

## Fault-Tolerant Control for Networked LPV Systems with Time-Varying Delays (Postprint)

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### Abstract

For a class of networked linear parameter-varying (LPV) systems with time-varying delays and Lipschitz nonlinearities, the fault-tolerant control problem is studied for the case where external disturbances exist and actuators and sensors experience simultaneous random faults. Bernoulli distribution sequences are used to describe the random faults in actuators and sensors, and the free-weighting matrix method is applied to deal with the time-varying delays. According to the Lyapunov-Krasovskii stability theorem and linear matrix inequality (LMI) method, sufficient conditions for the existence of an  $H_\infty$  fault-tolerant controller are obtained. Then, by employing approximate basis functions and gridding techniques, the infinite-dimensional LMI problem is converted into a finite-dimensional LMI problem, and the corresponding fault-tolerant controller gains are derived. Finally, the effectiveness of the designed method is verified through numerical simulation.

### Full Text

## Fault-Tolerant Control for Networked LPV Systems with Time-Varying Delays

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**Abstract:** This paper investigates the fault-tolerant control problem for a class of networked linear parameter-varying (LPV) systems with time-varying delays and global Lipschitz nonlinearities, subject to external disturbances and simultaneous random faults in both actuators and sensors. Randomly occurring faults are modeled as Bernoulli distributed white sequences with known conditional

probability distributions, and time-varying delays are handled using the free weighting matrix method. Based on Lyapunov-Krasovskii stability theory and linear matrix inequality (LMI) techniques, sufficient conditions for the existence of an  $H_\infty$  fault-tolerant controller are derived. The infinite-dimensional LMI problem is then converted to a finite-dimensional one using approximate basis functions and gridding techniques, yielding the corresponding fault-tolerant controller gains. Finally, numerical simulations demonstrate the effectiveness of the proposed method.

**Keywords:** fault-tolerant control; linear parameter-varying systems; time-varying delays; linear matrix inequality (LMI)

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## 0 Introduction

In recent years, fault-tolerant control (FTC) for dynamic systems has attracted significant attention due to increasingly stringent requirements for system performance, safety, and reliability in practical applications [?]. FTC enables maintaining near-ideal system performance and ensures stability in the presence of faults. Most research has focused on fault-tolerant control for linear time-invariant systems; however, investigating fault-tolerant control for linear parameter-varying systems is crucial due to system variability [?].

Fault-tolerant control research can be broadly divided into two categories: active fault-tolerant control, which requires controller parameter readjustment after faults occur [?], and passive fault-tolerant control, similar to robust control techniques [?]. The concept of fault-tolerant control first took shape in 1971 [?] and was formally introduced at the 1986 American Control Conference summit. Since the 21st century, with the rise of networked systems and control demands for parameter-varying systems such as unmanned aerial vehicles and missiles, fault-tolerant control for networked LPV systems has gradually become a research hotspot. Lee et al. [?] pioneered the integration of LPV systems with fault-tolerant control research in 2008, proposing a robust control-based method that derived stability conditions and corresponding  $H_\infty$  performance indices. In China, Professor Weng Zhengxin and his students from Huazhong University of Science and Technology initiated research combining networked LPV system control methods with fault-tolerant control systems [?].

Building upon this foundation, reference [?] established an augmented fault model for actuator complete or partial failures in networked control systems with long time delays, parameter uncertainties, and external disturbances, ensuring closed-loop system stability. Reference [?] considered networked control systems with time-varying delays and unknown actuator faults, employing improved Jensen inequalities and Lyapunov stability theory to derive sufficient conditions for both closed-loop stability and  $H_\infty$  performance satisfaction. Associate Professor Wu Dinghui from Jiangnan University applied networked LPV system fault-tolerant control to wind energy conversion systems [?], using LPV

convex decomposition to obtain a convex polytopic system model for pitch actuator faults, and designed corresponding LPV fault-tolerant controllers via LMI techniques to reduce fault impacts on generator dynamic performance. Reference [?] addressed unknown faults in multiple sensors using a distributed zero-processing strategy, designing sub-controllers individually and combining them convexly to obtain the final controller, thereby reducing linearization errors and ensuring system stability. Reference [?] examined networked control systems with time-varying delays and unknown actuator faults, deriving stability and  $H_\infty$  performance conditions through improved Jensen inequalities and Lyapunov theory. Reference [?] investigated guaranteed-cost active fault-tolerant controller design for networked control systems with packet dropouts and transmission delays, employing piecewise constant controllers and formulating the design as a convex optimization problem solvable with existing software.

