他监督算法与无监督算法

代表性论文
[1] Xueming Yan, Han Huang , Yaochu Jin, et al. Neural Architecture Search Via Multi-hashing Embedding and Graph Tensor Networks for Multilingual Text Classification. <i>IEEE Transactions on Emerging Topics of Computational Intelligence</i> , 2023. (Accepted)
[2] Chen Liang, Xueming Yan , ZiLong Wang, Han Huang, Neural Architecture Search with Heterogeneous Representation Learning for Zero-Shot Multi-Label Text Classification. International Joint Conference on Neural Networks (IJCNN2023), Gold Coast, Australia. 2023

应用场景

虚拟律师



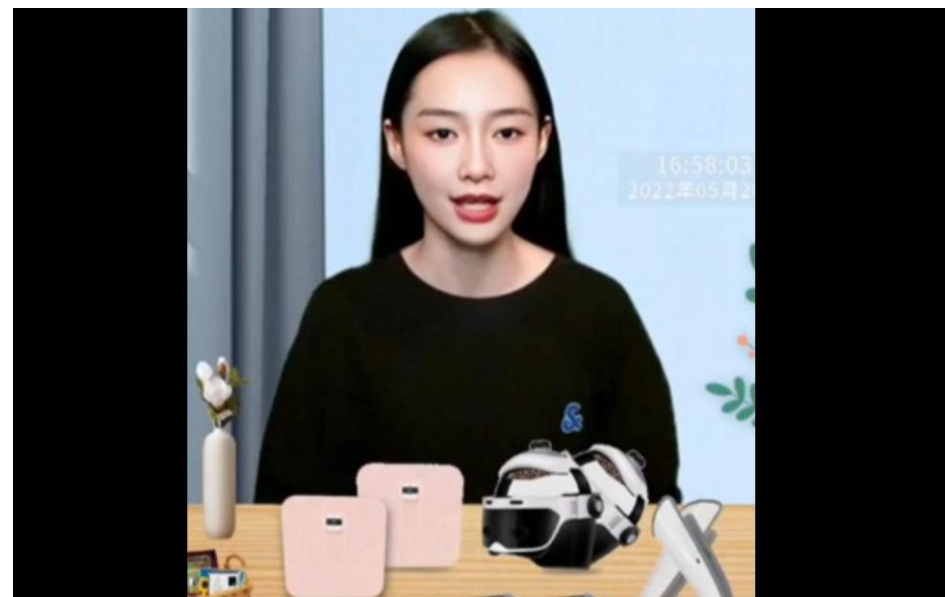
虚拟医生



虚拟课堂答疑辅导



虚拟主播





华南理工大学
South China University of Technology



智能算法研究中心

基于智能优化的自主机器人系统控制 策略生成及仿真测试方法

汇报人：向毅 副教授、博导

华南理工大学 软件学院

2025年11月



团队负责人 向毅，博士，副教授，博士生导师

广东省优秀青年（青年提升）基金获得者，兼任中国运筹学会模糊信息与工程分会理事、广东省计算机学会软件工程专委会秘书长，担任国际期刊Mathematics的客座编辑、2025 International Seminar on Theoretical Computer Science的特邀联合主席。

- **主持科研项目：**国家自然科学基金、广东省自然科学基金（青年提升/优青、面上）、广州市科技计划项目、中国博士后基金等；
- **发表学术论文：**以第一作者或通讯作者身份在ACM TOSEM、IEEE TSE、IEEE TEVC、IEEE TCYB、ICSE、ISSTA、中国科学：信息科学和软件学报等专业学术期刊和会议上发表论文**40**多篇，代表作入选ESI；
- **获得知识产权：**授权国家发明专利**7**项；
- **制定标准：**以主要完成人制定了全国团体标准T/CI 083-2023《无源码的白盒化测试标准》；
- **获奖情况：**2024年度广东省计算机学会优秀论文一等奖、2018年度ACM中国广州分会的优秀博士学位论文奖、2020年度中国仿真学会智能仿真优化与调度专业委员会优秀博士学位论文奖、2024年度广东省计算机学会教育教学成果奖一等奖和2023年度广东省科技进步二等奖；
- **合作企业：**中国电科旗下的普华基础软件、TCL云创科技有限公司、微科智检、泰一科技等

