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

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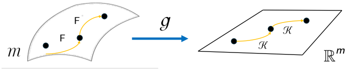
Adaptive Control for Underactuated Robots leveraging Koopman Operators and Reinforcement Learning for Dynamic Robustness

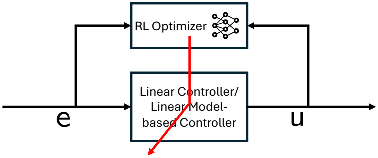
Sep 2024 - Present (ongoing)

Main motivations:

1. Data-driven methods offer an alternative for modeling systems with complex dynamics.
2. The Koopman operator maps nonlinear systems to a higher-dimensional observable space, enabling linear dynamics and control.
3. The effectiveness of data-driven approaches relies on the quality and range of the data.
4. Reinforcement learning will serve as an online optimizer to tune hyperparameters, addressing unmodeled dynamics and reducing sensitivity to external disturbances.



$$F: \; x_k \rightarrow x_{k+1}$$
$$g: \; x_k \rightarrow y_k$$
$$\mathcal{K}: \; y_k \rightarrow y_{k+1}$$
$$x_k \in \mathcal{m}, \; y_k \in \mathbb{R}^m$$



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Improving and Optimizing Adaptive Controllers via Disturbances Observers and Reinforcement Learning

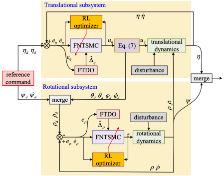
Sep 2023 - Aug 2024

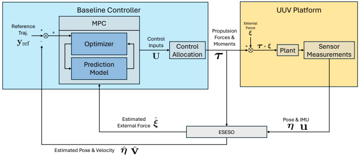
Main Motivations:

1. Conventional controllers offer robust performance but often lack disturbance rejection capabilities.
2. Tuning controller parameters is typically a complex, empirical process that may not guarantee optimal performance.

Methodology:

1. An Error-State Extended State Observer (ESESO) was proposed and developed, leveraging system and sensor dynamics to enhance model-based controller performance.
2. A Fixed-Time Disturbance Observer (FTDO) was utilized to improve nonlinear controllers, with parameter optimization achieved through Proximal Policy Optimization (PPO) neural networks.
3. The proposed adaptive framework was subsequently tested using Nonlinear Model Predictive Control (NMPC) and Sliding-Mode Control (SMC).

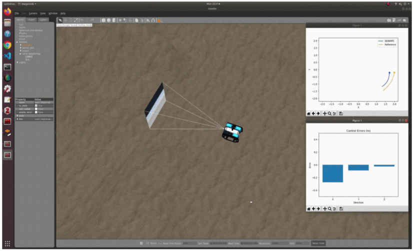


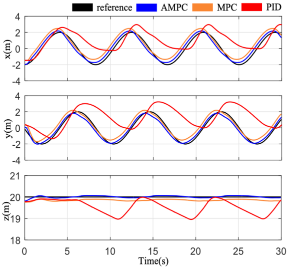


Improving and Optimizing Adaptive Controllers via Disturbances Observers and Reinforcement Learning (cont'd)

Implementations:

- An Adaptive Model Predictive Control for Unmanned Underwater Vehicles Subject to External Disturbances and Measurement Noise
  - The ESESO is applied to improve the prediction model of UUV MPC.
  - Validation was done through SITL simulation.

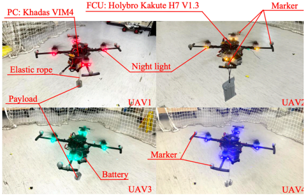


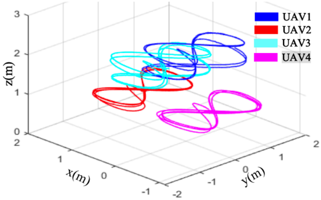


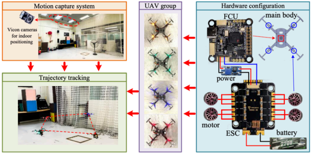
Improving and Optimizing Adaptive Controllers via Disturbances Observers and Reinforcement Learning (cont'd)

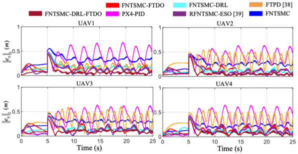
Implementations:

- Fixed-Time Adaptive Consensus Control for Multi-Quadrotor Subject to External Disturbances Via Deep Reinforcement Learning
  - The SMC + FTDO + RL control strategy was applied for UAV-swarm.
  - Validation was done through both simulation and physical experiments.