Most existing literature considers either sensor or actuator faults separately, rarely addressing simultaneous faults. Moreover, with advancing network technology, the impact of network-induced delays cannot be ignored. This paper comprehensively considers adverse factors including time-varying long delays in network communication channels, external disturbances, and simultaneous random faults in sensors and actuators affecting networked LPV systems. We employ the free weighting matrix method from [?] to handle time-varying delays and utilize Lyapunov-Krasovskii stability theory to derive sufficient conditions for  $H_\infty$  fault-tolerant controller existence. The infinite-dimensional LMI problem is then converted to a finite-dimensional one using approximate basis functions and gridding techniques [?].

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## 1 Problem Formulation

Consider the networked LPV closed-loop system with the structure shown in [Figure 1: see original paper]:

$$\begin{cases} x(k+1) = A_0(\rho_k)x(k) + A_1(\rho_k)x(k-d_k) + B(\rho_k)u(k) + R(\rho_k)\omega(k) + f(x(k)) \\ z(k) = C(\rho_k)x(k) + D(\rho_k)\omega(k) \end{cases}$$

where  $x(k) \in \mathbb{R}^n$  is the state vector,  $u(k) \in \mathbb{R}^m$  is the control input,  $z(k) \in \mathbb{R}^r$  is the controlled output, and  $\omega(k) \in \mathbb{R}^q$  is the external disturbance input belonging to  $l_2[0, \infty)$ .  $A_0(\rho_k)$ ,  $A_1(\rho_k)$ ,  $B(\rho_k)$ ,  $C(\rho_k)$ ,  $D(\rho_k)$ , and  $R(\rho_k)$  are known constant matrices of appropriate dimensions. The parameter vector  $\rho_k$  is measurable in real-time. For notational convenience, we denote  $\rho_k$  as  $\rho$ .

The nonlinear vector function  $f(x(k))$  satisfies the global Lipschitz condition:

$$\|f(x(k))\| \leq \|Gx(k)\|, \quad \|f(x(k)) - f(y(k))\| \leq \|G(x(k) - y(k))\|$$

where  $G$  is a known constant matrix of appropriate dimensions.

The time-varying delay  $d_k$  is a positive integer with lower bound  $d_1$  and upper bound  $d_2$ , satisfying:

$$0 < d_1 \leq d_k \leq d_2, \quad \forall k$$

Let  $\tau = d_2 - d_1$ . When  $\tau = 0$ , the delay is time-invariant (constant); when  $\tau \neq 0$ , the delay is time-varying.

**Actuator Fault Model:** Introduce the fault matrix  $H = \text{diag}\{h_1, h_2, \dots, h_n\}$  where  $h_i$  ( $i = 1, 2, \dots, n$ ) are mutually independent random variables. When  $h_i = 1$ , the  $i$ -th sensor operates normally; when  $h_i = 0$ , the  $i$ -th sensor completely fails; when  $0 < h_i < 1$ , the  $i$ -th sensor experiences partial failure. Since  $h_i$  are random variables, we have:

$$E\{H\} = \mathbb{H} = \text{diag}\{\bar{h}_1, \bar{h}_2, \dots, \bar{h}_n\}, \quad \bar{h}_i = E\{h_i\}$$

$$\tilde{H} = \text{diag}\{\tilde{h}_1, \tilde{h}_2, \dots, \tilde{h}_n\}, \quad \tilde{h}_i = h_i - \bar{h}_i$$