问题背景：机器人在复杂场景常面临动态环境和物理损伤等风险，这严重影响功能甚至导致任务失败，因此提升机器人损伤后的自我恢复和适应能力成为关键挑战。

关键问题1：在物理损伤不可预知的情况下，如何生成具备足够多样性与稳健性的机器人控制策略，以便在损伤发生时能够快速找到有效的替代方案？

关键问题2：在物理损伤发生时，如何在候选控制策略中快速识别并选取最优策略，以实现高效的损伤适应？



解决方案：针对关键问题1，构建了用于机器人控制策略生成的多目标质量-多样性优化模型，并设计相应的多目标MAP-Elites智能算法，以生成一组兼具高质量与高多样性的控制策略集合。

多目标质量-多样性优化模型

$$\arg \max_x [f_1(x), f_2(x)]$$

目标函数 f1：前进距离 f2：消耗成本

行为特征

1、接触时间比例。即每一回合步数中，第*i*条腿接触地面的时间比例。

$$bc_i = CT_i = \frac{\sum_{t=1}^T c_i(t)}{T}$$

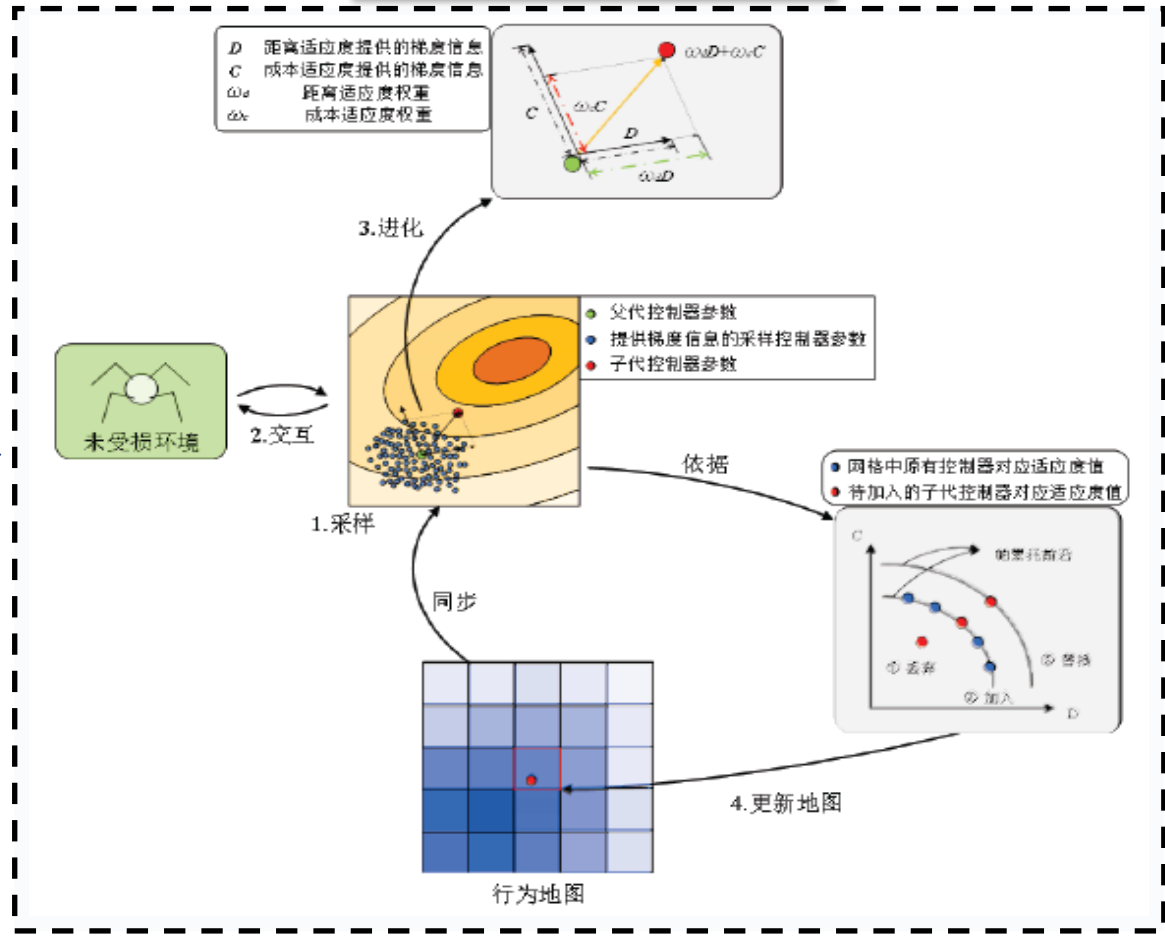
2、质心移动距离。即每一回合步数中，模拟机器人质心在水平/垂直方向上移动的距离。