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Non-Robocentric Dynamic Landing for Quadrotor UAVs

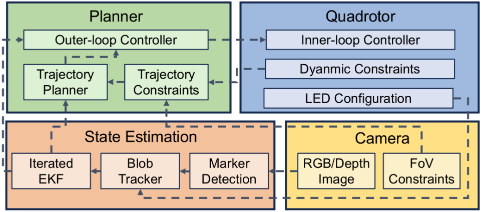
Sep 2022 - Aug 2023

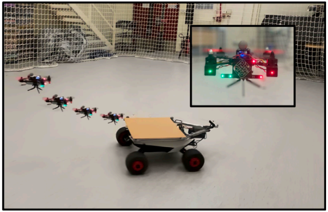
Main motivations:

1. In some applications, UAVs does not neccessitate onboard exteroceptive sensors such as cameras and LiDARs.
2. This poses an interesting research problem for UAV performing dynamic landing.

Methodology:

1. Adopted and refined an Iterated Extended Kalman filter (IEKF) for relative state estimation in an offboard fashion. The IEKF can be seen as a single time-step factor graph optimization (FGO) on SE(3) manifold.
2. Formulated a constrained convex optimization problem to design the landing trajectory with Bezier curves. A feedforward PID controller in non-inertial frame was also designed.

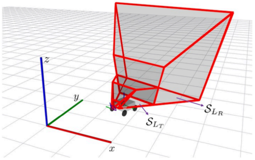


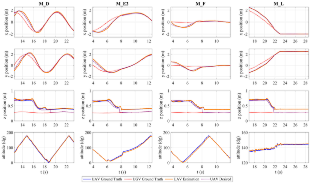


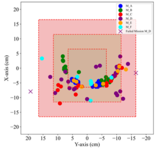
Non-Robocentric Dynamic Landing for Quadrotor UAVs (cont'd)

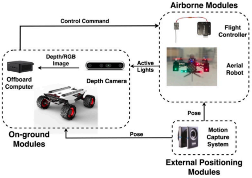
Implementation:

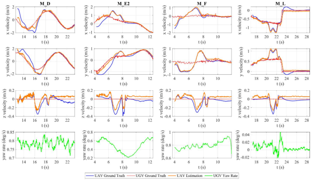
1. Conducted physical experiments with a UAV-UGV heterogeneous system.
2. The dynamic landing performance is comparable with conventional landing configuration.

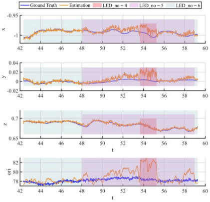












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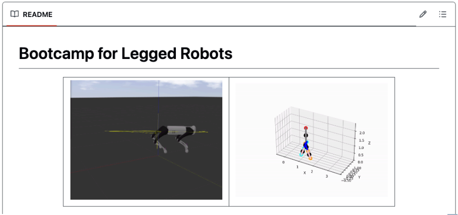
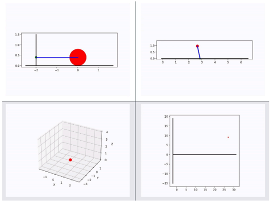
Numerical Modelling & Simulation: A Bootcamp for Legged Robotics via Biped and Quadruped Simulation

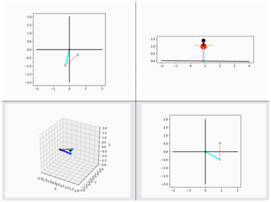
Description:

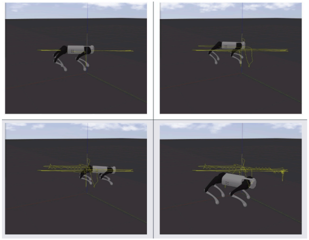
1. This self-initiated project aimed to strengthen my understanding of numerical modeling and simulation, focusing on the complexities of legged robot dynamics.
2. Project Contents:
   - **Biped:** Developed a Python simulation environment and implemented a feedback linearization controller using Dormand-Prince (RKDP) for hybrid systems. Visualizations were generated with `matplotlib`.
   - **Quadruped:** Created a force controller for dynamic gaits of quadrupeds within a ROS/Gazebo simulation environment. All gait controllers were implemented in C++.
3. 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.
4. Links: `bootcamp_repo`.

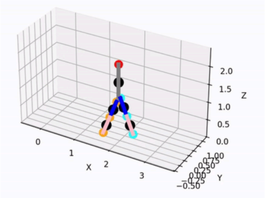


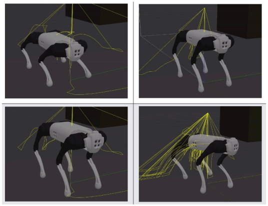
Snapshots from above:











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

Description:

1. Through the Hong Kong Cross-Institutional Course Enrolment Scheme (info), I pursued advanced courses to deepen my understanding of optimization concepts and techniques.
2. 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.
   - **Learning Dynamic Factors for Optimization-based SLAM:** Proposed a vision-dynamic SLAM framework utilizing factor graph optimization. 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.
   - **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.
3. Tools Used:
   - **Software:** Python, PyTorch, Matlab.
   - **Mathematical Concepts:** Convex sets, convex functions, convex optimization, 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.
4. Links: `convex_course_repo`, `vd_slam_repo`, `ml_course_repo`.

Optimization Design: Courses in Convex, Linear, Stochastic Optimization, & Machine Learning

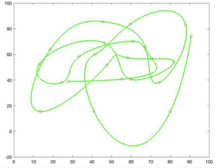
Snapshots from above:

- Convex Solver for Minimum Snap Trajectory Optimization

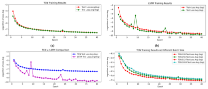
Algorithm 1 Infeasible Start Newton Method

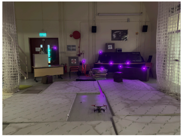
Given starting point $x \in \mathbf{dom} f$, ν, tolerance $\epsilon > 0$, $\alpha \in (0, 1/2)$, $\beta \in (0, 1)$.
Repeat
  1. Compute primal and dual Newton steps $\Delta x_{\mathrm{nt}}, \Delta \nu_{\mathrm{nt}}$.
  2. Backtracking line search on $\|r\|_2$
    $t \leftarrow 1$
    while $\|r(x +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

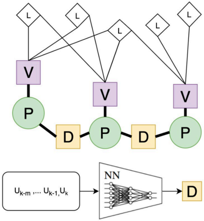
Until
  $Ax = b$ and $\|r(x, \nu)\|_2 \le \epsilon$



- Learning Dynamic Factor for Optimization-based SLAM







$$
\begin{aligned}
\mathcal{X} &= [\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_k, l_0, l_1, \ldots, l_i], \\
&\quad \textit{where } \; k \in [0, n], i \in [0, m], && (1) \\
\mathbf{x}_k &= [\mathbf{p}, \mathbf{R}] \in \mathcal{M}, && (2) \\
\mathcal{M} &= \mathbb{R}^3 \times \mathbb{SO}(3) = \mathbb{SE}(3), && (3) \\
l_i &\in \mathbb{R}^3. && (4)
\end{aligned}
$$