**Sensor Fault Model:** Introduce the fault matrix  $M = \text{diag}\{m_1, m_2, \dots, m_n\}$  where  $m_i$  ( $i = 1, 2, \dots, n$ ) are mutually independent random variables. When  $m_i = 1$ , the  $i$ -th actuator operates normally; when  $m_i = 0$ , the  $i$ -th actuator completely fails; when  $0 < m_i < 1$ , the  $i$ -th actuator experiences partial failure. We have:

$$E\{M\} = \mathbb{M} = \text{diag}\{\bar{m}_1, \bar{m}_2, \dots, \bar{m}_n\}, \quad \bar{m}_i = E\{m_i\}$$

$$\tilde{M} = \text{diag}\{\tilde{m}_1, \tilde{m}_2, \dots, \tilde{m}_n\}, \quad \tilde{m}_i = m_i - \bar{m}_i$$

When both sensor and actuator faults occur simultaneously, the state feedback controller is described as:

$$u(k) = K(\rho)Hy(k) = K(\rho)HMx(k)$$

where  $K(\rho) \in \mathbb{R}^{m \times n}$  is the controller gain.

**Objective:** Design a state feedback controller (9) that simultaneously handles random actuator and sensor faults, ensuring the networked LPV system (11) satisfies the following  $H_\infty$  performance constraints:

- a) **Asymptotic Stability:** When  $\omega(k) = 0$ , for each initial state  $x(0, \sigma)$ , we have  $\lim_{k \rightarrow \infty} E\{\|x(k)\|^2\} = 0$ , meaning the networked LPV closed-loop system (11) is asymptotically stable.

- b) **H $\infty$  Performance:** Given a scalar  $\gamma > 0$ , for all non-zero  $\omega(k) \in l_2[0, \infty)$ , the networked LPV closed-loop system (11) achieves H $\infty$  performance  $\|z(k)\|_2 < \gamma\|\omega(k)\|_2$  under zero initial conditions.

Substituting (9) and (10) into (1), the networked LPV closed-loop system can be described as:

$$\begin{cases} x(k+1) = \bar{A}_0(\rho_k)x(k) + A_1(\rho_k)x(k-d_k) + R(\rho_k)\omega(k) + f(x(k)) \\ z(k) = C(\rho_k)x(k) + D(\rho_k)\omega(k) \end{cases}$$

where  $\bar{A}_0(\rho_k) = A_0(\rho_k) + B(\rho_k)\mathbb{H}K(\rho_k)\mathbb{M}G$  and  $\bar{A}_1(\rho_k) = A_1(\rho_k) + B(\rho_k)\mathbb{H}K(\rho_k)\mathbb{M}G$ .

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## 2 Stability Analysis

Using the free weighting matrix method, we construct the following Lyapunov-Krasovskii functional:

$$V(k) = V_1(k) + V_2(k)$$

where

$$V_1(k) = x^T(k)P(\rho_k)x(k) + \sum_{j=k-d_k}^{k-1} y^T(j)Z(\rho_k)y(j) + \sum_{\theta=-d_2+1}^0 \sum_{j=k+\theta-1}^{k-1} y^T(j)Z(\rho_k)y(j)$$

$$V_2(k) = \sum_{l=k-d_2}^{k-d_1-1} x^T(l)Q(\rho_k)x(l)$$

with  $y(k) = x(k+1) - x(k)$ .

**Lemma 1 [22] (Schur Complement):** For a given symmetric matrix  $S = \begin{bmatrix} S_{11} & S_{12} \\ S_{12}^T & S_{22} \end{bmatrix}$  where  $S_{11}$  and  $S_{22}$  have appropriate dimensions, the following three conditions are equivalent:

1.  $S < 0$
2.  $S_{11} < 0$  and  $S_{22} - S_{12}^T S_{11}^{-1} S_{12} < 0$
3.  $S_{22} < 0$  and  $S_{11} - S_{12} S_{22}^{-1} S_{12}^T < 0$

Define the forward difference of the Lyapunov-Krasovskii functional as  $\Delta V(k) = V(k+1) - V(k) = \Delta V_1(k) + \Delta V_2(k)$ .

