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Optimization of Nonlinear PID Controller for Nonlinear Robotic systems

Summary

When a control input is required to generate a fast response, conventional linear PID controllers suffer from undesirable large oscillations and large overshoots (Seraji, 1998; So, 2019). Many authors have solved this problem with different versions of nonlinear PID controllers, which instead use variable gains, using a nonlinear function, usually in terms of the system error.

The vision of this project is to develop a novel system solution for nonlinear control systems, with the focus on optimising nonlinear PID controller for nonlinear robotic applications. The project is industry driven, well timed and represents a step-change in robotics and control technology. The results will be validated in both simulation and hardware implementation.

Aims and Objectives

The project will develop a new optimization algorithm to tune nonlinear PID controllers to optimize the performance and stability of nonlinear systems response with focus on robotic applications. This aim will be fulfilled by achieving the following objectives:

(O1) Analysis of exiting tuning algorithms for nonlinear PID.

(O2) Modelling a general class of nonlinear robotic systems.

(O3) Determine the performance criteria required for the feedback control system.

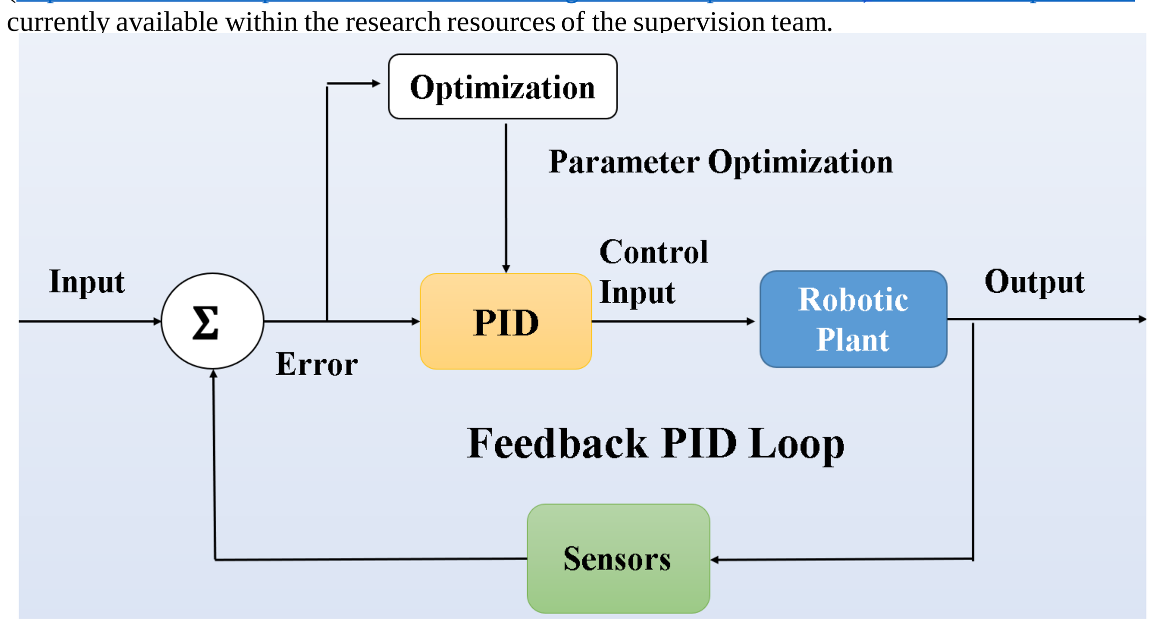
(O4) Synthesis a nonlinear PID controller.

(O5) Propose an optimization algorithm to tune the controller parameters, using real-time sensor inputs.

(O6) Validate the controller performance in simulation to determine the stability and performance of the feedback loop.

(O7) Finalise the tuning algorithm based on the simulation results. **(O8)** Validate the results in real environment with hardware implementation.

The proposed algorithm will be tested on a small inspection robot (https://www.robotshop.com/uk/rosbot-20-lidar-rgbd-robotic-platform.html). This robotic platform is currently available within the research resources of the supervision team.



