Research Experiences of Candidate Patrick Li-Yu Lo

Patrick Li-Yu Lo

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Outline

1. **Research Highlight**
   - Adaptive Control for Underactuated Robots leveraging Koopman Operators and Reinforcement Learning for Dynamic Robustness
   - Improving and Optimizing Adaptive Controllers via Disturbances Observers and Reinforcement Learning
   - Non-Robocentric Dynamic Landing for Quadrotor UAVs
2. **Engineering Arsenals**
   - **Numerical Modelling & Simulation:** A Bootcamp for Legged Robotics via Biped and Quadruped Simulation
   - **Optimization Courseworks:** Convex, Linear, Stochastic Optimization, & Machine Learning
   - **Full Stack Development in Robotics:** Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control

Adaptive Control for Underactuated Robots leveraging Koopman Operators and Reinforcement Learning for Dynamic Robustness

Sep 2024 - Present (ongoing)

This project aims to solve the adaptability problem of data-driven controllers (Koopman-based control) in the context of underactuated robots.

- Project Content:
  - Exploring data-driven solutions for systems with **complex dynamics** such as quadrotors & quadrupeds.
  - Leveraging the **Koopman operator** to enable linear control of nonlinear systems.
  - Integrating **reinforcement learning (RL)** to optimize hyperparameters, adapt to unmodeled dynamics, and enhance robustness.

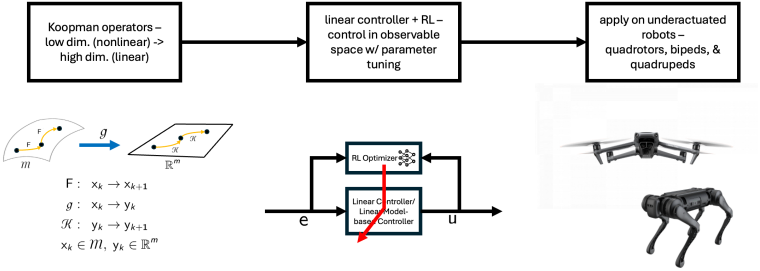

Figure 1: The working pipeline of the adaptive Koopman-based controller.

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An Adaptive Model Predictive Control for Unmanned Underwater Vehicles Subject to External Disturbances and Measurement Noise

Sep 2023 - Aug 2024

This project aims to improve the disturbance rejection capability of model-based controllers in the context of unmanned underwater vehicle (UUV).

- Project Content:
  - Developed an **Error-State Extended State Observer (ESESO)** leveraging system and sensor dynamics to enhance model-based controller performance.
  - Tested the ESESO with **Nonlinear Model Predictive Control (NMPC)** for an UUV and improving its prediction model to achieve trajectory tracking accuracy.
  - Analyzing the proposed ESESO with **Lyapunov stability analysis**.

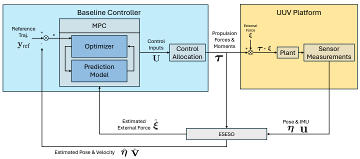
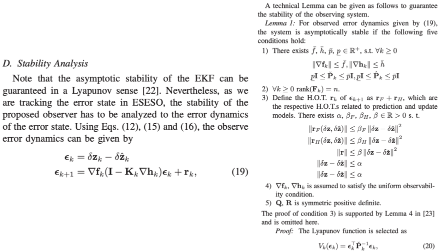


Figure 2: Block diagram of the proposed ESESO + NMPC for UUV



D. Stability Analysis

Note that the asymptotic stability of the EKF can be guaranteed in a Lyapunov sense [22]. Nevertheless, as we are tracking the error state in ESESO, the stability of the proposed observer has to be analyzed to the error dynamics of the error state. Using Eqs. (12), (15) and (16), the observe error dynamics can be given by

$$\begin{aligned} \boldsymbol{\epsilon}_k &= \delta\mathbf{z}_k - \delta\hat{\mathbf{z}}_k \\ \boldsymbol{\epsilon}_{k+1} &= \nabla\mathbf{f}_k(\mathbf{I} - \mathbf{K}_k\nabla\mathbf{h}_k)\boldsymbol{\epsilon}_k + \mathbf{r}_k, \end{aligned} \tag{19}$$

A technical Lemma can be given as follows to guarantee the stability of the observing system.