$$bc_i = dx_i = x(T) - x(0)$$





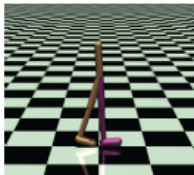
3、机器人速度

算法求解

多目标MAP-Elites



实验验证

环境名	s 维度	a 维度	BC 维度	说明	环境示例
Ant	27	8	4	bc_1 : 第 1 条腿与地面的接触时间比例	
				bc_2 : 第 2 条腿与地面的接触时间比例	
				bc_3 : 第 3 条腿与地面的接触时间比例	
				bc_4 : 第 4 条腿与地面的接触时间比例	
Half-Cheetah	17	6	2	bc_1 : 前腿与地面的接触时间比例	
				bc_2 : 后腿与地面的接触时间比例	
Hopper	11	3	4	bc_1 : 质心移动距离	
				bc_2 : 智能体沿 x 轴水平移动速度	
				bc_3 : 智能体沿 z 轴垂直移动速度	
				bc_4 : 足部与地面的接触时间比例	
Humanoid	53	21	4	bc_1 : 左脚前脚掌与地面的接触时间比例	
				bc_2 : 左脚后脚跟与地面的接触时间比例	
				bc_3 : 右脚前脚掌与地面的接触时间比例	
				bc_4 : 右脚后脚跟与地面的接触时间比例	
Walker2d	17	6	2	bc_1 : 前脚掌与地面的接触时间比例	
				bc_2 : 后脚跟与地面的接触时间比例	

与单目标方法比较

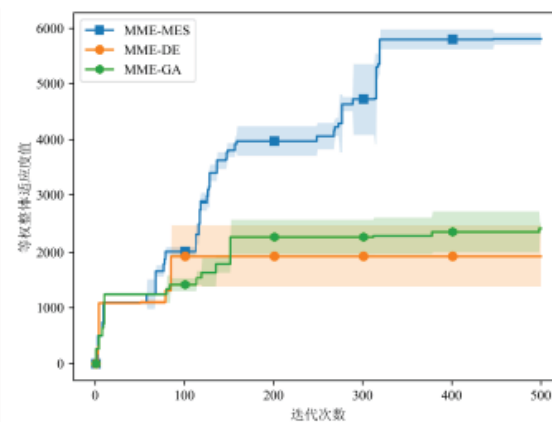
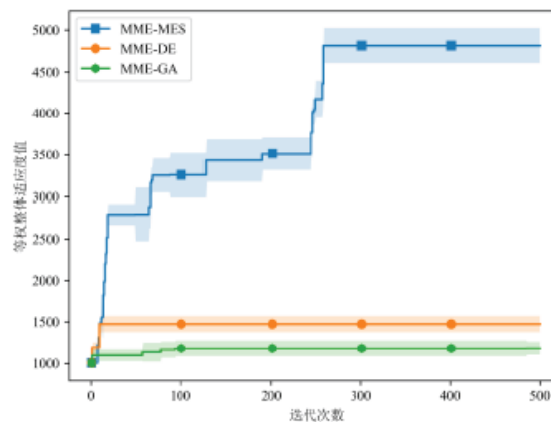
3-3 MME-MES 与 ME-ES 对比结果值

	Ant	HalfCheetah	Hopper	Humanoid	Walker2d
MME-MES	4816.00	5811.72	3456.63	4202.43	5267.87
ME-ES	4551.33	5513.94	1225.30	2343.76	5059.59

与多目标方法比较

MME-MES 与其他多目标算法对比结果值

	Ant	HalfCheetah	Hopper	Humanoid	Walker2d
MME-MES	4816.00	5811.72	3456.63	4202.43	5267.87
MOEA/D	1229.35	1705.01	1182.14	391.70	1133.15
SPEA2	1132.33	175.87	262.92	372.61	426.17
NSGA-II	1468.25	5102.04	-	-	-