Literature

The Linear **PID controller** specifies values of the proportional, integral, and derivative gains, as constants that once they have been tuned to optimize the controller for a specific type of problem, they are left almost unchanged.

$$u_{conv} = K_p e + K_I \int e + K_D \dot{e}$$

In addition, when a control input is required to generate a fast response, conventional linear PID controllers suffer from large oscillations and large overshoots, which are undesirable (Seraji, 1998; So, 2019). To solve this problem, many authors have suggested different versions of **Nonlinear PID controllers**, which instead use variable gains, using a nonlinear function and usually are in terms of the system error.

Controller	Advantages	Disadvantages
2-DoF PID	1) Simple, but more complex than conventional PID. (Suthar, 2015) 2) Handles both set point response and disturbance response simultaneously. (Suthar, 2015) 3) Handles better nonlinearities, compared to the conventional PID. (Suthar, 2015)	1) Has more variables to tune than conventional PID, Increasing computational complexity, compared to conventional PID (Mohan et al., 2019a). 2) Disturbances and noise decrease performance (Mohan et al., 2019a).
FO-PID	1) More Robust for most applications (Shah and Agashe, 2016). 2) Limited order of integration and differentiation (Shah and Agashe, 2016). 3) Derivative + Integral order offer control flexibility (Cao and Cao, 2006).	1) Stability is potentially lost for orders higher than 2 (Shah and Agashe, 2016). 2) Increased computational complexity due to higher number of design variables (Cao and Cao, 2006; Shah and Agashe, 2016).
Fuzzy-PID	1) Can perform well with complex plants, even if the model is not known. (Arun and Mohan, 2016) 2) Various non-linear methods can be used to analyse and design a fuzzy PID controller to minimize trial and error. (Arun and Mohan, 2016) 3) It can be easily implemented on many digital platforms. (Arun and Mohan, 2016) 4) It guarantees stability, and as a result it reassures of safety critical projects. (Arun and Mohan, 2016)	1) Requires a lot of trial and error to choose the required fuzzy sets. This means experienced human is needed for the trial and error. (Arun and Mohan, 2016) 2) Precise understanding and analysis of the controller is not possible. (Arun and Mohan, 2016)
2-DoF FO-Fuzzy-PID	1) Efficiently handles multiple issues (Mohan et al., 2019a). 2) Additional degrees of freedom (Mohan et al., 2019a). 3) Incorporates Fuzzy logic (Mohan et al., 2019a). 4) Fractional Order flexibility (Mohan et al., 2019a).	1) Longer computational time to tune (Mohan et al., 2019a). 2) More design variables. 3) Sampling time affects optimization time (Mohan et al., 2019a). 4) Increased computational complexity (Mohan et al., 2019a).

Optimization problems concern the **minimization/maximization** of a dynamical problem, according to an objective (cost) function that evaluates the problem at hand. The objective function comprises of the control variables that can be changed, that the optimal solution depends on. As a result, a common optimization problem is formulated as:

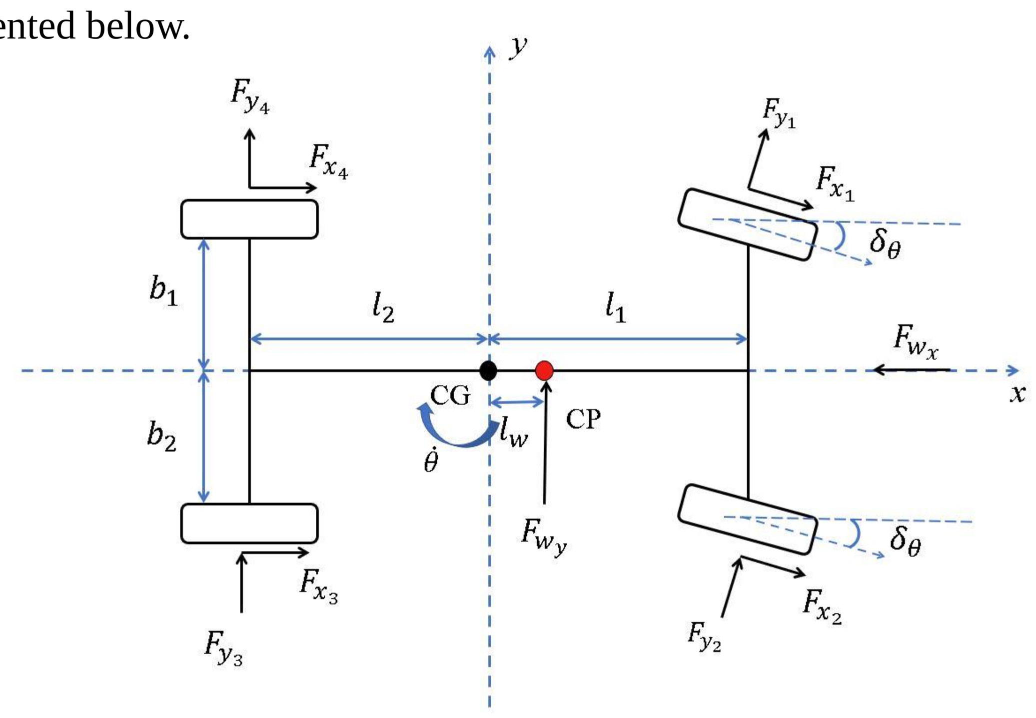
$$\textit{minimize}\ f(\boldsymbol{x}),$$
$$\textit{subject to:}\quad g_i(\boldsymbol{x}) = 0, c_i(\boldsymbol{x}) \le 0, lb \le \boldsymbol{x} \le ub$$

In mathematical optimization theory, every problem is a minimization problem, maximization problems are simply considered as minimization problems of the **negative** of the objective function.

Optimization Scheme	Advantages	Disadvantages
PSO (Cheng et al., 2018)	1) Simple 2) Fast convergence to optima 3) Can solve MOO/SOO 4) No derivatives needed 5) Achieves Global Optimality	1) Exploration versus exploitation 2) Parameter setting and fair/unfair comparison to other optimization algorithms. 3) Population diversity
GA (Vijayakumar and Manigandan, 2016)	1) Global optima 2) Reliable 3) Accurate	1) Complex 2) High Computing costs 3) Repeating the algorithm provides different solutions.
ACO (Bell and McMullen, 2004; Vijayakumar and Manigandan, 2016)	1) Good for combinatorial optimization. 2) Accurate for small problems. 3) It is a great candidate for hybridization.	1) Not good for highly complex/highly dimensional problems. 2) works best for combinatorial type of optimization problems.
Surrogate (Vu et al., 2017; Wang et al., 2020)	1) Fast 2) High performance 3) Efficient 4) Accurate 5) Great for hybridization to solve higher dimensional complexity with other algorithms.	1) Not appropriate for high dimensional problems > 10. 2) Advanced use of statistical learning. 3) A plethora of different regression models.
DE (Das, Mullick and Suganthan, 2016)	1) Flexible 2) Versatile 3) Robust 4) Applicable to a wide variety and difficult optimization problems.	1) Underperforms in high dimensional problems.
PRO (Samareh Moosavi and Bardsiri, 2019; Fayek, 2021)	1) Robust 2) Outperformed most state-of-the-art methods. 3) lowest number of iterations to reach solution. 4) finds global optima.	1) New method and has not been tested in many fields of research. 2) Many modifications, adds complexity to the algorithm selection process. 3)

Application to Self-Driving Cars

Self-driving cars are a great example of highly nonlinear dynamical systems with highly coupled dynamics that causes them to be so complex to apply control systems to and requires highly sophisticated methods. The method proposed in this project will be tested in a simulation of a self-driving car, with the nonlinear dynamical model presented below.



