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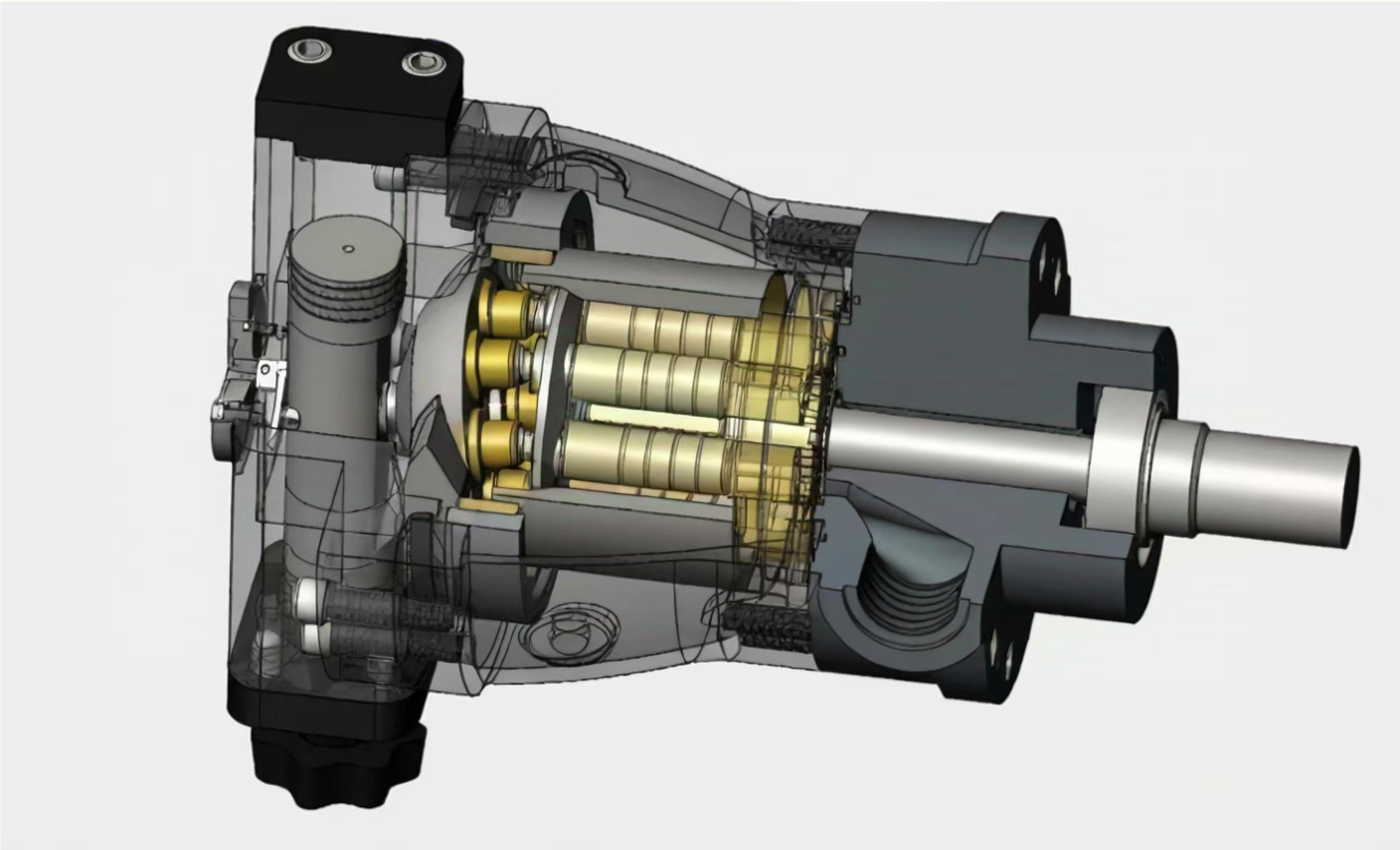
柱塞泵故障诊断与剩余寿命预测
Piston pump fault diagnosis and RUL prediction

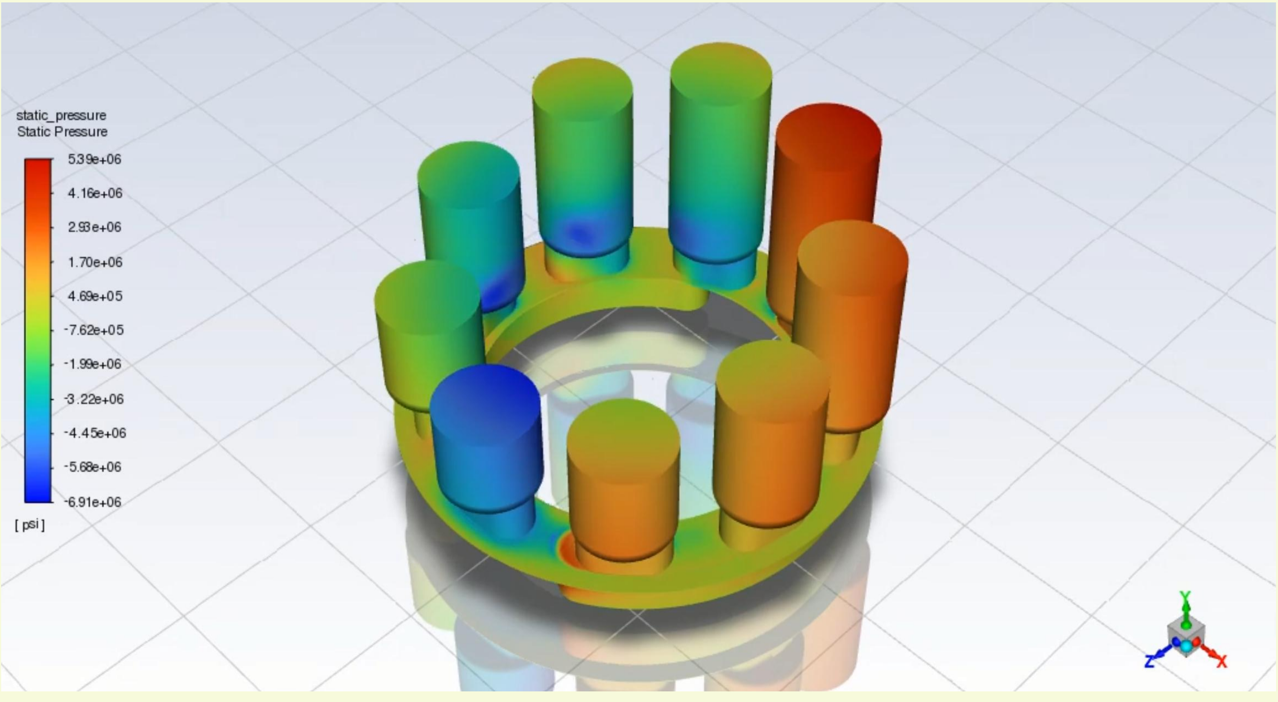
背景与挑战 Background and Challenges

柱塞泵作为液压系统的“动力心脏”，在工程机械、航空航天、水利工程和国防装备等领域中承担着关键的动力传递功能。然而，柱塞泵结构复杂，工况恶劣，故障形式多样，退化规律多变。故障会导致柱塞泵泄漏量激增和运动精度下降，严重影响系统稳定性和寿命。此外，故障预测与健康管理（PHM）技术在工业场景中的应用仍受限于机理不清、多源数据融合困难等问题。本研究揭示复杂工况下柱塞泵配流盘磨损与球头间隙增大两种典型故障的失效机理，探索退化模型与现场数据动态融合的柱塞泵故障诊断方法，对柱塞泵剩余寿命进行预测。

Plunger pumps, as the hydraulic system's "power heart", play a vital role in key power transmission in fields like construction machinery, aerospace, hydraulic engineering, and national defense equipment. However, their complex structure, harsh working conditions, diverse failure modes, and variable degradation patterns make them prone to failures. Failures can cause increased leakage and reduced motion accuracy, severely impacting system stability and lifespan. Moreover, the application of Prognostics and Health Management (PHM) technology in industrial scenarios is restricted by issues like unclear failure mechanisms and difficulties in multi-source data fusion. This study reveals the failure mechanisms of two typical plunger pump faults - distributor plate wear and increased ball joint clearance - under complex working conditions. It also explores a plunger pump fault diagnosis method that dynamically integrates degradation models with field data to predict the pump's remaining service life.



研究内容 Research Work



● 柱塞泵故障机理Piston pump failure mechanism

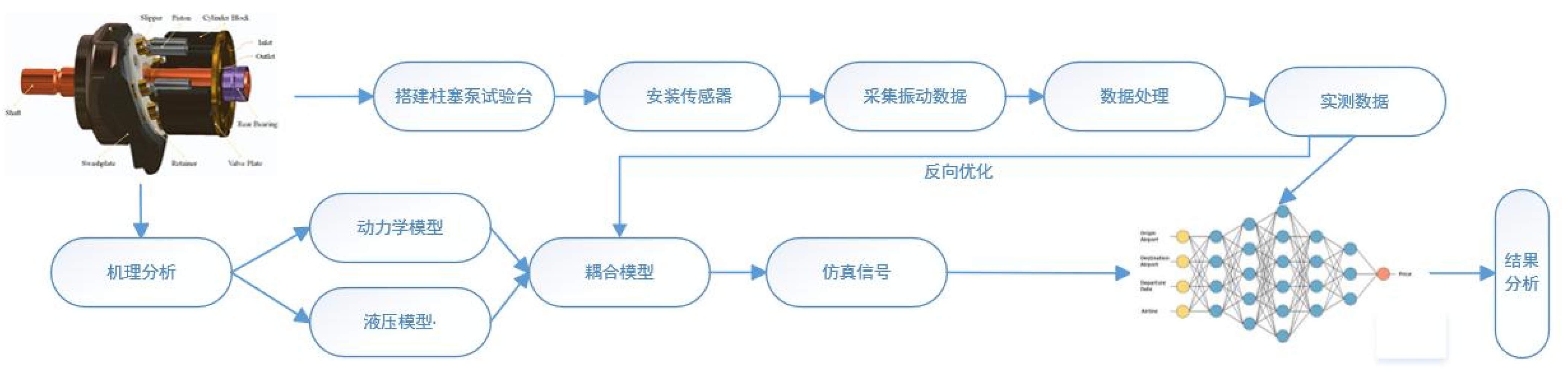
柱塞泵主要的故障机理为配流副磨损以及球头间隙增大。配流副在启停，重载，表面粗糙度较大时，摩擦副处于混合润滑状态，产生磨粒磨损。而球头间隙是由多种应力共同导致，故障机理复杂。针对配流副磨损，研究混合润滑状态下磨粒磨损机理，从能量传递角度分析其对能量耗散的影响，以实现对配流副磨损故障的精准诊断。针对球头间隙增大，通过建立结合磨损机理与神经网络的球头间隙演化模型，并利用多传感器能量特征融合的贝叶斯网络方法实现球头间隙增大故障的动态监测与诊断。

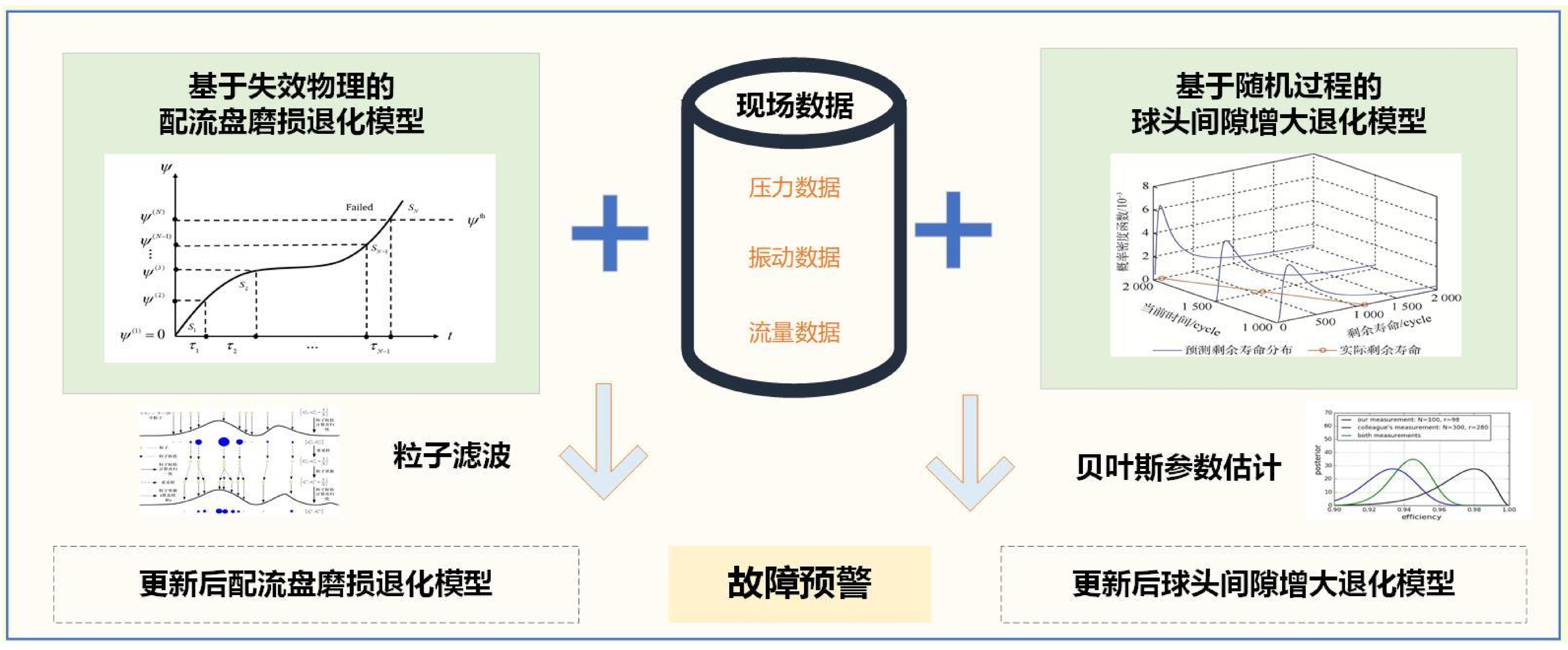
Plunger pump failures stem from wear in internal friction pairs (distribution pairs) and increased ball head clearance. Distribution pairs experience abrasive wear under mixed lubrication during start-stop, heavy loads, and high surface roughness. Ball head clearance, caused by multiple stresses, has a complex failure mechanism. Research focuses on abrasive wear in mixed lubrication for precise diagnosis of distribution pair wear, analyzing energy dissipation. For ball head clearance, a model combining wear mechanics and neural networks, alongside Bayesian network methods using multi-sensor energy features, enables dynamic monitoring and diagnosis.

● 模型与数据融合的故障诊断方法Fault Diagnosis Method Based on Model and Data Fusion

利用预先建立的数学模型描述柱塞泵在不同工况下的运行特性，同时引入现场传感器采集的实时数据对模型进行校正和优化。这种动态融合通过迭代更新消除模型假设与实际运行偏差，增强对故障特征的捕捉能力，从而在原理上保证诊断结果与真实故障状态的高度一致性，适用于复杂多变的操作环境。

This method uses math models to describe how plunger pumps work in different conditions, then adjusts them with real-time sensor data. By updating repeatedly, it reduces gaps between the model and reality, improving fault detection and ensuring accurate diagnoses in tough, changing environments.





● 基于数模融合的柱塞泵剩余寿命预测方法 RUL Prediction Method for Piston pump Based on Digital-Model Integration

首先建立基于失效物理的配流副磨损退化模型与基于随机过程的球头间隙增大退化模型。在此基础上，考虑到载荷以及退化规律的不确定性，基于粒子滤波方法与贝叶斯估计将在线数据与退化模型相融合，更新退化模型参数，并利用更新后的退化模型动态估计各柱塞泵剩余寿命。

First, establish a physics-of-failure-based wear degradation model for valve plates and a stochastic-process-driven clearance enlargement degradation model for spherical joints. Considering load uncertainties and degradation randomness, we integrate real-time data with these models through particle filtering and Bayesian estimation to dynamically update model parameters and predict remaining useful life of each plunger pump.

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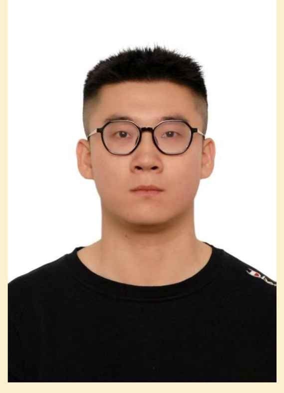
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山西省基础研究计划（产业发展类）联合资助项目
多柱塞泵并联泵站关键部位故障监测与预测
Shanxi Provincial Basic Research Program (Industrial Development) Joint Funding Project
Monitoring and prediction of failure of key components of multi-plunger parallel pumping station

液压基础件及机电装备低碳智能化——高端装备智能控制与健康服役

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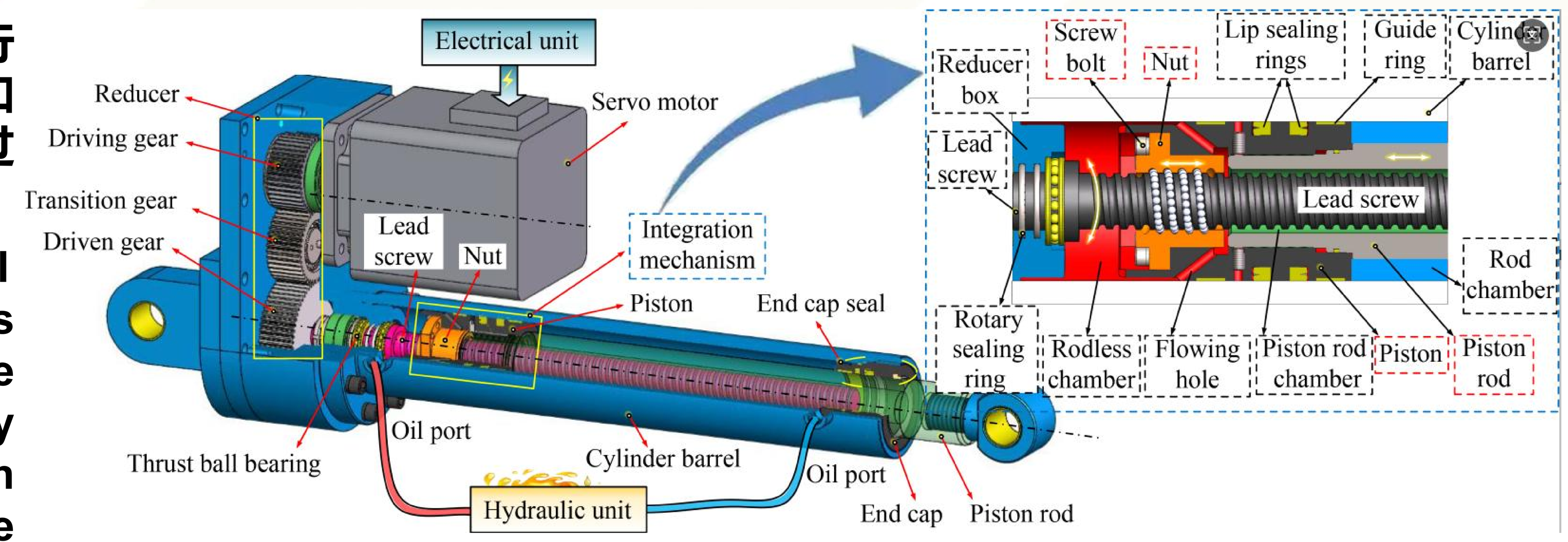
双动力执行器故障机理及剩余寿命预测
Failure mechanism and RUL prediction of Screw piston composite load-bearing heavy-duty linear actuator

背景与挑战 Background and Challenges

双动力执行器（机电液混合驱动直线执行器）是一种集成电机驱动与液压驱动的新型执行器，通过刚性连接电机机械传动部件与液压缸活塞，使其兼具电机驱动的高效控制性能和液压驱动的高功率密度特性。其优势在于：轻载时由电机驱动实现精准运动，重载时通过液压驱动提供动力，显著降低能耗并提升承载能力。

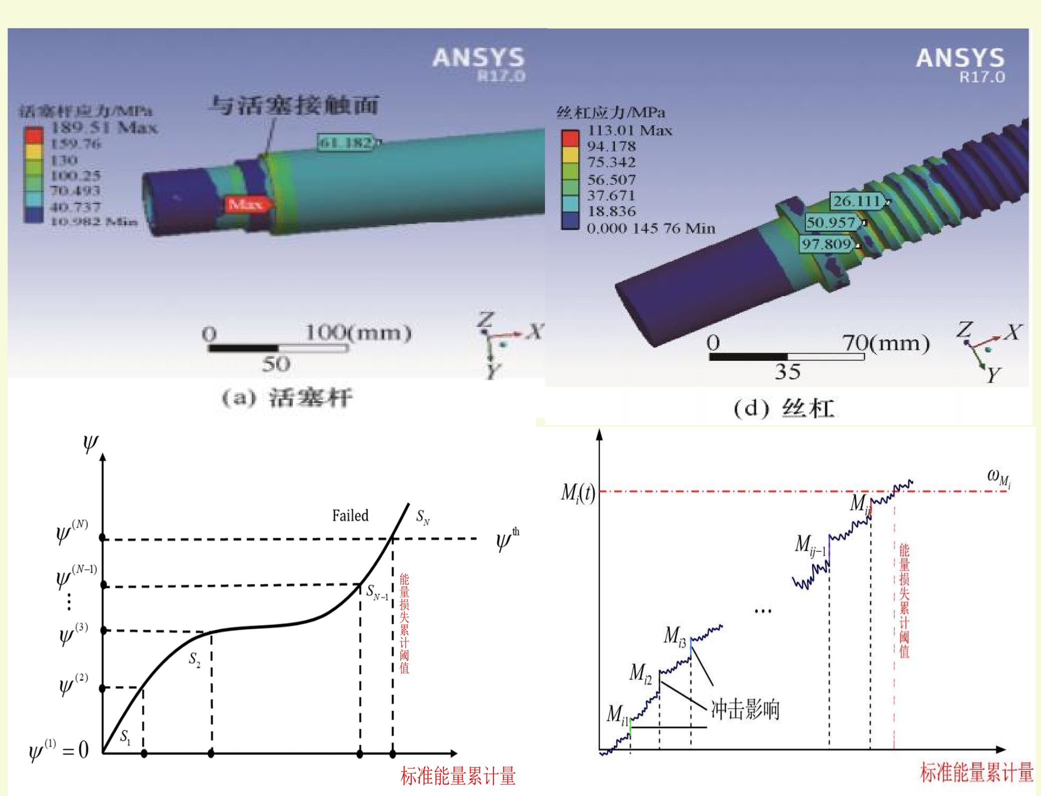
Screw piston composite load-bearing heavy-duty linear actuator(electromechanical and hydraulic hybrid drive linear actuator) is a new type of actuator that integrates motor drive and hydraulic drive, which combines the efficient control performance of motor drive and the high power density characteristics of hydraulic drive by rigidly connecting the mechanical transmission parts of the motor and the piston of the hydraulic cylinder. The advantage is that the motor drive enables precise movement at light loads, and the hydraulic drive provides power at heavy loads, significantly reducing energy consumption and increasing load capacity.