Lemma 1: For observed error dynamics given by (19), the system is asymptotically stable if the following five conditions hold:

1) There exists $\bar{f}$, $\bar{h}$, $\bar{p}$, $\underline{p} \in \mathbb{R}^+$, s.t. $\forall k \geq 0$

$$\|\nabla\mathbf{f}_k\| \leq \bar{f}, \|\nabla\mathbf{h}_k\| \leq \bar{h}$$
$$\underline{p}\mathbf{I} \leq \check{\mathbf{P}}_k \leq \bar{p}\mathbf{I}, \underline{p}\mathbf{I} \leq \hat{\mathbf{P}}_k \leq \bar{p}\mathbf{I}$$

2) $\forall k \geq 0$ rank$(\mathbf{F}_k) = n$.
3) Define the H.O.T. $\mathbf{r}_k$ of $\boldsymbol{\epsilon}_{k+1}$ as $\mathbf{r}_F + \mathbf{r}_H$, which are the respective H.O.T.s related to prediction and update models. There exists α, β_F, β_H, $\beta \in \mathbb{R} > 0$ s. t.

$$\begin{aligned} \|\mathbf{r}_F(\delta\mathbf{z}, \delta\hat{\mathbf{z}})\| &\leq \beta_F \|\delta\mathbf{z} - \delta\hat{\mathbf{z}}\|^2 \\ \|\mathbf{r}_H(\delta\mathbf{z}, \delta\check{\mathbf{z}})\| &\leq \beta_H \|\delta\mathbf{z} - \delta\check{\mathbf{z}}\|^2 \\ \|\mathbf{r}\| &\leq \beta \|\delta\mathbf{z} - \delta\check{\mathbf{z}}\|^2 \\ \|\delta\mathbf{z} - \delta\hat{\mathbf{z}}\| &\leq \alpha \\ \|\delta\mathbf{z} - \delta\check{\mathbf{z}}\| &\leq \alpha \end{aligned}$$

4) $\nabla\mathbf{f}_k$, $\nabla\mathbf{h}_k$ is assumed to satisfy the uniform observability condition.
5) $\mathbf{Q}$, $\mathbf{R}$ is symmetric positive definite.

The proof of condition 3) is supported by Lemma 4 in [23] and is omitted here.

Proof: The Lyapunov function is selected as

$$V_k(\boldsymbol{\epsilon}_k) = \boldsymbol{\epsilon}_k^\top \check{\mathbf{P}}_k^{-1} \boldsymbol{\epsilon}_k, \tag{20}$$

Figure 3: Overview of the stability analysis for the proposed ESESO.

An Adaptive Model Predictive Control for Unmanned Underwater Vehicles Subject to External Disturbances and Measurement Noise (cont'd)

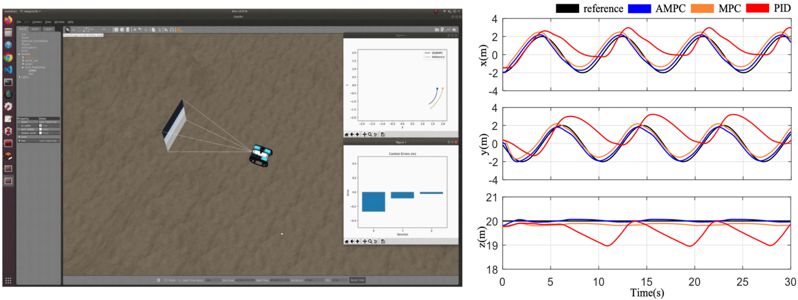


Figure 4: The validation platform (ROS + Gazebo) and the final results.

- Links: `project_repo`, `paper`.