**Theorem 1:** Given positive integers  $d_1, d_2$  and a scalar  $\gamma > 0$ , if there exist real matrices  $P(\rho) > 0, Q(\rho) > 0, Z(\rho) > 0$ , semi-positive definite matrices  $X_{11}, X_{22}, X_{12}$ , and matrices  $N_1, N_2$  of appropriate dimensions such that:

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} & 0 \\ * & \Phi_{22} & 0 \\ * & * & -\gamma^2 I \end{bmatrix} < 0$$

where

$$\Phi_{11} = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \bar{A}_0^T(\rho)P(\rho)R(\rho) \\ * & \varphi_{22} & \bar{A}_1^T(\rho)P(\rho)R(\rho) \\ * & * & R^T(\rho)P(\rho)R(\rho) - \gamma^2 I \end{bmatrix}$$

$$\varphi_{11} = \bar{A}_0^T(\rho)P(\rho)\bar{A}_0(\rho) - P(\rho) + Q(\rho) + (d_2 - d_1 + 1)X_{11} + N_1 + N_1^T$$

$$\varphi_{12} = \bar{A}_0^T(\rho)P(\rho)\bar{A}_1(\rho) + (d_2 - d_1 + 1)X_{12} - N_1 + N_2^T$$

$$\varphi_{22} = \bar{A}_1^T(\rho)P(\rho)\bar{A}_1(\rho) - Q(\rho) + (d_2 - d_1 + 1)X_{22} - N_2 - N_2^T$$

then the networked LPV system (11) is asymptotically stable and achieves  $H_\infty$  performance  $\gamma$ .

**Proof:** We first construct free weighting matrices. From (16), for any matrices  $N_1, N_2$  with appropriate dimensions, we have:

$$2 [x^T(k)N_1 + x^T(k - d_k)N_2] \times \left[ x(k) - x(k - d_k) - \sum_{l=k-d_k}^{k-1} y(l) \right] = 0$$

Then, by introducing arbitrary semi-positive definite matrices  $X = \begin{bmatrix} X_{11} & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix} \geq 0$ , we obtain:

$$\sum_{l=k-d_k}^{k-1} \zeta_1^T(k)X\zeta_1(k) - \sum_{l=k-d_k}^{k-1} \zeta_1^T(k)X\zeta_1(k) \geq 0$$

where  $\zeta_1(k) = [x^T(k) \quad x^T(k - d_k)]^T$ .

Adding the left-hand sides of (19) and (20) to the right-hand side of (18) yields:

$$E\{\Delta V(k)\} \leq E\{\zeta_2^T(k)\Xi\zeta_2(k) + \zeta_2^T(k)\Gamma^T P(\rho)\Gamma\zeta_2(k) + \zeta_2^T(k)\Psi\zeta_2(k) + \omega^T(k)\omega(k)\}$$

where  $\zeta_2(k) = [x^T(k) \quad x^T(k - d_k) \quad \omega^T(k)]^T$ , and  $\Xi, \Gamma, \Psi$  are defined matrices. Applying Lemma 1 and combining with (21) yields the inequality  $\Phi < 0$ . By Lyapunov-Krasovskii stability theory, system (11) is asymptotically stable.

Next, we prove  $H_\infty$  performance. For any non-zero  $\omega(k)$ , from (22) we have:

$$E\{\Delta V(k)\} + E\{z^T(k)z(k)\} - \gamma^2 \omega^T(k)\omega(k) < 0$$

Summing from  $k = 0$  to  $\infty$  and using zero initial conditions  $V(0) = 0$ , we obtain:

$$\sum_{k=0}^{\infty} E\{\|z(k)\|^2\} < \gamma^2 \sum_{k=0}^{\infty} \|\omega(k)\|^2$$

which verifies that the networked LPV system (11) is not only asymptotically stable but also satisfies the  $H_\infty$  performance constraint  $\gamma$  for all non-zero  $\omega(k)$ . This completes the proof.