双动力执行器适用于飞机等重载场合，发生故障会导致严重后果。然而，其高集成度与多物理场耦合特性（机械、液压、热力学）使得故障机理复杂，故对其进行预测性维护十分重要。

Dual-power actuators are suitable for heavy-duty applications such as aircraft, where failure can lead to serious consequences. However, its high level of integration and multiphysics coupling (mechanical, hydraulic, thermodynamic) make the failure mechanisms complex, so predictive maintenance is important.

研究内容 Research Work



- **双动力执行器故障机理分析Analysis of the failure mechanism of Screw piston composite load-bearing heavy-duty linear actuator**

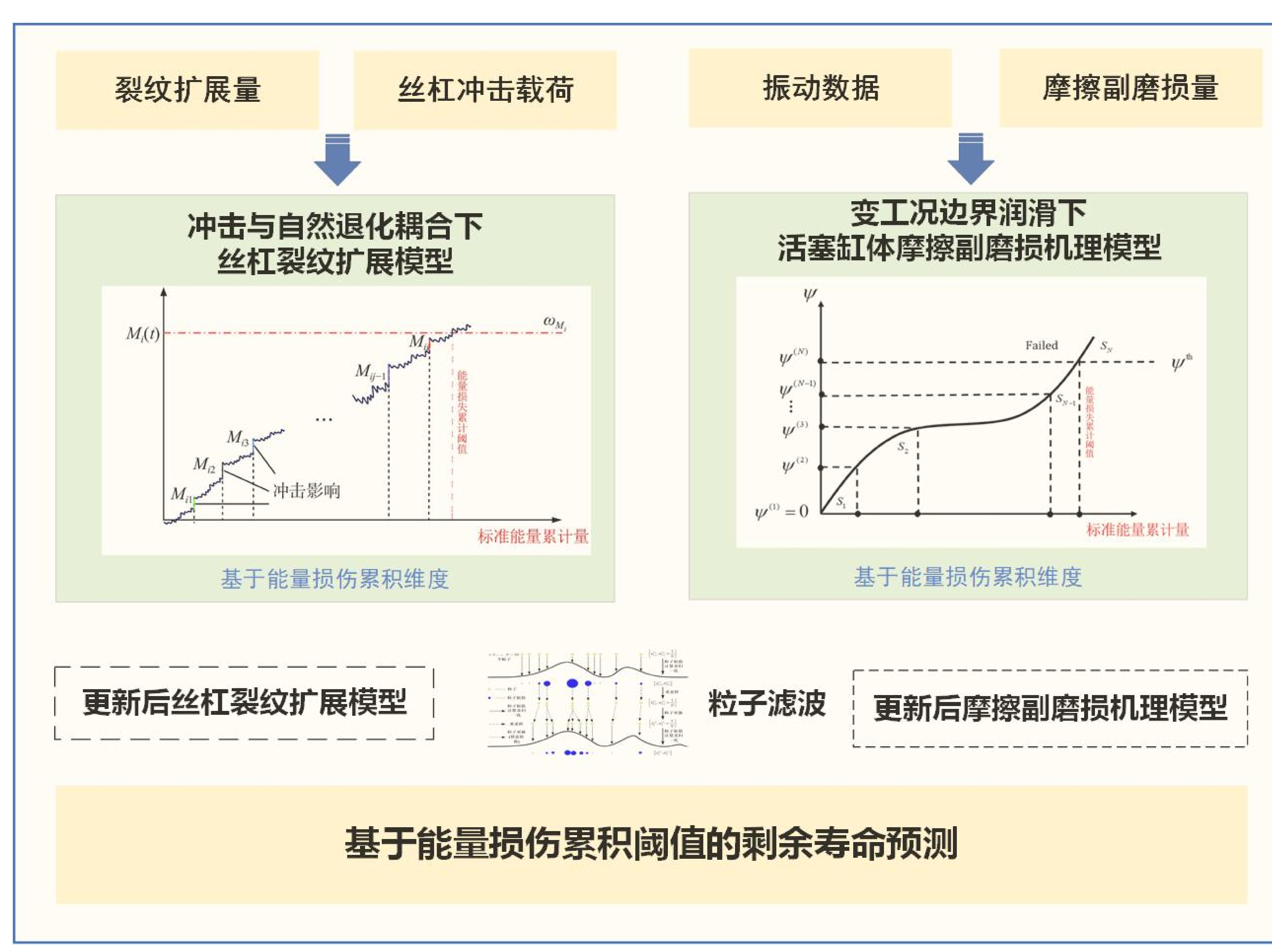
针对双动力执行器丝杠以及中空结构的活塞杆长期承受高频动态载荷，导致丝杠与活塞接触面产生裂纹，从而产生异响，卡滞，甚至导致传动失效的故障模式，构建了冲击与自然退化耦合的丝杠裂纹扩展模型。针对螺母高速运动时，活塞与缸体摩擦副处于边界润滑状态，导致黏着磨损及磨粒磨损的故障模式，构建了变工况边界润滑下活塞缸体摩擦副磨损机理模型。

The failure mechanisms of Screw piston composite load-bearing heavy-duty linear actuator primarily involve the following aspects. Firstly, the lead screw and the hollow-structured piston rod endure long-term high-frequency dynamic loads, leading to cracks at the contact surface between the lead screw and the piston, which results in abnormal noise, jamming, and even transmission failure. In response, this study has developed a lead screw crack propagation model that couples impact and natural degradation. Secondly, during high-speed motion of the nut, the friction pair between the piston and the cylinder operates under boundary lubrication conditions, causing adhesive wear and abrasive wear. Accordingly, this study has established a wear mechanism model for the piston-cylinder friction pair under varying operating conditions of boundary lubrication.

- **基于能量累积损伤的双动力执行器剩余寿命预测 RUL Prediction for Linear Actuator Based on Energy Damage Accumulation Threshold**

针对双动力执行器丝杠冲击-退化耦合裂纹扩展模型、变工况边界润滑下活塞缸体摩擦副磨损机理，提出了以标准能量累积量为基准的寿命预测框架。对于冲击与自然退化耦合的丝杠裂纹扩展，通过能量守恒原理统一量化冲击损伤（瞬时能量注入）与自然退化（连续能量耗散）的耦合效应，建立能量-损伤-寿命的精准映射关系；对于变工况边界润滑下活塞缸体摩擦副磨损，建立变工况边界润滑下的摩擦功累积模型，引入润滑状态因子与载荷波动系数，量化摩擦能量耗散与性能退化表征量动态响应关系；基于能量损失累积角度，突破传统时间维度寿命预测的局限，实现依据实际载荷能量谱的自适应剩余寿命计算。

This study develops a standardized energy accumulation-based lifespan prediction framework for Screw piston composite load-bearing heavy-duty linear actuator. For lead screw crack propagation (impact-degradation coupling), it unifies instantaneous energy injection (shock damage) and continuous energy dissipation (natural degradation) via energy conservation, establishing precise energy-damage-lifespan mapping. For piston-cylinder friction pair wear under variable-condition boundary lubrication, a friction work accumulation model integrates lubrication state factors and load fluctuation coefficients to quantify dynamic friction energy dissipation and performance degradation. By transcending time-based approaches, the framework enables adaptive remaining lifespan prediction using real-world load energy spectra.



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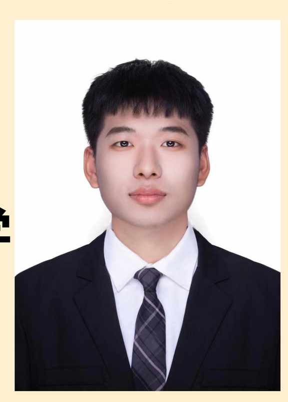
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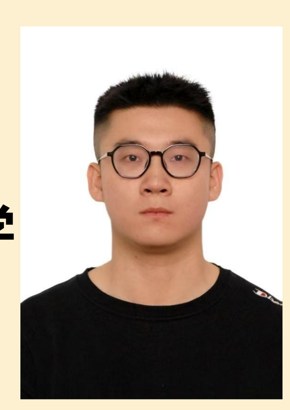
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项目支撑 Funding Support

国家自然科学基金面上项目（51875385）
新型液电混合原理高能效驱动重型机械臂的设计理论与方法
National Natural Science Foundation of China
Design theory and method of a new hybrid principle of high-energy efficiency to drive a heavy-duty robotic arm

液压基础件及机电装备低碳智能化——高端装备智能控制与健康服役

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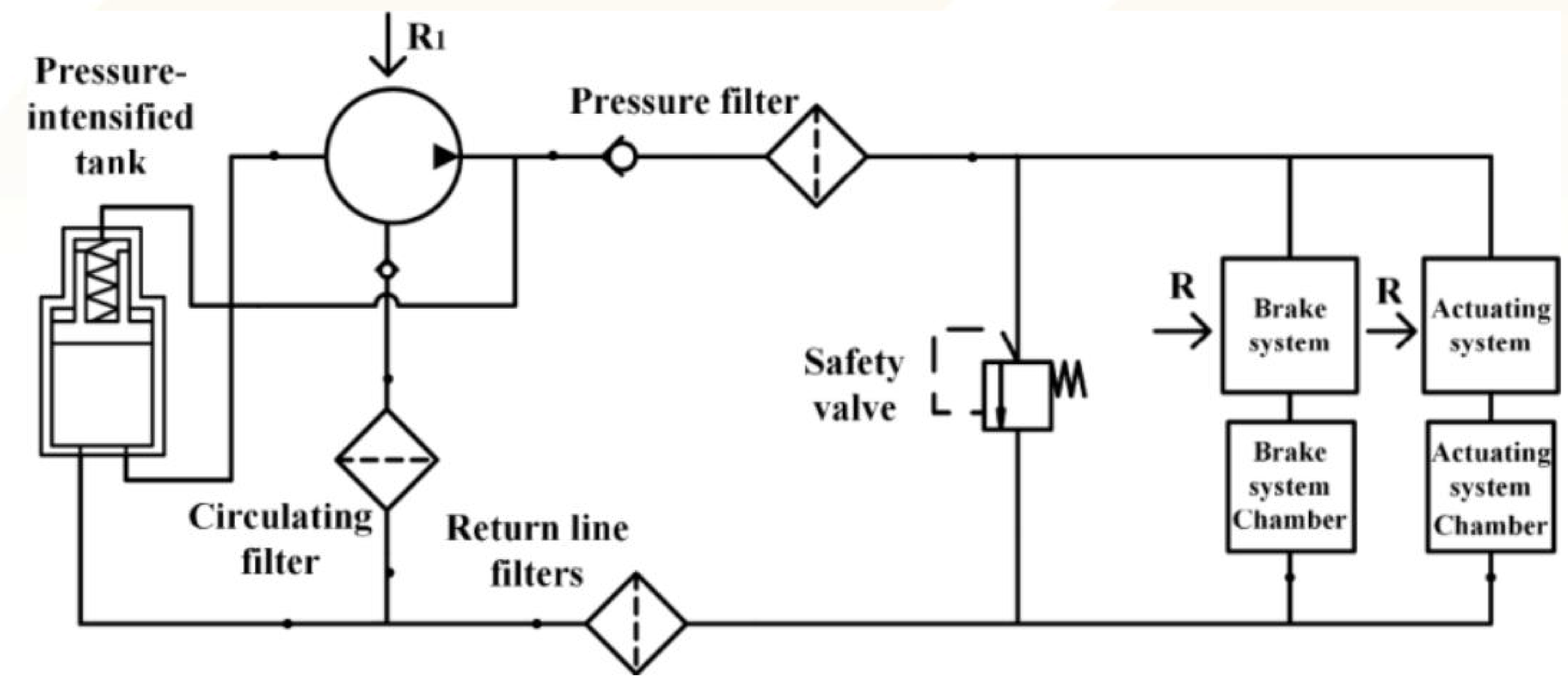
基于物理信息神经网络的航空油滤健康状态监测与预测
Health Status Monitoring and Prognostics of Aviation Oil Filters Based Physics-informed Neural Networks

背景与挑战 Background and Challenges

油液污染是导致航空液压系统故障的主要原因之一，据统计，超过70%的液压系统故障是由于油液污染导致。油滤作为保障机载液压系统清洁度的重要辅助元件，通过过滤油液中的污染物，防止因污染颗粒导致的部件磨损、堵塞和压力波动，保障系统稳定运行。然而，随着运行时间的增加，油液的过滤性能会逐渐降低直至失效。为确保系统安全，传统维护采用定期更换滤芯的预防性方法，但存在过度成本与极端工况失效的风险。故障预测与健康管理（PHM）是一种先进的维护管理方法，通过持续监控、诊断和预测来优化维护成本与故障风险之间的平衡。

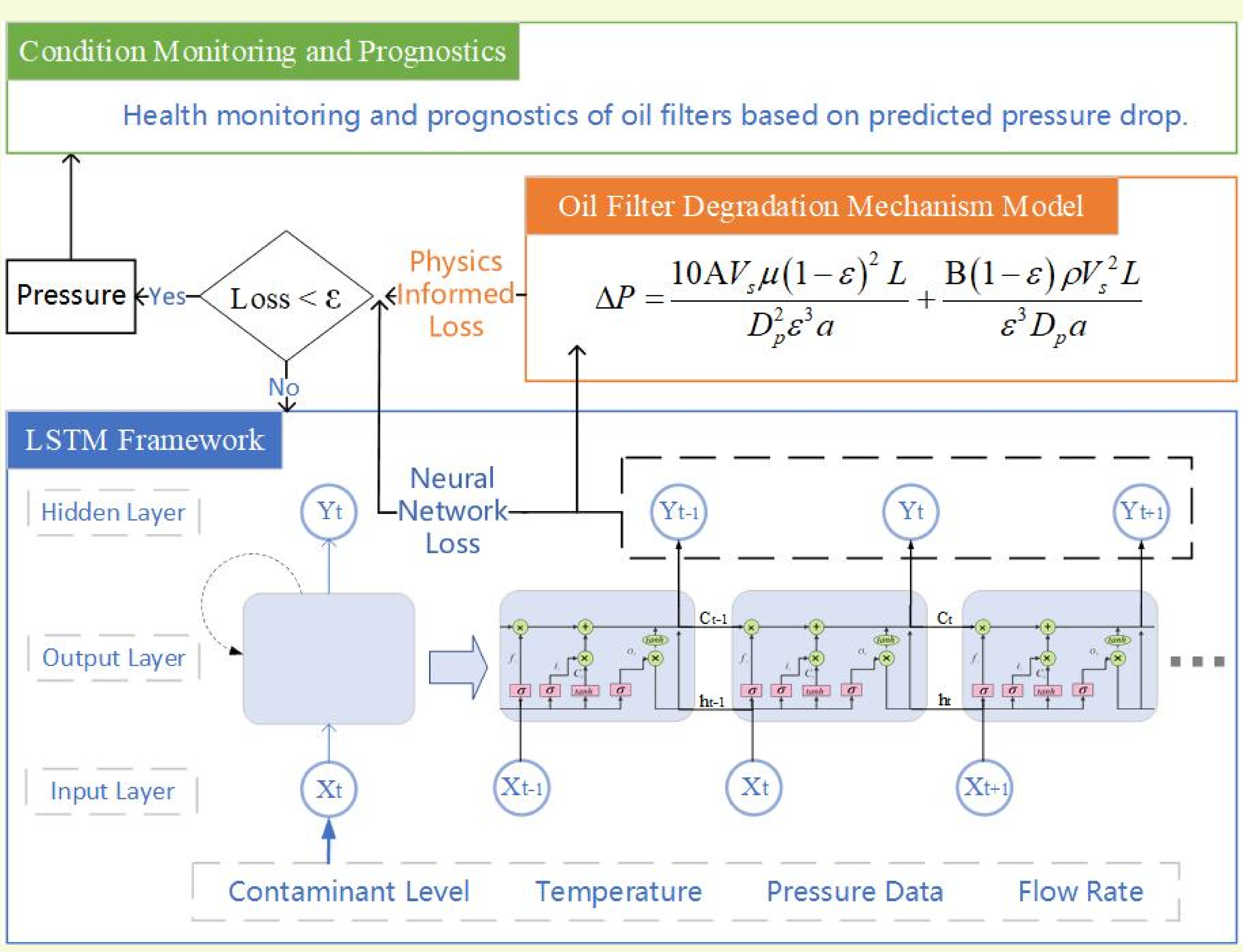
Oil contamination drives over 70% of hydraulic failures.Aircraft systems use filters to trap contaminants, but the filters degrade with use. While scheduled filter replacements ensure safety, they risk resource waste and unexpected failures. Prognostics and Health Management (PHM) addresses this through real-time monitoring and Remaining Useful Life (RUL) prediction, balancing maintenance efficiency with system reliability.



剩余寿命预测(RUL)是PHM的核心，其主流方法大致可分为三类：基于物理知识驱动的机理模型、基于数据驱动的黑箱模型以及混合模型。然而，油滤性能退化呈现多物理场耦合特性，现有物理模型难以动态感知复杂工况下的退化规律，数据驱动模型受限于退化数据稀缺性与黑箱特性，混合模型虽部分结合两者优势，但普遍存在知识嵌入深度不足、物理约束与数据特征耦合机制缺失等技术瓶颈。因此，构建物理机理与数据驱动的深度结合模型(PINN)，开发兼具可解释性与实时性的高精度预测框架，成为了突破航空油滤PHM技术瓶颈的关键路径。

Remaining Useful Life (RUL) prediction is the core of PHM,with three predominant methodologies: physics-based modeling, data-driven approaches, and their hybrid integrations.However, Oil filter degradation involves multi-physics coupling, yet current methods face limitations: physics models lack dynamic degradation tracking, data-driven approaches suffer from sparse data and poor interpretability, and hybrid models struggle with deep knowledge integration. Physics-informed neural networks (PINN) offer a solution by combining physical principles with data-driven learning, enabling interpretable, real-time, and precise predictions.