Fixed-Time Adaptive Consensus Control for Multi-Quadrotor Subject to External Disturbances Via Deep Reinforcement Learning

Sep 2023 - Aug 2024

This project aims to improve the adaptability of nonlinear controllers in the context of multi-agent UAVs.

- Project Content:
  - Proposed an RL + Disturbance Observer (DO) to improve the adaptability of nonlinear controllers.
  - Integrated a **Fixed-Time Disturbance Observer (FTDO)** with a parameter optimizer based on **Proximal Policy Optimization (PPO)**.
  - Validated with **Sliding-Mode Control (SMC)** on UAV-swarm formation control.

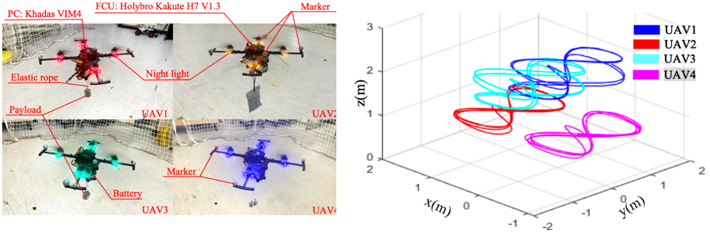


Figure 5: The experiments conducted for framework RL + DO + SMC with a team of 4 UAVs.

- Links: rl_train_repo, paper.

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Non-Robocentric Dynamic Landing for Quadrotor UAVs

Sep 2022 - Aug 2023

This project aims to solve the dynamic landing problem of UAV without onboard exteroceptive sensors, i.e., to land a "blind" UAV with external signals from moving platform.

- Project Content:
  - Refined an **Iterated Extended Kalman filter (IEKF)** to conduct relative state estimation - a single time-step **factor graph optimization (FGO) on SE(3) manifold**.
  - Formulated **a constrained convex optimization** problem to design the landing trajectory with **Bézier curves** and designing a feedforward PID controller in non-inertial frame.

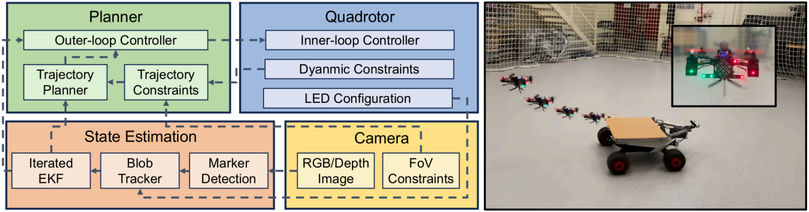

Figure 6: The system architecture of the proposed landing system and the cover image of the research.

Non-Robocentric Dynamic Landing for Quadrotor UAVs (cont'd)

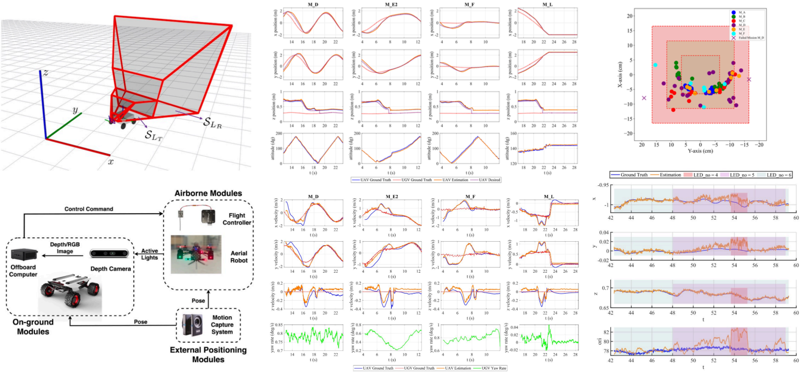

Figure 7: The far left two images show the on-computer visualization and the hardware configuration. The rest of the images display the experimental data acquired from extensive testing.

- Links: youtube_video, research_repo, paper.

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Numerical Modelling & Simulation: A Bootcamp for Legged Robotics via Biped and Quadruped Simulation

This self-initiated project aimed to strengthen my understanding of numerical modeling and simulation, focusing on the complexities of legged robot dynamics.