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### 3 Fault-Tolerant Controller Parameter Solution

**Theorem 2:** For given positive integers  $d_1, d_2$  and a scalar  $\gamma > 0$ , if there exist real matrices  $P(\rho) > 0, Z(\rho) > 0, Q(\rho) > 0$ , symmetric matrices  $X_{11}, X_{22}, X_{12}$ , and matrices  $N_1, N_2, K(\rho)$  of appropriate dimensions such that:

$$\begin{bmatrix} \Omega_{11} & \Omega_{12} & 0 \\ * & \Omega_{22} & 0 \\ * & * & -\gamma^2 I \end{bmatrix} < 0$$

where

$$\Omega_{11} = \begin{bmatrix} \nu_{11} & \nu_{12} & A_0^T(\rho)P(\rho)R(\rho) \\ * & \nu_{22} & A_1^T(\rho)P(\rho)R(\rho) \\ * & * & R^T(\rho)P(\rho)R(\rho) - \gamma^2 I \end{bmatrix}$$

$$\nu_{11} = A_0^T(\rho)P(\rho)A_0(\rho) - P(\rho) + Q(\rho) + (d_2 - d_1 + 1)X_{11} + N_1 + N_1^T$$

$$A_0(\rho) = A(\rho) - B(\rho)\alpha K(\rho)\beta G$$

$$A_1(\rho) = A_1(\rho) + B(\rho)\alpha K(\rho)\beta G$$

then the networked LPV system (11) is asymptotically stable with  $H_\infty$  disturbance attenuation level  $\gamma$ , and the fault-tolerant controller gain is  $K(\rho)$ .

**Proof:** Define  $H_1 = \text{diag}\{P^{-1}, I, I, I, I, I\}$  and  $H_2 = \text{diag}\{P^{-1}, P^{-1}, P^{-1}\}$ . Multiply inequality (12) on the left and right by  $H_1^T$  and  $H_1$ , respectively, and multiply inequality (13) on the left and right by  $H_2^T$  and  $H_2$ , respectively. This yields two transformed inequalities. Since the term  $K^T(\rho)B^T(\rho)P(\rho)B(\rho)K(\rho)$  in (32) is nonlinear, preventing direct solution via LMI toolbox, we perform a transformation. Because  $P(\rho) > 0$ , we have  $Z(\rho) \geq P^{-1}(\rho)Z(\rho)P^{-1}(\rho)$ , which leads to:

$$K^T(\rho)B^T(\rho)P(\rho)B(\rho)K(\rho) \geq K^T(\rho)B^T(\rho)Z(\rho)B(\rho)K(\rho)$$

Substituting all these expressions into inequalities (31) and (32) yields inequalities (27) and (28). Therefore, system (11) is not only asymptotically stable but also satisfies the  $H_\infty$  performance constraint  $\gamma$  for all non-zero  $\omega(k)$ . Moreover, the controller gain can be obtained as  $K(\rho) = K(\rho)P^{-1}(\rho)$ . This completes the proof.

**Remark 1:** Since the parameter  $\rho$  varies, inequalities (27) and (28) actually represent an infinite-dimensional set of LMIs. Using approximate basis functions and gridding techniques, this can be converted to a finite-dimensional LMI problem. Select approximate basis functions:

$$P(\rho) = \sum_{j=1}^f f_j(\rho)P_j, \quad Q(\rho) = \sum_{j=1}^f f_j(\rho)Q_j, \quad Z(\rho) = \sum_{j=1}^f f_j(\rho)Z_j$$

where  $f_j(\rho)$  are basis functions. Then apply gridding techniques to solve the finite-dimensional LMI problem.

## 4 Numerical Simulation

This section presents numerical simulations to verify the proposed method, using data from a wind turbine generator model with the following parameter matrices:

$$A_0(\rho_k) = \begin{bmatrix} 0.2 + 0.1 \sin(\rho_k) & 0.5 & 0.2 \\ 0.1 & 0.57 + 0.3 \sin(\rho_k) & 0.76 \\ 0 & 0 & 0.51 \end{bmatrix}, \quad A_1 = \begin{bmatrix} 0.21 & 0.12 & 0.09 \\ 0 & 0.46 & 0.76 \\ 0.57 & 0 & 0.48 \end{bmatrix}$$

$$B(\rho_k) = \begin{bmatrix} 0.41 + 0.4 \sin(\rho_k) & 0.28 & 0 \\ 0.63 & 0.32 & 0 \\ 0.10 & 0.51 & 0.12 \end{bmatrix}, \quad R = \begin{bmatrix} 0.3 \\ 0.5 \\ 0.1 \end{bmatrix}$$