研究内容 Research Work



- **基于Ergun方程的油滤性能退化机理 Physical Model of Oil Filter Performance Degradation Based on Ergun Equation**

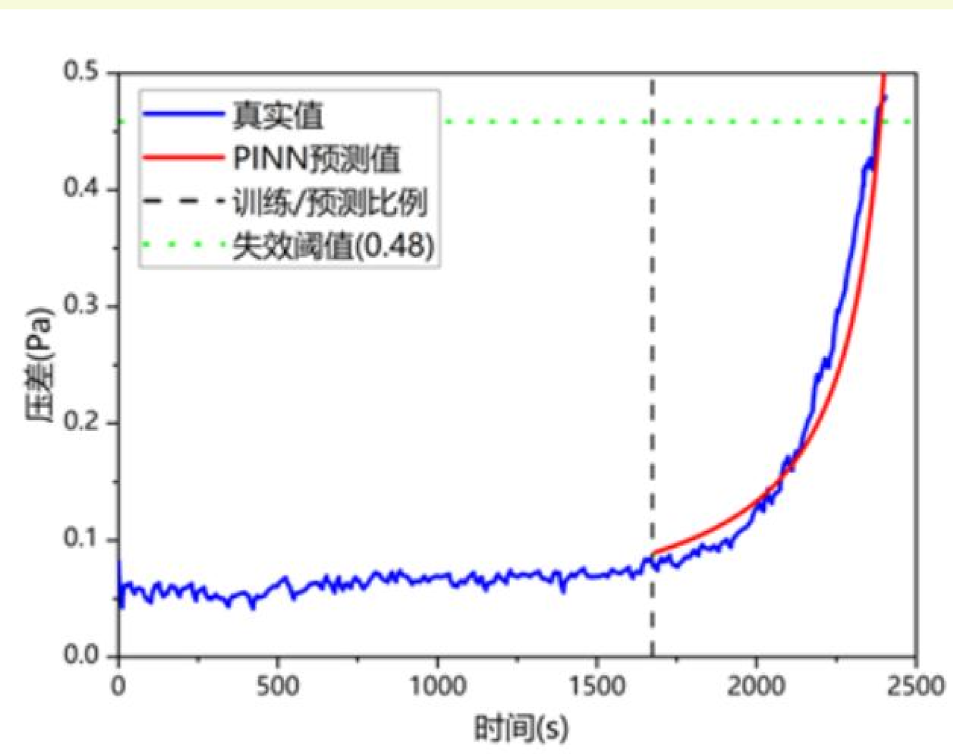
油滤性能退化建模的关键在于选取合适的表征参数，其中滤芯压差因其明确的物理特性和单调增长规律成为理想选择。油滤退化过程呈现典型三阶段特征：清洁阶段、堵塞阶段与受限阶段。基于此，修正Ergun方程被用于建立压差与过滤面积、流速、滤饼厚度及孔隙率等关键参数的定量关系模型。
Oil filter degradation modeling focuses on pressure differential as the key parameter, exhibiting three phases: clean filtration, clogging, and restricted growth. A modified Ergun equation quantifies relationships between pressure differential and critical factors like filtration area, flow rate, and porosity.

- **基于LSTM的油滤压差预测神经网络 LSTM-based neural network for oil filter differential pressure prediction**

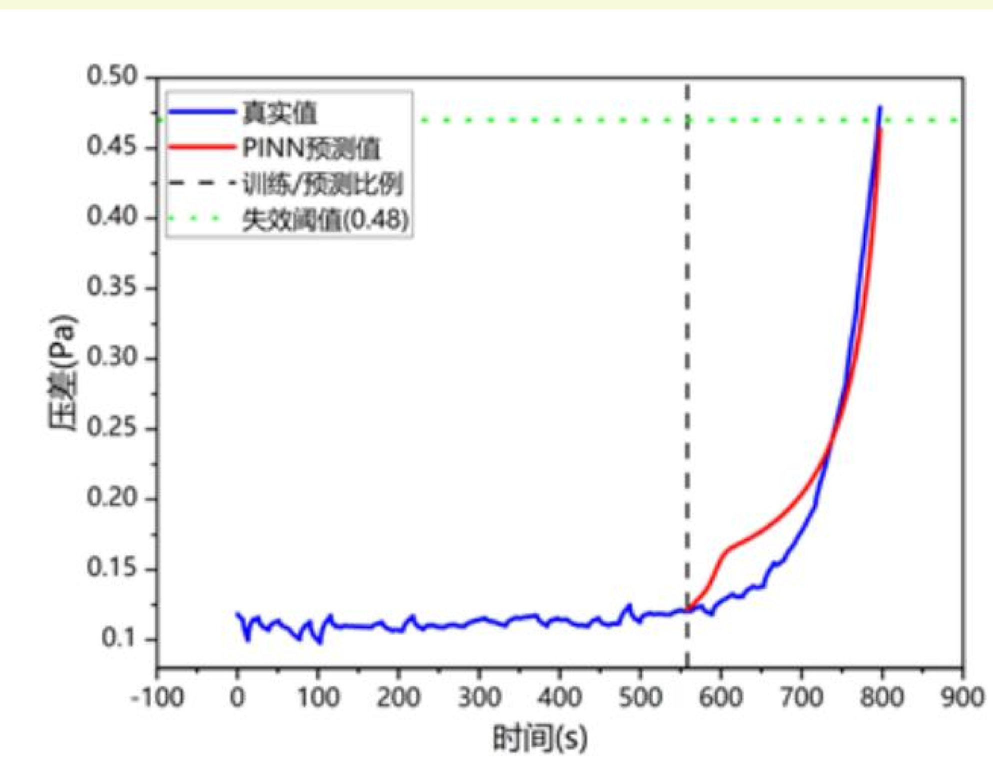
长短期记忆神经网络（LSTM）在时序预测方面具有显著优势，可用于油滤性能退化预测。该模型采用三层LSTM结构，通过遗忘门、输入门和输出门的门控机制，结合滑动窗口处理历史压差数据，有效捕捉油滤退化过程中的时间依赖特征。模型将修正Ergun方程转化为物理正则化项。
LSTM neural networks excel in time-series prediction and are suitable for oil filter degradation forecasting. The model uses a three-layer LSTM structure, leveraging forget, input, and output gates to capture temporal dependencies in pressure drop data via a sliding window. It integrates a modified Ergun equation as a physical regularization term.

- **基于PINN的油滤健康状态监测与预测 Health Status Monitoring and Prognostics of Aviation Oil Filters Based PINN**

本研究提出一种基于物理信息神经网络（PINN）的油滤健康状态监测与预测方法，通过融合Ergun方程与LSTM神经网络，克服传统数据驱动模型对大规模样本的依赖，在小样本场景下实现稳定可靠的性能评估。该方法利用物理方程约束网络训练过程，有效提升模型对油滤运行特性的表征能力，提高了健康状态监测与预测的精度，并增强的模型的可解释性。
This study proposes a PINN-based method for oil filter health monitoring and prediction, combining the Ergun equation with LSTM to reduce reliance on large datasets. By embedding physical constraints, the method improves accuracy and interpretability, enabling reliable performance evaluation with limited data.



(a)流量30L/min 温度40°C 浓度1mg/L



(b)流量70L/min 温度40°C 浓度1.5mg/L

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科技部民机专项
民机液压XX故障机理与智能化监测技术研究
MOST Civil Aircraft Special Project
Intelligent Monitoring and Failure Mechanism Analysis of XX in Civil Aircraft Hydraulic Systems

民机液压系统关键部位故障诊断

Fault Diagnosis for Key Components of Civil Aircraft Hydraulic Systems

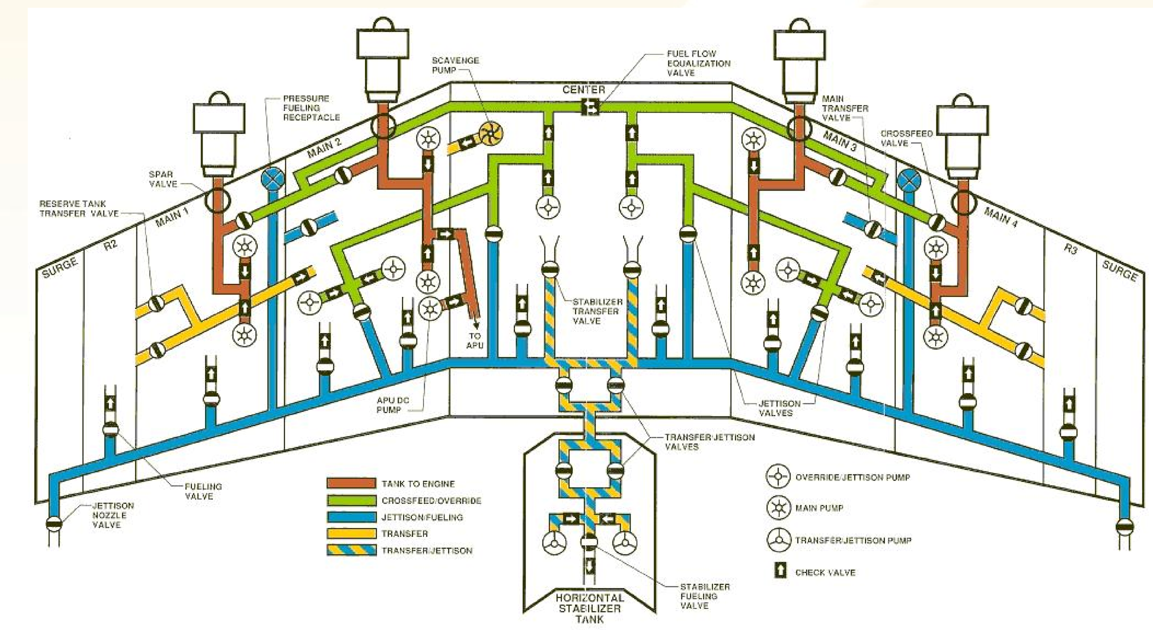
背景与挑战 Background and Challenges

液压系统作为飞机关键操控机制的核心组成部位，控制着起落架收放、制动系统以及飞行舵面等关键部位，直接决定了飞行控制的精准性与可靠性。系统中优先阀、防火切断阀和油滤元件作为核心功能单元，分别承担动态流量分配、紧急油路隔离与油液污染物过滤的职责。一旦发生故障，便会导致严重的后果，危机飞行安全。因此，实现对关键部位的高效故障诊断，是保障飞行安全、降低运维成本的核心需求。

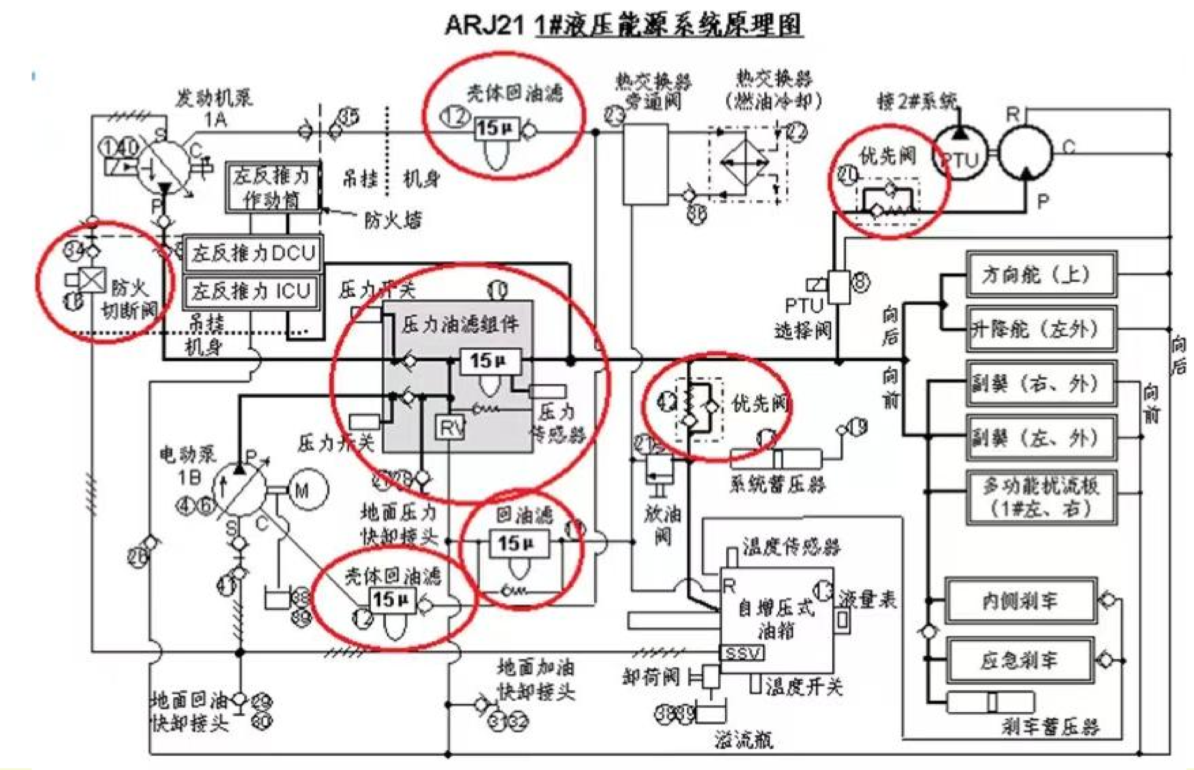
The hydraulic system is essential for flight control and safety in civil aircraft, operating critical components such as landing gear, brakes, and flight control surfaces. Key elements like the priority valve (flow distribution), fire shutoff valve (emergency isolation), and oil filter (contaminant removal) are vital for system performance. Failures in these components can severely compromise flight safety, making efficient fault diagnosis crucial for ensuring reliability and reducing operational risks.

然而，液压系统关键部位故障诊断面临多重技术瓶颈：一方面，故障呈多元性且耦合性强——优先阀、防火切断阀无法正常开启关断、油滤元件堵塞等故障特征相互耦合；另一方面，系统传感器配置严格受限（仅部署压力、流量等基础传感器），无法直接监测阀芯位移、滤芯堵塞率等深层状态参数，导致故障表征信息获取不充分。因此，开发基于有限传感器的多故障解耦诊断方法，对实现民机液压系统关键部位的精准诊断至关重要。

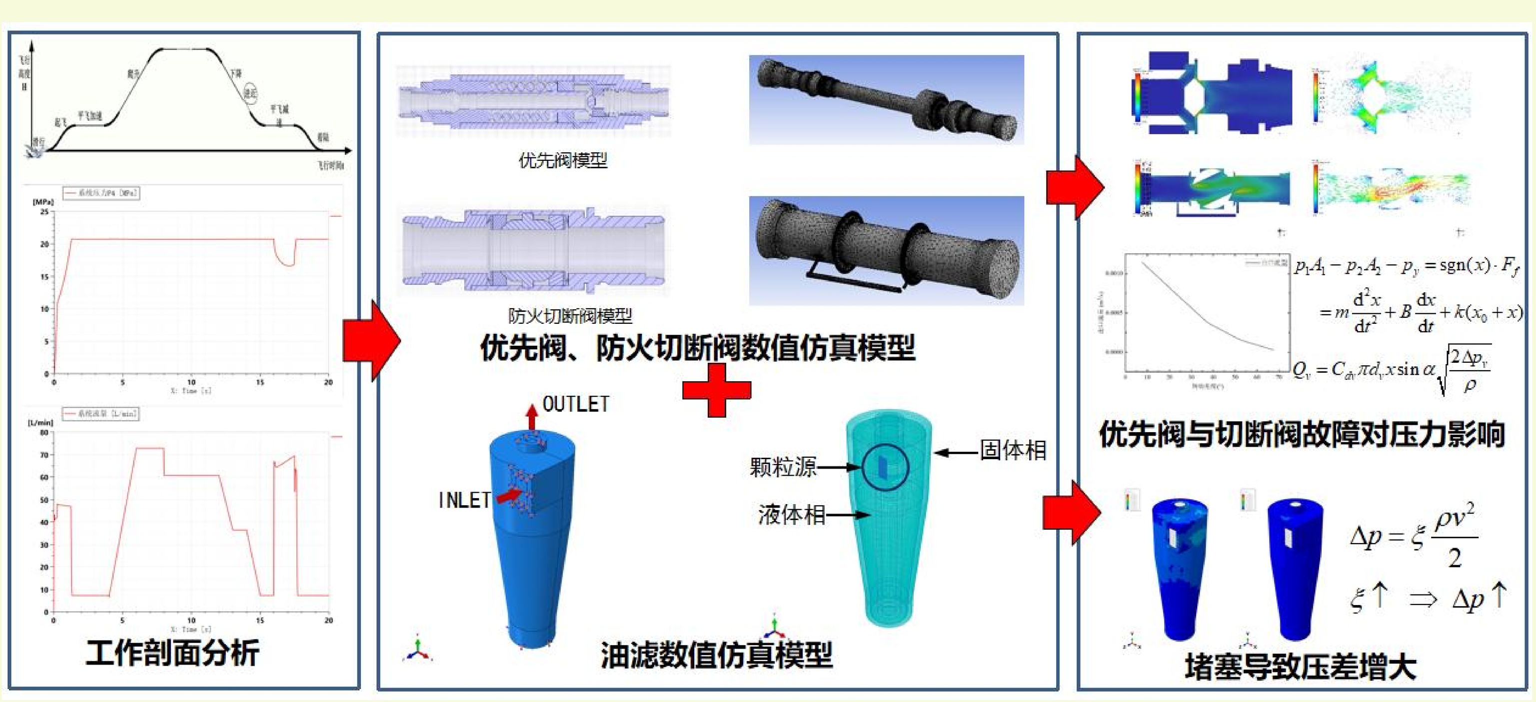
Fault diagnosis for key hydraulic components faces significant challenges. Fault mechanisms are complex and coupled, such as priority valve response lag, fire shutoff valve sealing degradation, and oil filter clogging. Sensor limitations (e.g., only pressure and flow sensors) prevent direct monitoring of critical parameters like valve displacement or clogging rates, while noise and fluid pulsation mask weak fault signals, leading to high early fault detection failures. High-precision diagnosis is crucial for proactive health monitoring and cost reduction.

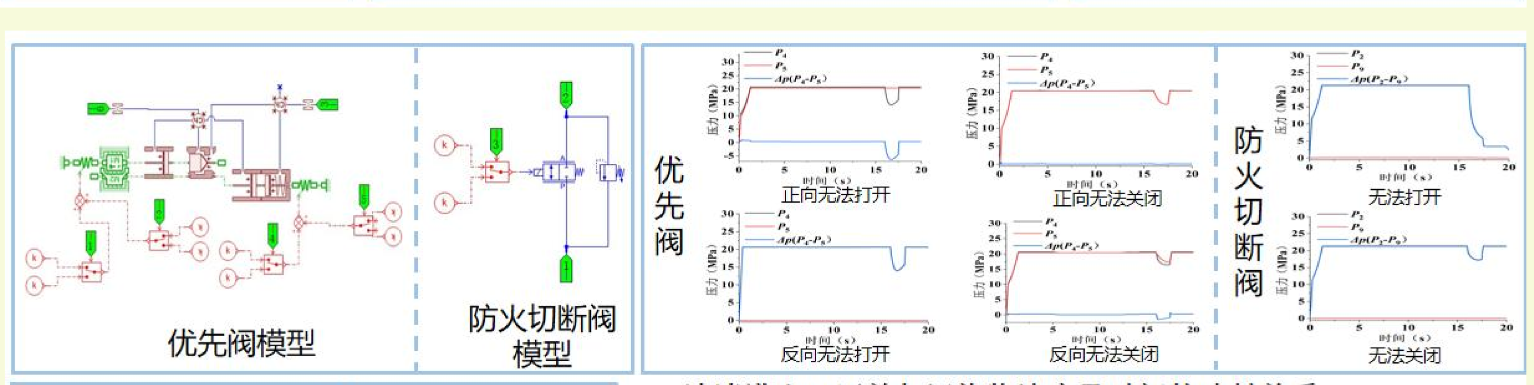


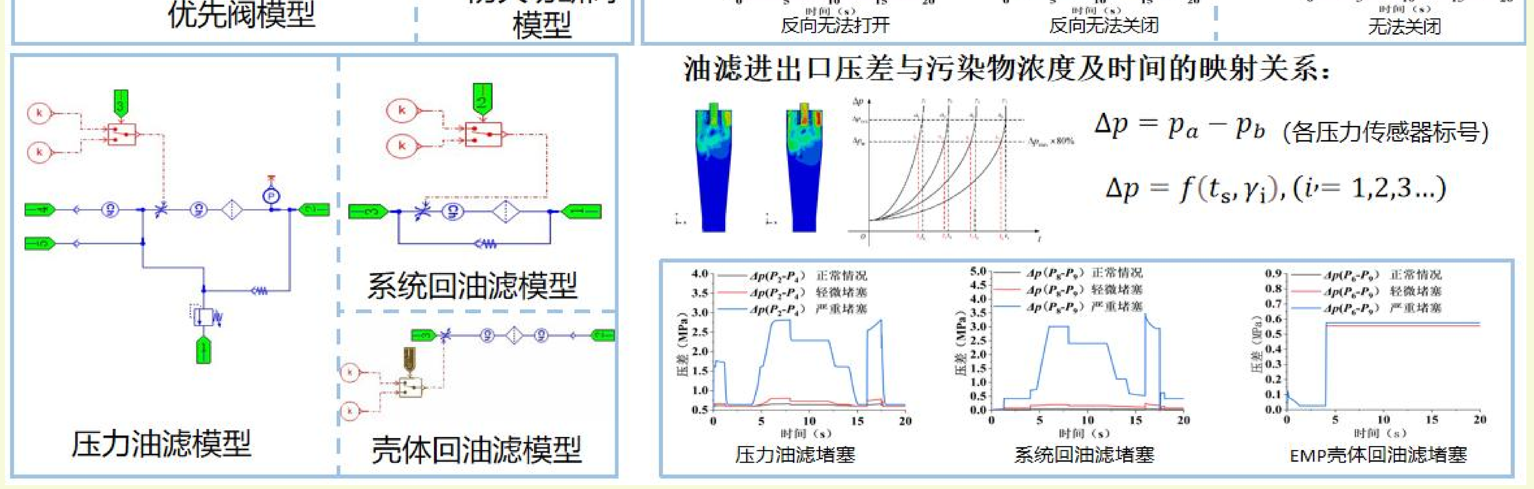
ARJ21 1#液压能源系统原理图



研究内容 Research Work







- **优先阀、防火切断阀、油滤元件故障机理 Fault mechanisms of the priority valve, fire shutoff valve, and oil filter element.**

针对优先阀、防火切断阀无法正常开启关断、油滤元件堵塞等典型故障模式，建立元件三维模型，结合飞行剖面下的压力、流量和温度等工况载荷变化情况，应用有限元理论进行了多物理场耦合分析，揭示了优先阀卡滞的流场机理、防火切断阀在高温环境下的结构变形与密封失效、以及油滤堵塞造成的压降显著增大等故障机理。通过对关键部件应力分布、流场特性和动态响应的系统分析，建立了故障模式与系统性能衰减的定量关系。

For typical faults like priority valve sticking, fire shutoff valve failure to open/close, and oil filter clogging, 3D models were developed. Finite element analysis under flight profile conditions revealed fault mechanisms: abnormal pressure from valve sticking, sealing failure under high temperatures, and pressure drop due to clogging. Stress, flow, and dynamic response analyses established quantitative links between faults and system performance degradation.