- Project Contents:
  - Developed a Python-based physical simulation environment **from scratch** for 2D/3D simulations using a **Dormand-Prince (RKDP)** forward integrator.
  - Implemented a **feedback linearization controller** for hybrid systems - 2D/3D Biped, 2D/3D manipulator, Raibert hopper.
  - Developed a dynamic gait controller for quadrupeds capable of performing **joint-level force control** in the ROS/Gazebo (C++) simulation environment.

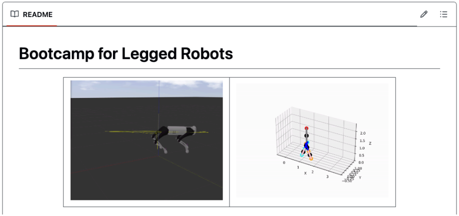

Figure 8: The screenshot of the simulator Github repo.

Numerical Modelling & Simulation: A Bootcamp for Legged Robotics via Biped and Quadruped Simulation (cont'd)

- Tools Used:
  - **Software:** Python/PyTorch, C++, OSQP, ROS, Gazebo, & Unitree SITL.
  - **Modeling and Control:** Euler-Lagrange equations, Poincaré maps, Dormand-Prince forward simulation, forward/inverse kinematics, polynomial optimization, feedback linearization, quadratic programming, & cycloid trajectory.
- Links: bootcamp_repo.

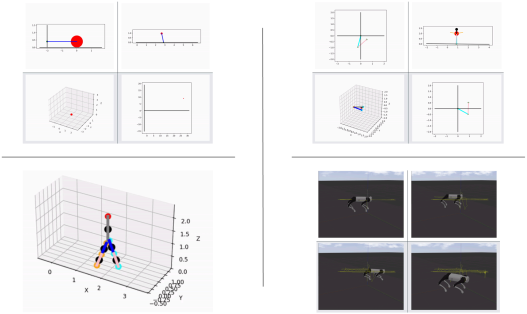

Figure 9: Snapshots of the project, which includes simulations of simple hybrid system, 2D/3D simulators, Raibert hopper, 2D/3D bipeds, and a UniTree quadruped that can execute Trot, Crawl, and Pronk gaits.

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Optimization Courseworks: Convex, Linear, Stochastic Optimization, & Machine Learning

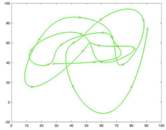
My learning in optimization and machine learning throughout the years.

- Course Projects:
  - **Convex Solver for Minimum Snap Trajectory Optimization:** Developed a **convex solver from scratch** using Newton's method with an infeasible start. The solver was applied to compute minimum snap trajectories for quadrotors using **differential flatness** (`convex_course_repo`).

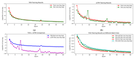
Algorithm 1 Infeasible Start Newton Method

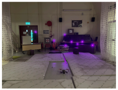
Given starting point $x \in dom f$, ν, tolerance $\epsilon > 0$, $\alpha \in (0, 1/2)$, $\beta \in (0, 1)$.
Repeat
  1. Compute primal and dual Newton steps $\Delta x_{\text{nt}}, \Delta \nu_{\text{nt}}$.
  2. Backtracking line search on $\|r\|_2$
    $t \leftarrow 1$
    while $\|r(x + t\Delta x_{\text{nt}}, \nu + t\Delta \nu_{\text{nt}})\|_2 > (1 - \alpha t)\|r(x, \nu)\|_2$
      $t := \beta t$
  3. Update, $x \leftarrow x + t\Delta x_{\text{nt}}, \nu \leftarrow \nu + t\Delta \nu_{\text{nt}}$

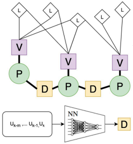
Until
  $Ax = b$ and $\|r(x, \nu)\|_2 \leq \epsilon$



  - **Learning Dynamic Factors for Optimization-based SLAM:** Proposed a vision-dynamic SLAM framework utilizing **factor graph optimization (FGO)**. The dynamic factor was learned from control input signals using a **Temporal Convolutional Network (TCN)**, and the SLAM algorithm was implemented **from scratch** with LED landmarks (`vd_slam_repo`).