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

where

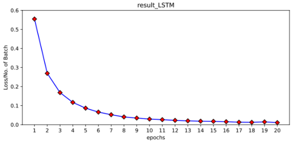
$$
\begin{aligned}
r_{\mathcal{D}}(\cdot) &= \sum_{k=1}^{n} \| (\mathbf{x}_k \boxminus \mathbf{x}_{k-1}) \boxminus \mathbf{d}_{k-1}^{k} \|_{\mathbf{R}_d}^2 && (6) \\
r_{\mathcal{V}}(\cdot) &= \sum_{k=0}^{n} \sum_{i=0}^{m'_k} \| \mathbf{K} \mathbf{x}_k l_i - \mathbf{z}_i \|_{\mathbf{R}_p}^2, && (7) \\
\mathcal{D} &= \{ \mathbf{d}_{k-1}^{k} | k = 1, \ldots n \}, \\
\mathcal{L} &= \{ \mathbf{l}_i | i = 1, \ldots m \}, \\
\mathcal{Z} &= \{ \mathcal{Z}_k | k = 1, \ldots n \}, \\
\mathcal{Z}_k &= \{ \mathbf{z}_i | i = 1, \ldots m'_k \}, \\
\mathbf{R}_d &\in \mathbb{R}^{3 \times 3}, \\
\mathbf{R}_v &\in \mathbb{R}^{6 \times 6}, \\
\mathbf{K} &\in \mathbb{R}^{3 \times 3}. && (8)
\end{aligned}
$$

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

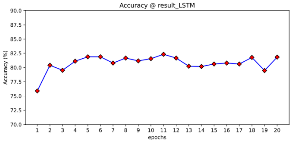
Snapshots from above (continued):

- Long Short-Term Memory (LSTM) for Natural Language Processing (NLP)

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

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

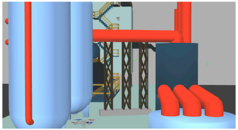
Description

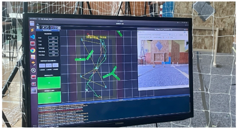
1. Throughout the years, I have participated in multiple projects, showcasing my expertise in full-stack development for autonomous systems, covering localization, perception, planning, and control modules.
2. Projects:
   - **UAV Navigation and Defect Detection in GPS-Denied Environments:** Led a team of four during my master's program to compete in the 2023 IEEE ICUAS UAV competition. Our mission involved vision-based UAV navigation and crack detection. I developed the path planning, trajectory optimization, and finite-state machine for the control module, contributing to our team's first runner-up finish among 39 teams.
   - **Autonomous UGV with LiDAR Localization Module:** During my master's program, I implemented the LiDAR Odometry and Mapping (LOAM) algorithm to develop an autonomous UGV. I designed the nonholonomic wheel-robot controller and compared the localization accuracy of LOAM with GPS/GNSS modules.
   - **Dynamic Object Tracking/Following Quadrotor UAV Using Deep Learning:** In my undergraduate honors project, I developed a quadrotor capable of tracking and following dynamic objects. I utilized V-SLAM developed by our lab and self-coded the perception, path planning, and control modules for the aerial robot.
3. Tools Used:
   - **Software/Hardware:** Python, PyTorch, C++, OSQP, ROS, Gazebo, PX4/Ardupilot SITL/Firmware, GPS in PX4, and AgileX UGV.
   - **Algorithms:** YOLO, A*, minimum snap trajectories, PID, LOAM, EKF, and V-SLAM.
4. Links: icuas_news, ugv_gazebo, object_tracking_uav_repo.

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

Snapshots from above:

- UAV Navigation and Defect Detection in GPS-Denied Environments (IEEE ICUAS Competition)

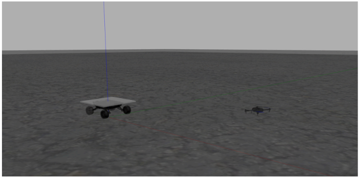




Full Stack Development in Robotics: Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control (cont'd)

Snapshots from above (continued):

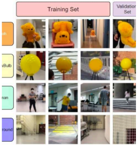
- Autonomous UGV with LiDARs Localization Module

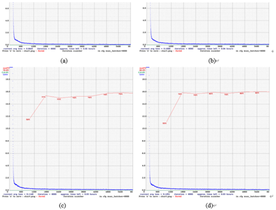


Full Stack Development in Robotics: Projects in Estimation, Perception, Path Planning, Trajectory Optimization & Control (cont'd)

Snapshots from above (continued):

- Dynamic Object Tracking/Following Quadrotor UAV Exploiting Deep Learning





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