针对优先阀、防火切断阀无法正常开启关断、油滤元件堵塞等典型故障模式，建立了AMESim液压系统仿真模型，实现了故障工况下系统特性的动态仿真。通过对阀芯运动、弹簧特性和节流孔道的精确建模，模拟了优先阀正反向开关故障、防火切断阀无法关闭等典型失效状态，并基于飞行剖面载荷条件进行了仿真分析。

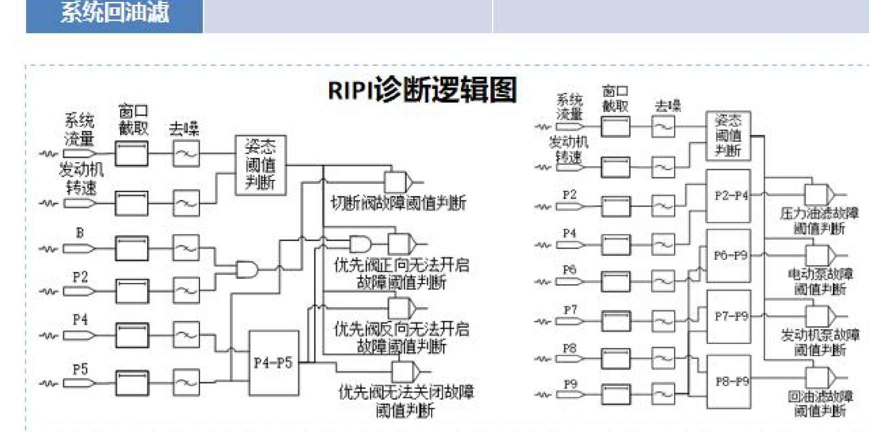
For typical fault modes such as priority valve and fire shutoff valve failure to open/close, and oil filter clogging, an AMESim hydraulic system simulation model was developed to rapidly predict system dynamics under fault conditions. By accurately modeling spool movement, spring characteristics, and throttle orifices, the simulation replicated typical failure states, including priority valve switching faults and fire shutoff valve failure to close. Dynamic simulations were performed under flight profile load conditions.

- **基于远端独立压力信息（RIPI）的故障诊断方法Fault Diagnosis Method Based on Remote Independent Pressure Information (RIPI)**

依据系统现有远端压力传感器的现实条件，针对优先阀和防火切断阀无法开启、无法关断及油滤堵塞提出基于远端独立压力信息（RIPI）的故障诊断方法。通过分析远端压力信号的动态变化特征，实现对关键部件故障的精准定位与早期预警。

Based on existing remote pressure sensors, a fault diagnosis method using Remote Independent Pressure Information (RIPI) is proposed for faults such as priority valve and fire shutoff valve failure to open/close, and oil filter clogging. By analyzing dynamic characteristics of remote pressure signals, it enables precise fault localization and early warning for key components.

元件	典型故障	故障诊断方法
优先阀	无法开启、无法关断	基于远端独立压力信息（RIPI）的故障诊断方法
防火切断阀	无法开启、无法关断	
压力油滤	堵塞	
壳体回油滤		
系统回油滤		



诊断结果及演示

经仿真故障数据验证：
优先阀、防火切断阀无法开启、关断诊断精度达95%；
压力油滤、系统回油滤堵塞故障的精度达96%。
壳体回油滤堵塞故障的精度达92%。

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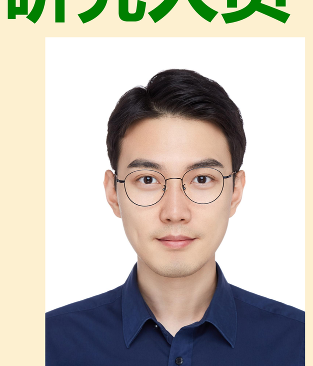
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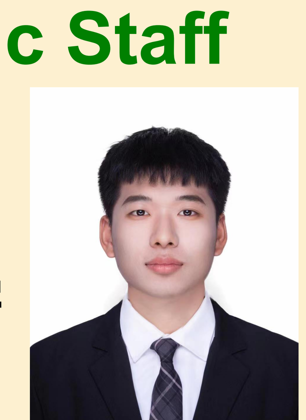
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项目支撑 Funding Support

科技部民机专项
民机液压XX故障机理与智能化监测技术研究
MOST Civil Aircraft Special Project
Intelligent Monitoring and Failure Mechanism Analysis of XX in Civil Aircraft Hydraulic Systems

太原理工大学 TAIYUAN UNIVERSITY OF TECHNOLOGY

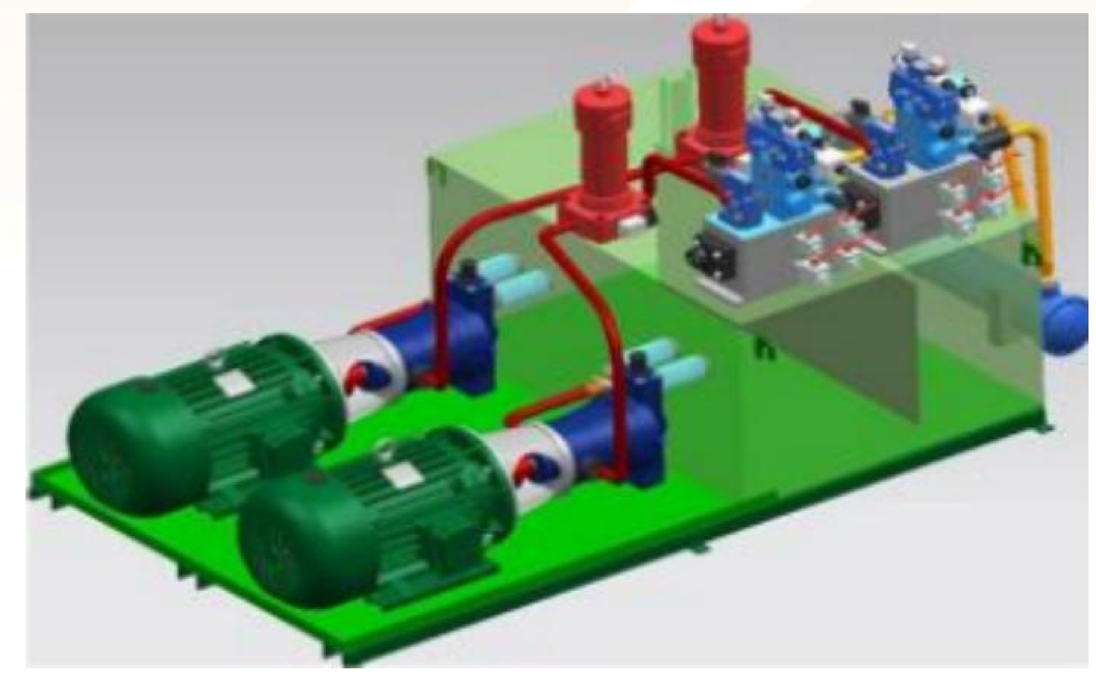
基于贝叶斯网络的多柱塞泵并联泵站故障诊断方法

Fault Diagnosis Method for Multi-Plunger Pump Parallel Pump Stations Based on Bayesian Networks

背景与挑战 Background and Challenges

液压泵是液压系统的动力“心脏”，在液压系统中起着非常重要的作用。面对场景中高压大流量的液压需求，往往通过多柱塞泵并联工作来提供足够的流量。以太重榆液公司产品服务的万吨压机为例，需要通过40台液压泵并联驱动提供动力。在这些重大应用场景中，液压系统的安全可靠运行至关重要。一旦其中某个柱塞泵发生故障，不仅影响整个泵站的流量输出，而且还会增加其余柱塞泵的工作负荷，缩短泵站使用寿命、造成其他并联柱塞泵故障，进而导致启闭机或压力机无法正常工作，造成巨大的经济损失，威胁人民群众生命安全。

The hydraulic pump is the core of the hydraulic system, responsible for providing power. In scenarios requiring high pressure and large flow rates, multiple piston pumps are typically connected in parallel. For instance, the 10,000-ton press serviced by Yuci hydraulic factory requires 40 hydraulic pumps operating in parallel. The safe operation of the hydraulic system is critical. If one pump fails, it not only affects the flow output but also increases the load on the remaining pumps, shortening their service life and potentially causing equipment shutdown, leading to economic losses and safety risks.

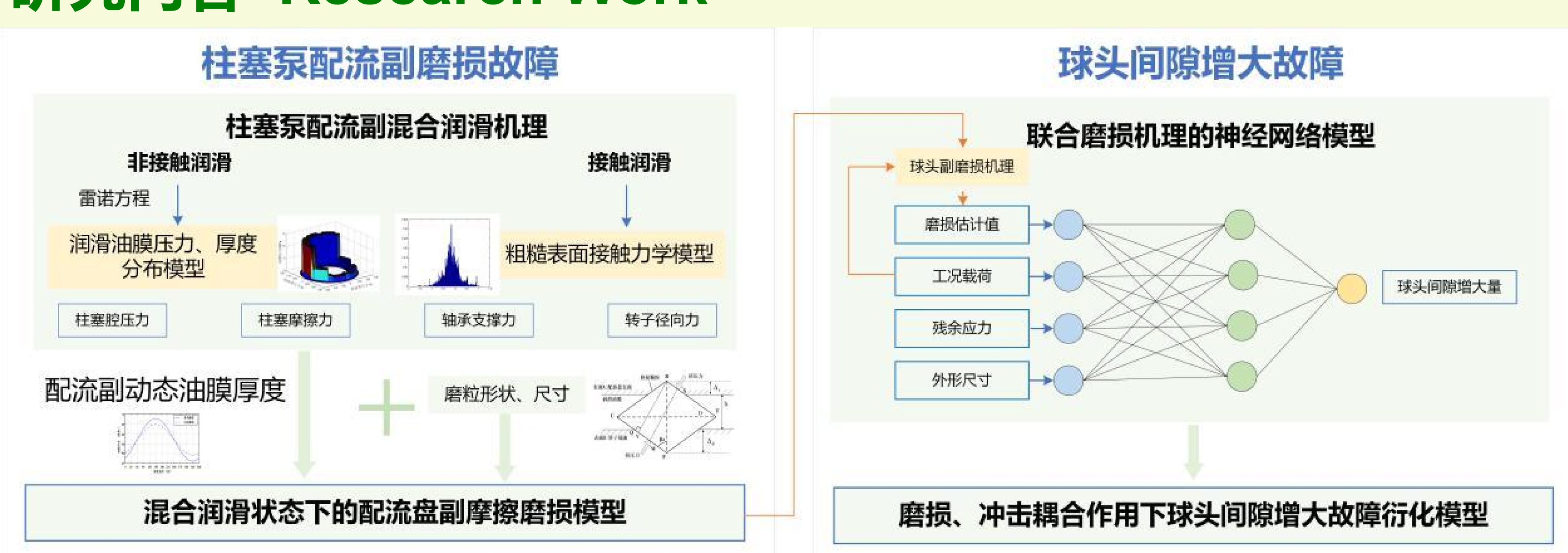


并联泵站模型

并联泵站系统通常由多个泵和设备并联工作，柱塞泵结构复杂、故障模式多样，相关失效机理研究尚不完备；单个泵故障会对相邻柱塞泵以及系统上下游产生耦合影响，且工况环境恶劣、传感器检测状态不稳定、特征信息易湮灭，信号与故障映射关系不明确；受实际工况载荷、样本差异以及随机环境因素的影响，各柱塞泵退化轨迹具有不确定性。这些都给多柱塞泵并联泵站的故障监测与预警带来挑战。

Parallel pump stations use multiple pumps working together, but plunger pumps are complicated and can fail in many ways, with research on these failures still limited. If one pump fails, it can affect nearby pumps and the entire system. Harsh conditions, unreliable sensors, unclear signals, and random factors like load and environment make pump wear unpredictable. These issues make it tough to monitor faults and warn about problems early in multi-pump stations.

研究内容 Research Work



● **复杂工况下柱塞泵配流副磨损和球头间隙增大演化规律**

Study on Wear and Clearance Evolution in Plunger Pumps under Complex Conditions

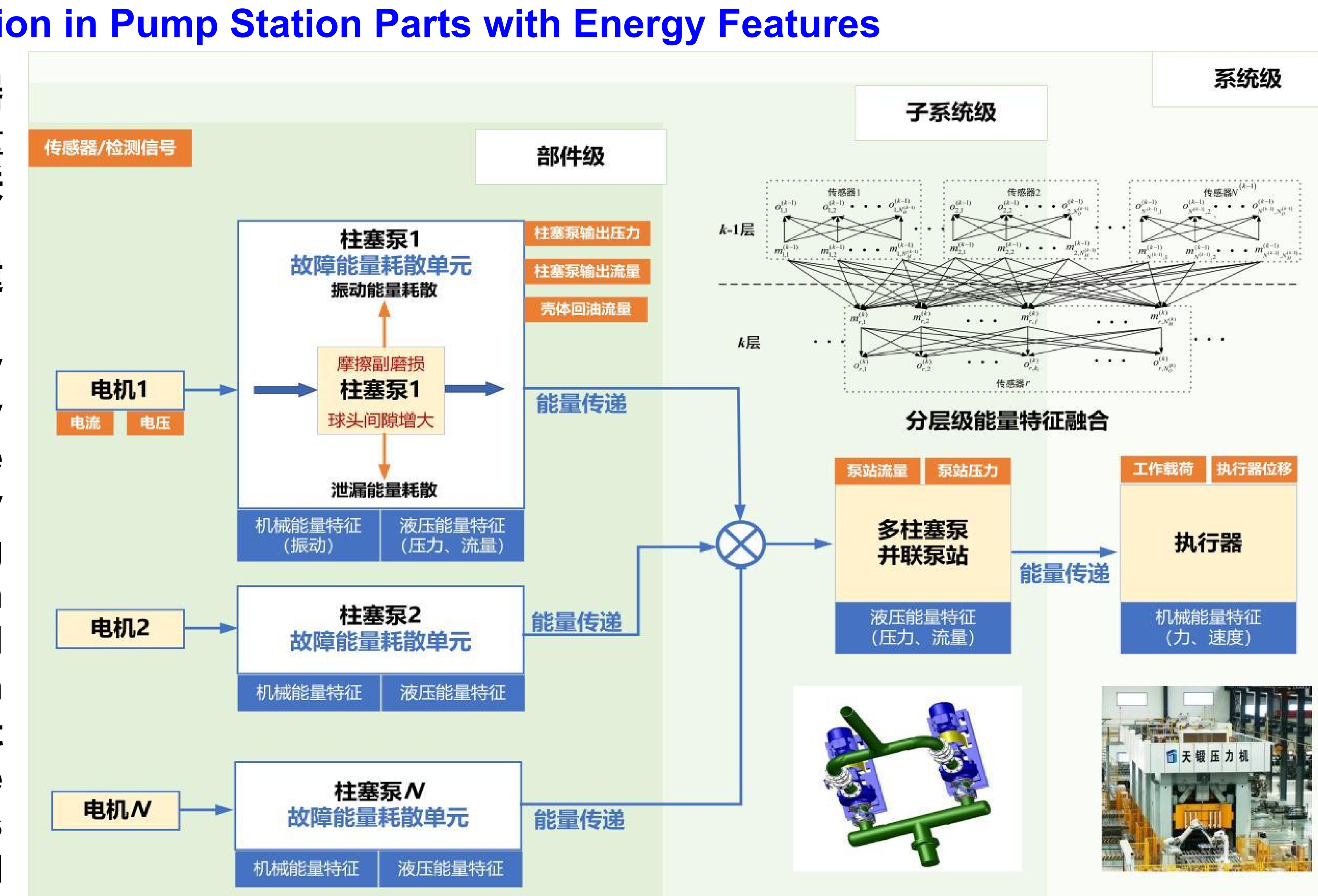
针对配流副混合润滑状态下的磨粒磨损机理，考虑柱塞腔压力、柱塞摩擦力、转子径向力、轴承支撑力矩等外部载荷变化，分别基于雷诺方程和粗糙表面接触力学，建立接触区与非接触区油膜厚度与压力分布规律，结合磨粒尺寸探索混合润滑状态下配流副磨粒磨损机理。其次，针对球头间隙增大故障，在摩擦磨损机理的基础上，考虑冲击载荷与残余应力，建立联合磨损机理与神经网络的球头间隙增大演化模型，揭示磨损、冲击以及残余应力耦合作用下球头间隙增大规律。

Regarding the abrasive wear mechanism of the valve train under mixed lubrication state, considering the variations of external loads such as the pressure in the plunger cavity, the friction force of the plunger, the radial force of the rotor, and the supporting torque of the bearing, based on the Reynolds equation and the contact mechanics of rough surfaces, the laws of oil film thickness and pressure distribution in the contact area and the non-contact area are established respectively. Combined with the abrasive particle size, the abrasive wear mechanism of the valve train under mixed lubrication state is explored. Secondly, for the fault of increased ball head clearance, based on the friction and wear mechanism, considering the impact load and residual stress, a model for the evolution of increased ball head clearance based on the combined wear mechanism and neural network is established, revealing the law of increased ball head clearance under the coupling effect of wear, impact and residual stress.

● **多层级能量特征综合的并联泵站关键部件故障状态监测方法研究** **Study on Fault Detection in Pump Station Parts with Energy Features**

从液压传动本质——能量传递的角度出发，充分挖掘多层级能量耗散与传递规律，基于多传感器信息所构建的能量特征开展柱塞泵并联泵站故障状态监测。首先，建立柱塞泵故障状态下的能量耗散模型，从能量角度揭示故障状态与振动、泄漏等能量耗散过程的映射关系；其次，建立并联泵站能量传递模型，描述柱塞泵故障状态对相邻柱塞泵、并联泵站以及整个系统的影响；最后，在不同层级上布局用于收集能量特征的传感器，考虑系统分层结构和多传感器信息特征互补，建立基于贝叶斯网络的并联泵站故障诊断方法。

From the perspective of the essence of hydraulic transmission - energy transfer, fully explore the hierarchical energy dissipation and transfer laws, and based on the energy characteristics constructed from multi-sensor information, conduct fault state monitoring of parallel pump stations for piston pumps. Firstly, establish an energy dissipation model under the fault state of piston pumps, revealing the mapping relationship between the fault state and energy dissipation processes such as vibration and leakage from the energy perspective; Secondly, establish an energy transfer model for parallel pump stations, describing the influence of the fault state of piston pumps on adjacent piston pumps, parallel pump stations, and the entire system; Finally, layout sensors for collecting energy characteristics at different levels, considering the hierarchical structure of the system and the complementary information characteristics of multiple sensors, and establish a parallel pump station fault diagnosis method based on Bayesian networks.