$$C = [0.1 \quad 0.1 \quad 0.1], \quad D = 0.6, \quad d_1 = 1$$

The nonlinear term is selected as  $f(x(k)) = \begin{bmatrix} 0.3 \sin(0.1x_1(k)) \\ 0.3 \cos(0.1x_2(k))/x_2(k) \\ 0.3(\sin(0.1x_3(k)) - \cos(0.1x_3(k))) \end{bmatrix}$  with Lipschitz matrix  $G = \text{diag}\{\sin(0.1), \cos(0.1), \cos(0.1)\}$ . The external disturbance is  $\omega(k) = -0.1k \sin(k)e^\pi$ . The time-varying parameter is  $\rho(k) = 2 \sin(k)$ . The objective is to design a controller ensuring  $H_\infty$  performance  $\gamma$ .

Using gridding techniques, the parameter space of  $\rho(k)$  is divided into ten grids. The basis functions are selected as  $f_1(\rho) = 1$  and  $f_2(\rho) = \sin(\rho)$ . Applying MATLAB LMI toolbox to minimize the  $H_\infty$  performance index  $\gamma$  yields:

**Scenario 1:** Actuator fault expectation  $\alpha = \text{diag}\{0.9, 0.8, 0.7\}$  with variance  $\alpha_2 = \text{diag}\{0.3, 0.2, 0.1\}$ ; sensor fault expectation  $\beta = \text{diag}\{0.8, 0.8, 0.8\}$  with variance  $\beta_2 = \text{diag}\{0.2, 0.2, 0.1\}$ . Maximum delay bound  $d_2 = 3$ . The optimized controller gain  $K(\rho)$  and minimum disturbance attenuation rate  $\gamma = 0.6312$  are obtained.

**Scenario 2:** Actuator fault expectation  $\alpha = \text{diag}\{0.90, 0.90, 0.90\}$  with variance  $\alpha_2 = \text{diag}\{0.3, 0.2, 0.1\}$ ; sensor fault expectation  $\beta = \text{diag}\{0.90, 0.90, 0.90\}$  with variance  $\beta_2 = \text{diag}\{0.2, 0.2, 0.1\}$ . Maximum delay bound  $d_2 = 2$ . The optimized  $\gamma = 0.7133$  and controller gain  $K(\rho)$  are obtained.

**Scenario 3:** Actuator fault expectation  $\alpha = \text{diag}\{0.80, 0.80, 0.80\}$  with variance  $\alpha_2 = \text{diag}\{0.3, 0.2, 0.2\}$ ; sensor fault expectation  $\beta = \text{diag}\{0.80, 0.80, 0.80\}$  with variance  $\beta_2 = \text{diag}\{0.2, 0.2, 0.1\}$ . Maximum delay bound  $d_2 = 2$ . The optimized  $\gamma = 0.8011$  and controller gain  $K(\rho)$  are obtained.

The open-loop state response of the networked LPV system (1) is shown in [Figure 2: see original paper], demonstrating instability under actuator and sensor faults. The closed-loop state responses for different scenarios are shown in [Figure 3: see original paper] through [Figure 5: see original paper]. Comparing these results reveals that as the probabilities of random actuator and sensor faults increase and the delay bound grows, the system experiences larger overshoot and longer settling time, with degraded  $H_\infty$  performance. However, when the delay bound does not exceed 3 sampling periods, the designed  $H_\infty$  fault-tolerant controller maintains system stability with satisfactory performance.

Reference [?] studied only random actuator faults. While their simulation validated effectiveness, sensor faults caused prolonged overshoot and potential instability. In contrast, our controller comprehensively addresses simultaneous actuator and sensor faults, maintaining system stability under both fault types, thus verifying the proposed method's effectiveness.

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## 5 Conclusion

This paper investigated fault-tolerant control for networked LPV systems with time-varying delays, considering simultaneous random faults in actuators and sensors. Using the free weighting matrix method and Lyapunov-Krasovskii stability theory, sufficient conditions for asymptotic stability were derived, and a fault-tolerant controller satisfying  $H_\infty$  performance was designed. Numerical simulations demonstrated that the proposed controllers ensure system stability and achieve favorable performance indices, validating the method's effectiveness.

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*Note: Figure translations are in progress. See original paper for figures.*

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