$$\mathcal{X} = [\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_k, l_0, l_1, \ldots, l_i], \quad \textit{where} \ \ k \in [0, n], i \in [0, m], \tag{1}$$

$$\mathbf{x}_k = [\mathbf{p}, \mathbf{R}] \in \mathcal{M}, \tag{2}$$

$$\mathcal{M} = \mathbb{R}^3 \times \mathbb{SO}(3) = \mathbb{SE}(3), \tag{3}$$

$$l_i \in \mathbb{R}^3. \tag{4}$$

$$\mathcal{X} = \underset{\mathcal{X}}{\arg\min}\{r_{\mathcal{D}}(\mathcal{X}, \mathcal{D}, \mathbf{R}_d) + r_{\mathcal{V}}(\mathcal{X}, \mathcal{L}, \mathcal{Z}, \mathbf{R}_v)\}, \tag{5}$$

where

$$r_{\mathcal{D}}(\cdot) = \sum_{k=1}^{n} \|(\mathbf{x}_k \boxminus \mathbf{x}_{k-1}) \boxminus \mathbf{d}_{k-1}^k\|_{\mathbf{R}_d}^2 \tag{6}$$

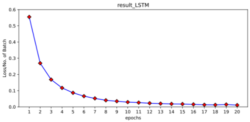
$$r_{\mathcal{V}}(\cdot) = \sum_{k=0}^{n} \sum_{i=0}^{m_k'} \|\mathbf{K}\mathbf{x}_k l_i - \mathbf{z}_i\|_{\mathbf{R}_p}^2, \tag{7}$$

$$\mathcal{D} = \{\mathbf{d}_{k-1}^k | k = 1, \ldots n\}, \quad \mathcal{L} = \{\mathbf{l}_i | i = 1, \ldots m\}, \quad \mathcal{Z} = \{\mathcal{Z}_k | k = 1, \ldots n\}, \quad \mathcal{Z}_k = \{\mathbf{z}_i | i = 1, \ldots m_k'\}, \quad \mathbf{R}_d \in \mathbb{R}^{3\times3}, \quad \mathbf{R}_v \in \mathbb{R}^{6\times6}, \quad \mathbf{K} \in \mathbb{R}^{3\times3}. \tag{8}$$

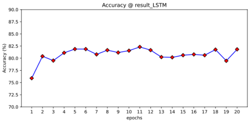
Optimization Design: Courses in Convex, Linear, Stochastic Optimization, & Machine Learning (cont'd)

- Course Projects (cont'd):
  - **Bi-Directional Long Short-Term Memory (Bi-LSTM) for Sentiment Analysis:** Designed and implemented a **Bi-LSTM** to classify sentences as positive or negative. The model was trained and tested on the SST-2 dataset ml_course_repo.

idx int32 0 – 67.3k	sentence string · *lengths* 2 – 268	label class label 2 classes
0	hide new secretions from the parental units	0 negative
1	contains no wit , only labored gags	0 negative
2	that loves its characters and communicates something rather beautiful about human nature	1 positive
3	remains utterly satisfied to remain the same throughout	0 negative
4	on the worst revenge-of-the-nerds clichés the filmmakers could dredge up	0 negative
5	that 's far too tragic to merit such superficial treatment	0 negative
6	demonstrates that the director of such hollywood blockbusters as patriot games can still turn out a small , personal film…	1 positive



(a) LSTM Loss v. Epochs



(b) LSTM Accuracy

Optimization Design: Courses in Convex, Linear, Stochastic Optimization, & Machine Learning (cont'd)

Summary:

- **Tools Used**: Python, PyTorch, Matlab.
- **Subject Learned**: Convex sets, convex functions, convex problems, duality, convergence analysis, linear programming, integer programming, stochastic programming, robust optimization, linear learning models, statistical estimation, neural networks, support vector machines, gradient descent algorithms (Momentum, Adagrad, Adam, Stochastic, Proximal), regularization, ensemble methods, and generalization theory, Markov process decision, Q-Learning, Deep Q-Network, twin-delayed deep deterministic (TD3), proximal policy optimization (PPO).