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项目支撑 Funding Support

山西省基础研究计划（产业发展类）联合资助项目

多柱塞泵并联泵站关键部位故障监测与预测

Shanxi Provincial Basic Research Program (Industrial Development) Joint Funding Project

Monitoring and prediction of failure of key components of multi-plunger parallel pumping station

TAIYUAN UNIVERSITY OF TECHNOLOGY 1902
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TAIYUAN UNIVERSITY OF TECHNOLOGY

面向工程机械液压系统的能量耗散故障诊断方法
Energy Dissipation-Based Fault Diagnosis Method for Hydraulic Systems in Engineering Machinery

背景与挑战 Background and Challenges

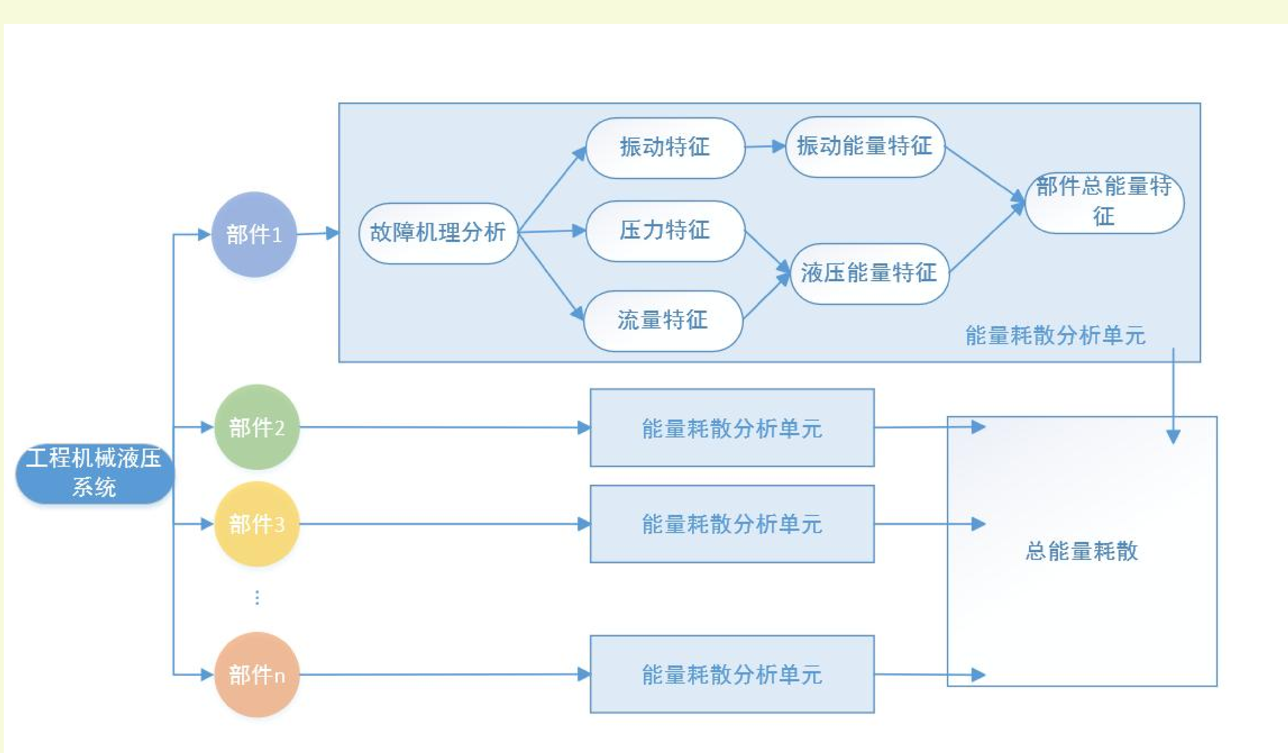
液压系统是挖掘机、装载机等工程机械设备的核心动力部件，负责传递能量和控制动作。对液压系统的故障诊断是保障工程机械设备可靠性和效率的关键。然而，液压系统组成元件复杂多样（如液压泵、控制阀、液压缸等），故障模式种类繁多（如内部泄漏、磨粒磨损、管路堵塞），且往往表现为多故障耦合状态，导致单一故障源的定位具有较高的不确定性。此外，工程机械通常运行于高温、高湿、多尘或强振动的恶劣工况下，致使传感器采集的信号易受干扰而失稳。同时，液压系统关键参数（如压力、流量、振动）的监测信号与具体故障之间的映射关系模糊，故障特征的提取与分析面临显著的技术难度。这些因素共同构成了工程机械液压系统故障诊断的重大挑战。

Hydraulic systems, crucial for construction machinery like excavators and loaders, face significant diagnostic challenges. Their complex components (pumps, valves, cylinders) exhibit diverse failure modes (leakage, wear, blockages), often in coupled multi-fault states. Harsh operating conditions (high temperature, vibration, contamination) cause sensor signal interference, while ambiguous mapping between monitoring parameters (pressure, flow, vibration) and specific failures complicates feature extraction and analysis, creating substantial fault identification uncertainties.

液压系统的核心功能是能量的传递与分配，其运行状态可通过能量参数（压力、流量、振动、温度）直观表征。由于流量参数测量成本过高，且面临传感器安装受限、流体特性干扰等问题，运用能量耗散进行故障诊断陷入瓶颈。运用压力补偿控制流量方法，以控制代替测量，可低成本获取精确流量，为实现能量耗散的故障诊断提供保证。

The core functionality of hydraulic systems lies in energy transmission and distribution, with operational status being intuitively characterized by energy parameters (pressure, flow rate, vibration, and temperature). However, flow parameter measurement faces challenges including excessive costs, sensor installation constraints, and fluid characteristic interference, creating bottlenecks for fault diagnosis through energy dissipation analysis. By implementing pressure compensation control methods for flow regulation - using control strategies to replace direct measurement - this approach enables cost-effective acquisition of precise flow data. This technological advancement ensures reliable implementation of energy dissipation-based fault diagnosis systems.

研究内容 Research Work



● 关键元部件故障机理与表征 Key Component Failure Mechanisms and Characterization

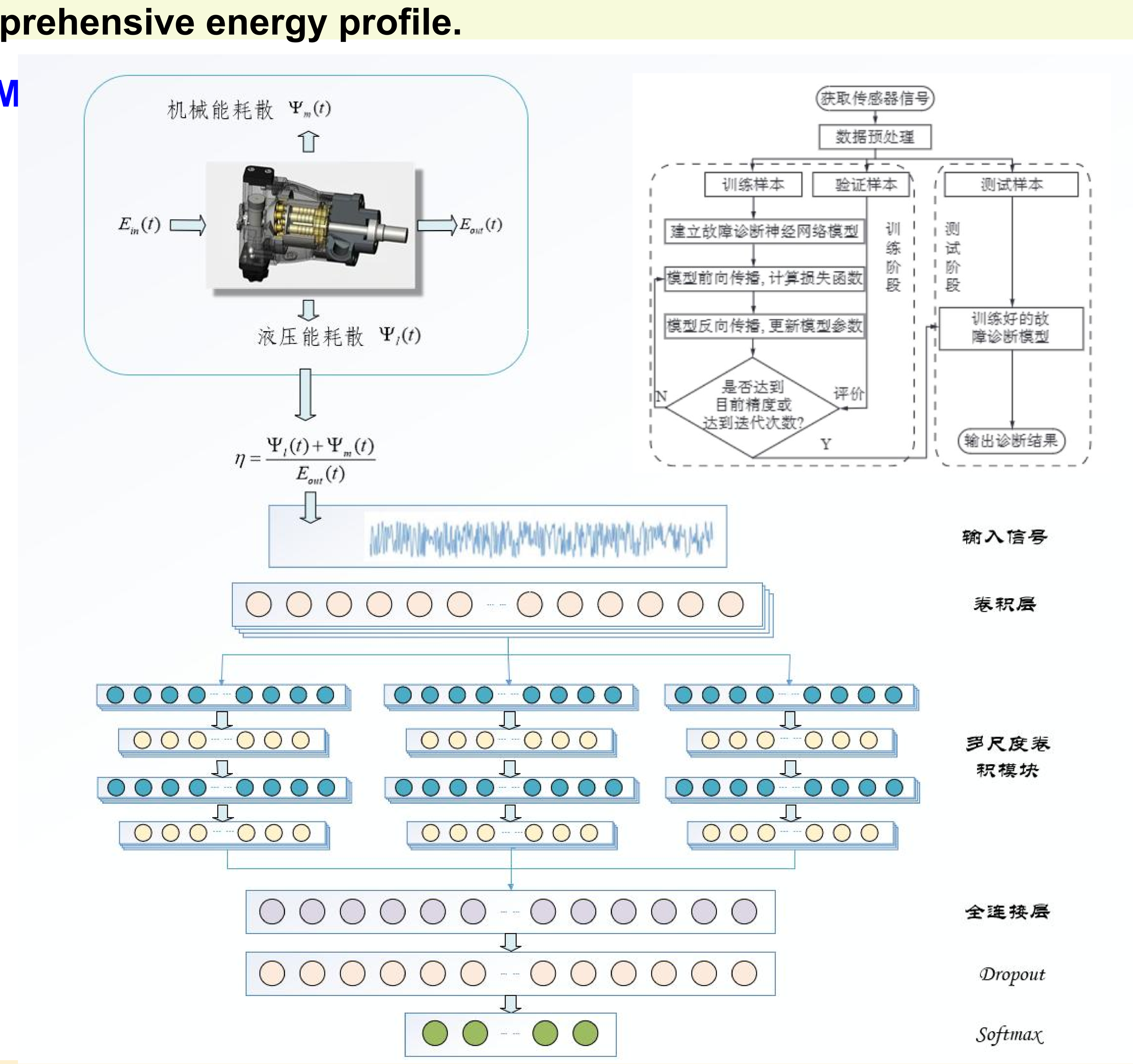
根据液压系统部件的不同特性，对各部件进行故障机理分析，如液压泵部件机械磨损导致振动增加，引发振动能量耗散；液压阀内泄露导致压力、流量变化，引发液压能量耗散；液压缸磨损导致动力学参数改变，内泄露导致液压参数变化，引发机械与液压能量耗散。得到各部件能量信息表征，整合为总能量表征。

Based on the distinct characteristics of hydraulic system components, mechanism analysis was conducted for key components: mechanical wear in hydraulic pumps induces vibration amplification with vibrational energy dissipation; internal leakage in hydraulic valves alters pressure/flow characteristics, causing hydraulic energy dissipation; hydraulic cylinder wear modifies dynamic parameters while internal leakage shifts hydraulic parameters, leading to combined mechanical and hydraulic energy dissipation. Energy signatures of individual components were derived and integrated into a comprehensive energy profile.

● 基于能量耗散的多尺度一维卷积神经网络故障诊断 Energy Dissipation-Based Multi-Scale 1D Convolutional Neural Network for Fault Diagnosis

根据元部件能量耗散分析，可得到部件能量耗散量。为避免工况导致的能量变化影响，将部件能量耗散效率作为故障信息特征参数。为方便提取故障局部重要特征，提高诊断准确性，采用多尺度一维神经网络。利用 3 个不同尺寸的卷积核进行卷积操作，不同的滤波器获取信号不同频段的故障特征，实现提高模型预测精度，每个分支都有两层卷积层和两层池化层；提取特征后将 3 种特征展平，并输入全连接层并进行分类。将提取的故障特征信息导入模型进行训练，并利用反向传播过程实现模型参数更新。

Based on component-level energy dissipation analysis, energy dissipation quantities were derived. To mitigate interference from operational condition-induced energy fluctuations, energy dissipation efficiency was adopted as the fault signature parameter. A multi-scale 1D neural network was employed to enhance diagnostic accuracy by capturing localized fault features. The network utilized three parallel branches with convolutional kernels of varying sizes (e.g., 3×1, 5×1, 7×1) to extract multi-frequency fault features. Each branch contained two convolutional layers and two pooling layers for hierarchical feature learning. The flattened features from all branches were concatenated and fed into fully connected layers for classification. The model was trained by integrating fault features, with parameters updated via backpropagation for optimization.



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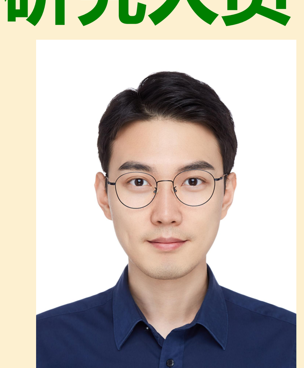
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项目支撑 Funding Support

山西省基础研究计划（产业发展类）联合资助项目
多柱塞泵并联泵站关键部位故障监测与预测
Shanxi Provincial Basic Research Program (Industrial Development) Joint Funding Project
Monitoring and prediction of failure of key components of multi-plunger parallel pumping station

液压基础件及机电装备低碳智能化——高端装备智能控制与健康服役

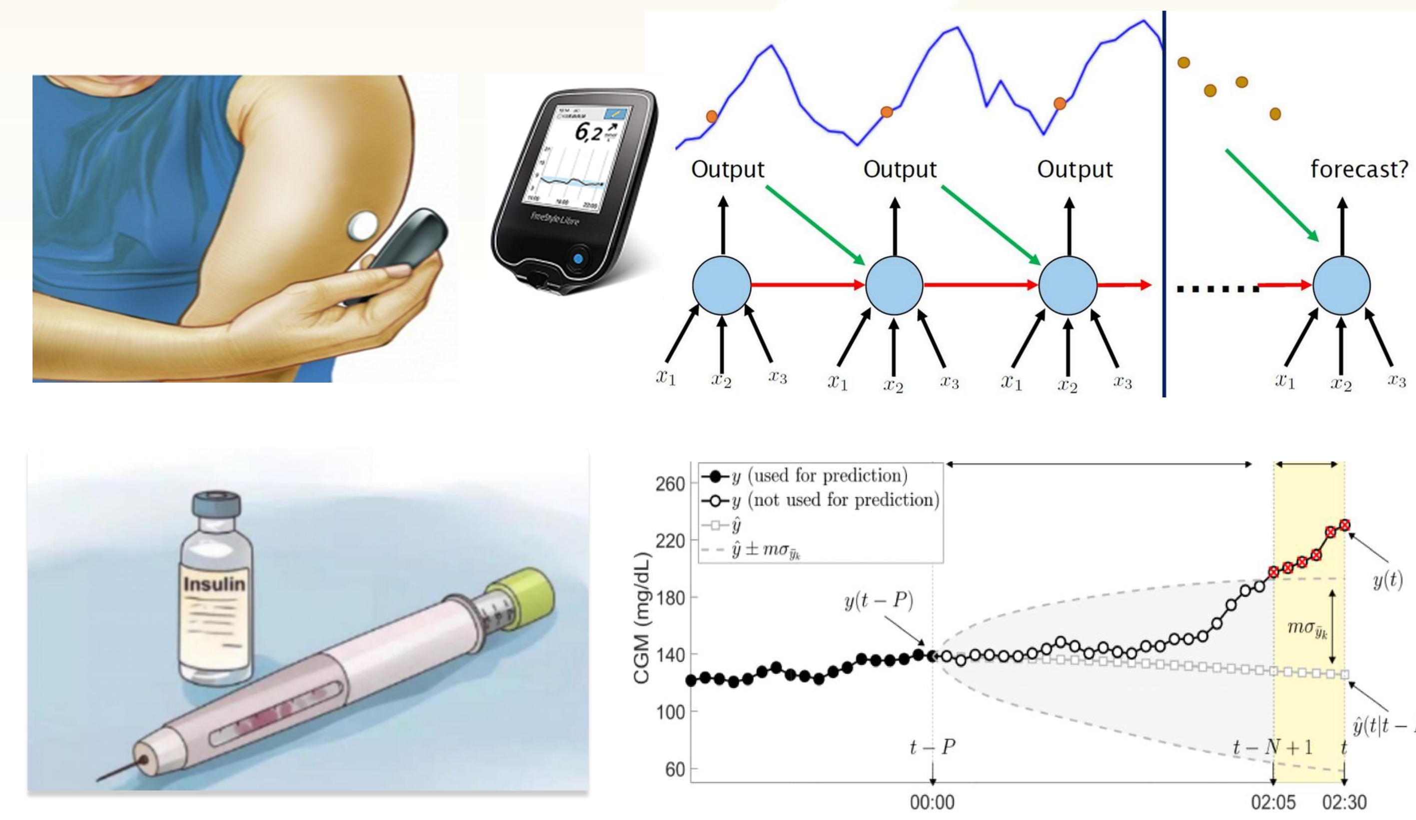
基于血糖代谢物理机理神经网络模型的血糖预测

Physics-informed glucose-insulin neural network model for glucose prediction

背景与挑战 Background and Challenges

糖尿病是威胁人类健康的第三大疾病，患者通常需要依靠血糖水平来指导胰岛素注射。因此，准确预测血糖变化对患者和医生至关重要。目前，血糖预测方法可以分为生理知识驱动和数据驱动两类。但是，生理知识驱动方法的复杂性和对个体差异的适应性不足，限制了其在实际应用中的效果和实用性。数据驱动方法利用临床数据训练得到血糖预测模型，尤其是深度学习模型因其强大的拟合能力被广泛应用。

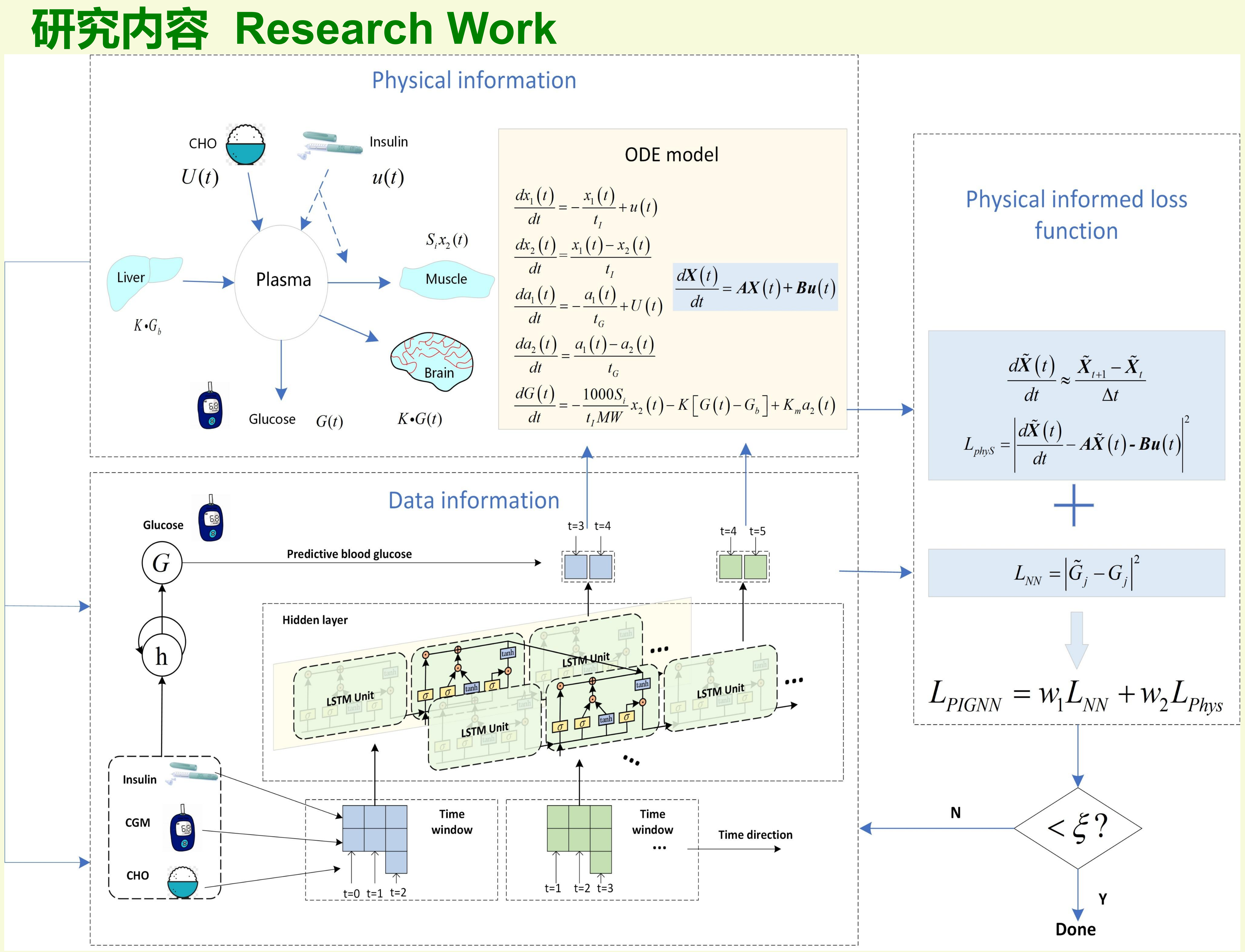
Diabetes stands as the third most significant threat to human health, with patients often relying on blood glucose levels to guide insulin administration. Consequently, accurate prediction of blood glucose fluctuations is of paramount importance for both patients and healthcare providers. Currently, methods for blood glucose prediction can be categorized into two types: those driven by physiological knowledge and those driven by data. However, the complexity of physiologically knowledge-driven methods and their insufficient adaptability to individual differences limit their effectiveness and practicality in real-world applications. Data-driven methods, on the other hand, utilize clinical data to train blood glucose prediction models, with deep learning models, in particular, being widely adopted due to their powerful fitting capabilities.