在不同模拟环境中，提出方法的最佳适应度值提升了100到2500不等，且能生成多样化的行为策略集合

解决方案：针对关键问题2，构建了机器人损伤恢复问题的多目标优化模型，并设计相应的多目标贝叶斯算法，从而快速找到能够使得机器人从损伤情形中恢复过来的高性能控制器参数。

多目标优化模型

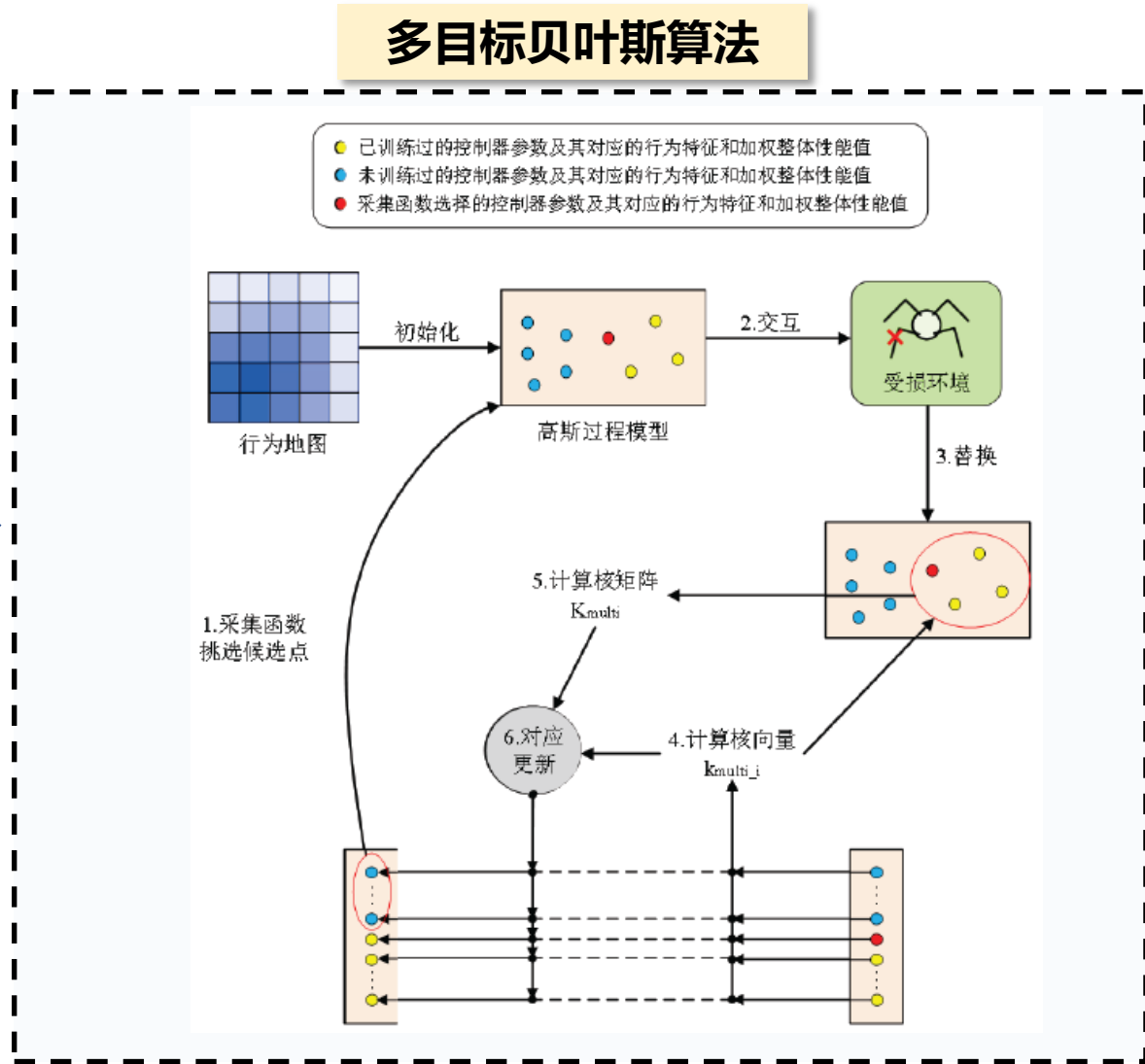
$$\arg \max_{\theta} \mathbb{E} [\omega_1 f_1(\theta), \omega_2 f_2(\theta)]$$