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Full Stack Development in Robotics: Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control

This section highlights my robotics full-stack development expertise, refined over the years and showcased through diverse projects.

- **UAV Navigation and Defect Detection**
  - Led a team in the **2023 IEEE ICUAS competition**, achieving **1st runner-up** among 39 teams.
  - Developed path planning, trajectory optimization, and a finite-state control module for vision-based UAV navigation and crack detection.
  - Links: `youtube_video`, `icuas_news`.
  - Tools: Python, PyTorch, C++, OSQP, ROS, Gazebo, PX4/Ardupilot SITL/Firmware.
  - Algorithms: YOLO, A*, minimum snap trajectories, IIR, and V-SLAM.

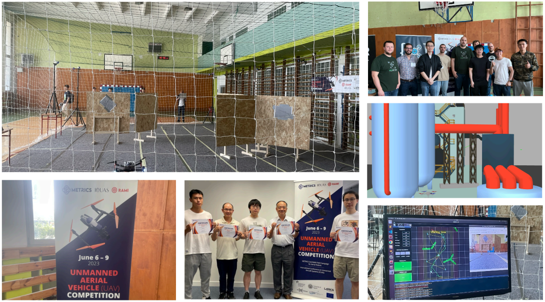

Figure 10: Photos from the 2023 IEEE ICUAS UAV Competition.

Full Stack Development in Robotics: Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control (cont'd)

- **Autonomous UGV with LiDAR Localization Module**
  - Implemented the LiDAR Odometry and Mapping (LOAM) algorithm to develop an autonomous UGV.
  - Designed the nonholonomic wheel-robot controller and compared the localization accuracy of LOAM with GPS/GNSS modules.
  - Links: `youtube_video`, `ugv_gazebo`.
  - Tools: Python, PyTorch, C++, ROS, Gazebo, GPS in PX4, AgileX UGV.
  - Algorithms: A*, PID, LOAM.

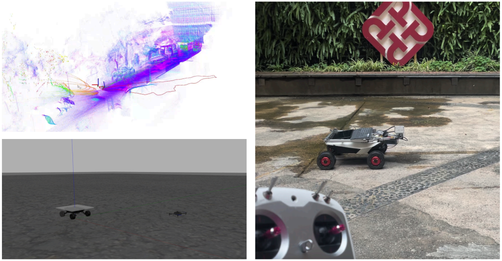

Figure 11: The designed autonomous UGV based on the AgileX platform.

Full Stack Development in Robotics: Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control (cont'd)

- **Dynamic Object Tracking/Following Quadrotor UAV Using Deep Learning**
  - Developed a quadrotor UAV capable of tracking and following dynamic objects.
  - Utilized V-SLAM developed by our lab and self-coded the perception, path planning, and control modules for the aerial robot.
  - Links: youtube_video, object_tracking_uav_repo.
  - Tools Used: C++, OSQP, ROS, Gazebo, PX4/Ardupilot SITL/Firmware.
  - Algorithms Used: YOLO, minimum snap trajectories, PID, EKF, and V-SLAM.

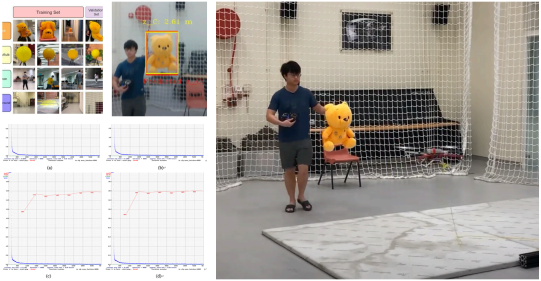

Figure 12: The object tracking UAV project was the Honour's project for my **undergraduate studies**. The above displays the final experiment.

For more details, feel free to click the icons below to visit my personal website or GitHub!
Thank you for your time!