然而，尽管深度学习已经在血糖预测领域有了长足发展，由于血糖个性化数据稀缺、糖尿病医疗设备计算资源有限、黑盒模型可解释性差，其在实现大规模临床应用时仍面临挑战。如何用较少数据量达到较高预测精度？如何如何在计算资源有限的设备上实现高效且准确的深度学习模型部署？如何开发具有高可解释性的数据驱动模型？以提高临床实践中的接受度和信任度.

However, despite significant advancements in the application of deep learning for blood glucose prediction, its widespread clinical adoption still faces challenges due to the scarcity of personalized glucose data, limited computational resources in diabetes medical devices, and the poor interpretability of black-box models. How can we achieve higher prediction accuracy with limited data? How can we deploy efficient and accurate deep learning models on devices with constrained computational resources? How can we develop highly interpretable data-driven models to enhance their acceptance and trust in clinical practice?

研究内容 Research Work



- **基于血糖代谢物理机理的神经网络模型 Physics-informed glucose-insulin neural network model（PIGNN）**

针对数据驱动方法存在的个性化数据稀缺、计算资源要求高、可解释性差等问题，本研究充分利用血糖代谢机理模型中的物理信息。通过在神经网络中加入血糖代谢动力学模型，提出基于血糖代谢物理机理的神经网络模型。

In response to the challenges faced by data-driven methods, such as the scarcity of personalized data, high computational resource requirements, and poor interpretability, this study fully leverages the physical information from glucose metabolism mechanistic models. By incorporating a glucose metabolism dynamics model into the neural network, a novel neural network model based on the physical mechanisms of glucose metabolism is proposed.

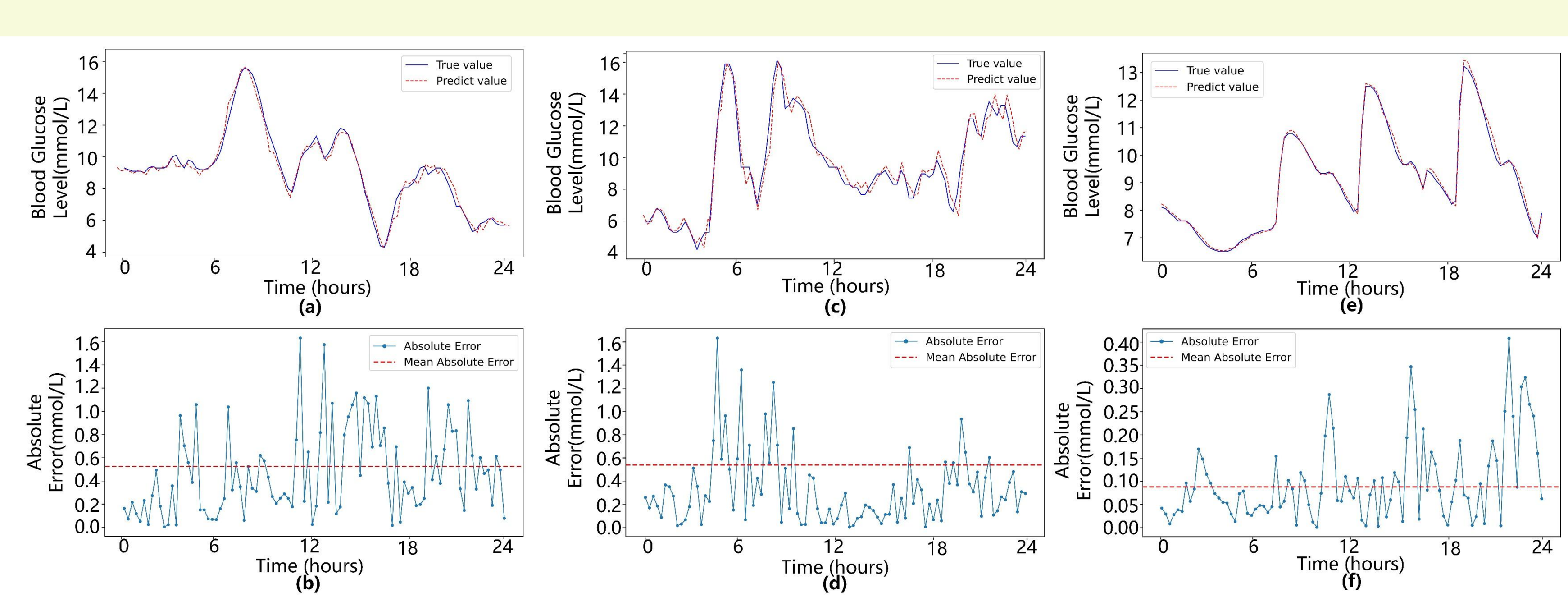
具体来说，研究采用长短期记忆神经网络（LSTM）作为基础框架，基于团队前期建立的血糖代谢动力学模型设计其输入特征及时间窗口。此外，通过引入物理信息约束的损失函数对网络进行训练，用以缩小神经网络的参数搜索空间，增强神经网络性能和可解释性。

Specifically, the research employs a Long Short-Term Memory (LSTM) neural network as the foundational framework, with input features and time windows designed based on the team's previously established glucose metabolic dynamics model. Additionally, by introducing a physics-informed constrained loss function to train the network, the parameter search space of the neural network is narrowed, thereby improving its performance and interpretability.

- **基于PIGNN模型的血糖预测 Blood Glucose Prediction Based on the PIGNN Model**

在数据不充足情况下，通过较少量的血糖监测数据、胰岛素输注数据与碳水化合物摄入数据训练PIGNN模型。基于更新数据和训练好的PIGNN模型动态预测未来30分钟后的血糖水平（PH=30min），为糖尿病患者的个性化血糖管理提供支持。

In scenarios with insufficient data, the PIGNN model is trained using a limited amount of blood glucose monitoring data, insulin infusion data, and carbohydrate intake data. Leveraging the updated data and the trained PIGNN model, it dynamically predicts blood glucose levels 30 minutes into the future (PH=30min), providing support for personalized blood glucose management in diabetic patients.



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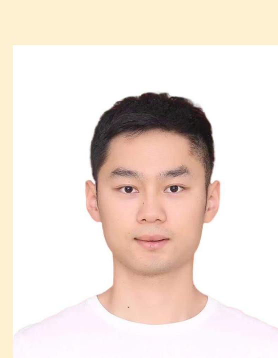
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国家自然科学基金青年基金（52205065）

多重不确定性下胰岛素泵组故障诊断方法研究

National Natural Science Foundation of China

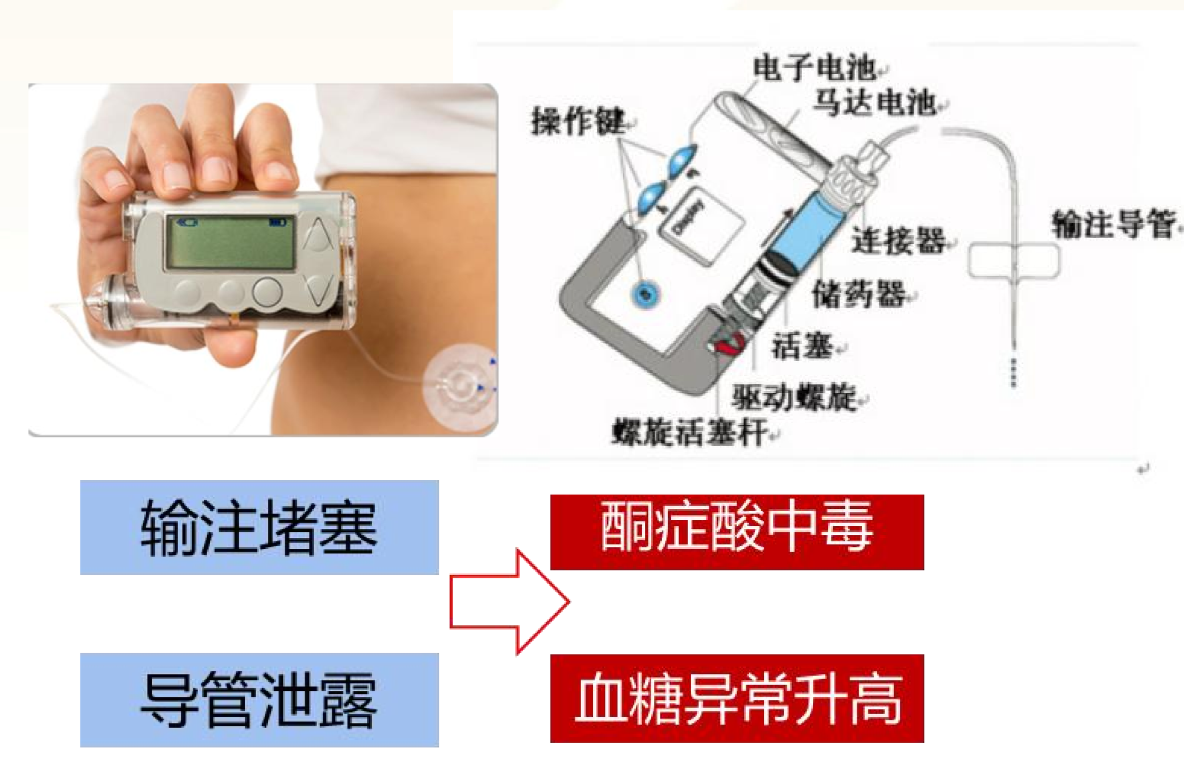
Research on fault diagnosis method of insulin pump set with multiple uncertainties

基于数字孪生的胰岛素泵故障诊断
Fault Diagnosis of Insulin Pumps Based on Digital Twin Technology

背景与挑战 Background and Challenges

外源性胰岛素输注是 I 型和部分 II 型糖尿病患者主要的临床降糖、控糖手段。便携式持续皮下胰岛素输注系统（简称胰岛素泵）是目前先进的胰岛素输注设备。当胰岛素泵及其组件发生故障时，胰岛素不能正常按剂量输出，由此导致的血糖异常升高可能引发酮症酸中毒等严重后果，严重时甚至危及患者生命安全。因此，快速、精准诊断胰岛素泵组故障是保证胰岛素泵安全使用的关键。

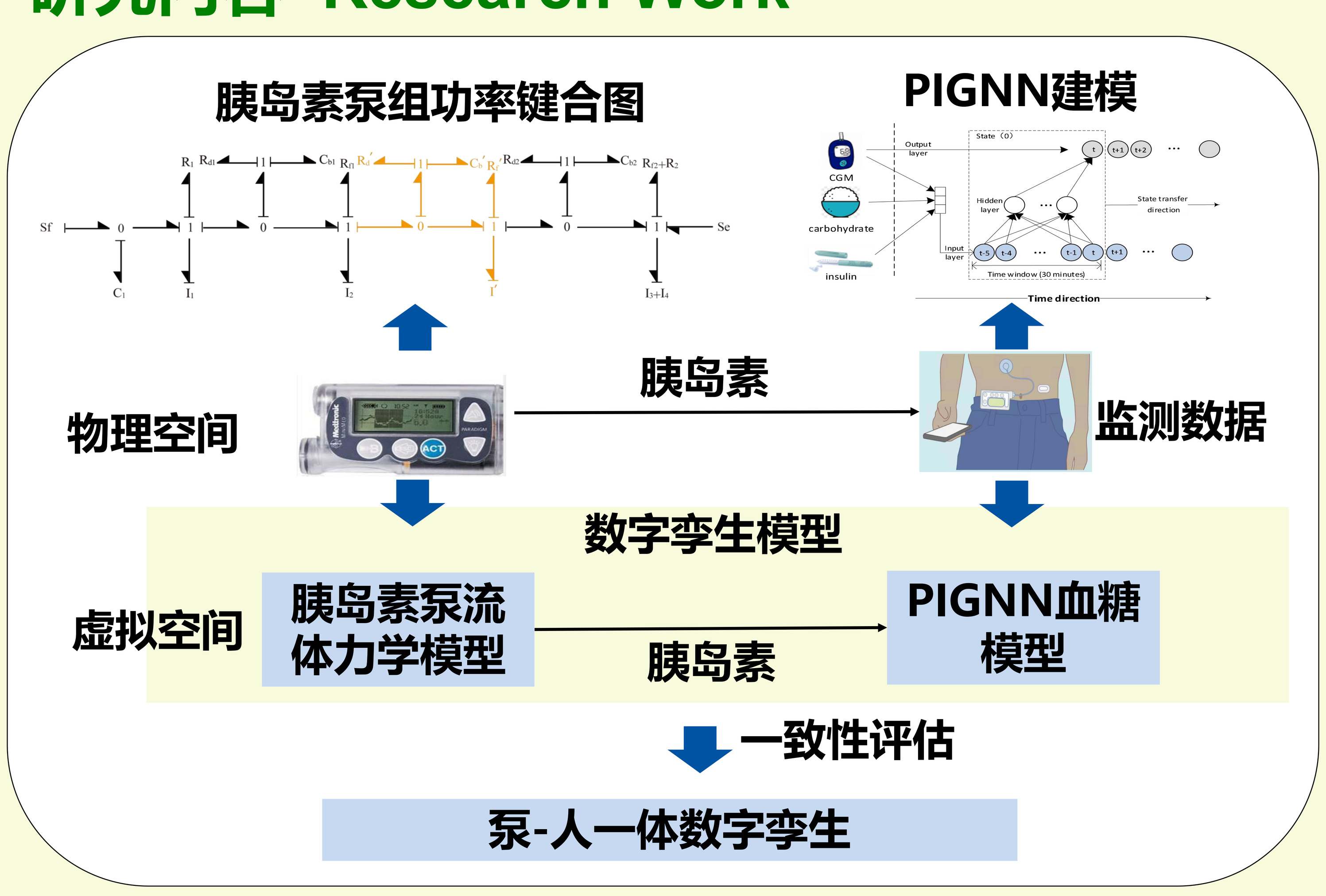
Exogenous insulin infusion is a primary clinical method for lowering and controlling blood glucose in patients with Type I and some Type II diabetes. The portable continuous subcutaneous insulin infusion system, commonly known as the insulin pump, represents the forefront of insulin delivery technology. When the insulin pump or its components malfunction, insulin may not be delivered at the prescribed dosage, potentially leading to dangerously high blood glucose levels and severe complications such as ketoacidosis, which can be life-threatening. Therefore, the rapid and accurate diagnosis of insulin pump component failures is crucial to ensuring the safe use of insulin pumps.



但是，高精度胰岛素泵故障诊断面临以下挑战：一方面，胰岛素泵故障参数难以直接测量；另一方面，由于胰岛素泵发生故障之后患者必须立即检查或更换设备，导致故障数据匮乏。数字孪生技术可以对多领域模型进行高保真实时仿真，本研究提出基于数字孪生模型用于胰岛素泵组故障诊断。

However, high-precision fault diagnosis of insulin pumps faces the following challenges: on one hand, the fault parameters of insulin pumps are difficult to measure directly; on the other hand, since patients must immediately inspect or replace the device after an insulin pump fails, fault data is scarce. Digital twin technology enables high-fidelity real-time simulation of multi-domain models. This study proposes a fault diagnosis method for insulin pump systems based on digital twin models.

研究内容 Research Work



- **泵-人一体高保真数字孪生模型构建 The high-fidelity digital twin model of pump-human integration digital twin**

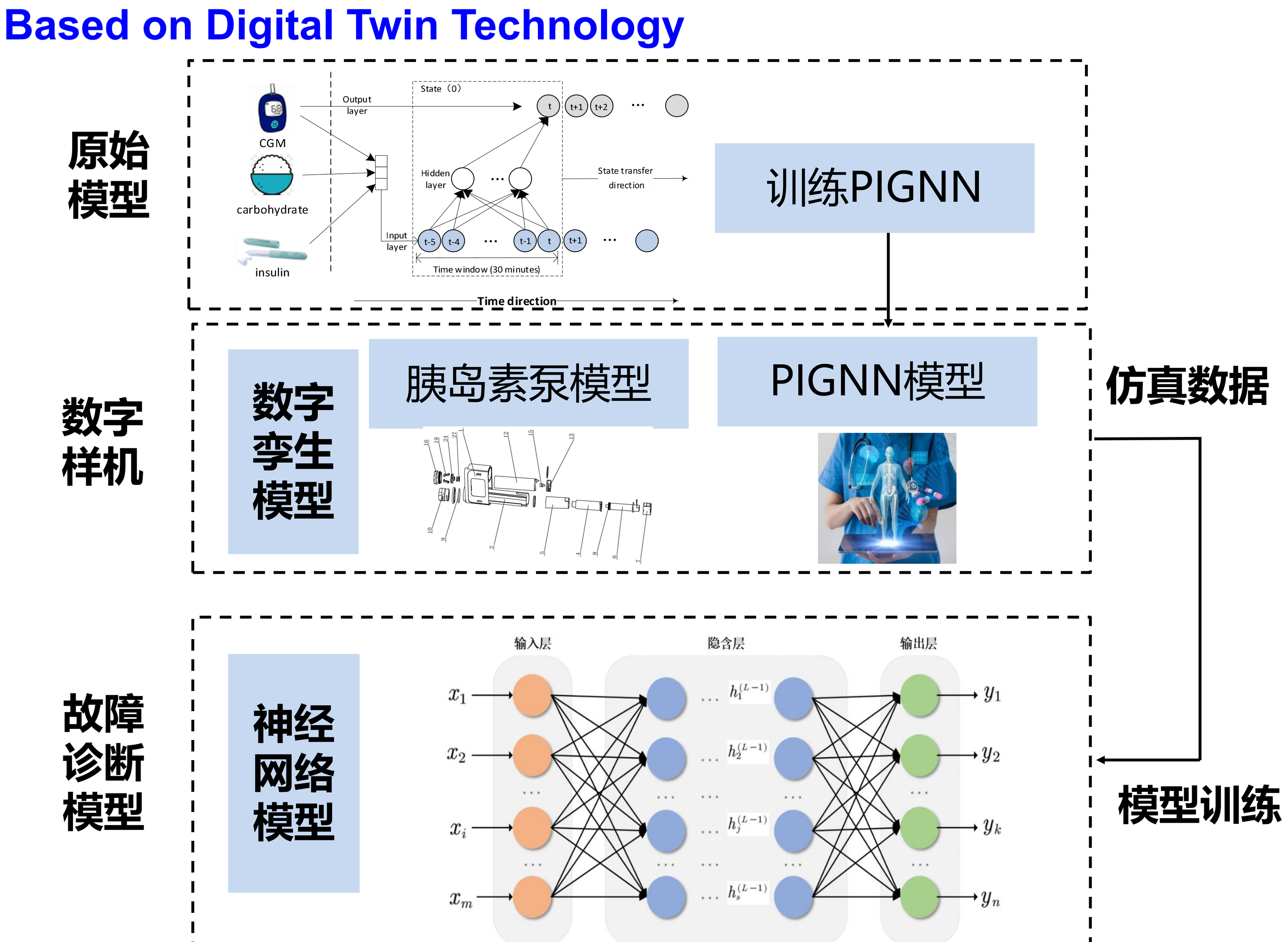
胰岛素泵调节血糖过程中涉及胰岛素泵的流体传动模型和人体的血糖代谢模型两个部分，针对胰岛素泵多能域、流固耦合问题，基于功率键合图构建胰岛素泵流体传动模型，针对血糖代谢机理复杂、个体差异大的问题，基于PIGNN构建血糖代谢模型，通过胰岛素输注量作为中间变量将两模型联合，构成泵-人一体数字孪生模型。在此基础上，引入一致性评价准则，对孪生模型进行更新。形成高保真泵-人一体数字孪生模型。

The process of blood glucose regulation by an insulin pump involves two components: the fluid transmission model of the insulin pump and the blood glucose metabolism model of the human body. To address the challenges of multi-energy domains and fluid-structure coupling in insulin pumps, a fluid transmission model of the insulin pump is constructed based on power bond graphs. To tackle the complexities of blood glucose metabolism mechanisms and significant individual variations, a blood glucose metabolism model is developed using PIGNN. By utilizing insulin infusion rates as an intermediate variable, these two models are integrated to form a pump-human digital twin model. Building upon this framework, a consistency evaluation criterion is introduced to update the twin model, resulting in a high-fidelity pump-human integrated digital twin model.