目标函数

$$f_1 \sim GP(\mu_1, \sigma_1^2)$$
$$f_2 \sim GP(\mu_2, \sigma_2^2)$$

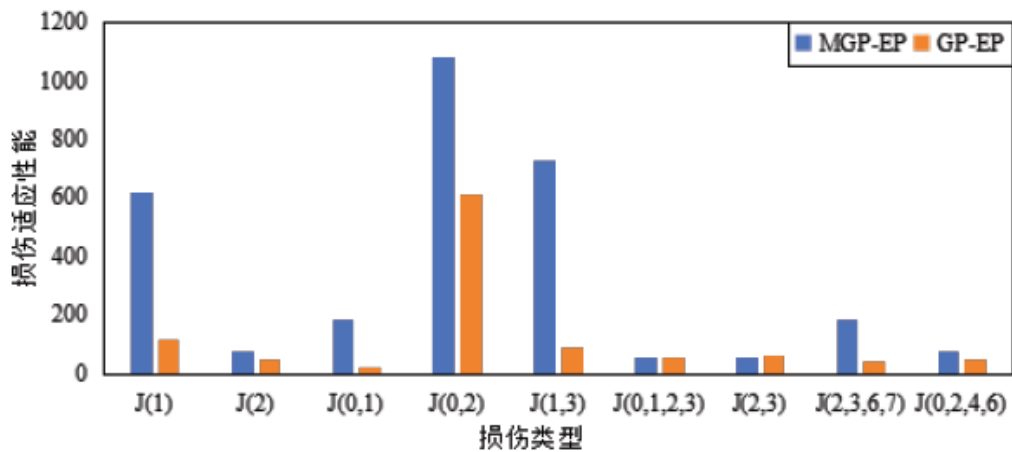
其中， f_1 反映了控制器参数在损伤环境中的预测行走距离， f_2 反映了控制器参数在损伤环境中的预测能量消耗，两个性能指标是直接反映控制器优劣的标量值。

算法求解

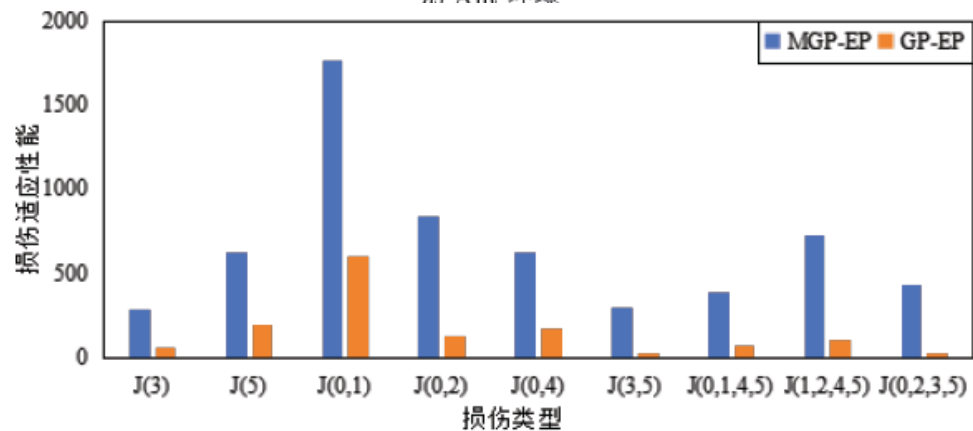


实验验证

与主流方法比较



a) Ant 环境



b) HalfCheetah 环境

UR
损伤环境设置
搜索过程监控
损伤适应展示
登录

损伤环境设置

模拟机器人类型

Ant

损伤关节数量

2

损伤类型

足1踝关节&腿2截关节

设定环境

a) Ant 环境

b) HalfCheetah 环境

c) Hopper 环境

d) Walker2d 环境

实验结果表明，所提出的方法在较少的评估次数（5-15 次）内可找到接近最优的控制器参数，优于主流方法



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感谢各位专家批评指正！**



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