$$m(\dot{V}_x - \dot{\theta}V_y) = F_{x_1}\cos\delta_\theta + F_{y_1}\sin\delta_\theta + F_{x_2}\cos\delta_\theta + F_{y_2}\sin\delta_\theta + F_{x_3} + F_{x_4} + F_{w_x}$$

$$m(\dot{V}_y + \dot{\theta}V_x) = F_{x_1}\sin\delta_\theta + F_{y_1}\cos\delta_\theta + F_{x_2}\sin\delta_\theta + F_{y_2}\cos\delta_\theta + F_{y_3} + F_{y_4} + F_{w_y}$$

$$I_z\ddot{\theta} = [F_{x_1}\cos\delta_\theta + F_{x_4} + F_{y_1}\sin\delta_\theta]b_1 - [F_{x_2}\cos\delta_\theta + F_{x_3} + F_{y_2}\sin\delta_\theta]b_2 + [F_{x_1}\sin\delta_\theta - F_{y_1}\cos\delta_\theta - F_{x_2}\sin\delta_\theta - F_{y_2}\cos\delta_\theta]l_1 + [F_{y_3} + F_{y_4}]l_2 - F_{w_y}l_w$$

Self driving cars are an active area of research, with advancements needed in control systems and methods of controlling its speed and steering angle. Autonomous vehicles are described with a complicated set of non-linear highly couples systems of non-linear differential equations and a lot of research has been conducted on the design of a suitable control system that will provide smooth and accurate steering control of the vehicle, which is important for road safety. In research literature one method of simplifying the dynamical model is by assuming constant longitudinal velocity and decoupling the longitudinal dynamics from the lateral and yaw dynamics. Active disturbance rejection control (ADRC) was successfully used for the steering control of a self driving car, and it was found to be exponentially stable control, using Lyapunov exponents analysis (Chu *et al.*, 2018). It was also shown that ADRC successfully kept the test vehicle in the lane within a 0.1 m of lateral offset error (Chu *et al.*, 2018). It was also shown that ADRC performed better than a conventional PID controller, with a maximum lateral offsets of 0.03 m and 0.16 m during straight and curved lane keeping manoeuvers, respectively (Chu *et al.*, 2018).

From the literature studied in a review paper of self-driving cars, it has been observed that there isn't much research conducted in steering of autonomous vehicles, using non-linear or 2-DoF PID controllers tuned with optimization schemes. From the review paper traditional PID controllers that do not implement tuning (optimization), are unable to adapt to external disturbances and become computationally expensive (Rasib *et al.*, 2021). PID-based control methods have been extensively used, with one application in Pulse Width Modulation that improved the control and reduced the overshooting of steering control in dynamic roads (Rasib *et al.*, 2021).

In another research conducted on self-driving vehicles of 4 wheel independent steering and 4 wheel independent drive, (4WIS, and 4WID), PID and sliding mode control (SMC) was implemented for the steering and longitudinal speed control of the vehicle. With highly complicated and coupled non-linear dynamics SMC controller managed to successfully control yaw rate and longitudinal velocity on the 4WID and 4WIS, improving results compared to conventional methods (Li, Du and Li, 2016). These control methods work for road vehicle velocity capacities, since the higher the velocity the higher the oscillations in the controller outputs, while using SMC and PID together, which still yielded improved results than conventional methods (Li, Du and Li, 2016).

Methodology

The project will build its progress on two parallel aspects (analytically and experimentally):

1. The results will be derived mathematically to make sure they are conclusive and rigours.
2. This will be done using advanced nonlinear dynamic mathematical tools.
3. Results will be demonstrated on both simulation, using **MATLAB** and **Simulink**, and hardware implementation to prove the concept and show the applicability.
4. The controller and the algorithm will be tested under different potential disruptions that might be faced in a real-world situation.

Importance/Impact

Robotics and autonomous systems (RAS) have been identified as one of the main Eight Great Technologies within the UK that the government would like to support and fund. Drawing on analysis by McKiney, the recent UK governmental strategy on Robotics and Autonomous Systems (RAS 2020 Strategy) estimated that RAS technologies would have an impact on global market between $1.9 and 6.4 trillion per annum.

This project is aligned with these facts and the outcome of the proposed research will have a strong positive impact on many robotics related industries including:

- manufacturing,
- self-driving cars,
- space rovers and satellites, as well as
- medical surgery assistance robots.

Images taken by: NASA, Possessed Photography, and SpaceX with FREE LICENSE BY UNSPLASH

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