- **基于数字孪生的胰岛素泵组健康状态监测 Health Status Monitoring of Insulin Pump Systems Based on Digital Twin Technology**

针对胰岛素泵故障参数难以直接通过传感器测量的问题，考虑到数字孪生模型具有映射实体状态为虚拟动态模型的能力，开展基于数字孪生的健康状态监测方法。通过所构建的高保真泵-人一体高保真数字孪生模型，生成丰富的故障样本与故障数据，用于训练反映故障参数与血糖的映射关系的观测器。最后，基于动态采集的人体血糖数据流对胰岛素泵故障参数实时估计，间接反映胰岛素泵健康状态。当故障参数大于设定阈值时，胰岛素泵判定为故障并报警。

Addressing the challenge of directly measuring fault parameters in insulin pump through sensors, and considering the capability of digital twin models to map the state of physical entities into virtual dynamic models, a health status monitoring method based on digital twins is developed. Utilizing the constructed high-fidelity pump-human integrated digital twin model, a wealth of fault samples and data are generated to train an observer that reflects the mapping relationship between fault parameters and blood glucose levels. Finally, real-time estimation of insulin pump fault parameters is conducted based on dynamically collected human blood glucose data streams, indirectly reflecting the health status of the insulin pump. When fault parameters exceed a set threshold, the insulin pump is determined to be in a fault state, triggering an alarm.



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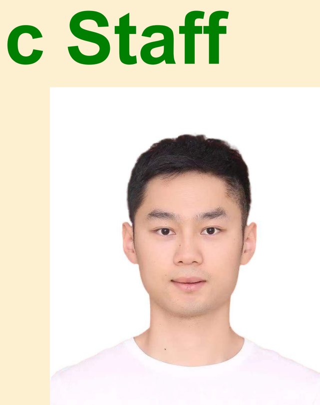
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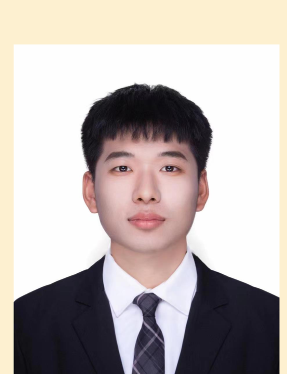
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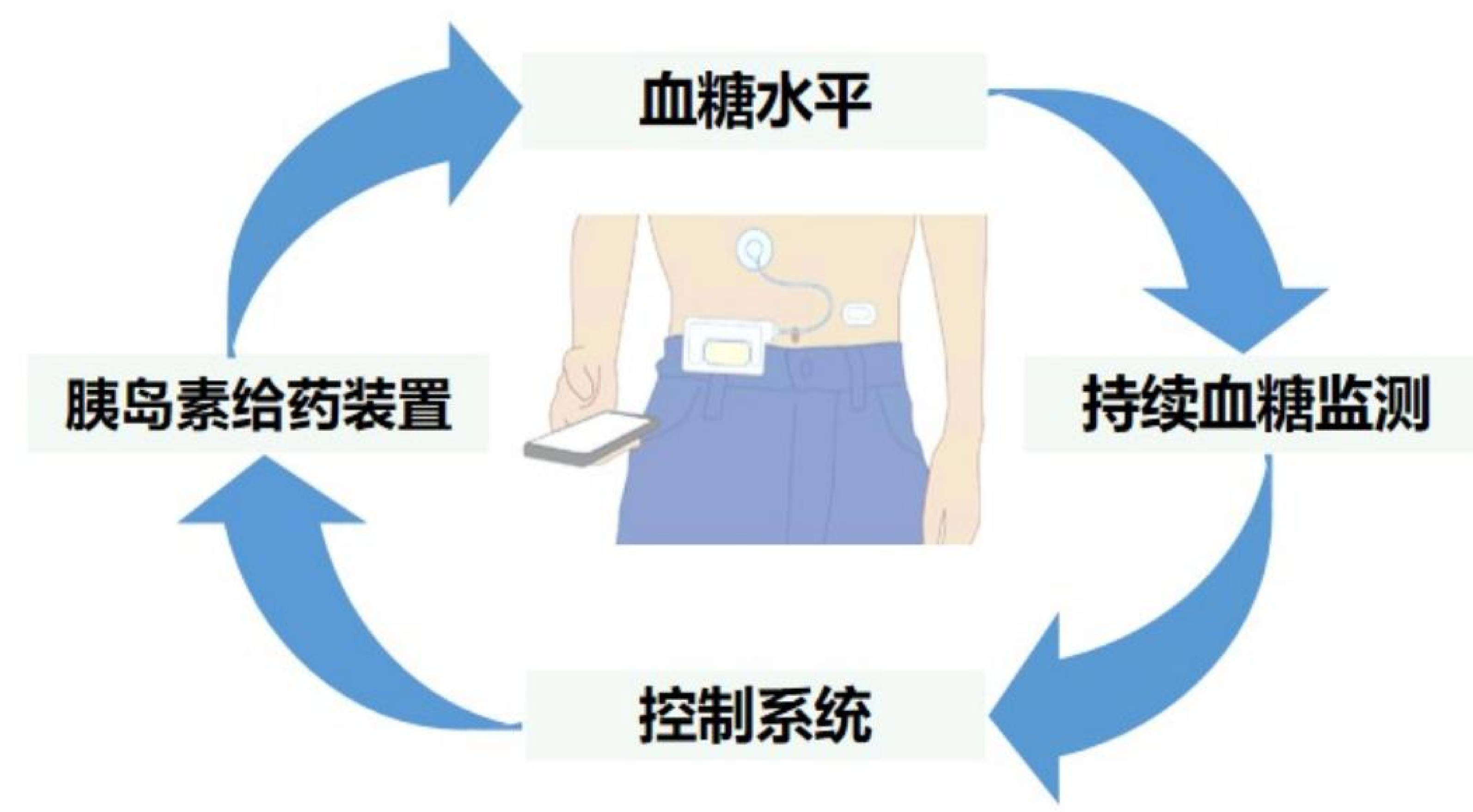
国家自然科学基金青年基金（52205065）
多重不确定性下胰岛素泵组故障诊断方法研究
National Natural Science Foundation of China
Research on fault diagnosis method of insulin pump set with multiple uncertainties

太原理工大学
TAIYUAN UNIVERSITY OF TECHNOLOGY

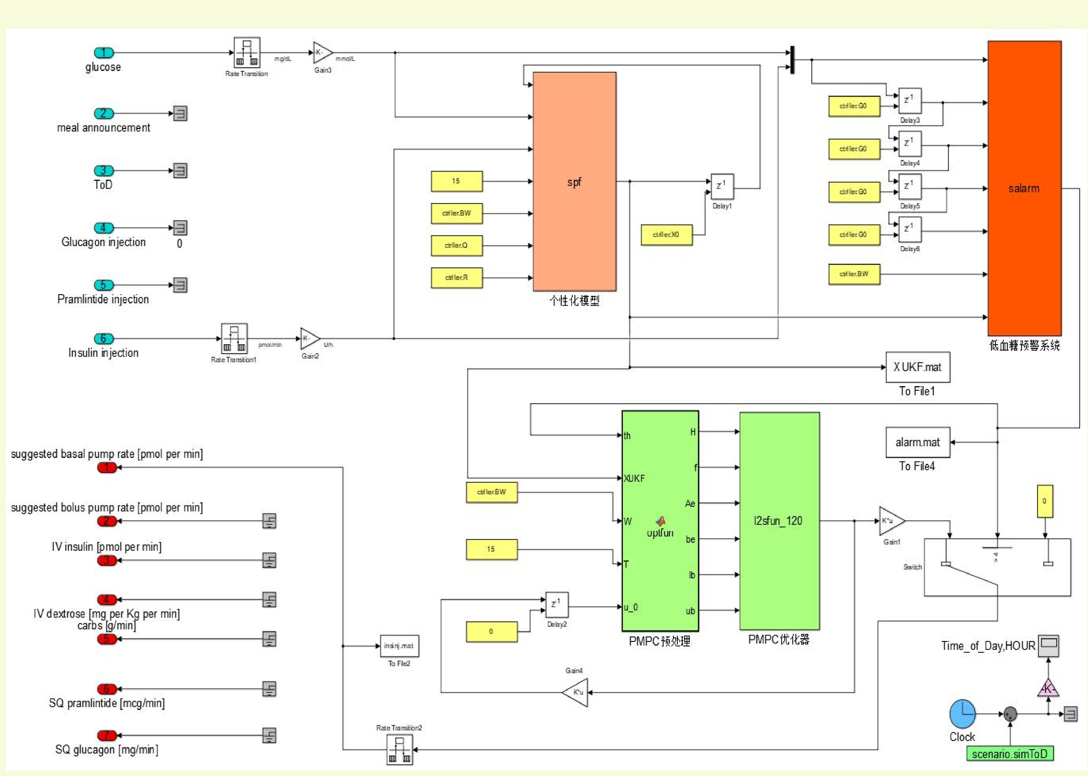
全闭环人工胰腺仿真与实现
In Silico Simulation and Implementation of a Fully Closed-Loop Artificial Pancreas System

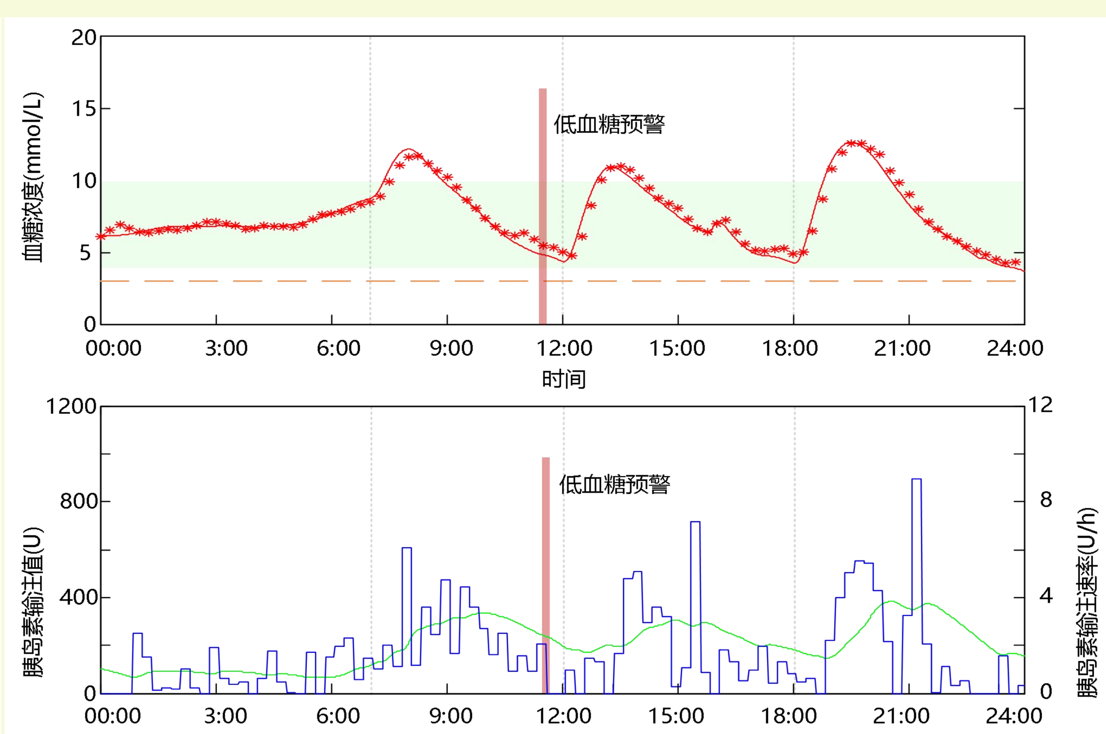
背景与挑战 Background and Challenges

全闭环人工胰腺是糖尿病管理的革命性技术，通过实时动态调节胰岛素输注可实现全状态人工血糖闭环调节，是血糖闭环调节的终极目标。这种真正意义上的全自动人工血糖闭环调节系统是当前的研究难点。实际应用中对血糖闭环调节系统的可靠性、稳定性以及适应性都提出了很高的要求，真实人体中验证血糖控制算法风险较大，血糖数据难以实时采集是全闭环人工胰腺难以实现应用的技术难题。The fully closed-loop artificial pancreas represents a revolutionary technology in diabetes management. By enabling real-time dynamic adjustment of insulin infusion to achieve comprehensive artificial blood glucose closed-loop regulation, it stands as the ultimate goal of blood glucose closed-loop control. However, developing a truly autonomous artificial blood glucose closed-loop regulatory system remains a critical research challenge. Practical applications impose stringent demands on the reliability, stability, and adaptability of closed-loop blood glucose regulation systems. Key technical obstacles hindering its implementation include the high risks associated with validating blood glucose control algorithms in vivo and the difficulty of real-time blood glucose data acquisition, which collectively pose significant technical barriers to the practical application of fully closed-loop artificial pancreas systems.



研究内容 Research Work



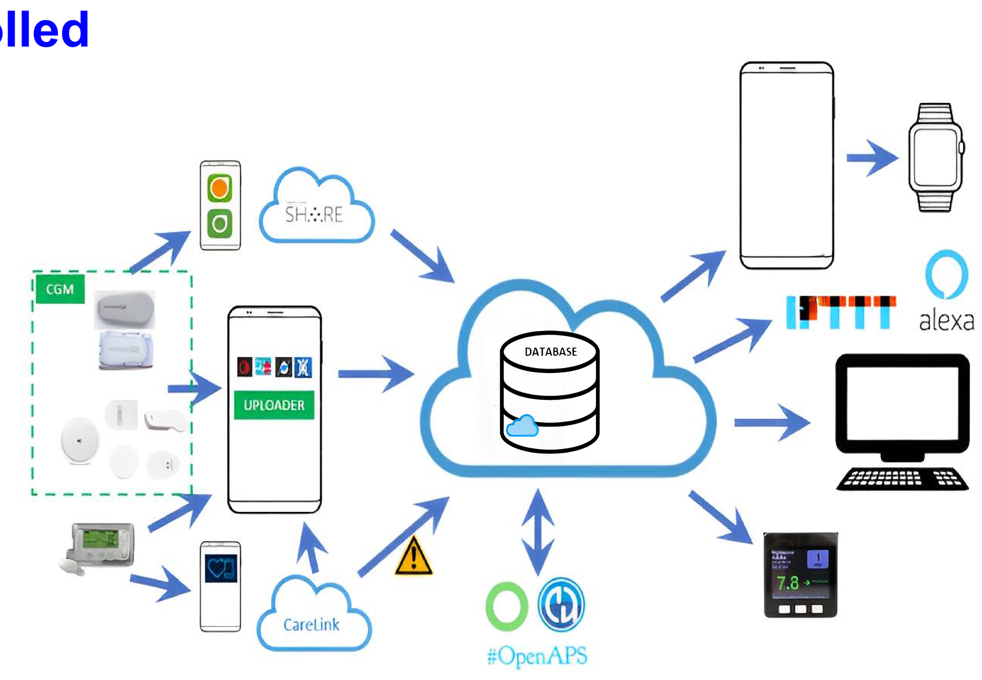


- **全闭环控制人工胰腺仿真Closed-loop control strategy for artificial pancreas systems**

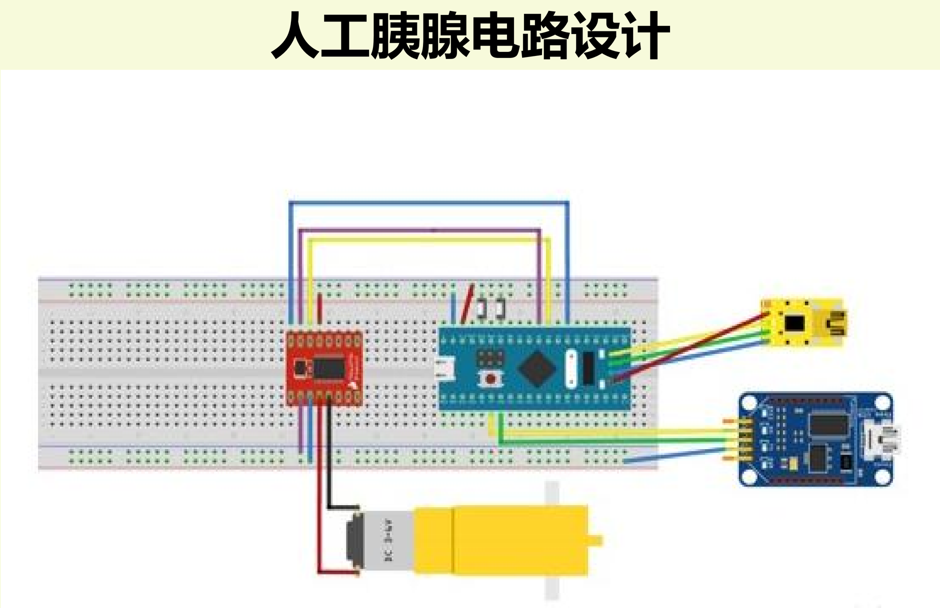
基于FDA认证的UVa/Padova模拟器搭建个性化的模型预测控制（MPC）算法，使用模拟器生成的虚拟 1 型糖尿病患者测试控制算法对血糖的调控能力。为后续全闭环控制人工胰腺实现提供有力的理论与技术支撑。A personalized Model Predictive Control (MPC) algorithm was developed and implemented using the FDA-approved UVa/Padova simulator, and its blood glucose regulation performance was rigorously tested on virtual type 1 diabetes mellitus (T1DM) patient cohorts generated by the simulator. This approach establishes a robust theoretical and technical foundation for advancing the realization of fully closed-loop artificial pancreas systems, addressing critical challenges in clinical translation through high-fidelity in silico validation.

- **全闭环控制人工胰腺实现——血糖数据多端可视化平台Fully Closed-Loop Controlled Artificial Pancreas – Blood Glucose Data Multi-Device Visualization Platform**

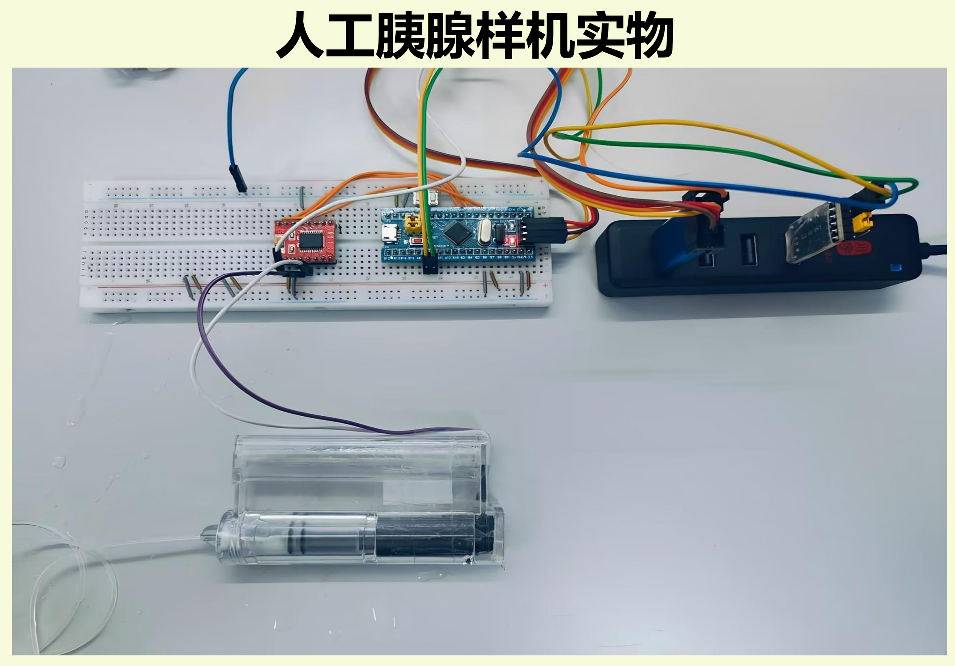
血糖数据多端可视化平台是一个云应用程序，糖尿病患者可以使用多设备端来实时查看、存储和共享来自连续血糖监测传感器的数据。设置完成后，血糖数据多端可视化平台可充当人工胰腺的血糖数据存储库，为人工胰腺实时采集血糖数据提供支持。The Blood Glucose Data Multi-Device Visualization Platform is a cloud-based application that allows diabetic patients to view, store, and share data from continuous glucose monitoring (CGM) sensors in real-time across multiple device endpoints. Once set up, the platform serves as a blood glucose data repository for artificial pancreas systems, supporting real-time data collection for artificial pancreas operations.



人工胰腺电路设计



人工胰腺样机实物



- **全闭环控制人工胰腺实现——胰岛素输注系统Fully Closed-Loop Controlled Artificial Pancreas – Insulin Infusion System**

胰岛素输注系统根据对血糖数据多端可视化平台采集的实时血糖数据进行计算分析给出最佳的胰岛素输注方案，并控制胰岛素给药装置进行胰岛素的输注，实现人工胰腺全闭环控制。The Insulin Infusion System performs computational analysis on real-time blood glucose data collected by the Blood Glucose Data Multi-Device Visualization Platform, generates optimal insulin infusion regimens, and controls insulin delivery devices to administer precise doses, thereby achieving fully closed-loop control of artificial pancreas systems.

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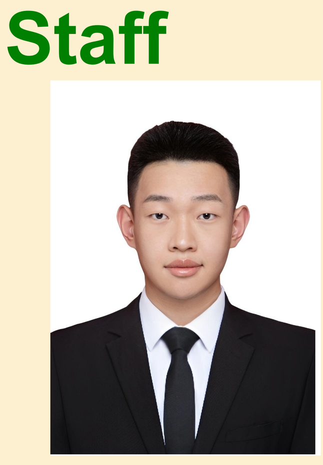
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山西省高等学校科技创新计划

基于数据-模型动态融合的个性化血糖代谢系统建模与控制方法研究

Shanxi Province Higher Education Institutions Science and Technology Innovation Program

Research on Personalized Glucose Metabolism System Modeling and Control Methods Based on Dynamic Data-Model Fusion

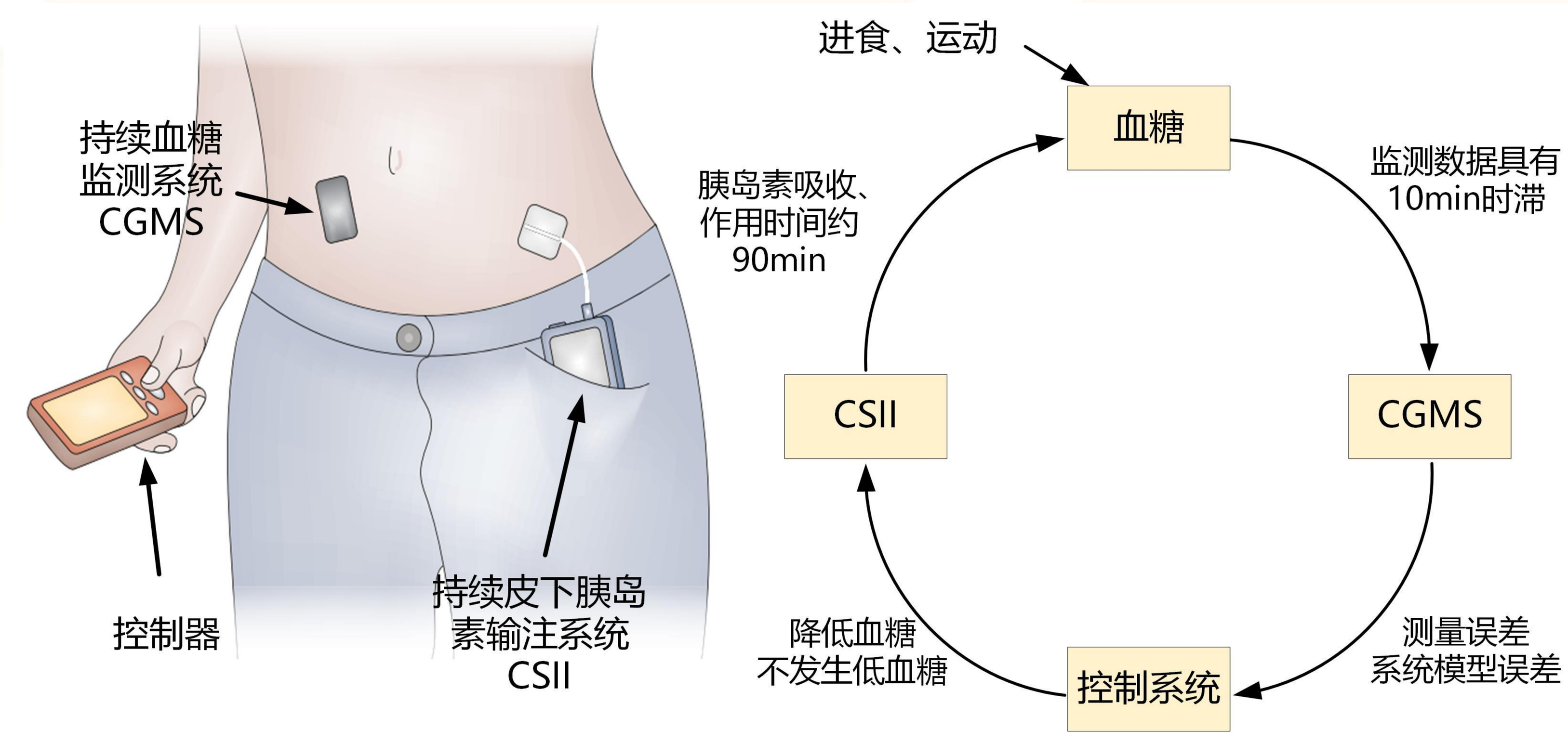
基于胰岛素动态调节的糖尿病精准治疗

Precise Treatment of Diabetes Based on Real-time Insulin Regulation

背景与挑战 Background and Challenges

糖尿病是威胁人类健康的第三大疾病。外源性胰岛素输注是有效治疗手段，但当前的输注方案以定时定量输注为主，不能根据患者身体状况实时调整，易导致患者血糖波动范围较大、低血糖频发等不良后果。人体血糖闭环控制系统（人工胰腺）被认为是最有前景的治疗方法，该方法基于已有的血糖监测系统与胰岛素输注系统，结合控制系统形成血糖闭环控制系统，可以实现胰岛素的自适应按需输注，提高糖尿病患者生活质量与生存率。

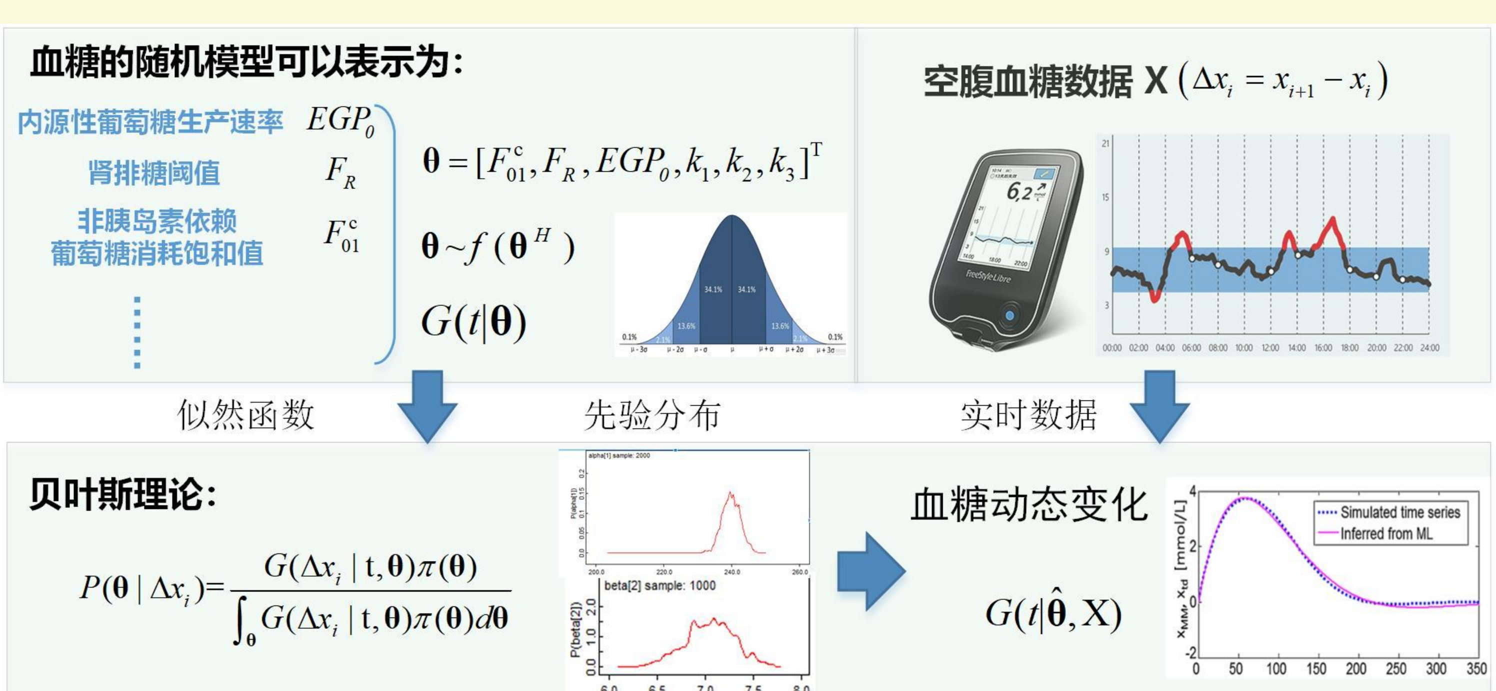
Diabetes mellitus is the third biggest disease threatening human health. Insulin infusion treatment is effective while current infusion schemes can not be adjusted in real time according to physical condition and has many adverse consequences. Closed-loop blood glucose control system (Artificial pancreas) is considered to be the most promising method, which combines existing blood glucose monitoring system and insulin infusion system as well as a closed-loop control system, can achieve self-adaptive insulin infusion and improve living quality and survival rate of diabetic patients.



血糖变化规律个体差异大、影响因素多，既与自身的葡萄糖代谢能力有关也与外界的碳水化合物与胰岛素的输注量有关，已知的生理机理模型并不能精准描述各种生理状态下的血糖变化规律；血糖调节具有大时滞性与非对称性风险，目前的控制方法难以实现对血糖的实时、精准、快速、安全调控。因此，如何揭示患者自身的血糖代谢能力、外界环境扰动下血糖的变化规律以及设计安全有效的控制方法称为发展血糖闭环控制系统的关键。

There are significant individual differences and many influencing factors in blood glucose regulation, which is related to both intra-corporal glucose metabolism and intake of external carbohydrate and insulin; Besides, blood glucose regulation is severely time delayed and asymmetric, therefore, depicting the metabolic ability of blood glucose, revealing the blood glucose regulation mechanism under external disturbances and designing a safe, fast and effective control method are the keys to build the closed-loop blood glucose control system.

研究内容 Research Work



● 复杂不确定下的内源性葡萄糖代谢机理Endogenous glucose metabolism mechanism with complex uncertainty

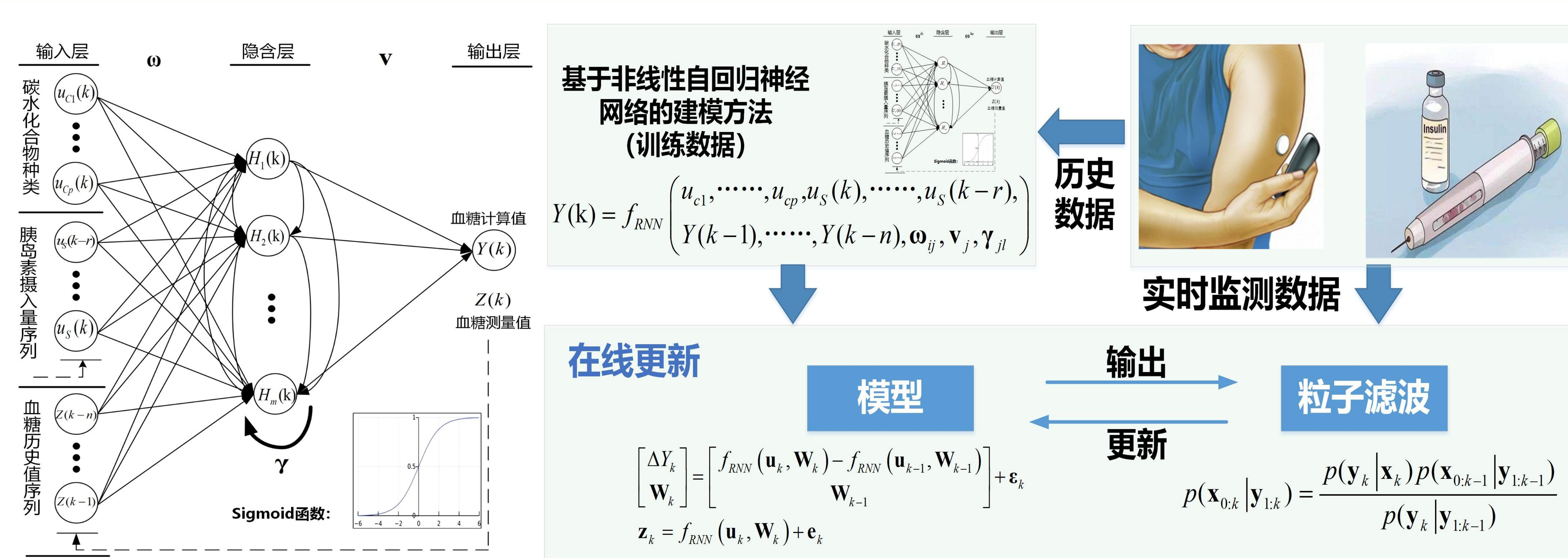
内源性葡萄糖是空腹状态下的葡萄糖的主要来源，其代谢规律既与自身胰岛素分泌能力、各组织器官对葡萄糖代谢能力等因素有关，也与运动、睡眠等生活状态有关，具有很强的不确定性。引入随机过程对个体的差异性以及随机性进行描述，基于贝叶斯理论将实时采集到的血糖信息与基于生理机理的随机模型相融合，精确刻画内源性葡萄糖的实时代谢规律，揭示空腹状态下血糖的而变化规律。

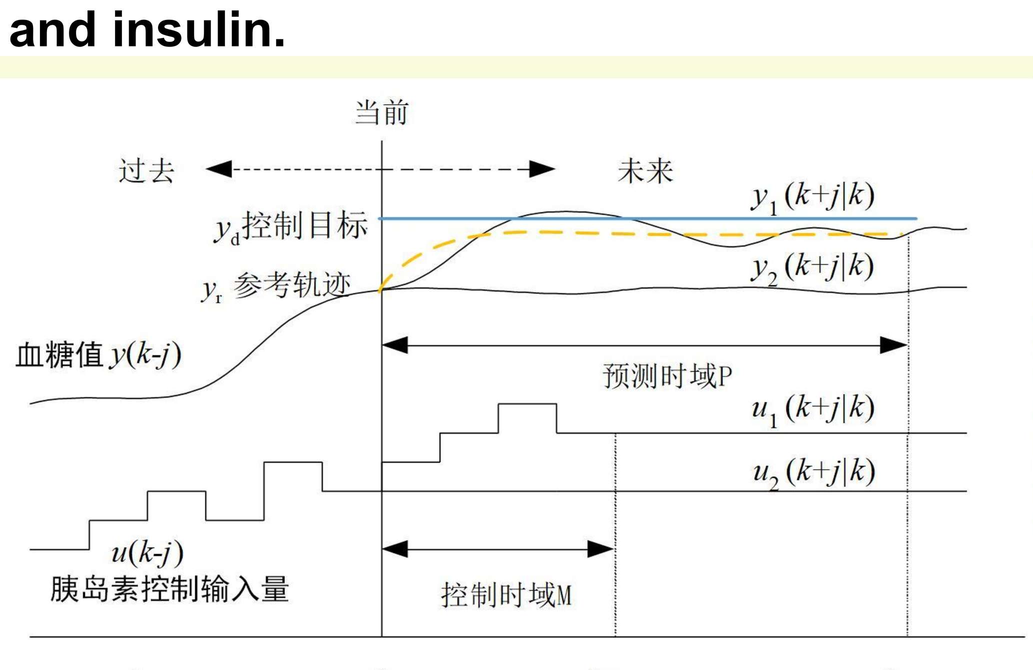
Endogenous glucose is the main source of glucose in the state of fasting. Its metabolism is related to intra-corporal insulin secretion, glucose metabolism of relevant tissues and organs, as well as exercise, sleep and other uncertain factors. Random process is introduced to describe individual differences and randomness. Based on Bayesian theory, real-time blood glucose information is fused with physiological-based random model. The real-time metabolic mechanism of endogenous glucose is accurately depicted, and the change law of blood glucose in fasting state is revealed.

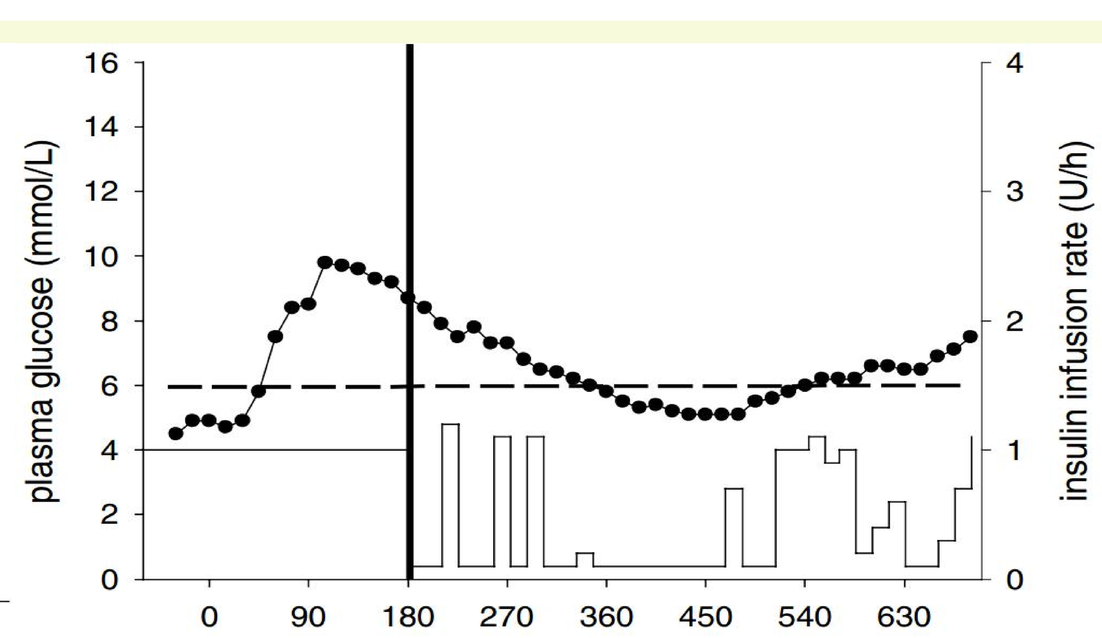
● 碳水化合物与胰岛素耦合作用下血糖变化规律Blood glucose regulation under the coupling of carbohydrate and insulin

基于批量糖尿病患者的持续血糖监测系统与持续皮下胰岛素输注系统，采用循环神经网络训练包含碳水化合物、胰岛素摄入量以及血糖数据等多信息的数学模型，基于粒子滤波不断融合实时信息，获得可精确描述碳水化合物和胰岛素耦合输入下血糖变化规律的动态模型。

Based on the data of CGMS and CSII, a mathematical model with multi-information including carbohydrate, insulin intake and blood glucose data of mass diabetic patients is trained using circulating neural network. The real-time information of object is fused by particle filter to obtain the accurate dynamic model of blood glucose under the coupling of carbohydrate and insulin.







● 基于模型预测控制的胰岛素动态调控方法Dynamic control of blood glucose based on MPC

针对胰岛素调节系统的时滞性，基于空腹与餐后的葡萄糖代谢模型，采用模型预测控制理论，根据实时血糖值，滚动预测、优化胰岛素输注量，给出面向患者个体的胰岛素最佳输注方案，实现糖尿病的精准治疗。

Considering the time delay of insulin modulation system, based on the fasting and postprandial glucose metabolism model, using model predictive control theory and real-time blood glucose data, the infusion of insulin is predicted and optimized step by step, then the optimal insulin injection scheme for individual patient is given to achieve precise treatment.

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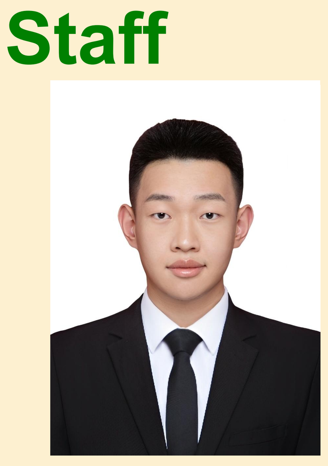

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Research on fault diagnosis method of insulin pump set with multiple uncertainties

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